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DEVELOPMENT OF PODZOL SOILS IN EAST AUSTRALIAN COASTAL SAND BARRIERS

by

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In Memory of Lois

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STATEMENT OF ORIGINALITY

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G.M. Bowman

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G.M. BOWMAN.

August, 1979.

INTRODUCTION

Soils are often used by geomorphologists to determine the relative ages of groundsurfaces or sedimentary deposits and to obtain information on palaeoenvironmental conditions. In addition, pedologists are also concerned with the effect of different pedogenic conditions on soil development; for both the geomorphologist and the pedologist *time* is usually the most significant aspect of such soil studies. The former uses soil development as an ordinal measure of time, while the latter uses time as a dimension within which all the other pedogenic factors may vary. The central theme of this thesis is the problem of pedogenesis in relation to time, from both the geomorphic and pedogenic points of view.

More specifically, the problem investigated herein is the role of time in the development of certain podzol soils in eastern Australia. These podzols are extensively developed in the freely drained, sandy, siliceous deposits that have accumulated during the Holocene, along the embayed eastern coastline from Tasmania to North Queensland. Comminuted marine shells deposited within these sediments have been radiocarbon dated to obtain maximum absolute ages (in ^{14}C years) for selected podzol soil profiles from a range of pedogenic environments. Data pertaining to the pedogenic environment of each profile are presented, and within this time-factorial framework, variations in certain physical and chemical characteristics of the podzol soils are examined. The thesis relates these variations to the interaction of the pedogenic factors and assesses the role of time as a factor in the development of the podzol soils.

Rates of podzolization under specified pedogenic conditions are determined and the implications of these rates for geomorphic research are considered.

The specific objectives of the study may be stated as follows:

1. To assess the extent to which the development of the podzol soils is a function of time.
2. To illustrate the effect on the soils of the non-temporal pedogenic factors.
3. To determine rates of podzolization.

The thesis has been divided into six chapters: the first chapter is devoted to an examination of the literature dealing with soil development in relation to time; the second chapter presents the theoretical base and the research design for the study; Chapter Three examines the pedogenic environments of the soil profiles under investigation; in the fourth chapter the soil data obtained during the study are presented and discussed, while the fifth chapter analyses these data in relation to the non-temporal pedogenic factors. Finally, Chapter 6 relates the soil characteristics to the time factor, compares the observed trends with those reported in the literature, and discusses the implications of the study for geomorphic research.

Appendices have been included at the end of the thesis giving information and data on radiocarbon dating, soil profile morphologies, soil organic matter, acid-extractable soil cation content and marine aerosol fallout. In addition, the appendices present scanning electron micrographs of sand grain surface textural features, sand grain organo-mineral coatings, and marine aerosol particles.

CHAPTER I

LITERATURE REVIEW

1.1 INTRODUCTION

The purpose of this review is to place the study in the context of the pedological literature. Accordingly, the first section follows the development of the most significant conceptual studies that have been made in relation to time and pedogenesis, and the second section examines (more critically) selected empirical studies of soil development in relation to time. At the end of the first section the selection of a factorial model for use in the thesis is justified, while at the end of the review of empirical studies their main short-comings are assessed.

1.2 DEVELOPMENT OF CONCEPTS

1.2.1 Introduction

Crocker (1952) and Huggett (1976) have both recognized two general concurrent trends in the literature on soil genesis. One trend, termed the "systems approach" by Huggett (p.261), is concerned with the actual processes which convert unaltered parent material into soil. The other, which Huggett calls the "functional factorial approach" (p.261), examines the soil, its properties and its development in relation to independent variables known as "soil-forming factors" (Jenny, 1941). As the latter approach to soil genesis has been adopted in the thesis, the literature review will be confined essentially to those conceptual pedological publications which either contribute to, or are critical of, the "functional factorial approach". Further, because the thesis is chiefly concerned with the *time* factor, the review will be restricted to theoretical contributions in which time in pedogenesis is dealt with specifically.

1.2.2 Early Contributions

The concept of time as a factor in soil development may be traced back to the pedological studies of Vasilii Dokuchaev wherein the "age of the country" (time) was recognized as one of five factors which are significant in the formation of soils (Dokuchaev, 1883, 1886). Local climate, parent material, plant and animal organisms, and relief were the other factors Dokuchaev identified. However, especially in his later writings, Dokuchaev (1899) tended to emphasize the climatic factor in soil development and it is this aspect of his work which led to the "zonal" concept in pedology which preoccupied his followers, especially in Russia, for many years after his death (Mikhailooskaia, 1939).

The publication of the book Factors of Soil Formation by Hans Jenny in 1941 reintroduced into the pedological literature Dokuchaev's pedogenic concept, but in a revised and more precise form. Jenny (1941) defined the soil as an open physical system with certain properties by which it can be characterized. He regrouped the pedogenic factors of Dokuchaev (1883, 1886) and Hilgard (1914) and redefined them so that each could be considered an independent variable capable of quantitative expression. Jenny then related any (or all) soil properties (s) to his redefined pedogenic factors in the form of a "fundamental equation" (Jenny, 1941, p.16):

$$s = f\ (cl, o, r, p, t, \ldots) \tag{1}$$

where cl = atmospheric climate, o = organisms, r = topography (relief), p = parent material and t = period of soil formation (time). The dots indicated that more factors could be introduced if required.

From his fundamental equation Jenny developed the hypothesis that by keeping all factors but one constant, and following changes in soil properties in relation to this single independent variable, it should be possible to isolate the role of each soil-forming factor. These relationships Jenny (1941) expressed in the following equations:

$$s = f\ (\text{climate})\ o, r, p, t, \ldots \tag{2}$$

$$s = f\ (\text{organisms})\ cl, r, p, t, \ldots \tag{3}$$

$$s = f\ (\text{topography})\ cl, o, p, t, \ldots \tag{4}$$

$$s = f\ (\text{parent material})\ cl, o, r, t, \ldots \tag{5}$$

$$s = f\ (\text{time})\ cl, o, r, p, \ldots \tag{6}$$

where the symbols have the same meaning as previously and represent the factors held constant. In a later paper these relationships were termed *climofunctions*, *biofunctions*, *topofunctions*, *lithofunctions* and *chronofunctions* respectively and were collectively referred to as the "five canonical functions of pedology" (Jenny, 1946, p.375). Jenny stated that, except in the laboratory, precise evaluation of these functions was not possible, but that useful approximations to single factor functions within a given field area could be obtained when the amount of change of a soil property conditioned by one factor, greatly exceeds the change conditioned by all other factors. He thought that this situation could occur where either one factor varies greatly and all others display comparatively little variation, or where some factors vary appreciably, but have little significance in determining changes in soil properties. Instead, the soil properties reflect comparatively small variations in a single determining factor. By defining soil as an assemblage of soil properties and equating variations in these assemblages with soil types and soil series, Jenny was able to apply his factorial model to the development of certain Californian soils. His method was to arrange the selected soil series in sequences which corresponded with his five pedological functions. The sequences were therefore termed: *chrono-*, *litho-*,*topo-*, *climo-* and *bio- sequences* (*ibid* ., p.377).

Jenny's 1941 and 1946 publications have had a profound effect on the development of pedological theory and on the design of empirical research studies since World War II. However, they have also been the cause of considerable debate, not the least of which has been concerned with Jenny's treatment of the time factor. For example, Nikiforoff (1942), Gerasimov (1947), Stephens (1947, 1951) and Robinson (1949) argued that in reality some, if not most, of the pedogenic factors have both dependent and independent aspects and hence Jenny's concept was too simplistic to cope with the complexities of pedogenesis. They also maintained that Jenny's inclusion of the time factor with the other factors was inappropriate. As Robinson (*ibid*., p.101) noted: "time itself cannot have any effect but intervenes as governing the amount or extent of operation of other factors". Stephens believed that this problem could be avoided by equating soil as an integral of the pedogenic factors against time, and hence suggested the equation:

$$S = \int f(C, O, R, W, P)\, dT \qquad (7)$$

where T (time) is independent and C (climate), O (organisms), R (relief), W (watertable), and P (parent material) can have both dependent and independent status (Stephens, 1947, p.171).

Crocker (1952), in an extensive review of Jenny's work, dealt in particular with the plant factor in pedogenesis. He did, however, also include comment on some of the criticisms that had been raised about the concept of pedogenic factors. Crocker acknowledged that Jenny's treatment of the time factor was unsatisfactory, especially in the way it implied that time could be held constant. However, he considered Stephens' equation had little scientific value as "...solution of it would be quite impracticable in view of the number of coexistent variables, and it does not permit a breakdown into simpler functions " (Crocker, 1952, p.145). Crocker also claimed Stephens had misused Jenny's (1941) concept of soil-forming factors by applying them outside their defined limitations as independent variables. Crocker also maintained that an alternative composite soil equation proposed by Stephens (1947, p.179) overemphasized the complexity of the situation. Crocker considered that a better approach would be to substitute for Jenny's fundamental equation (Equation 1) the two following equations:

$$s = f\ (cl,\ o,\ r,\ p,\ \ldots) \tag{8}$$

and

$$s = f\ (t) \tag{9}$$

where cl = climate, o = organisms, r = relief, p = parent material, ... = additional factors and t = time (Crocker, 1952). He stated that "the substitution of the two equations recognizes the especial role of the time factor, and that cl, o, r and p are functions of time ... at the same time the equations are explicit and susceptible of operation in providing functions in terms of the individual soil-forming factors" (*ibid*.,p. 145). By combining his two basic equations Crocker derived five *canonical functions*:

$$S_t = f(cl)\quad o,\ r,\ p,\ldots \tag{10}$$

$$S_t = f(o)\quad cl,\ r,\ p,\ldots \tag{11}$$

$$S_t = f(r)\quad o,\ p,\ cl,\ldots \tag{12}$$

$$S_t = f(p)\quad o,\ r,\ cl,\ldots \tag{13}$$

$$S_o,\ r,\ p,\ cl,\ldots = f(t) \tag{14}$$

Crocker claimed that the first four of these equations indicate that measurements of soil properties (S_t) are to be made simultaneously on soils of the same age and that this is precisely what Jenny had done in practice. Hence he saw no disparity between his set of functional equations and those proposed by Jenny (1941). His paper was therefore essentially a defence of Jenny's basic concepts.

In 1958 Jenny extended his work in theoretical pedology by publishing a paper on the role of the plant factor in the pedogenic function which was very much an extension of, and response to, the work of Major (1951) and Crocker (1952) on that factor. Jenny again employed his fundamental equation, but in this case he viewed the soil in more of an ecosystem context. As far as the time factor was concerned, the paper added little to Jenny's previous models, but was significant in that it reflected the trend towards a systems analysis approach which was at the time developing in pedology, in common with most other natural sciences (Huggett, 1976).

A pedological model which attracted considerable attention was proposed by Butler (1959) and involved the concept of soil cycles, or periodicity in soil development. Butler claimed his model was supported by the widespread occurrence of buried soils throughout the world. His soil cycle comprised a phase of instability, during which older soil surfaces are destroyed or buried, followed by a phase of stability, when soil development proceeds on the new surfaces. As time units these soil cycles (which Butler called K cycles) may be seriated to form a chronological system which, with the aid of radiocarbon dating, can be useful in pedogenic factorial studies. However, if based on paleosols it does possess inherent limitations: paleosols degrade over time (Gerasimov, 1971; Yaalon, 1975); the period of formation of a paleosol may be difficult to ascertain (see later discussion in Chapter 2), and Butler's association of K cycles with significant climatic changes and hence paleopedological conditions can be hard to substantiate for a given paleosol, which may in fact have been influenced by a variety of climates over the period of its formation. Consequently, Butler's K cycle model has found its main application in the stratigraphic correlation of geomorphic groundsurfaces using palaesol indicators (e.g., Butler, 1958, 1967; van Dijk, 1959; Churchward, 1961; Beattie, 1972; Walker and Green, 1976; Walker and Coventry, 1976) and in more localized studies of soil development sequences in alluvial floodplain and terrace deposits (e.g., Walker, 1962 a, b, 1970; Brewer and Walker, 1969).

1.2.3 The 'State Factor' Model

The influence of systems analysis and ecosystem concepts was very pronounced in Jenny's next theoretical contribution (Jenny, 1961). Here he examined the role of the soil-forming factors in a soil formation system, one he considered to be a typical open system. The soil-forming factors he had identified in his earlier papers he now combined into three "state factors of the soil system" which he thought could "define the state of the ecosystem or soil system" (*ibid.*, p.387).

These *state factors* were:

1. The initial state of the system or its assemblage of properties at time zero when pedogenesis starts *(Lo)*. This state factor combined the original parent material and relief pedogenic factors.

2. The external potentials of the energy fluxes that drive the system *(Px)*. In other words, the external elements outside the initial soil body which control the supply and loss of energy to and from the soil system. The original environmental factors, climate and organisms (flora and fauna), were equivalent.

3. The time, or the age of the system *(t)*, which is the period during which energy and matter have flowed.

Thus ecosystem properties (l), soil properties (s), vegetation properties (v), and animal properties (a) were related to *Lo*, *Px* and *t* in the *state factor equation* (*ibid*.):

$$l, s, v, a = f(Lo, Px, t) \qquad (15)$$

An *extended state factor equation* was derived by subdividing the state factors *Lo* and *Px* into their component parts. Thus:

$$l, s, v, a = f(cl, o, r, p, t, \ldots) \qquad (16)$$

where cl, o, r, p, t, ... represent the same factors as in Equation 1. Equation 16 was also applied to soil properties alone, in the form:

$$s = f(cl, o, r, p, t, \ldots) \qquad (17)$$

which although identical in form to his fundamental soil forming equation (Jenny, 1941), differs in that each soil property can be related individually to the state factors and thus the relationship is capable of statistical analysis and consequently numerical expression (*idem*).

In his 1961 paper Jenny also stressed that the relationship between any state factor and a given soil property was important for field work. Where the contribution of a state factor to the variation in a soil property becomes negligibly small, because either the range of the state factor is narrow (constancy of the factor in the area) or its effectiveness is slight, the factor need not be kept constant when examining other pedogenic relationships. Jenny further claimed that it was possible to find situations where the contribution of one state factor to an assemblage of soil properties outranks the combined contributions of all the other factors. Such cases of a dominant factor provide pedogenic sequences and functions. Jenny changed the usual notation of these equations so as to emphasize the constancy of a factor as well as its ineffectiveness, depending on the function in which it is included. Thus, for soil properties, the equations Jenny evolved were:

$$s = f\ (\mathit{cl},\ o,\ r,\ p,\ t, \ldots) \tag{18}$$

$$s = f\ (\mathit{o},\ cl,\ r,\ p,\ t, \ldots) \tag{19}$$

$$s = f\ (\mathit{r},\ cl,\ o,\ p,\ t, \ldots) \tag{20}$$

$$s = f\ (\mathit{p},\ cl,\ o,\ r,\ t, \ldots) \tag{21}$$

$$s = f\ (\mathit{t},\ cl,\ o,\ r,\ p, \ldots) \tag{22}$$

$$s = f\ (\ldots,\ cl,\ o,\ r,\ p,\ t) \tag{23}$$

The significance of this paper (Jenny, 1961) for time-factorial pedogenic studies was considerable. Of the original factors of soil formation first discussed by Jenny (1941) only time was retained as an independent state factor in the 1961 paper, all the other factors being combined into the state factors *Lo* and *Px*. This change not only recognized the criticisms that had been made about Jenny's original treatment of the time factor, but also emphasized the importance of time in pedogenesis. Further, the paper gave theoretical validity to the relaxation of some of the restraints that had been imposed in the earlier models (Jenny, 1941, 1946). In other words, factorial approximations were now permissible; where subdominant factor variation was ineffective, it could be disregarded. Thus, if a situation could be found where the time state factor was dominant and the other two state factors (*Lo* and *Px*) were ineffective, the latter could be justifiably ignored when assessing the effects of time on soil properties.

1.2.4 Recent Developments

In his book The Geography of Soil Bunting (1965) devoted a chapter to a discussion of the time factor in soil formation. He considered that time can not act independently of *space*, but he did not think that Jenny's fundamental equation would be improved by including another factor to cover the space dimension.

Bunting recognized four different ways in which the role of the time factor may be assessed: "(1) by the relative stage in soil development from a time zero; (2) by the rate of formation of a unit depth of soil or soil horizon; (3) by reference to the age of the slope, landform or weathering complex on which the soil is developed; and (4) by absolute dating of a part of the soil profile" (Bunting, 1965, p.78).

After reviewing examples of these different approaches Bunting concluded that the time factor is difficult to isolate with certainty as there are problems of intensity, retrogression and inertia inherent in soil development. However, he believed that it was "infinitely preferable to refer soils to absolute age, or to relative age of site, than to refer to such alleged criteria as 'young', 'mature' or 'old'; for soils may be older or younger than they appear..." (*ibid.*, p.86).

Two publications relevant to time-factorial pedogenic theory were published in 1970. Schelling (1970), writing on soil genesis and its implications for soil classification and soil survey, claimed that Jenny's (1941, 1961) expanded factorial theory had not been developed greatly, probably because of the difficulty of accurately measuring some factors, and the interdependence-interaction of others. Schelling also disagreed with the treatment of time as a state factor in the expanded theory. Although he thought time to be important in pedogenesis, he viewed its role differently from Jenny in that "the function of time is not only the duration of the course of the present soil forming process ... soil is a final product of processes that have changed with time and of the resulting accumulation, modification and neutralization of their respective effects" (Schelling 1970, p.185). Schelling diagramatically represented his general model of the relationship between the pedogenic factors and the permanent characteristics of the soil, but he did not elaborate upon it. The diagram appeared as follows:

input	black box	output
state factors ⇄	genetic processes	⇄ soil

In a second paper published that year and relevant to time-factorial pedogenic theory, Stevens and Walker (1970) examined the chronosequence concept in relation to soil formation. They gave a general definition of a chronosequence as: "a sequence of related soils that differ, one from the other, in certain properties primarily as a result of time as a soil-forming factor" (<u>Glossary of Soil Science Terms</u>, 1965). They also provided a more specific definition of their own: "a sequence of soils developed on similar parent materials and relief under the influence of constant or ineffectively varying climate and biotic factors, whose differences can thus be ascribed to the lapse of differing increments of time since the initiation of soil formation" (Stevens and Walker, 1970, p.333). If the absolute ages of soils of a chronosequence are known, rate - equations of soil formation can be derived and these are known as *chronofunctions.* Stevens and Walker then briefly considered some of the main contributions to the theory of soil-forming factors and examined the main concepts involved. The paper then proceeded to review a number of chronosequence studies, having first categorized them as either a) non-strict chronosequences, that is, those in which constancy of the soil-forming factors was insufficiently established or in which the groundsurfaces were not accurately dated, or b) those studies in which constancy of the soil-forming factors and accurate groundsurface dating probably had been achieved. Studies of the latter type were differentiated by Stevens and Walker (1970) according to the type of groundsurface in which the chronosequence had developed: man-made situations, aeolian drift deposits such as sand dunes, and surfaces deposited by glacial or alluvial action.

In their conclusion Stevens and Walker summarized the general trends in soil development which they believed could be recognized from various chronosequence studies. These trends will be discussed in the next section. Finally, Stevens and Walker (1970) gave some "desiderata" which they thought were essential if meaningful and comparable chronosequences were to be attempted in the future. They included the selection of minimally disturbed ecosystems for the chronosequence studies; reasonably accurate dating of groundsurfaces; soil-forming factors other than time must be constant, or vary ineffectively, or if this is not possible the variation must be known or estimated and its effects assessed. In addition, the authors thought it desirable that the whole ecosystem (rather than just the mineral soil and forest floor) should be studied, that glacial till was not a very suitable parent material for chronosequence studies although it was frequently used, and that properly randomized sampling within a statistically valid experimental framework should be employed whenever possible.

In the chapter of his book which dealt with the factors of soil formation, FitzPatrick (1971) claimed:

> Some workers, particularly Jenny (1941), have tried to demonstrate, quite unconvincingly, that these [soil-forming] factors are independent variables, i.e., each of them can change and vary from place to place without the influence of any of the others. Only time can be regarded as an independent variable, the other four depend to a greater or lesser extent upon each other, upon the soil itself or upon some other factor. (FitzPatrick, 1971, p.12).

Further, FitzPatrick believed that although many efforts had been made to show that some factors were more important than others, "such efforts are a little unrealistic since each factor is absolutely essential and none can be considered more important than any other, but locally one factor may exert a particularly strong influence" (*ibid.*, p.12).

Within his discussion of the time factor, FitzPatrick (*ibid.*, p.47) distinguished exogenous from endogenous soil evolution. The former results from change in the environmental factors over time, the latter from progressive development of soil features which in turn result in altered soil development. Thus FitzPatrick claimed that direct and indirect forms of soil development can occur over time.

Two years later Runge (1973) presented a paper on soil development sequences and energy models. Runge claimed that although soils are complex systems with many potential vectors influencing soil development, some vectors are more important than others and these can be used to construct a model. The energy source for Runge's model is the gravitational energy associated with running or percolating rainwater, and the model is, he claimed, based on chromatographic column principles. The model states that soil development (s) is a function of organic matter production (o), amount of water available for leaching (w) and time (t), thus:

$$s = f(o, w, t) \tag{24}$$

According to Runge, organic matter production is the *renewing vector* of the soil and amount of water available for leaching is the *developing vector;* both are *intensity factors* and are conditioned by *capacity factors* such as phosphorus availability, rainfall, runoff, runon, etc. Thus, as Runge stated (p.185), priority has been given to certain aspects of Jenny's (1941) fundamental equation.

Chesworth (1973 a,b) examined the role of parent material in the genesis of soils and his conclusion is of relevance to time-factorial pedogenic studies. He illustrated graphically how common primary igneous rocks tend to weather towards a composition relatively rich in SiO_2, Al_2O_3 and Fe_2O_3. This endpoint of weathering and (Chesworth claimed) soil development, was named the *residua system of chemical weathering.* As time progresses the weathering products of rocks as dissimilar as granite and basalt become more and more alike, so that eventually they become indistinguishable. Hence the parent rock effect is nullified given sufficient time, and according to Chesworth, this means that Jenny's requirement that the original soil-forming factors (or the state factors) be independent can not hold. "In other words, time has the result of modifying and ultimately nullifying the parent material effect so that only in young or relatively immature soils will the parent material exert its strongest influence on the soil-forming process: an influence that will be an inverse function of time " (Chesworth, 1973 b, p.224). Consequently, Chesworth stated that he agreed with Stephen's (1947) conclusion that time alone is the independent variable of the soil-forming process.

Dijkerman (1974) discussed the nature of pedology as a science and the role of data, models and theories within the discipline. In a comparison of the various models used in pedology (Dijkerman, 1974, Table III, p.78), the factorial model was classed as one which is applicable to any natural soil system and has the characteristics that it is "conceptual (verbal)" in nature, it has a "descriptive/explanatory function" and its design is "idealized". Dijkerman acknowledged that parts of Jenny's (1941) model of the factors of soil formation have been quantified, but he claimed that most of it was still entirely qualitative. Dijkerman also believed that the function of Jenny's model was coming to be regarded by pedologists as one which was less explanatory and more descriptive. Dijkerman claimed that the idealized design of the factorial model was apparent in the sequences (topo-, chono- etc.) usually studied. Such idealized designs are used because the soil system is usually so complex that it is not easily analysed, but Dijkerman also contended that the assumptions made in sequence studies about constancy of factors, often involve gross simplifications.

In later sections of Dijkerman's paper the concept of time in pedological studies was discussed in other contexts. For example, Dijkerman claimed that an important weakness of the "law of soil zonality" is that it overlooks the factor of time. He thought that soil-forming processes in the tropics and temperate zones were not always greatly different, but that it was the age of the soil which in many areas caused the main differences. Dijkerman believed that the hypothesis that, under certain circumstances, space and time could be considered interchangeable (*ergodic hypothesis;* Chorley and Kennedy, 1971, p.277-281) had not been seriously tested in pedology. Thus the study of chronosequences, where soils of different ages (representing different time states) are distributed in space, really depends on an untested ergodic hypothesis.

Birkeland's (1974) book Pedology, Weathering and Geomorphic Research dealt in some detail with the factors of soil formation, and has been viewed as a sequel to Jenny's (1941) monograph by Yaalon (1975). Birkeland gave a summary of Jenny's concepts, and the criticisms that have been expressed about them, as well as an extensive review of the many papers that attempt to apply the factorial approach to pedogenic-geomorphic problems. The main significance of Birkeland's book for this thesis is that, having examined the problems and weaknesses inherent in the factorial approach to pedogenic investigation, Birkeland concluded that nevertheless "the approach is basic to geomorphic research. Derived functions can be used in a quantitative sense...", in which case they are called sequences rather than functions, and "...chronosequences... are not without value in research..." (Birkeland, 1974, p.130).

Yaalon (1975) in a paper entitled *Conceptual Models in Pedogenesis : Can Soil Forming Functions be Solved?*, claimed that "the impact of Jenny's model on pedological research and thinking was seminal [and] though mostly applied in the explanatory rather than in the strictly quantitative way, the simplicity and clarity of the functional system stimulated the search for ... functions or sequences, provided insight into their interaction, and stimulated new trends in the study of soil-forming factors and their effects" (*ibid.*, p.190). Yaalon then reviewed the main post-1941 attempts at quantitative solutions of the environmental functions and also examined some of the papers that had been critical of the factorial model. When dealing with chrono-functions Yaalon mentioned Stephens (1947), Chesworth (1973 b) and Stevens and Walker (1970), and their respective views on the treatment of the time factor in the functional model. Whereas Harris (1971) and Vreeken (1975) thought that buried soils would probably be more reliable than surface soils when constructing chronosequences, Yaalon (1975) did not agree. He argued that post-burial diagenesis was an unknown factor and hence chronosequences and chronofunctions based on buried soils were as equally subject to errors as those based on surface soils.

Yaalon was also not very impressed by Runge's (1973) energy model. He thought that if quantification was the aim, then the substitution of only three parameters for the five or more used by Jenny (1941) and others, would not give the desired results. Specifically, Yaalon criticized the use of organic matter content as a substitute for the parent material (capacity) factor, as it would exclude the effect of rock mineral weathering in the soil. However, Yaalon did suggest that the model might be applicable to soil sequences on unconsolidated surficial deposits, where leaching is by far the major process of soil horizon differentiation. Apart from its "several omissions and commissions", Yaalon considered that the energy model "does not appear to be an advancement on the basic tenets of the functional system ... it is at best a new verbal dress for the same model" (*ibid.*, p.199).

Yaalon was also critical of Chesworth's (1973 b) paper on parent material and soil genesis. He claimed that Chesworth dealt with clay mineral genesis, rather than soil genesis, that the terminal state of the model as Si + Al + Fe would not appeal to geochemists because the trend of desilicification was masked and that the model excluded all pedomorphic surfaces that have been covered by sediments incorporating clays inherited from previous cycles of weathering. Yaalon also criticized Chesworth's ambiguous use of the concept of soil maturity, his dismissal of the possibility of soil equilibrium and steady state as trivial exceptions, and concluded that "Chesworth (1973) has in no way challenged the theoretical basis of Jenny's factorial approach " (Yaalon, 1975, p.201).

In the final section of his paper entitled "Prospects", Yaalon (*ibid.*) stated that the remaining constraints of Jenny's model are involved with difficulties in collecting data, but that these difficulties are not insurmountable. Finally, Yaalon did not believe that the soil-forming functions were capable of a simple quantitative solution because the degrees of freedom in the general soil-forming function are too large. However, he thought that collection of univariant and multiple regression functions must be the first step in the attainment of *general* solutions.

Yaalon's (1975) article prompted replies from both Huggett and Chesworth. Huggett (1976), though agreeing with some of Yaalon's views, contended that "the philosophical and theoretical bases of the 'systems approach' to the soil system and the 'functional, factorial approach' to the soil system differ quite fundamentally" (*ibid.*,p.261). He thought that Jenny's five soil-forming factors, rather than being "univariant soil system variables studied as co-active parts of a functioning whole, are generally 'external' to the soil system and are studied individually ..." (*ibid.*).

Huggett also maintained that the factorial approach was concerned with correlating soil-forming factors with certain characteristics of soil morphology, rather than relating driving forces of pedogenesis to soil system dynamics. Further, he claimed that it is unnecessary to use concepts such as soil-forming factors, as these have been replaced by "concrete ideas of the exchange of material and energy between a soil system and its environment, and the flux of material and energy through a soil system " (*ibid.*, p.262). However, Huggett also believed that, except in relation to univariate functions, Jenny's state factor concept is more in accord with the systems approach than his earlier 1941 model. Huggett disliked Schelling's (1970) model which equated state factors with the soil system, a black box with soil genetic processes, and outputs with the soil itself. Huggett saw this model as a misuse of systems terminology: the box should be white, the soil system a complex store, and inputs and outputs should consist of materials and energy. Huggett therefore saw the two approaches to soil genesis (systems and factorial) as alternatives, challenging or complementing each other, depending on one's viewpoint.

Chesworth (1976 a) was not so compromising. He claimed that Yaalon (1975) extensively misinterpreted his earlier paper (Chesworth, 1973 b) and he refuted these "inaccuracies" point by point. Some of the most significant points Chesworth (1976 a) raised in his "Rejoinder" were; that it was unreasonable for Yaalon (1975) to claim that the soil-forming factors have been constant, and therefore time-independent, considering the climatic changes that have occurred in the past 10,000 years or so; that Chesworth (1973 b) used the word "maturity" in a chemical and mineralogical, rather than temporal, sense; that the trend in soil development towards the *residua system* holds for cyclic as well as primary weathering products; that desilicification *can* be inferred from his ternary diagrams; and that pedogenic equilibrium or steady states are unreasonable concepts in the light of our knowledge of past climatic changes. Finally, Chesworth claimed that Jenny's 1942 [*sic*] differential equation:

$$ds = \left[\frac{\partial s}{\partial cl}\right]_{o,r,p,t} . dcl + \left[\frac{\partial s}{\partial o}\right]_{cl,r,p,t} . do + \left[\frac{\partial s}{\partial r}\right]_{cl,o,p,t} . dr + \left[\frac{\partial s}{\partial p}\right]_{cl,o,r,t} . dp + \left[\frac{\partial s}{\partial t}\right]_{cl,o,r,p} . dt \qquad (25)$$

could only be valid if all the factors were independent variables, and that as he had shown that at least two are not independent, Jenny's equation was wrong. In conclusion Chesworth (p.260) quoted FitzPatrick (1971, p.12): "... only time can be regarded as an independent variable ".

In reply Yaalon (1976) basically agreed with Huggett's (1976) comments and accepted the validity of the two approaches to pedogenesis, which he called "deterministic" (systems approach) and "functional" (factorial). Yaalon maintained that they are of equal value and complement each other. Factorial studies were useful, he claimed, when the pedogenic processes were too complicated for deterministic treatment.

Yaalon believed that the disagreement between himself and Chesworth (1976a) revolved on the definition of the size and nature of the system considered, and on how large the inevitable fluctuations in the causative determinants may be before it was necessary to redefine the system. He argued that short-term fluctuations are often of no consequence in soil development as the environment must persist within certain limits for sufficient time to leave its mark on the soil.

Chesworth (1976b) in a "Further Rejoinder" had the last word. He stated that Yaalon (1976) had not attempted to counter the simple, mathematically based rejection of Jenny's equation in his "Rejoinder" and he claimed that their disagreement was more basic than Yaalon appreciated, being "concerned with the rigorous use of precise thermodynamic terms namely ... equilibrium and steady states"(Chesworth, 1976b, p.265). Chesworth also argued that Yaalon did not use the terms correctly and that in the "natural world where spontaneous change is the rule, equilibrium and steady states do not hold" (*ibid.*,p.266).

1.2.5 Implications for the Present Study

Two inter-related questions of considerable relevance to the present study emerge from the foregoing literature review. First, is the time-factorial approach a theoretically valid method of pedogenic investigation; second, given that the approach *is* valid, which version of the factorial model could be best employed in the present study? These issues are discussed below.

Most critics of the functional factorial model have been concerned with Jenny's (1941) original definition of the soil-forming factors as independent variables: for example, Nikiforoff (1942), Stephens (1947, 1951), Robinson (1949) and Chesworth (1973a, 1976a,b). These critics have claimed that not all Jenny's factors are independent, although they have generally acknowledged that the time factor is independent and capable of evaluation. In his later contributions Jenny recognized these criticisms and attempted to negate them by reformulating his fundamental equation, firstly in terms of dominant and subdominant (ineffective) pedogenic factors (Jenny, 1946) and later by means of state factors (*idem* , 1961). It is significant that the revised factorial models have received little attention from subsequent critics, who have been mostly concerned with the limitations of the original fundamental equation (e.g., FitzPatrick, 1971; Chesworth, 1973b, 1976a,b) or with the general usefulness of the factorial approach (e.g., Dijkerman, 1974; Huggett, 1976). However, it should also be noted that the conceptual validity and the utility of Jenny's model have been strongly defended by other writers, for example, Crocker (1952), Birkeland (1974) and Yaalon (1975, 1976), and that the various factorial models have formed the basis of many pedogenic field studies, a small proportion of which are reviewed in the next section.

As a result of these considerations Jenny's (1961) state factor equation and its derivatives have been chosen to form the theoretical base of the present investigation. As applied to soil properties, the extended state factor equation (Equation 17) appears to be identical to the fundamental equation (Equation 1). It differs however, in that only *time* is recognized as a non-composite, independent state factor, all the other factors previously identified (Jenny, 1941, 1946) being combined into the two state factors *Lo* and *Px*, to avoid problems of factor interdependence. In addition, the revised formulation permits factorial approximations using chronosequences, where subdominant factor variability is insignificant or ineffective. Thus the state factor equations incorporate the best features of Jenny's functional factorial models, avoid the criticisms relating to factor independence, and may be validly applied to the field situation by the use of chronosequences. The application of the state factor model will be considered in more detail in Chapter 2.

1.3 REVIEW OF EMPIRICAL TIME - PEDOGENIC STUDIES

1.3.1 Introduction

A large number of pedological field studies have been explicitly or implicitly based on the functional factorial model of pedogenesis. Many such studies have been reviewed by Jenny (1941), Crocker (1952), Stevens and Walker (1970), Birkeland (1974) and Yaalon (1975). However, the following review of empirical factorial studies will be more limited in its scope, in that only those studies which are relevant to this investigation will be examined.

Specifically, the review will be confined to those papers which deal with chronofunctions or chronosequences in relatively young soils (mainly Holocene) and which have been based on reasonably reliable and fairly accurate absolute dating frameworks (using radiocarbon techniques, dendrochronology, historical records, etc.). Further, because paleosols have not been investigated in the thesis, chronofunction or chronosequence studies which utilize paleosols will not be included in the review.

1.3.2 Summary of Literature

Prior to the introduction of radiometric dating techniques soil chronosequence studies were rare and those that had been undertaken were restricted to examining the initiation and early development of soils that could be dated by primitive dendrochronometric methods, by archaeological association, or by reference to historical records.

Salisbury (1922, 1925) studied the soils of coastal dune systems at Blakeney Point and Southport, England. However, only in the latter dune system was he able to accurately determine dune ages by reference to old maps and historical documents and by counting annual growth rings of *Salix repens*, which was an early colonizer of the hollows (slacks) between the prograding ridges. Ages of individual ridges at Southport ranged from two to 280 years. Salisbury (1925) established trends for carbonate content, pH and organic matter content. Carbonate showed an exponential trend decreasing rapidly from an average 6.3% in the youngest dunes, to an average 0.09% in the oldest (280 year) dunes. The pH curve showed the reverse trend; initial pH values of 8.2 did not fall to below pH 7.0 until the soil was well over 100 years old, then pH values fell rapidly to an average of 5.5 in the 280 year-old dunes (under heather). Organic matter content of some of the dunes was variable, probably because of human interference, but in general the trend showed a clear increase with soil age from about 0.35% in the youngest soils to 15% in the oldest. Salisbury believed that the rate of leaching of shell carbonate was probably more dependent on the size of the shell particles in the parent material, than on climatic factors. He thought a few large shells would be leached more slowly than many small shell pieces (of equivalent volume) because the surface : volume ratio would be much lower. Salisbury concluded that increasing acidity, increasing organic matter content and diminishing available salts were the main temporal trends in the early development of the soils he studied.

There are several apparent limitations to Salisbury's work. Although it is probable that the soil samples were from near the ground surface he did not give the depth of sampling, nor did he state whether samples were all from a consistent depth. The soil sequence was paralleled by a vegetation sequence, the effects of which Salisbury did not distinguish from age effects. Finally, in pedological terms the soils were very young and little more than incipient soil development was observed.

Jenny (1941) summarized some of the early European studies on soil - time relationships. Schreckenthal (1935) found a significant increase in the acidity, silt and clay fractions, and nitrogen content of eighty-year-old morainic deposits from the Mittelberg Glacier in the Tirol. On a longer time scale, Tamm (1920) examined podzolization in a series of alluvial terraces in northern Sweden, the ages of which were known with "considerable certainty" (Jenny, 1941 p.39). Jenny recalculated Tamm's original chemical data to illustrate the trend towards horizon differentiation with increasing age. The results showed that although large changes in the soil characteristics occurred in the initial stages of soil development, the magnitude of the changes decreased with age and tended towards a steady-state situation. It should be noted that Tamm's data (as analysed by Jenny) was based on only 3 soil ages; 100, 650 and 1500 years. Hence the changes in the indices may not have been as uniform, and the trends as definite, as Jenny claimed.

Jenny (1941) also briefly reviewed work by Aaltonen (1939), and Mattson and Lonnemark (1939). Aaltonen studied the formation of the illuvial horizon in sandy soils in Finland, and concluded that it grows from the bottom upwards, because colloidal particles are flocculated at greater depths in younger soils, than older soils. Aaltonen also thought that at the same time thickness of the eluvial horizon probably increases. According to Jenny, the work of Mattson and Lonnemark (1939) supported Aaltonen's conclusions.

Hussink (1938) described the leaching of calcium carbonate from Dutch polders of varying ages. He reported that initial near-surface concentrations of 9-10% were common in recently drained areas, and that this concentration progressively decreased as the polders aged, until virtually all carbonate was removed from polders 300 years or older.

Burges and Drover (1953) studied podzolization in a prograded coastal beach-ridge plain at Woy Woy, New South Wales. The results of their work will be considered in more detail in Chapter 3, as the Woy Woy barrier was resampled and radiometrically dated as part of the present investigation. It is relevant to note here however, that the age framework Burges and Drover postulated for the Woy Woy barrier system is considerably in error, a fact which affects the validity of most of their specific conclusions about rates of leaching and podzolization, although the general trends they identified across the barrier still apply. These trends include a general increase in the degree of podzolization across the barrier, with a zone of undifferentiated sands 200-300 yards wide on the seaward side, then a wide zone of iron podzols showing increasing profile development with increasing distance away from the beach, and finally a zone of well-defined humus podzols at the rear of the barrier system.

In the same year Dickson and Crocker (1953a) published the first part of a study based on a chronosequence of soils and vegetation near Mt. Shasta, California. The substrate was a series of mudflows which were assigned ages of 27, 60, 205, 566 and 1200+ years. These values were estimates of the age of the oldest trees growing on each flow, except that the oldest flow was considered, on soil morphology criteria, to be at least twice as old as the second oldest flow and was therefore assigned the age of 1200+ years. Obviously this dating technique is liable to considerable error, and Jenny (1965) has questioned the accuracy of these age estimates. Despite errors in dating, the general trends revealed by Dickson and Crocker (1953a,b, 1954) are probably still valid, and their soil sampling system did attempt to minimize variations in the other pedogenic factors as far as possible. Several soil parameters were measured on each mudflow. Apparent density showed a general decrease with time; pH showed a complex pattern of change with increasing age and did not seem to correlate well with any other soil property; soil colour, though fairly constant, did tend to decrease in *value* with age; free iron oxide increased only slightly with age and "there were no obvious horizons of accumulation within the two older soils" (p.177); soil moisture generally slightly increased with age and was related to the development of the organic profile; cation exchange capacity, exchangeable bases and exchangeable hydrogen all increased rapidly in the youngest profiles, then slowed, and subsequently exchangeable bases declined while exchange capacity and exchangeable hydrogen increased substantially (allegedly from

205 to 1200 years). Particle sizes were also analysed and were found to be very uniform throughout all the mudflows; no weathering was indicated. Heavy mineral analyses of the fine sand fraction indicated slight parent material variability and only slight pedogenic weathering of volcanic glass sand grains. X-ray diffraction analysis identified no weathering products in the soil samples.

In more general terms the study concluded that two phases of soil development could be recognized. First, the germination and survival of the effective disseminules, giving profiles with upper layers dominated by organic matter and lower layers still dominated by parent material. Then, with time, the evolution of the profile through weathering and eluviation of sesquioxides. However, the authors noted that mineralogical and particle size analyses did not show any appreciable weathering or clay formation.

Crocker and Major (1955) studied chronosequences of "soils" developed in glacial moraine at Glacier Bay, Alaska. As the maximum age of the moraine surfaces was only 200 years, all profile ages were determined by "analysis of historical data" (p.428) and can be considered very reliable. In a second paper Crocker and Dickson (1957) worked on very similar moraine chronosequences associated with the retreat of the Mendenhall and Hubert Glaciers in south-east Alaska. Again, the maximum age of the deposits was only 200 years, this being determined by dendrochronology and analysis of historical records. As the two investigations were very similar, and the results mutually consistent, the summary given by Stevens and Walker (1970) of the main trends apparent in both chronosequences is quoted below.

> Crocker and Major found a close correlation between plant species and rate of pH decline. Soil organic C increased from nearly zero to about 9, 7 and 5 kg/m^2 profile in approximately 200 years at Mendenhall, Hubert and Glacier Bay respectively, after which the rate of accumulation declined as apparent steady -states were achieved. The pattern of N-accretion generally followed organic C closely but C/N ratios, especially of L (litter) and FH (fermentation-humus) layers, widened considerably after the "transition" stage. At Glacier Bay there appeared to be a decline in total N after this transition, possibly related to the simultaneous demand for N by the rapidly-growing spruce forest. The apparent steady-state for N may have been relatively transitory, however; within 200 years less than $0.4kg/m^2/24"$ profile had accumulated at Hubert/Mendenhall, whereas two "late-glacial" moraines contained nearly $0.9kg/m^2/24"$ profile of N. Various depth functions for pH, bulk-density, organic C and N showed close similarities to those at Mt.Shasta, and admirably illustrated the effects of the organic cycle in first altering the upper horizons of the parent material.... there was a negligible degree of weathering and clay formation within the limited time-span of the Alaskan chronosequences (Stevens and Walker, 1970, p.343).

As with the Mt. Shasto investigation, the main limitations of these studies was their extremely short time span.

Olson (1958) based a soil-vegetation chronosequence study on sand dunes formed in the Lake Michigan Basin in Indiana. The ages of the older dunes were inferred from provisional radiocarbon analyses to be *c.* 12,000, *c.* 10,000 and *c.* 8,000 years, while the younger dune ages were based on two provisional C14 dates rounded to 3,500 and 2,500 years, with assumptions made about uniform progradation rates and lateral ridge correlations. The nature and source of the dated material were not given, nor were any details of the radiocarbon analyses. Some very young ridges were dated from historical records. Thus, although the age range of the soils was large, the dating was not very accurate and its reliability is questionable. Olson quotes the ages as $\pm$ 10-20% uncertainty, which gives a possible age range of 9,600 to 14,400 years, for the oldest dune.

In studying these dune soil ecosystems Olson adopted a classic factorial approach (Jenny, 1941, 1946; Major, 1951). He identified those factors that were physically independent of the local ecosystem, being either predetermined at the time of surface stabilization (parent material, surrounding topographic relief, hydrographic setting) or determined on such a large scale that the vicissitudes of the local system should generally have little effect on them (regional climate and biota). Olson claimed that Jenny's "factor function" approach was a very valuable guide, even though there never was more than a tentative approximation to his ideal single factor or multifactor model for the state of an ecosystem. Much of Olson's (1958) paper was concerned with successional vegetation changes. However, he also considered the soil chronosequence in some detail. The dunes were composed primarily of quartz sand, and Olson believed that soil development in this substrate reflected the level of organic matter and general biological activity. Colour showed increasing blackness in the surface soil with age, the early development of a light A_2 horizon, and much slower development of an orange B horizon. Silt and clay content increased slightly across the dune system, especially in the pre-6,000 year dunes, which may have been affected by late glacial loess accessions. Carbonate was rapidly leached from very young dunes, most free carbonate being removed from the surface soil in a few hundred years. The parent material varied significantly in organic matter content because of the inclusion of old soils, trees and beach debris. However, organic carbon still ranged from very low levels (<0.05%) in the newly-forming dunes, to high levels in the oldest soils. Nitrogen showed a fairly even rate of increase across the younger dunes, but was quite variable in the oldest dunes, probably because of forest fires. Apparent soil density decreased over time and soil moisture characteristics tended to increase linearly with nitrogen content. Cation exchange capacity of both surface and lower horizons also showed a general increase in proportion to increasing nitrogen content. This represented an initially rapid increase with time, and then subsequently a much slower rate of increase. Exchange acidity and exchangeable bases exhibited similar trends.

A well-dated, very comprehensive chronosequence study was published by Franzmeier and Whiteside (1963a, b) and Franzmeier *et al.*(1963). The soils examined were podzols developed in sand-textured material in Northern Michigan. The profiles were radiometrically dated at 2,500, 3,000, 8,000 and 10,000 years old. Many of the temporal trends observed by Olson (1958) were confirmed, such as declining pH, increasing organic matter content and leaching of carbonates and bases, but the work by Franzmeier and his associates was also important for its observations on mineral weathering, clay formation and micromorphological changes. Changes in the concentrations of extractable phosphorus, iron and aluminium were also examined.

Franzmeier *et al.*(1963,pp.55-56) reported their general conclusions on podzol formation by outlining the main stages in the genesis of the oldest soil in their chronosequence.

1. Additions of organic matter begin.
2. Carbonates dissolved and reaction products removed.
3. Basic cations in A_2 replaced by H^+ and a pH gradient established between A_2 and B horizons of podzol.
4. Organic acid dissolves primary phosphatic minerals in A_2 and soluble products transported to B horizon where they are precipitated.
5. Mineral weathering in A_2 releases Fe, Al, K, Mg cations. Sesquioxides are transported to the B horizon and precipitated on sand grains as thin coatings.
6. When sufficient active metal ions are concentrated on B horizon grains to saturate the functional groups of percolating humus solutions, humus (with some clay and sesquioxides) is immobilized as amorphous coatings on the sesquioxide coatings, resulting in marked segregation of organic carbon into horizons.
7. Clay in upper profile increases through weathering and is segregated into horizons.
8. Coatings on skeletal grains increase in thickness, eventually flake-off and occupy intergranular space as aggregates of coarse silt to very fine sand. This layer becomes the thin, low bulk density Bh horizon, the development of which may be correlated with stages in the vegetation succession.
9. Continual silt and clay formation in the upper part of the profile eventually results in a clay eluvial - illuvial sequence below the "podzol sequence".

As will be shown in later chapters, not all of the events outlined above are applicable to the podzol soils included in the present study. The highly siliceous nature of east Australian coastal sand barriers has resulted in very little clay and silt formation, and evidence suggests that the sands contain only very small amounts of primary phosphatic minerals (Stace *et al.*, 1968).

The Glacier Bay region of Alaska was the subject of a publication by Goldthwait *et al.*(1966) which was notable for its unified and comprehensive study of many aspects of the ecological succession in the area since the end of the Little Ice Age. The soils were examined by F.C. Ugolini who found the same trends as Crocker and Major (1955), but extended their work by reporting mechanical analyses and determinations of free iron oxides, cation exchange capacity and exchangeable bases. C.E.C. increased from 2.4me./100g in the parent material, to 16.6me./100g in an organic rich horizon of the oldest soil (250 years). Free Fe_2O_3 increased from 0.21% in the parent material to 0.63% in the iron rich horizon (5-10cms) of the oldest soil. Ugolini proposed that the soils represented a genetic sequence, starting with Regosols in the youngest deposits (0-15 years), proceeding to Podzolic Soils (80-100 years), then Brown Podzolic Soils (150 years), and finally to Podzols in the oldest soils (250 years plus). Stevens and Walker (1970, p.344) consider this sequence to be a "little unwarranted in view of the juvenile nature of the soils on such young surfaces ".

Another sand dune soil sequence has been examined by Cowie (1963, 1968), Syers and Walker (1969a,b) and Syers *et al.*(1970). Cowie (1963) carried out the original geomorphic investigation of the area, which is in the Manawatu district of the North Island of New Zealand, and assiged ages to the four major dune building phases that he recognized. The youngest coastal dunes, the Waitarere phase, Cowie dated at less than one hundred years; the next phase, the Motiuti, he considered to be about 500 years old, as it was related to Maori occupation of the district; the third phase (Foxton) was assigned an age of 2,000 - 3,000 years on the basis of a related radiocarbon date of 1800 years; and the oldest phase (Kaputaroa) Cowie thought comprised dune remnants of the last aggradational phase of the Last Glaciation, and on this basis, it was assigned an age of 10,000 - 15,000 years. The sediments of the Kaputaroa phase dunes were probably initially richer in ferromagnesian minerals, and poorer in shell debris, than the younger dune sediments.

Cowie (1968) found that the dune soils displayed distinct changes with increasing age: the depth of the A horizon increased due to additions of fresh sand and dust; organic matter content increased once sufficient colloidal material had accumulated for the soils to retain moisture in summer; sand grains weathered progressively, resulting in deeper, darker B horizons and increased silt and clay; profile compaction and B horizon mottling increased because of clay illuviation. Leaching was found to be not very strong, although it was sufficient to remove free lime early in the sequence, and to give an overall decrease in percentage base saturation, pH and citric acid - soluble phosphorus. Cowie noted that leaching did not result in a sand podzol and attributed this to "a combination of comparatively slow leaching under a moderate rainfall; a good reserve of weatherable minerals which, on weathering, replenish bases lost by leaching; and a good return of bases from an efficient organic cycle under deep rooting mull-forming vegetation" (*ibid.*,p.115). As will be shown later, the parent material and vegetation of Cowie's soil sequence are quite dissimilar to those of the east Australian barrier soils.

The papers by Syers and Walker (1969a,b) and Syers *et al.* (1970) deal with the same dune sequence as Cowie, but they used slightly different ages for the phases, sampled the soils more intensively and measured additional soil properties. Parent material, at time zero, was equated with beach sand (composition dominated by feldspar and quartz, but with minor augite, hornblende, hypersthene, mica and magnetite); using Cowie's (1963) age framework the Waitarere phase was given an age of 50 years, the Motuiti 500 years, the Foxton 3,000 and the Koputaroa 10,000 years. The authors believed that no sites had received additions of phosphatic fertilizer. Carbon, nitrogen and organic phosphorus all showed initial rapid increases with age, but subsequently slower gains after 3,000 years, with phosphorus almost reaching an apparent steady-state by 10,000 years. Total phosphorus decreased linearly from about 5,000 to 3,000 kg/ha/m profile over the sequence, in line with increases in carbon, nitrogen and organic phosphorus. Nitrogen increased from 800 to 10,500 kg/ha/m profile during the inferred 10,000 years of soil formation.

Of those soil studies which have used Butler's (1959) K cycle model (see Section 1.2.2), that by Brewer and Walker (1969) most closely approximates the factorial approach. It investigates five soils developed in alluvial terraces in the Macleay River valley, New South Wales, to determine changes in soil development with age. The soil series associated with each terrace was tentatively assigned to a K cycle, and the second and third youngest terraces were radiometrically dated at 3280$\pm$ 100 and 6425 $\pm$ 130 years, respectively. Parent material, assessed from the youngest soil profiles, was considered constant for all terraces and consisted of alluvium, dominated by quartz, biotite and fine grained argillaceous and medium-grained quartzite metasediments. The other pedogenic factors were not assessed, although the authors considered it likely that climate had changed considerably since the initiation of the first soil. Micromorphological observations suggested increased weathering with increasing profile age; clay mineralogy supported this trend by distinguishing three weathering stages in the five soil series (K5; K4; and K3 K2 K1); particle size analysis and illuvial - *in situ* clay depth functions also showed consistent trends with increasing soil age. Overall, the analyses indicated that the four youngest soils represent successive stages of soil development, whereas the oldest soil differs substantially, and has probably experienced significantly different environmental conditions (*ibid.*,p.304).

Stevens and Walker (1970) reported a chronosequence study of thirteen soils developed in alluvial terraces, kame terraces and glacial deposits in the South Island of New Zealand. This sequence had been previously investigated by Stevens (1968) and Mokma *et al.* (1970). Age of the deposits varied from time zero to 22,000 years, but ten of the soils were less than 1,000 years old. The method of determining profile age was not given, but Stevens and Walker (1970) claimed that some success had been achieved in keeping the soil-forming factors (other than time) constant or ineffectively varying. The sequence showed the development of infertile gley podzols from clay-rich bouldery glacial deposits and supported the findings of Franzmeier and Whiteside (1963a,b) and Franzmeier *et al.*(1963). The main conclusions of Stevens and Walker are:

1. A well-differentiated gley podzol formed in 5,000 years, having passed through a podzol stage during which the zone of maximum accumulation of "active" iron moved downward in the profile.
2. Initial soil changes (e.g., decreasing pH, increasing nitrogen and organic carbon) were closely correlated with surface organic matter accumulation.
3. Over 90% of original phosphorus was lost during the 22,000 years.
4. Proportion of fine material increased with age.
5. Inorganic phosphorus varied in a complex manner.
6. Apparent steady-states were achieved within the soil sequence for pH, total soil nitrogen, organic carbon, magnesium, calcium, potassium, "active" iron, organic phosphorus and non-occluded inorganic phosphorus. Total phosphorus and acid-extractable Ca-bound P decreased through the sequence.
7. After 12,000 years profile degradation was inferred from loss of organic carbon, nitrogen, cation - exchange capacity, exchangeable calcium, exchangeable magnesium, and phosphorus, probably because of the complete physical comminution of stones and gravels and hence the loss to the system of freshly weathered rock minerals.

In the same article Stevens and Walker (1970) summarized the general trends in pedogenesis that they thought were evident from the numerous chronosequence studies they had reviewed. Briefly, these trends are as follows:

1. Rapid initial changes, due mainly to accretion of surface organic matter, set up depth gradients in a number of soil parameters (e.g., pH, cation exchange capacity, exchangeable bases, bulk density, $CaCO_3$ content).

Changes in the "active" fractions of Fe and Al, and in the fractions of inorganic P, become apparent. The initial course of soil development is directly correlated with the advent, growth, and areal distribution of various vegetation associations.

2. Morphological changes, often tending towards podzolization. Eluviation - illuviation processes come to dominate pedogenesis.

3. Later evolution of the profile, with changes in the mechanical composition of the soil. This may be a period of apparent steady-state (dynamic equilibrium) when the rate of change of most soil characteristics is very slow. Soil components tend towards dynamic equilibrium at different rates; few reach an apparent steady-state at the same time.

4. A phase of soil degradation after the period of apparent steady-state has been indicated in some studies, but demonstrated only by Stevens (1968) and Stevens and Walker (unpublished work).

5. Nearly all chronosequence studies report that plants capable of fixing atmospheric N are present early in the vegetation succession. Later the N - fixing plants are eliminated, leaving other plants to utilize the accumulated N. Walker and Adams (1959) and Walker (1965) have propounded an hypothesis relating total and organic P to amount of weathering and leaching, or the passage of time.

1.3.3 Assessment

Although this review has been restricted to those chronosequence studies which used absolute soil age determinations, it is apparent that most studies are still unsatisfactory in some respects. Generally the studies show an over-emphasis on the development of very young soils, probably because these can be reliably dated by historical or archaeological methods. However, it is also likely that the considerable interest of ecologists in plant colonization of bare surfaces and subsequent successional changes, has led to this concentration on incipient soil development. While such short term chronosequences may be of use to ecologists, plant nutritionalists and agronomists, they are of only limited value in geomorphic research.

Even those chronosequences which do incorporate quite old soils have their limitations. Radiocarbon dating offers one of the most versatile and accurate techniques for determining the age of older soils, but when it has been used for this purpose:

1. the material dated is rarely mentioned in the report;
2. analytical techniques, correction factors, etc., are not given;
3. the relationship of the dated event to the initiation of soil development is rarely discussed; and
4. the dates are usually rounded to the nearest 500 or even 1,000 years.

Consequently the accuracy, and even the validity, of many radiocarbon dated soil chronosequences may be questioned.

Apart from inadequate dating, the other common problem with chronosequence studies is the lack of "control" over the other soil-forming factors. Many investigators have not ensured the constancy, or ineffective variation, of any other factors, merely assuming "time" to be dominant, but as Stevens and Walker (1970, p.346) have stated: "...while recognizing it is difficult or impossible to 'control' some of these [factors] (for example, past climate), some cognizance of the probable variations must be made, and some idea of possible effects on soil formation kept in mind".

Often it is the selection of chronosequences which causes factorial imprecision. Glacial debris has been used as a substrate for many chronosequence studies (e.g., Crocker and Major, 1955), but such parent material is typically very poorly sorted and leads to quite variable soil development, which is difficult to characterize. Dune sequences which have been formed by sediments from different source areas may suffer from a similar problem of inconsistent parent material (Syers and Walker, 1969a,b).

The location of a chronosequence can also affect its precision. Chronosequences which extend back to the early Holocene will have experienced greater climatic changes if located in a cold climate region, than if located in a more temperate area (Lamb, 1966). Consequently studies of chronosequences from areas such as northern Michigan (Franzmeier and Whiteside, 1963a,b) will have greater paleoenvironmental changes to contend with than those of comparable age from an area such as coastal New South Wales (Burges and Drover, 1953).

Inadequate soil sampling has also lessened the value of some chronosequence studies. Most investigations have sampled very few profiles of any given age in a chronosequence, and hence the representativeness of the sampled profiles is sometimes doubtful.

Selection of soil horizon samples by visual criteria may not result in the most appropriate samples to show the distribution of soil properties. For example, if a B horizon sample is taken from the level at which a podzol profile is stained darkest orange - brown it might not represent the level of maximum illuviation of any soil property, other than iron oxides. Consequently, properties such as pH, cation exchange capacity, aluminium concentration and many others may be poorly represented in the B horizon by such a sampling technique. Closely spaced, incremental sampling down the complete profile overcomes this problem but does result in very many more samples for analysis.

In the present study an attempt is made to overcome many of these problems by the use of a conceptual framework, sampling design and field and laboratory techniques most appropriate to chronosequence investigation.

CHAPTER II

CONCEPTUAL BASIS AND RESEARCH DESIGN

Chapter Two presents the conceptual basis of the study and outlines the research design that was employed. Accordingly, the chosen factorial model is discussed, its attributes are examined and the relevant pedogenic factors are identified and defined. The selection of suitable field areas and soil profiles, the design of profile sampling procedures, and the choice of soil parameters for study, are then discussed in turn.

2.1 CONCEPTUAL BASIS OF THE STUDY

2.1.1 Soil Systems and the Factorial Approach to Pedogenesis

Many workers in theoretical pedology have viewed the soil as an open system consisting of numerous subsystems organized in an hierarchical manner (e.g., Jenny, 1941; Simonson, 1959; Schelling, 1970; Yaalon, 1971; Dijkerman, 1974). These component subsystems are the basic units of investigation in most pedological research; they vary in size from systems as large as soil landscape bodies and soil catenas, down to the microscopic systems examined by soil micromorphologists. However, apart from differences in size, the systems are also different in type. Dijkerman (1974) has noted that pedologists are usually concerned with five of the natural systems identified by Chorley and Kennedy (1971), viz, morphological, cascading, process-response, control and ecosystems. Such systems are not mutually exclusive, each merely focusses attention on a different aspect of the same natural system (Dijkerman, 1974, p.75). Therefore the distinction drawn by both Crocker (1952) and Huggett (1976) between the "functional factorial approach" and what they called the "systems approach" is inappropriate in terms of the system types identified by Chorley and Kennedy (1971); the two approaches merely concentrate on different aspects of the same natural system - the soil. The "functional factorial approach" deals with morphological systems and ecosystems, whereas the "systems approach" is concerned with cascading systems, process-response systems and control systems (Dijkerman, 1974). Both approaches are, in effect, systems approaches and as Yaalon (1976, p.263) has stated: "each of them has merits of its own and there is nothing inferior in one or the other [they are] ... alternatives and ... complement each other".

2.1.2 The Chronosequence Model

As indicated in the literature review (1.1) the chronosequence model was formalized by Jenny (1946) who introduced the concept of soil sequences being used to obtain field approximations for his "five canonical functions of pedology", the *precise* evaluation of which he had come to realize were attainable "only under experimentally controlled conditions" (*ibid.*,p.376). In his paper the term *chronosequence* was used to describe a series of related soils which differed from one another primarily as a result of time as a soil-forming factor, the other factors being either constant, or varying ineffectively. Later, Jenny (1961) revised his model so that it consisted of three state factors (Equation 16), one of which was time. It is this form of the chronosequence equation that has been selected for use in the thesis, that is:

$$S = f(\underline{t}, cl, o, r, p, \ldots) \qquad (23)$$

where S = any or all soil properties, $\underline{t}$ = time, the dominant factor, and cl = climate, o = organisms, r = relief, p = parent material, and ... = unspecified factors - all of which are subdominant factors (Jenny, 1961). Parent material and relief together comprise the subdominant state factor *Lo* (initial state of the soil system) while climate, organisms and any unspecified factors comprise the other subdominant state factor *Px* (external flux potential).

Equation 23 provides a satisfactory theoretical basis for a chronosequence study, the subdominant component factors (cl, o, r, p, ...) may vary quite widely between the soils in the chronosequence, provided they are collectively ineffective in determining soil properties, compared to the influence of the dominant factor, time. Further, if any subdominant factor can be shown to have a negligible influence on the soil properties under investigation, it can be disregarded (Jenny, 1961). Such attributes allow chronosequences to be more easily formed than would otherwise be the case, the component soil profiles being drawn from areas of sometimes dissimilar pedogenic conditions, provided the subdominant factors have relatively little influence on soil properties. Even where the subdominant factor effect is significant, Jenny's (1961) revised chronosequence concept permits approximate solutions to be obtained, provided allowance can be made for the influence of the varying subdominant factors (Stevens and Walker, 1970). Thus, this factorial model avoids the criticisms made about earlier versions by Gerasimov (1947), Stephens (1947), Gerasimov *et al.* (1950) and Robinson (1949), that valid chronosequences were almost impossible to find because of the strict requirement of subdominant factor constancy.

2.1.3 Definition of the Soil-Forming Factors

Most of the factor definitions employed in the study are similar to those formulated by Jenny (1941, 1946, 1961), but have been modified and expanded to make them relevant to the pedogenic environment of east Australian coastal sand barrier systems.

Time - The dominant state factor is here defined as the age of the soil system, which is equivalent to the interval of time that has elapsed since initiation of soil development at time zero (Jenny, 1941). It is measured in radiocarbon years before the present, that is, before the calendar year A.D. 1950.

Although it is realized that the non-linear ^{14}C time scale can be transformed into "supposedly linear" sidereal calendar time (Whitrow, 1972) by the use of radiocarbon: dendrochronometric calibration curves (Olsson, 1970, 1974; Clarke, 1975) this "correction" has not been applied to the dates reported in the thesis because of the conclusions of Polach (1976, p.276) regarding the applicability and limitations of the technique.

It should be noted that all dates reported in the thesis are $\delta^{13}C$ (and where appropriate *environment* or *ocean reservoir*) corrected, and hence are mutually comparable. However, rate equations based on these dates are subject to a variable (but generally small) error, because of the non-linearity of the ^{14}C time scale.

Appendix 1 gives analytical information for each age determination and shows the corrections that have been applied. All marine shell dates have been normalised to $\delta^{13}C = +1.0 \pm 1.0‰$ unless a measured $\delta^{13}C$ value was available. In addition, dates on marine shells have been further corrected (lowered) by 450 ± 35 ^{14}C years to compensate for the *oceanic reservoir effect* and to make them comparable to terrestrial environment wood dates (Gillespie and Polach, 1977). Such dates are referred to as ages BP* or yrs*, as recommended by Stuiver and Polach (1977).

As mentioned in Section 2.1.2, the subdominant state factor *Lo* comprises both parent material and relief.

Parent Material - This is defined as the state of soil system at soil formation time zero (Jenny, 1941). It is assumed in the thesis that sediment in the C horizon of each soil has been relatively unaffected by pedogenic processes, and hence that its textural, mineral and chemical characteristics closely approximate those of the soil parent material. The validity of this assumption depends on the degree of vertical homogeneity within the original sedimentary deposit. Analyses of the mean size, sorting and mineralogical composition of the sediments are reported in Chapter 3 and confirm the conclusions of Hails (1967) that, in terms of these parameters, the barrier sediments are vertically homogenous.

Relief - Three elements of the relief factor are distinguished in the thesis.

1. Slope: defined as the average gradient of the boundary between the soil and the atmosphere in the immediate vicinity of the soil profile under investigation. This aspect of the relief factor has been held constant for all soil profiles in the study by sampling only beneath ridge crests or swale floors, or where ridge-swale relief is non-existent; that is, only where the groundsurface is horizontal.

2. Topographic position: the two topographically extreme soil sampling locations on a beach-ridge plain are ridge crests or swale floors. Although both ridge and swale soil profiles were initially sampled, and although ridge/swale soil differences are examined in Chapter Five, to standardize results and to facilitate comparisons most soil profiles were sampled beneath swales. The locations of all soil profiles are given in the tables in Chapter Three.

3. Watertable depth: defined as depth to the permanent watertable. It is approximated by depth to the watertable at the time of soil sampling. Borehole observations by the writer, extending over several

years, have indicated that watertable depth fluctuations are not very substantial in the barriers studied. The maximum watertable fluctuation observed was only 15% of the water-table depth (measured at the time the soil was sampled).

The subdominant state factor *Px* consists of climate, biota and any specified additional factors.

Climate - Climate is here defined as average long-term meteorological conditions and therefore refers to atmospheric or environmental climate, rather than to soil climate, which is a soil-dependent variable (Crocker, 1952).

An important assumption made in the study is that any palaeoclimatic fluctuations that have occurred since the termination of the Postglacial Marine Transgression (*c*.6000-6500 ^{14}C years BP*; Thom and Chappell, 1975) have not significantly affected soil development in the coastal sand barriers of eastern Australia. Although significant climatic fluctuations during this period have been demonstrated by studies in semi-arid areas of Australia (Bowler, 1971; Bowler *et al.*, 1976; Rognon and Williams, 1977) and from alpine and sub-alpine sites in New South Wales (Costin, 1972), North Queensland (Kershaw, 1974) and New Guinea (Bowler *et al.*, 1976; Webster and Streton, 1978), interpreting the magnitude and significance of these events for the maritime climates of eastern Australia is not yet possible.

The palaeoclimatic implications of coastal landform features, such as transgressive dunes, dune blowouts and eroded coastline segments, have been discussed by Thom (1974,

1978) and Thom *et al.*(1978). However, such studies have not provided information about the magnitude and frequency of past climatic events which can be used in this thesis.

Both a macro and micro component of the climatic factor have been distinguished and applied, in the course of the study.

1. Macroclimate: has been equated with regional climate and is represented by the usual parameters of rainfall, temperature and humidity.

2. Microclimate: the only climatic element subsumed under this heading in the present study is airborne salt fallout. The close proximity to the sea of the soils under investigation results in substantial marine aerosol accessions (Hsu and Whelan, 1976), and it has been hypothesized by several writers that this might differentially affect soil development (e.g., Downes, 1954; J.C.Corbett quoted by Shepherd, 1970). Therefore, marine salt accession has been assessed by the use of short-term sodium chloride fallout data for selected soil study sites on the New South Wales barriers. Appendix 7 contains a discussion of the methods of aerosol collection and analysis employed and presents the results, the pedogenic implications of which are assessed in Chapter Five.

<u>Biota</u> - The organic factor in pedogenesis has been the subject of considerable debate in the literature (for example, Major,

1951; Crocker, 1952; Jenny, 1958; Olson, 1958), most attention being devoted to vegetation (rather than fauna), as this is generally considered to be more important (Crocker, 1952). Thus, in this study as in virtually all chronosequence studies in the literature, the plant factor has been used as a close approximation to the biotic factor.

Two definitions of the plant factor have been employed so as to provide both a theoretical base and a practical, working definition.

The *effective disseminule factor*, after Crocker (1952), is represented by a floristic list of species now present on each barrier (or in each barrier region), and includes those colonizing biotypes lost from the soil sites during vegetation succession since time zero. The effective disseminule factor is therefore a concept which makes vegetation a strictly independent pedogenic factor, constant for all soil sites on a given barrier system. However, the distribution and composition of barrier vegetation is patently non-uniform (see Chapter 3), and hence the effective disseminule factor does not adequately distinguish vegetation at a fine-enough scale to be useful in the study.

To overcome the above problem, the *plant factor*, as redefined for practical purposes, is the species mix in the vicinity of each soil site under investigation and is represented by a floristic list. Such a definition arguably renders the plant factor non-independent; however, the writer maintains that this definition of the plant factor, and its field application, are valid under the relaxed chronosequence provisions envisaged by Jenny (1946, 1961). Further, the use of a dual definition (*effective disseminule factor* and *plant factor*) allows the similarity of the vegetation on the New South Wales barriers to be demonstrated, and yet also allows intra-barrier vegetation patterns to be assessed.

Additional Factors - No additional pedogenic factors were included in the study, although fire would have been a possibility. However, with the exception of one field area mentioned in Chapter Three, data are not available on bushfire occurrence, or its pedogenic effects.

2.1.4 Summary

The conceptual basis of the thesis is closely associated with Jenny's (1946, 1961) revised factorial model, in which three pedogenic state factors are recognized: time, initial state of the soil system (*Lo*), and external energy flux potential (*Px*).

In the foregoing discussion each of the state factors has been defined for application in the thesis. The dominant state factor, time (equivalent to soil age), is measured in environmentally corrected radiocarbon years. The subdominant state factor *Lo* consists of parent material and relief; parent material characteristics are assessed in the thesis by analyses of C horizon samples, and three aspects of relief are recognized - slope, topographic position and watertable depth. The third state factor, *Px*, comprises climate and biota. Macro and micro-climate are distinguished, and the biotic factor is defined in terms of the effective disseminule factor and the plant factor, the latter being used in relation to individual soil sites.

2.2 EXPERIMENTAL DESIGN

Given the objectives of the study and its theoretical-conceptual framework the next phase of the investigation — experimental design — was concerned with three main problems. These are:

1. Determination of suitable soil sampling locations.
2. Selection of specific soil profiles for study.
3. Choice of soil parameters.

2.2.1 Determination of Soil Sampling Localities

2.2.1.1 Geomorphological constraints. The selection of suitable soil sampling localities was predetermined to a large extent by the physical environment and geomorphic history of the east coast of Australia.

As typical "intrazonal" soils (Baldwin *et al*, 1938), the podzols of eastern Australia are found almost exclusively in sandy, siliceous deposits which experience a humid climate (Stace *et al.*, 1968). The coastal podzols are therefore confined to marine and aeolian sedimentary bodies (Northcote *et al.*, 1975), of Holocene and Pleistocene age (Langford-Smith and Thom, 1969). However, coastal podzols of Pleistocene age have been excluded from this study for, whether developed in the predominantly marine sands of an Inner Barrier (Thom, 1965) which accumulated during the Last Interglacial period (Marshall and Thom, 1976), or in aeolian sediments of probable Last Glacial age, these soils are not suitable for investigation using a factorial model because of the considerable and unquantifiable fluctuations in pedogenic conditions that they have experienced since their initiation. Furthermore, useful chronosequences of these Pleistocene soils are very hard to recognize because of the complete leaching of incorporated shell material, which precludes absolute radiocarbon age determinations, even when the ages of the soils fall within the range of this dating technique. As coral debris is exceedingly rare in these Pleistocene sediments uranium-series dating is not a generally applicable alternative technique.

Similar restrictions limit the usefulness in time - factorial studies of podzols formed in Holocene coastal dunes. Although the ages of such soils are within the range of radiocarbon dating, it is rare for the usually low concentrations of incorporated shell debris to survive subaerial leaching and to provide a basis for radiometric age determinations. However, one aeolian morphostratigraphic situation which occurs on the east coast of Australia does provide an *apparent* age framework for pedogenic studies. This is where a podzol profile has developed in relation to the current groundsurface of an aeolian sedimentary body and is underlain by one or more buried soil profiles. Carbon from any such paleosol may be used to establish a maximum age for all overlying profiles (including the contemporary soil) and a minimum age for all underlying paleosols. Where the carbon is in the form of charcoal pieces lying on a natural fire surface, it is probably safe to assume that it was associated with the burial of that surface by fresh sand accessions, following a fire and consequent groundsurface instability. Hence, the carbon should provide an indication of when the buried soil profile ceased developing, and should also give a minimum age for all other underlying paleosols.

Where a suitable succession of paleosols exists in aeolian deposits, and where sufficient dates can be obtained, it should be possible to calculate maximum age ranges for the development of each paleosol and for the surface soil. However, it is doubtful whether it is valid to correlate the degree of profile development of such soils with their respective maximum age ranges, for two reasons. First, there are unknown time-gaps inherent in these age ranges; between deposition of the carbon on the fire surface and burial of that surface by sand, and between this burial and the initiation of podzol development on the newly stabilized overlying groundsurface. Second, once buried and cut off from pedogenic processes a soil profile starts to degrade and this usually proceeds with time (Gerasimov, 1971). Hence the apparent degree of development of a buried podzol may not reflect the time it took to develop. For these reasons podzol soils developed in Holocene aeolian deposits were considered unsuitable for inclusion in the study.

On the basis of morphostratigraphic investigation, Thom (1974) categorized sand barriers of Holocene age on the New South Wales coast, and Thom *et al.* (1978)[1] further refined and extended this model. Of the four main depositional types recognized in the later paper the *prograded barriers* provide the most suitable geomorphic context for a time-factorial pedogenic study. Of the other three main barrier types, the *episodic transgressive* barrier type, formed by substantial aeolian accretion, was considered unsuitable for the reasons discussed above. The modes of geomorphic development of the *stationary* and *receded* barrier types have yielded stable groundsurfaces with a limited age range (Thom *et al.*,1978) and hence the ages of the podzols developed beneath these surfaces also vary little in age. For this reason stationary and receded barriers were also considered unsuitable for inclusion in the study.

2.2.1.2 Prograded barriers as sampling localities. The morphology of specific east Australian prograded sand barriers have been studied by many workers including Davies (1958, 1961), Bird (1961, 1965, 1973), Thom (1965), Hails (1968, 1969), Hails and Hoyt (1968), Langford-Smith and Thom (1969), Bird and Hopley (1969), Hopley (1970, 1971) and Wright (1970). However, it has only been in recent years

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1. B.G.Thom, H.A.Polach and G.M.Bowman, 1978. *Holocene age structure of coastal sand barriers in New South Wales, Australia.* Publication of Geography Department, Faculty of Military Studies, University of New South Wales. 86pp. This publication incorporates radiocarbon age determinations and field observations obtained during the investigation reported in this thesis.

that extensive drilling and adequate numbers of radiocarbon dates have resulted in a more comprehensive knowledge of the evolution of these morphostratigraphic features (Thom 1974, 1978; Ly, 1976, 1978; Thom *et al.*, 1978).

In general terms, a prograded bay barrier usually consists of a transgressive marine sand body which accumulated with the rising post glacial sea-level up to about 6000 years ago, and which grades landwards into backbarrier lagoonal sands and muds (Thom *et al.*,1978). This sand sheet is overlain by a regressive sand wedge which thickens seawards and is exposed at the surface as a multiple beach-ridge plain. The surface trend of the beach ridges is nearly always subparallel to the present shoreline. Individual ridges consist of sandy sediment that was deposited in a nearshore or beach environment and which was subsequently thinly capped by aeolian sand. The evolution of such beach ridges has been discussed at some length in the Australian coastal geomorphology literature; for example, Davies (1957), McKenzie (1958), Bird (1960), Thom (1964) and Jenkin (1968).

In New South Wales, regressive sand barrier facies usually date to about 5000 to 6000 ^{14}C yrs BP* at their landward side, and become progressively younger seaward. Progradation of the regressive facies by beach-ridge accretion was intermittent but possibly synchronous between barriers (Thom *et al.*, 1978). Age determinations on shell obtained from beneath the seaward-most stabilized ground-surfaces of prograded barriers in New South Wales range from 4000 to 1000 ^{14}C years*, but most barriers ceased prograding by about 3000 yrs BP* (Thom *et al.*, 1979, in prep.). Since this type of barrier ceased prograding, large foredunes, consisting of intermittently reworked marine-aeolian sediments, have accumulated along their seaward margins, immediately behind the beach zone.

Prograded bay barriers possess two attributes which make them ideal for time-factorial pedogenic studies.

1. The soils that develop in them are dateable. The marine sand which lies beneath each ridge and swale is of beach or nearshore origin, and usually contains a proportion of biogenic carbonate in the form of comminuted shell debris. This material is quite suitable for radiocarbon dating (see: Gillespie and Polach, 1977; Thom *et al.*, 1978), and an age determined in this way provides a maximum age for the overlying groundsurface, and hence also for the podzol developed in it. There is, however, a potential for a time-gap to exist between the death of the shells, their burial in the beach or nearshore zone, and the seaward progradation of the barrier to cover the site. Observations of contemporary beach-ridge accretion on prograding shores have shown that ridges can be constructed very rapidly when sediment supply is adequate (Olson, 1958; McKenzie, 1958), and the episodic accretion of the regressive facies of east Australian sand barriers under conditions of abundant sediment supply must therefore have resulted in rapid beach-ridge formation within each accretional episode (Thom, 1978). Sand stabilization by vegetation such as *Spinifex hirsutus*, *Festuca littoralis*, *Hydrocotyle* Spp. and *Scaevola calendulacca* would be very effective

under such conditions (Pidgeon, 1940; McDonald, 1971), and hence podzolization, in its broadest sense, could be initiated as soon as the groundsurface stopped receiving large additions of new sand.

Average accretion rates for the Australian beach-ridge plains studied by Thom *et al.* (1978) vary from 77 to 106 C14 years per ridge, but average rates for specific accretionary episodes within these barriers vary from 13 to 171 C14 years per ridge (Thom *et al.*, 1978, Table 2, Column 6). These rates are all essentially within the statistical uncertainty inherent in radiocarbon age determinations (±1 standard deviation). As any time lags that occurred within a progradational episode must have been of much shorter duration than the average ridge-rate for the episode, it is apparent that such time-lags must have been so short that they do not detract from the usefulness of this method of dating podzol development.

In Chapter Three consideration is given to problems of sample contamination by anomalously old reworked shell material. However, as Thom *et al.* (1978) and Polach *et al.* (1979, in press) point out, these problems are not common, are usually apparent, and can be avoided by multiple dating techniques. The latter have been carried out in the present investigation, whenever considered necessary (see Chapter 3 for details).

2. Prograded barriers provide a systematic spatio-temporal framework for time-factorial pedogenic investigations. A

transect which crosses a prograded bay barrier normal to the trend of the beach ridges is time (age) transgressive, whereas one which parallels the beach-ridge pattern is essentially time (age) synchronous, the precision of the relationship being determined by the rate at which the ridges developed (Thom *et al.*, 1978). The implication of this ergodic framework (Chorley and Kennedy, 1971) is that dated chronosequences of podzol soils may be obtained by sampling across a beach-ridge plain, whereas podzol profiles of the same age may be sampled along any beach ridge or swale. In the latter case bio-, litho-, (micro)climo- and even topo-sequences and functions are possible, depending on pedogenic conditions (Jenny, 1941, 1961). Further, by combining profiles from different barriers, not only is the temporal range of the framework extended, but where more than one profile of equivalent age exists, it is possible to examine a wider range of pedogenic conditions than is available on a single barrier. This is especially important in assessing the pedogenic effect of relief and parent material variations, but it can also be useful in studying vegetation effects.

The simple and regular morphology of a beach-ridge plain allows the relief factor in podzol development to be assessed. A podzol soil that has developed beneath adjacent ridge and swales should be free from significant parent material, age, and possibly plant factor variations, and hence should allow the topographic factor to be examined. If soil profiles are sampled only beneath ridges (or only beneath swales), the topographic effect is negated. However, comparisons of ridge or swale profiles may require some allowance to be made for the depth of the watertable, as this is in part a function of absolute elevation above sea level (Shepherd, 1970).

As mentioned in Section 2.1.3, the quartz-dominated mineral assemblage that constitutes the regressive facies of Holocene beach-ridge plains in eastern Australia is usually fairly homogenous in both texture and mineral composition (Hails, 1964, 1967; Shepherd, 1970; Ly, 1976). The sediment is largely derived from reworked Pleistocene deposits which accumulated on the continental shelf during the Last Glacial low sea level stage (Thom, 1974). However, even where local sediment sources are significant, the higher lithic to quartz ratio apparent in the sediments, allows the parent material variation to be assessed.

2.2.1.3 <u>Distribution of prograded barriers in eastern Australia</u>. Prograded barriers of Holocene age are not uncommon on Australia's eastern coast and have been reported by many workers. Davies (1959, 1961) has studied Holocene prograded beach-ridge plains on the east and north coast of Tasmania, and Dimmock (1957) noted such a feature on Flinders Island in Bass Strait. In the Gippsland region of eastern Victoria Bird (1961, 1965) has studied prograded barriers, some of which are Holocene in age. They have also been reported from the southern, central and lower northern parts of the New South Wales coast by Burges and Drover (1953), Hails (1968, 1969), Thom (1965) and Langford-Smith and Thom (1969).

Holocene prograded barriers are less common on the upper north coast of New South Wales, being mainly confined to the more embayed sections between Nambucca Heads and the mouth of the Clarence River (Langford-Smith and Thom, 1969). Where the broad deltaic plains of the northern rivers form the coastline, the extensive beach-ridge plains are of Pleistocene age (Marshall and Thom, 1976).

Hails (1964) and Coaldrake (1961) have studied the coastal lowlands of southern Queensland and have identified scattered areas of beach ridges of probable Holocene age, although Pleistocene barriers and massive Pleistocene—Holocene dune fields are more typical of this area. In tropical north Queensland, Bird and Hopley (1969) and Hopley (1970) have identified Holocene beach-ridge plains similar in morphology to those in southeastern Australia.

Many of the papers referred to above mention the podzol soils that have developed in the beach-ridge plains and several describe the differences in profile development that may be observed along a seaward to landward transect across the barriers (e.g., Bird, 1961, 1965; Davies, 1959, 1961; Burges and Drover, 1953).

2.1.1.4 Selection of specific bay barriers. Prograded beach-ridge barriers were selected on a systematic, rather than random, basis. Justification of the use of this procedure, and its implications for statistical manipulation of the data, are discussed in the next section. All barriers chosen have two features in common: they display distinct beach-ridge morphology, and hence their prograded nature was not in doubt prior to dating, and all are relatively wide (seaward to landward), and thus offered the best chance of a large age range coupled with a low average accretion period for each beach ridge.

The detailed characteristics of each barrier selected are given in the appropriate sections of Chapter Three. Most of the barriers selected are located in New South Wales. The reasons for this are:

1. The geomorphic history of New South Wales barriers is much better known, and more radiocarbon age determinations are available for these barriers, than for barriers from the other eastern states.
2. To obtain a sufficient number of soil profiles of different ages, and to ensure as large a range of profile ages as possible, it was necessary to sample profiles from a group of barriers where all were in a region of fairly uniform pedogenic conditions. The central and southern coast of New South Wales has a relatively uniform climate, an homogenous vegetation, and a relatively high concentration of suitable barrier types. Also, for logistic and financial reasons it was not considered feasible to conduct extensive fieldwork interstate. Therefore, the main group of barriers were chosen from the southern and central coast of New South Wales, and two additional barriers were selected, one from north Queensland and one from Tasmania, so that substantial differences in the macroclimatic factor could be incorporated into the study.

2.2.2 <u>Soil Sampling</u>

2.2.2.1 <u>Sampling problem</u>. A major problem associated with the design of this investigation was one that is quite common in the earth sciences. It arises from two conflicting considerations: one the one hand the requirement of a random population sampling scheme if the unbiased validity of many of the statistical tests which may be applied to the sample data is to be ensured; on the other hand, there is the need to obtain the maximum amount of useful information from the necessarily limited number of samples that it is possible to obtain and analyse (Griffiths, 1967).

Although simple random sampling of soil profiles is a statistically useful sampling technique (Krumbein and Graybill, 1965) it certainly is not very efficient for, as Hammond and McCullagh (1974, p.114) have noted, "...random samples tend to include clusters and leave gaps unless the random sample is very large ".

In this investigation the selection of most barriers was mainly predetermined by the availability of morpho-stratigraphic information and radiocarbon dates. Consequently, the choice of barriers was not random in the statistical sense, although a combination of stratified random sampling and systematic sampling was used for the location of soil profile sites on the barriers, and for the depth sampling of each profile. This subject is discussed in more detail below.

2.2.2.2 Sampling framework. Krumbein and Graybill (1965) have distinguished between a *target population*, whose members are not all available for sampling, and a *sampled population*, a subset of the target population which is available for sampling. As Harvey (1969, p.367) noted: "Strictly speaking, probabilistic inferences can be made only from the sample to the sampled population, but these conclusions may be extended to the target population on the basis of substantive judgement *and only on that basis*. This kind of situation is very common in geography".

In the thesis this distinction has been maintained. The target population consists of podzol soils developed in the Holocene siliceous sand barrier systems of eastern Australia, whereas the sampled population is restricted to podzols developed in the barriers actually sampled as part of the investigation. Consequently, any statistical inferences made about the sampled population, and applied to the target population later in the thesis, are applied entirely on the basis of substantive judgement. Such an approach is necessary because the selection of barriers for study was made on a non-random basis and could therefore have introduced systematic sample bias. However, the writer is of the opinion that the selection of barriers was representative of the target population, and therefore, that the sample statistics may be legitimately applied to the target population, within a strict factorial pedological framework. Where this has been done in the thesis it is always acknowledged as such.

2.2.2.3 Sampling procedures. Harvey (1969, p.359) has maintained that: "the selection of a sampling procedure, like the selection of an appropriate geometry or the selection of any mathematical language, is an empirical problem. It depends upon an empirical assessment of the reasonableness, efficiency, and feasibility, of a given design in the light of a given objective ".

The objective of the sampling scheme used in this study was to adequately and efficiently sample the spatial variability of the soils in those barriers which constitute the sampled population. Because soils are *spatially anisotropic* (Jenny, 1941), three-dimensional sampling was required: first, to sample the areal distribution of the soils, and second, to sample their vertical variation.

Areal Sampling Procedure. - Although the basic areal sampling unit was termed above a *soil profile* (because of pedological convention) the concept has been used in this study much in the sense of FitzPatrick's (1971) *pedounit*, and is therefore a three (rather than two)-dimensional column of soil, containing sufficient material from each sample depth for adequate laboratory characterization.

The selection of soil profile sites from the sampled population of barriers was by way of a *stratified random sampling scheme* (Berry and Baker, 1968; Krumbein, 1959). As Harvey (1969, p.363) has noted, stratified random sampling is much more efficient than simple random sampling, especially where there is a linear trend in the population distribution. This was known to be the case from preliminary investigations of the barrier soils by the writer, and from comments about the soils in the literature; for example, Bird (1961, 1965), Davies (1959, 1961) and Burges and Drover (1953).

Thus, each barrier was first stratified into three zones, wherein the central zone covered the maximum width of the beach-ridge plain (seaward-landward), while the two lateral zones were not usually as wide, because of the configuration of the bedrock embayments.

A transect line across the full width of the barrier was randomly located within the central zone of each barrier (except Rheban where this was precluded by barrier morpho-stratigraphy). An additional transect line was established in one of the lateral zones at each barrier (except Rheban), with the choice of the zone and the actual location of the transect line (normal to the beach-ridge pattern), again being randomly determined.

Each barrier was then re-stratified, this time *parallel* to the beach-ridge pattern, and hence normal to the original transect line(s). This stratification was based on prior knowledge of the soils of each barrier; such a procedure was recommended by Griffiths (1967, p.24). A soil study site was then randomly located on each segment of each transect line. At each soil site the simple distinction of the beach-ridge crest and the swale floor allowed one soil profile to be located in each topographic position. Where ridge/swale topography was locally so subdued that the area was essentially flat, only one soil profile was located at the site. At Woy Woy, Rheban and Cowley only swale soil profiles were sampled, because of logistic considerations.

Thus, stratified random sampling was used to locate the soil profiles on the barriers: it was used to locate transect lines, locate soil profile sites, and even individual ridge and swale soil profiles.

<u>Vertical Sampling Procedure</u>.- As vertical soil property changes are of major importance in this study, channel sampling (Griffiths, 1967) was considered most inappropriate, as was simple random depth sampling, which would yield poor profile coverage (Hammond and McCullagh, 1974). Judgement sampling has long been the main soil profile sampling procedure because a minimum number of samples can be used to represent a profile. However, judgement sampling is based on visual criteria (observed horizons) which may be misleading or inappropriate for some soil parameters, and hence may introduce bias into the sample. For the same reasons stratified random sampling, which is also based on visible horizon criteria and hence is virtually identical to judgement sampling, was also considered unsatisfactory.

The technique used was *systematic depth sampling*, whereby samples were taken at a fixed depth increment, starting at the surface of the mineral soil and proceeding down to the watertable. The main increment used was 30 centimetres (approximately 1 foot), but in the upper part of each profile (above about 60 cms) smaller increments were used (15 centimetres) to ensure that the closer spacing of soil horizons at this level would be adequately sampled. Intermediate samples were also taken when necessary, to include thin horizons and other pedological features.

Each soil sample taken from a pit was a *compound sample*, 3 centimetres thick (vertically), 60 centimetres wide (across the profile face, parallel to the beach ridge), and 10 centimetres deep (1800 cm^3). As it was not possible to dig soil pits deeper than two metres, a shell-type, hand-operated sand auger was used to obtain samples from below the base of the pit down to the watertable, which was occasionally deeper than six metres. These samples were uncontaminated, and the depth of the sample was always accurately determined. The only problems were that the sample was disturbed, and that its presampling shape was different to that of the pit samples - that is, the auger samples were columnar, about 10 centimetres long and about 5 centimetres in radius (786 cms^3). Each auger sample was centred on the required depth, and because these samples were from the lower part of the soil profile, the technique did not affect the accuracy or validity of the sampling scheme. Sampling below the watertable was not possible with the available augering equipment, but marine shell for radiometric dating was obtained from below the watertable by casing the auger hole and then using a hand operated sludge-pumping technique developed by the writer.

The spatial location of each soil sample was therefore determined by stratified random sampling in the areal dimensions, and by systematic depth sampling in the vertical dimension. Thus, each sample can be related to those above and below it by causal association (based on pedological theory), and can also be related through statistical inference to the three dimensional soil body that it represents.

2.2.3 Choice of Soil Properties

2.2.3.1 Criteria for selection. The soil properties used to monitor podzol development within the chronosequences, were selected using the following criteria:

1. The soil properties should be time-dependent in that they reflect the passage of time, given a balance of pedogenic factors.
2. The properties should characterize podzol development and the processes which are responsible for podzolization.
3. The properties should be of an "averaging" type, reflecting long-term trends, and not particularly sensitive to short-term fluctuations caused by seasonal environmental changes.
4. Both physical and chemical properties should be included.
5. Both the long and short-term accumulative and dissipative processes which operate in podzol formation,

should be reflected in the range of properties selected.

6. The properties should be useful in geomorphic research (not just relevant to biological soil science).

7. The soil properties should be relatively easy to measure in the field or laboratory, whichever is more appropriate.

8. The properties should also be relatively stable during transport and storage of soil samples.

2.2.3.2 Soil properties used in the study. The range of properties used in the investigation gave a broad coverage of the criteria listed above, yet were few in number and therefore could be comprehensively investigated. The properties are:

1. Soil profile morphology, which incorporates a range of soil profile characteristics, most of which are visible or permit assessment in the field. Included in the profile morphology category are the boundary configuration, thickness, colour, texture and structure of each horizon, as well as the presence of organic matter, the presence of marine shell debris and soil reaction (pH). For convenience, the laboratory determined moisture content of the soil is also included in this category.

2. Concentration of selected cations, namely, iron, magnesium, aluminium, calcium, manganese and sodium.

3. Organic matter content of the soil.
4. Quartz sand grain surface textures.
5. Organic-mineral grain surface coatings.

Details of the analytical techniques used to investigate each of these soil properties are given in the appropriate sections of Chapter Four, and in the Appendices. Clay mineralogy and soil micromorphology were also considered for use in the study. However, after preliminary investigations, it was found that the amount of clay in the podzol profiles was so small (see Chapter 3) that neither technique could be successfully applied.

Although Stevens and Walker (1970) recommended standardization of the soil properties used in chronosequence studies, many of the properties used in chronosequence investigations in the literature were considered inappropriate for use in the present study. The use of such properties as soil nitrogen content, carbon/nitrogen ratios, cation exchange capacity and available phosphorus, illustrate a preoccupation on the part of many investigators with the vegetative and plant nutritional aspects of pedogenesis. While these properties may be valid monitors of soil development, they are not compatible with criteria (1) and (3) above, and they certainly contradict criterion (6).

The complete absence of clay minerals from the quartzose barrier soils of eastern Australia (see Chapter Four), precludes the use of measures of clay formation, alteration and translocation, such as those discussed by Barshad (1964) and Birkeland (1974).

2.3 SUMMARY

In this chapter the conceptual basis of the thesis has been established and the research design discussed. In Section 2.1 Jenny's (1961) revised state factor model was outlined, its attributes and validity examined, and the pedogenic factors (as applied in the study) were defined.

The discussion about experimental design dealt with the suitability of various coastal deposits for chronosequence studies, the distribution of suitable sand barrier deposits in eastern Australia, and the choice of specific barriers for study. In addition, the location of soil study sites, the soil sampling procedures employed, and the selection of soil properties for study, were also discussed.

CHAPTER III

PEDOGENIC ENVIRONMENT

3.1 INTRODUCTION

The basic objective of this chapter is to present information about the pedological environments of the soil profiles studied, so that the factors of soil formation relevant to each profile may be assessed, and quantified as far as possible.

The information is presented at three levels of specificity. At the most general level, regional geology, macroclimate, vegetation and soils are described, so as to portray the physical setting of the New South Wales, north Queensland and Tasmanian sand barriers (Section 3.2).

At the second level of specificity, the environmental characteristics of individual barriers are discussed (Section 3.3); namely, morphostratigraphic configuration, geomorphic development, age structure, sediment characteristics, local climate and vegetation patterns (effective disseminule factor).

At the most specific level, information is used to define as precisely as possible the factors of soil formation applicable to each sampled soil profile; that is, profile age, parent material, relief, climate (macro and micro) and the plant factor are all assessed (Section 3.4).

A total of six sand barriers are discussed in this chapter: four from New South Wales, one from north Queensland

FIGURE 3.1

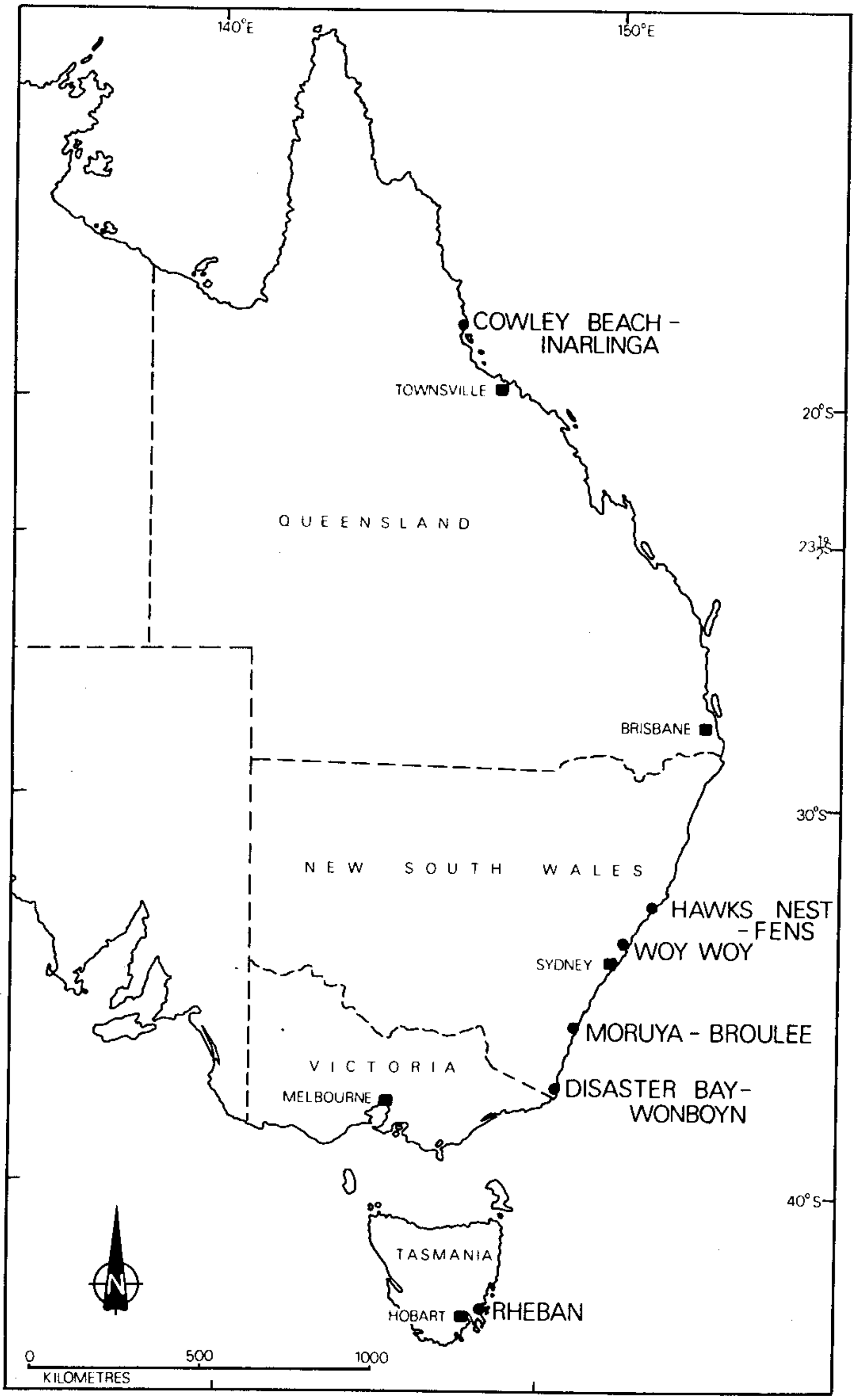

Figure 3.1 Location map of Eastern Australia, showing the six study barriers.

(Cowley-Inarlinga), and one from Tasmania (Rheban Spit).

3.2 REGIONAL SETTING

3.2.1 New South Wales Barriers

Figure 3.1 shows the location of the four New South Wales sand barriers: the Hawks Nest - Fens Outer Barrier, and the Woy Woy - Umina, Moruya - Broulee and Disaster Bay - Wonboyn beach-ridge plains. Large scale maps of each barrier are included in Section 3.3.1.

3.2.1.1 Geology. The four New South Wales barriers are located within three geological provinces.

1. New England Fold Belt. The Fens barrier is situated on the southern margin of this Palaeozoic province, near the confluence of the Tamworth and East Coast Troughs (Osborne, 1950; Brown *et al.*, 1968). The rocks, predominantly of sedimentary and volcanic origin, have been heavily deformed (probably at the end of the Permian; Branagan and Packham, 1970), resulting in north to northwest trending faults, folds and strata which have strongly influenced the drainage pattern and have allowed deep coastal embayments to develop. Erosion-resistant bedrock outliers, consisting of lithologies such as the Carboniferous Gilmore and Nerong Volcanics (Engel, 1962), now form several offshore islands and prominent headlands. These have considerably influenced the pattern of sediment accumulation during the Quaternary.

2. Sydney Basin. The Woy Woy - Umina beach-ridge plain is located towards the centre of the Sydney Basin, on sedimentary rocks of Triassic age. These include the Gosford Sandstone

(Narrabeen Group) and the overlying Hawkesbury Sandstone, both of which are near horizontally bedded, resistant quartzose sandstones, with occasional clay lenses and well-developed rectilinear joint patterns.

Locally, joint patterns have probably exerted the greatest structural control on the evolution of the Woy Woy area, but the Yarramalong Syncline, which runs a few kilometres to the west, may have had a more subtle regional influence. The dissected character of the Hornsby Plateau around Broken Bay has resulted from uplift during the Tertiary (Packham, 1969), or probably even earlier (Young, 1978), and subsequent bedrock erosion by the drainage system in relation to lowered base levels during glacial low sea level periods (Albani and Johnson, 1974).

3. Southern Fold Belt. Both the Moruya and Disaster Bay beach-ridge plains are located within this province, with Palaeozoic sedimentary rocks of the Lachlan Geosyncline predominating (Branagan and Packham, 1970). The region has had a complex deformational history, with major folding movements occurring from the Early Palaeozoic through to the Carboniferous, resulting in north to south trending outcrops of the main lithologies. The latter include (?) Cambrian and Ordovician metasediments, Silurian/Siluro-Devonian granites and Devonian sedimentary rocks in the Moruya district, and Upper Devonian to Upper Ordovician granites, rhyolites and sedimentary rocks around Disaster Bay. In addition, small areas of Tertiary basalt are found around Moruya and extensive fluviatile gravel deposits cap bedrock

highs in the vicinity of both barriers. A Late Tertiary date has usually been assigned to the elevation of the hinterland areas of the New South Wales south coast (e.g., Browne, 1969), but it has been recently argued that final uplift probably occurred very much earlier, certainly no later than Mid-Tertiary, with much of the area elevated during Early Tertiary or even Cretaceous times (Young, 1978, p.90).

From the above descriptions it is apparant that the regional geology of the three areas is distinctly different, although strong structural control and (meta-) sedimentary rock types are a feature of each area.

3.2.1.2 Climate. Table 3.1 presents a range of average annual climatic statistics for each of the New South Wales barrier localities. To facilitate comparison, statistics are also given for the north Queensland and Tasmanian barriers.[1]

In relation to the New South Wales localities, it is apparent that latitudinal trends exist in some of the annual statistics given in the table, although the magnitude of the trends is variable. For example, both mean and median annual precipitation decrease noticeably with increasing latitude, although the differences between the Fens and Woy Woy values are not substantial. In contrast, mean daily

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1 More detailed climatic statistics are included in Section 3.3.3.

TABLE 3.1

ANNUAL CLIMATIC STATISTICS FOR THE SIX BARRIER SYSTEMS.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
BARRIER	MET. STATION	LATITUDE	DISTANCE (Km) FROM MIDDLE OF BARRIER TO MET. STATION	ELEVATION DIFFERENCE, MET.STATION AND BARRIER (m)	ANNUAL PRECIPITATION					ANNUAL TEMPERATURES			ANNUAL MEAN RELATIVE HUMIDITY %	EVAPORATION APPROXIMATE ANNUAL mm.	THUNDERDAYS AVERAGE NO. PER ANNUM.	PRESCOTT'S (1949) SOIL LEACHING INDEX
					MEAN mm.	MEDIAN mm.	RAINDAYS no.	INTENSITY INDEX ($\overline{X}$/RAINDAYS)	SUMMER: WINTER RATIO DJF:JJA ONDJFM:AMJJAS	MEAN DAILY MAXIMUM °C	MEAN DAILY MINIMUM °C	MEAN DAILY AVERAGE °C				$\frac{P}{E^{0.73}}$
COWLEY BEACH-INARLINGA, NORTH QUEENSLAND.	INNISFAIL MOURILYAN	17°31'S. 17°35'S.	17 12	3 0	3644 3392	3579 3377	155 146	23.5 23.2	0.31 0.56 0.30 0.53	27.5 -	19.5 -	23.5 -	76 -	2500	5-10	12.1
HAWKS NEST - FENS OUTER BARRIER	NELSON BAY	32°43'S.	12	11	1332	1293	139	9.6	1.33 1.34	22.6	13.7	18.2	66.5	1800	20	5.6
WOY WOY - UMINA	NARARA (GOSFORD)	33°24'S.	11	25	1308	1249	105	12.5	0.77 0.87	22.8	10.7	16.8	-	1800	20	5.5
MORUYA HEADS-BROULEE	MORUYA HEADS	35°55'S.	3	5	931	885	105	8.9	0.74 0.82	20.0	11.0	15.5	71	1650	5-10	4.2
DISASTER BAY-WONBOYN	GREEN CAPE	37°16'S.	9	13	766	750	122	6.3	0.91 0.90	18.0	12.1	15.1	80	1500	10-15	3.7
RHEBAN SPIT, TASMANIA.	ORFORD RHEBAN	42°34' 42°38'	11 2.5	4 25	710 650	670 590	128 122	5.5 5.3	1.10 1.11 0.98 0.96	17.9 -	7.1 -	12.5 -	66 -	1100	<5	4.3

average temperature differs by only 3^{o}C between the four barrier localities, although once again the north to south diminishing trend is evident. Average annual evaporation displays a similar minimal trend, which is reflected in Prescott's (1949) Soil Leaching Index (Column 17). The remainder of the climatic statistics in Table 3.1 do not show distinct latitudinal changes and, in fact, most vary only slightly between the four New South Wales localities. The New South Wales climatic values tend to be intermediate between those for Cowley Beach - Inarlinga (north Queensland) and those for Rheban Spit (Tasmania), with substantial differences between the values for the Queensland and New South Wales stations. This situation is reflected in the climatic classifications that have been applied to the various localities. Köppen (1936) would designate the Fens and Woy Woy areas as *Cfa* (warm, with uniform rain, hot summers), but would classify the Moruya and Disaster Bay regions as *Cfb* (warm, uniform rain, long mild summers). The Rheban area would also be classed as *Cfb*. Cowley Beach (Innisfail) is designated as *Af*, which symbolizes a hot, rainy climate with no dry season. In comparison, Thornthwaite (1933) would designate the Fens, Woy Woy and Moruya regions as *BB'r* (humid and warm with good moisture in every season) but would distinguish the Disaster Bay area as *CB'r* (subhumid and warm with good moisture in every season). Rheban falls into the latter category and Cowley Beach is classed as *AB'* (super-humid, warm climate).

In general terms, the Köppen and Thornthwaite climatic classifications recognise only minor differences between the climates of the New South Wales localities and Rheban, but strongly distinguish these climatic types from that at Cowley Beach.

3.2.1.3 Vegetation. On the basis of the predominant regional native vegetation forms and subforms, Specht (1970) has classed the vegetation of both the Fens and Woy Woy areas as *Open-Forest*, with *Shrubby Open-Forest* being the most common subform. *Open-Forest* consists of tall *Eucalyptus* trees, 10-30 metres high, of forest form with flat crowns, and with boles longer than the depth of crown. The *Shrubby Open-Forest* subform is a typical *Open-Forest*, with a well-developed understory of xeromorphic shrubs and a sparse herbaceous stratum. According to Williams (1955), the chief determinant of his synonymous vegetation form *Dry Sclerophyll Forest*, is intermittent soil moisture stress and soil nutrient deficiencies, both particularly important factors in sandy coastal soils (Stace, *et al.*, 1968).

Specht (1970) classed the regional vegetation of the Moruya - Disaster Bay area as *Tall Open-Forest*, which is dominated by evergreen, forest-form *Eucalyptus* trees giving a foliage cover of 30-70 percent. These trees are often over 30 metres tall, with a dense understorey of small trees, large shrubs, tree ferns, etc. Fire has a profound effect on the development of this vegetation sub-form, post-fire regeneration occurring mostly from seed (*idem*, p.52).

3.2.1.4 Soils. Two soil classification schemes have been used in the literature to categorize and describe the predominant *district* soils of the four New South Wales barrier localities. Stace *et al.* (1968) have used *Great Soil Groups*, arranged by degree of profile development and degree of leaching, while Northcote (1974) and Northcote *et al.* (1975) have employed a symbolic descriptive system which relates to the visual physical properties of the soil profile (*profile form*). Table 3.2 presents both the Stace and Northcote classifications of the soils of the New South Wales, north Queensland and Tasmanian barrier localities. The extensive area of unconsolidated sediment in the Newcastle Bight-Myall Lakes region (Fens locality) has enabled a distinction to be drawn between the soils typical of the sandy areas, and those developed on the hinterland bedrock. This distinction has not been made in the other localities.

It is apparent from Table 3.2 that a range of soil types occurs at the barrier localities, although similar district soils are found in both the Fens and Disaster Bay areas. The Cowley and Rheban soil classifications are discussed below.

3.2.2 Cowley Beach - Inarlinga Barrier, North Queensland

The Cowley barrier is located about 100 kilometres southeast of Cairns, in the tropical, high rainfall area of north Queensland (see Figure 3.1 for location). The barrier was selected primarily to provide a strong climatic contrast to the New South Wales and Tasmanian localities.

3.2.2.1 Geology. The Cowley - Inarlinga region lies within the Hodgkinson Trough, a northern sedimentary basin of the Palaeozoic Tasman Geosyncline. The oldest and most extensive

TABLE 3.2

DOMINANT SOILS OF THE BARRIER LOCALITIES

BARRIER	CLASSIFICATION		
	STACE *et al.* (1968)	NORTHCOTE *et al.* (1975)	
	Great Soil Group	Principal Profile Form	Description
FENS (district soils)	Soloths	Dy 3.41	Duplex soils; acid, pedal conspicuously bleached A_2, mottled yellow.
(local soils)	Podzols and Humic Podzols	Uc 2.33	Bleached sands; uniform coarse textured, conspicuous A_2 and pan in B horizon.
WOY WOY	Yellow Earths	Gn 2.74	Massive earths (gradational texture); coherent porous B horizon, conspicuously bleached A_2.
MORUYA	Prairie Soils	Gn 3.21	Structured earths (gradational texture); acid, brown, with smooth ped fabric, no A_2.
DISASTER BAY	Soloths	Dy 3.41	Duplex soils; acid, pedal, conspicuously bleached A_2, mottled yellow.
COWLEY	Not determined	Um 6.34	Uniform, medium textured soils; deep and friable, with distinctly pedal profile, structured B horizon of smooth-faced peds, no A_2 horizon.
RHEBAN	Solodized Solonetz and Solodics	Db 1.42	Brown duplex soils; with neutral, hard,pedal profile and bleached A_2 horizon.

rocks in the vicinity of the barrier are Siluro-Devonian in age, and are known as the Barron River and Barnard Metamorphics (Queensland Geology Sheet, 1:2½ million, 1975). This formation consist of strongly metamorphosed greywackes, shales and basic volcanic rocks, with occasional thin limestones (Brown *et al.*, 1968). Carboniferous volcanics and Permian granites are also found inland from the Cowley barrier, as are the extensive Tertiary and Pleistocene basalt flows which cap the Atherton Tableland. Offshore, the Great Barrier Reef is composed of Holocene and Pleistocene coralline limestone, resting on a wide platform of (?) Tertiary strata (Maxwell, 1968).

3.2.2.2 Climate. The most notable feature of the climate of the Cowley Beach - Inarlinga region is the extremely high annual rainfall. The annual mean (Table 3.1, column 6) and median (column 7) rainfall for both Innisfail and Mourilyan are well in excess of 3000 mm (118 inches), with the Innisfail figures exceeding 3500 mm (138 inches). It is probable that the annual average precipitation at the Cowley Beach-Inarlinga barrier is similar to the Mourilyan value.

Average number of raindays per year at both Mourilyan and Innisfail (Table 3.1, column 8) are somewhat higher than at the other study barriers, and the intensity index (column 9) is considerably higher. Rainfall is summer dominated (column 10), resulting from a combination of southeasterly trade winds, monsoonal conditions and tropical cyclones (Gentilli, 1972). However, both Mourilyan and Innisfail receive (on average) a minimum of 81mm during each month of the year, and therefore no month is really dry.

As is to be expected for an area located within the tropics ($17^{o}40'$ South), the annual temperature figures (Table 3.1 columns 11, 12 and 13) are moderate to warm, but mean annual relative humidity (at Innisfail) is not as high as might be expected, and is in fact lower than the figure for Disaster Bay (see column 14). Annual evaporation is considerably higher in this north Queensland area than it is at any of the other barrier localities (column 15), but the average number of thunderstorms per year is comparatively low (column 16). The Prescott Soil Leaching Index for Innisfail (column 17) is much greater than it is for the other study barriers, indicating that more intense soil leaching conditions exist in the Cowley region.

In general terms, the climate of the Cowley area may be classed as humid and tropical, with prevailing summer rainfall.

3.2.2.3 Vegetation. Specht (1970) classified the native vegetation of the Cowley region as *Layered Open-Forest*, with areas of *Closed-Forest* (equivalent to Williams (1959) *Rain Forest*) located on the margins of the region, especially on the high rainfall slopes to the west. *Layered Open-Forest* possesses the characteristics of the *Open-Forest* form, previously described in relation to the New South Wales barriers (Section 3.2.1.3), but also typically displays at least two substrata of tropical shrubs and herbs.

3.2.2.4 Soils. Stace *et al.* (1968) were not able to allocate the soils of the coastal plain of northeast Queensland to a Great Soil Group, because of a lack of descriptive information on which to base an evaluation. However, Northcote *et al.* (1975) did classify these soils (see Table 3.2). They were symbolized as *Um 6.34*, and described as deep friable soils, with distinctly pedal profiles of uniform medium texture, having structural B horizons of smooth-faced peds, and no A_2 horizons (*ibid.*, p.42).

3.2.3 Rheban Spit, Tasmania

Rheban is located on the mid-east coast of Tasmania, about 60 kilometres northeast of Hobart (see Figure 3.1 for general location).

3.2.3.1 Geology. The vast dolerite sill that dominates the geology of central and eastern Tasmania, forms the main rock type in the area around Rheban. The dolerite was intruded into Permian and Triassic sediments in the Middle Jurassic and is of the tholeiitic quartz-dolerite association, rich in silica and calcium, but poor in iron, sodium and titanium (McDougall, 1961a, 1961b). Apart from the dolerite and unconsolidated Quaternary deposits, the only other lithologies in the Rheban area are: small outcrops of Triassic quartzose and feldspathic sandstones (Hale, 1962); uplifted Permian sedimentary rocks on nearby Maria Island (Banks, 1962); and scattered outcrops of Upper Devonian - Lower Carboniferous granites and granodiorites (Spry and Banks, 1962).

Faulting has been almost continuous throughout the Cainozoic in Tasmania, but the more significant movements were probably in the early Tertiary, when tensional stresses broke the state into a series of horsts and grabens with a general north to north-west trend (Solomon, 1962). Rheban lies within the Oyster Bay Graben, which is bounded by north-trending faults just to the west of Orford and Triabunna, and on the east by a fault system through the Freycinet Peninsula and Maria Island (Figure 3.14). The Mercury Passage and Oyster Bay occupy the southern end of the flooded graben.

3.2.3.2 Climate. Although rainfall statistics are available for the Rheban meteorological station (located adjacent to Rheban Spit), temperature records have not been kept and it is necessary to use data for Orford, located about 11 kilometres north of Rheban. Table 3.1 incorporates the available annual climatic statistics for both stations.

Annual mean and median precipitation are less for Rheban, than for Orford (Table 3.1, columns 6 and 7), and in this case the Rheban figures are obviously more appropriate for Rheban Spit. The annual precipitation figures for both stations are the lowest of all the barrier localities examined. Annual average number of raindays (column 8) are similar for Rheban and Orford, and are midway in the range of values for the New South Wales barriers. However, the precipitation intensity index (column 9) is lower than for any of the other barriers, and hence rainfall is more evenly balanced between summer and winter at Rheban, than it is at the other barrier localities.

The average annual temperature figures for Orford (columns 11 to 13) are consistent with the trend of decreasing temperature with increasing latitude. This is most evident in the mean daily average and mean daily minimum temperatures, which are substantially lower than the corresponding figures for Disaster Bay (columns 12 and 13). Both average annual evaporation (column 15) and the average number of thunderdays per year (column 16) are lower at Rheban than they are at any of the New South Wales localities. Prescott's Soil Leaching Index for Rheban approximates the value for Moruya, and exceeds the figure for Disaster Bay (column 17).

As noted earlier, Köppen (1936) would designate the Rheban climate *Cfb* (warm, uniformly distributed rain, long mild summers), whereas in terms of Thornthwaite's (1933) classification it would be *CB'r* (subhumid and warm, with good moisture in every season).

3.2.3.3 Vegetation. Williams (1955) mapped the Tasmanian east coast region around Rheban as having a *Temperate Woodland (Mixed)* vegetation, and he described the dominant subform as *Sclerophyll Shrub Woodland.* This subform has:

> ... a prominent layer of low sclerophyll xeromorphic shrubs with very few perennial herbaceous plants, although those that have perennating buds beneath the soil surface (geophytes) and short-lived annuals are frequently seasonally prominent. The best development seems to occur in those regions with a pronounced summer drought ... on soils with a very low nutritional status ... leached sands and lateritic soils (*ibid.*, pp.9-10).

Temperate Woodland (Mixed) became simply *Woodland* in Specht's (1970) vegetation classification. *Woodlands* are dominated by evergreen *Eucalyptus* trees with a foliage cover of 10 - 30%. The trees usually assume a woodland form, with rounded crowns, and the length of the bole is usually less than the depth of the crown. The formation is developed under a lower rainfall than the *Open-Forest* formations of the New South Wales barriers, but tends to grade into the latter when it is located in intermediate rainfall areas (*ibid.*, p.54). The Rheban district is such an intermediate rainfall region. Ground fires occur periodically in *Woodlands*, but rarely destroy the dominant trees; most of the understorey species regenerate readily, either from underground root-stocks or from seed (*ibid.*, p.55).

3.2.3.4 Soils. Stace *et al.* (1968) assigned the dominant soils of the east coast of Tasmania to the *Solodidized Solonetz and Solodic* Great Soil Groups. These soils display:

> ...strong texture differentiation with a very abrupt wavy boundary between A & B horizons, a well-developed bleached A_2 horizon, strong coarse columnar or blocky B horizons, and acid A & B horizons grading to strongly alkaline B - C horizons (*ibid.*, p.161).

Northcote *et al.* (1975) classified the soils of this area as *Db1.42*; that is, neutral, hard, pedal, Brown Duplex soils, with bleached A_2 horizons. They are described as having a distinct texture contrast between the hard-setting A horizons and the moderately to strongly pedal, clayey B horizons, of which the uppermost layer (at least 15 cms thick) is whole-coloured and brown (*ibid.*, p.116). *Db1.42* is specifically mentioned as reaching its most extensive development in eastern Tasmania, where these soils have formed on dolerite (*ibid.*, p.118).

3.3 SAND BARRIER CHARACTERISTICS

The environmental information contained in this section is more specific than that given in relation to the Regional Setting (Section 3.2). It pertains to the pedogenic environment of the individual beach-ridge plains and forms the basis for the detailed pedogenic factor data presented in Section 3.4 (Soil Site Pedogenic Characteristics).

3.3.1 Barrier Morphostratigraphy, Geomorphic Evolution and Age Structure

In the following discussion the morphostratigraphy and geomorphic development of each beach-ridge plain is outlined and its age structure is determined. This information is used in Section 3.4 to assign ages to the various soil sample sites located on the beach-ridge plains.

3.3.1.1 Hawks Nest-Fens Barrier. The Fens Embayment contains both a Pleistocene Inner Barrier and a Holocene Outer Barrier (Thom, 1965), separated by an interbarrier depression, 1-2 kilometres wide (Langford-Smith, 1969). A Fens Embayment locality map is given in Figure 3.2.

The Hawks Nest - Fens Outer Barrier beach-ridge plain is about one kilometre wide and over 13 kilometres long (length to width ratio, 1:0.08). It contains about 20 distinct ridges and a wide foredune complex which rises to over 12 metres above mean sea-level. The foredune complex consists of active sand along much of its length, but towards the northern end, near Dark Point, the foredune has degenerated into a free-moving sand sheet which has encroached

FIGURE 3.2

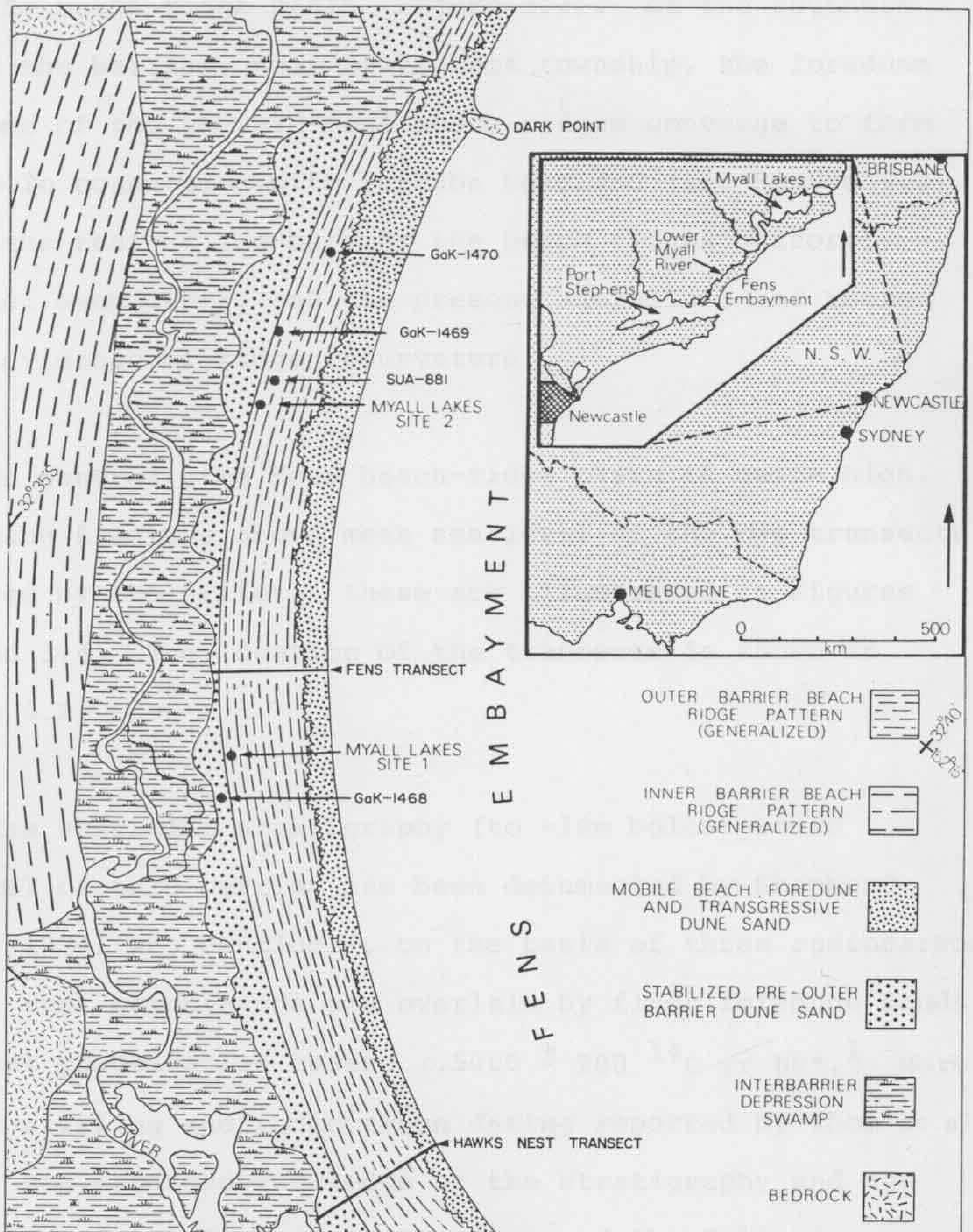

Figure 3.2 Map of the Fens Embayment, showing the Outer Barrier beach-ridge plain, part of the Inner Barrier, and the Interbarrier Depression. Also shown are the locations of the Fens and Hawks Nest transect lines, the location of the Myall Lakes soil sites, and the sampling sites for some ^{14}C dates.

upon the beach-ridge plain (Figure 3.2). At the southern end of the barrier, near Hawks Nest township, the foredune and some of the seaward-most beach ridges converge to form a tombolo connection with Yacaaba Headland (see Figure 3.2). Along the rest of the barrier the beach ridges uniformly parallel each other, and the present shoreline, and there is no evidence of ridge recurvature.

In general, the Fens beach-ridge plain is quite high, averaging 6 metres above mean sea-level at the two transects surveyed by the writer; these are illustrated in Figures 3.3 and 3.4. The location of the transects is shown in Figure 3.2.

The surficial stratigraphy (to -10m below ground surface) of this barrier has been documented by Shepherd (1970, 1974) who concluded, on the basis of three radiocarbon dates, that beach sands are overlain by finer foredune sands and that progradation ceased *c.*5000 $\pm$ 200 ^{14}C yr BP*.[1] More recent drilling and radiocarbon dating reported by Thom *et al.* (1978) has expanded knowledge of the stratigraphy and age structure of the Fens Outer Barrier, and the following discussion is based on this work, with additional information subsequently obtained by the writer (Thom *et al.*, 1979, in prep.). The stratigraphy, as shown in Figure 3.3, is based on a section located 7 kilometres north of Hawks Nest (see Figure 3.2). This section involves six holes drilled

1. The asterisk denotes an *environmentally (ocean reservoir) corrected* date. See explanation in Section 2.1.3.

FIGURE 3.3

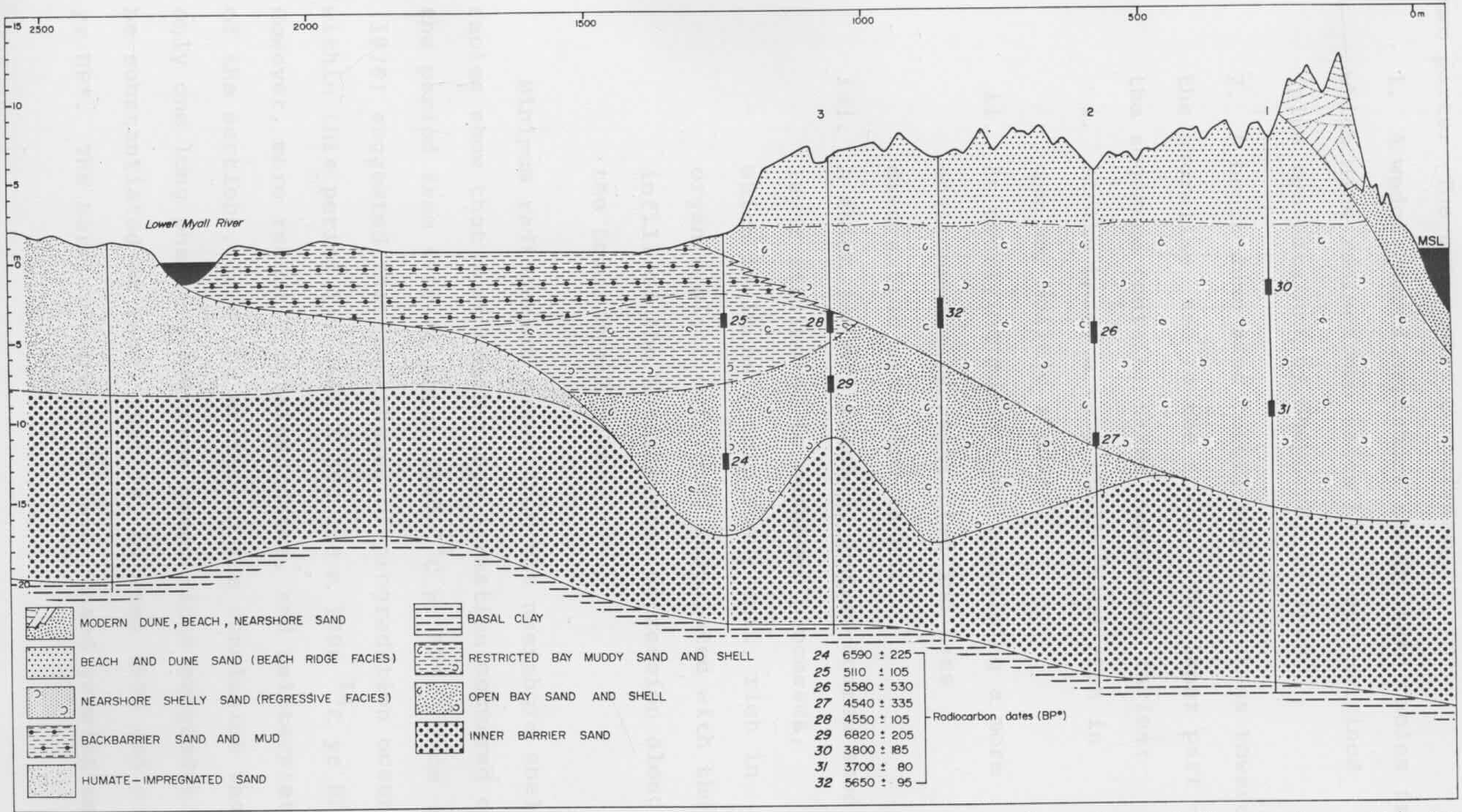

Figure 3.3 Cross-section of the Fens Outer Barrier along the Fens transect line (see Figure 3.2), showing soil/drill hole sites, facies, and ^{14}C age distribution. All dates are environmentally corrected years BP*. The Inner Barrier is to the left of the Lower Myall River. After Thom *et al.* (1978).

into the Inner Barrier basement, and can be divided into two parts. The outer part comprises:

1. A wedge-shaped nearshore shelly sand facies from which nine radiocarbon dates have been obtained (plus two obtained by Shepherd, 1974).

2. A beach-dune sand cover, which thickens towards the shoreline and to the north. The inner part of the sequence contains three *backbarrier* facies:

   i. At the base, a very shelly sand, rich in *open bay* mollusc species.

   ii. An overlying muddy sand containing a more environmentally restricted and less diversified estuarine fauna.

   iii. A thick (3-5m), leached, medium-coarse sand layer attributed to washover processes, which includes a thin sandy unit, rich in organic plant detritus, associated with the infill of the interbarrier depression along the Lower Myall River.

Minimum radiocarbon dates from the nearshore shelly facies show that most beach-ridge formation occurred during the period from 4900 to about 3300 ^{14}C yr BP*. Thom *et al.* (1978) suggested that two phases of progradation occurred within this period (*c.* 4600 $\pm$ 300 and *c.* 3700 ^{14}C yr BP*). However, more recently obtained dates, and reinterpretation of the sections, lead the writer to the conclusion that only one long phase of Holocene beach-ridge progradation can be substantiated at Fens, that is, between 4900 and 3300 ^{14}C yr BP*. The barrier appears to have ceased growing seaward

FIGURE 3.4

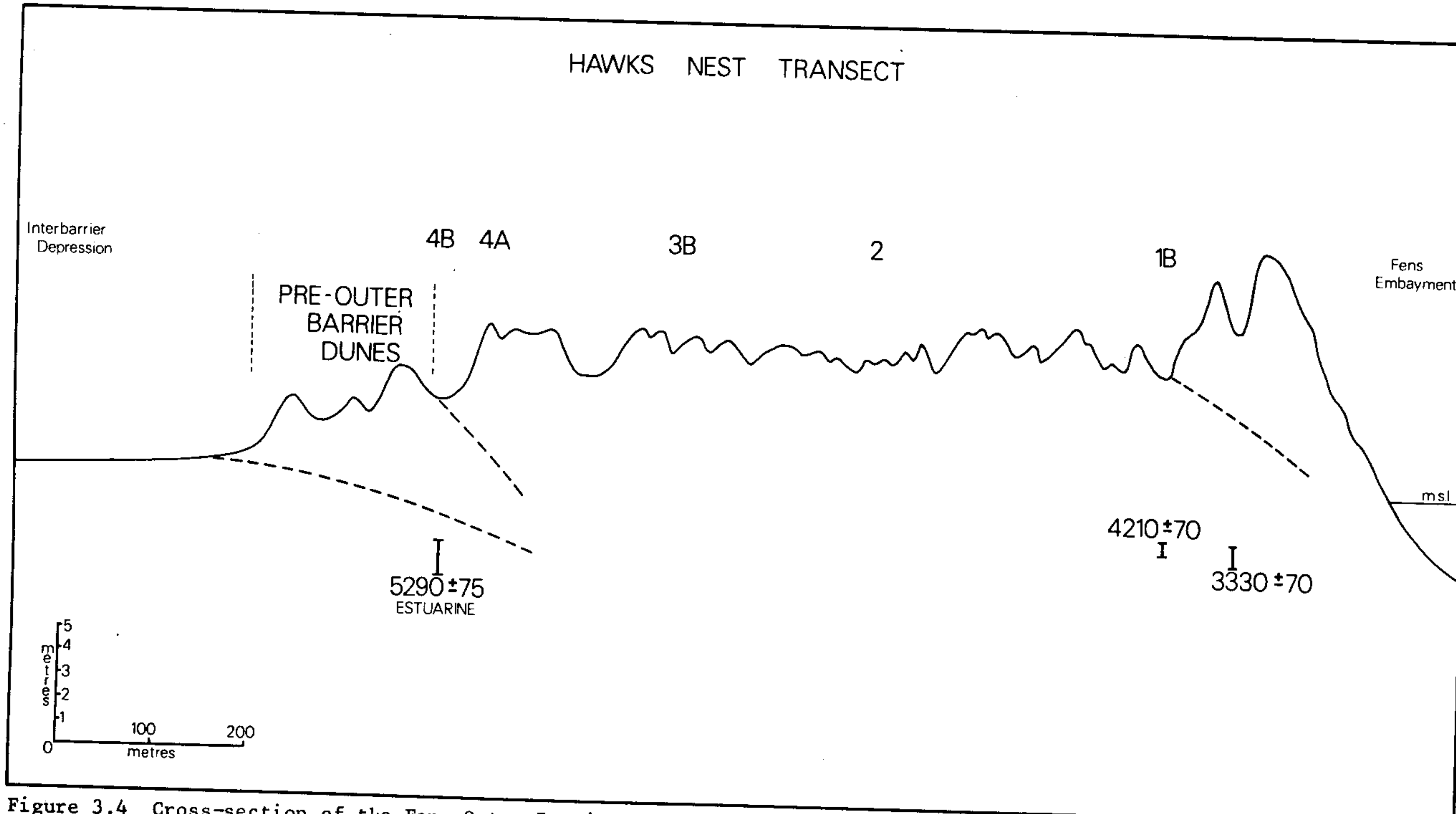

Figure 3.4 Cross-section of the Fens Outer Barrier along the Hawks Nest transect line (see Figure 3.2), showing the location of soil/drill hole sites and the depth of shell samples used for ^{14}C dating. The ages are environmentally corrected years BP*.

since 3300 ^{14}C yr BP*, or alternatively, the barrier has been eroded back to its present position, removing later phases of progradation. Although the latter may have happened to a minor degree, the height and mass of the established foredune, its complex structure involving locally buried soils, and the position of the headlands, limit the likelihood of extensive past barrier growth seaward of the present shoreline.

The age structure of the *backbarrier*, or quiet-water deposits, suggests the near-vertical growth of the Outer Barrier between 7000 and 6000 ^{14}C years* ago. From the mollusc composition, a sandy partially enclosed bay is inferred, which opened to the south toward Port Stephens (Figure 3.2). The rich shelly facies rises close to present sea-level in this direction. At the site of the Fens section it dates 6600 to 6800 ^{14}C years* at 13m below MSL (see C14 numbers 24 and 29 on Figure 3.3), but 4 kilometres to the south near the Hawks Nest transect, a similar fauna dates 5300-5000 ^{14}C years BP* (ANU-1665, SUA-883, Appendix 1-2) at -4m MSL and reflects the post - 6000 yr BP* infilling of the interbarrier depression. Figure 3.3 shows a restricted shallow-water muddy sand, recovered at -4m MSL, containing *Anadara trapezia* and oyster shells (*Ostrea* spp.), which date 5110 $\pm$ 105 ^{14}C yr BP* (ANU-1666) and which also relate to the infilling. A slightly older date (5830 $\pm$ 145 ^{14}C yr BP*, GaK-1468, Appendix 1-2) was obtained on a similar fauna by Shepherd (1970, 1974). The latter shells were recovered at a depth of 2m below MSL, near the site of the Fens section (see Figure 3.2 for location), indicating that the inter-barrier depression infilled progressively towards the south.

The following stages can be recognized in the development of the Outer Barrier at Fens:

1. A low-relief barrier, which only partially enclosed a faunal-rich sandy bay, was initiated within the Fens embayment at least 7000 ^{14}C years* ago, when sea-level was approximately 10 to 15 m below its present position.

2. For a period of 500 to 1000 ^{14}C years after sea-level reached its present position, the innermost beach ridge of the Outer Barrier formed a highly mobile open-ocean shoreline, subject to periodic washover and aeolian instability. Relevant dates for this feature are SUA-881 (5920 ± 75 ^{14}C yr BP*) and ANU-1530 (5650 ± 95 ^{14}C yr BP*, see Appendix 1-2). Behind this barrier estuarine conditions and species diversity became progressively more restricted to the south, that is, towards Port Stephens.

3. The Outer Barrier commenced progradation approximately 4900 ^{14}C yr BP*. Critical dates for this event are GaK-1469 (4930 ± 80 ^{14}C yr BP*) and GaK-1470 (4950 ± 80 ^{14}C yr BP*), both from within the nearshore shelly facies; their locations are shown in Figure 3.2. ANU-1528 (4550 ± 105 ^{14}C yr BP*), on estuarine shells from near the contact with coarse beach sands of the initial washover barrier, and ANU-1336 (4540 ± 335 ^{14}C yr BP*), both relate to shell deposited well

after progradation had commenced (see Figure 3.3). Progradation continued (perhaps intermittently) until at least 3300 ^{14}C yr BP*. Dates SUA-882 (4210 $\pm$ 70 ^{14}C yr BP*), ANU-1531 (3800 $\pm$ 185 ^{14}C yr BP*), ANU-1532 (3700 $\pm$ 80 ^{14}C BP*) and SUA-884 (3330 $\pm$ 70 ^{14}C yr BP*) are all from this progradational phase. The sampling locations of these dates are indicated in Figures 3.3 and 3.4. One open-ocean shell-hash date from the sequence is considered to have been reworked from the washover barrier deposit, and is thus *anomalously old* (ANU-1335, 5580 $\pm$ 530 ^{14}C yr BP*).

4. Over the last 3300 ^{14}C years* or so, a complex foredune has developed along the seaward margin of the Outer Barrier. This foredune is now undergoing extensive aeolian erosion, especially at the northern end. Estuarine conditions are now confined to the southern end of the interbarrier depression, near Port Stephens. Elsewhere the depression and backbarrier sand flat are covered by a fresh to brackish-water swamp.

3.3.1.2 <u>Woy Woy - Umina Barrier</u>. The Woy Woy - Umina barrier system fills a large area between Broken Bay and Brisbane Water, on the lower central coast of New South Wales, about 40 kilometres north of the centre of the City of Sydney. Figures 3.5 and 3.6 show the location of the barrier and its general configuration. The Woy Woy barrier has previously been studied by Burges and Drover (1953), who worked on its pedological and morphological characteristics,

FIGURE 3.5

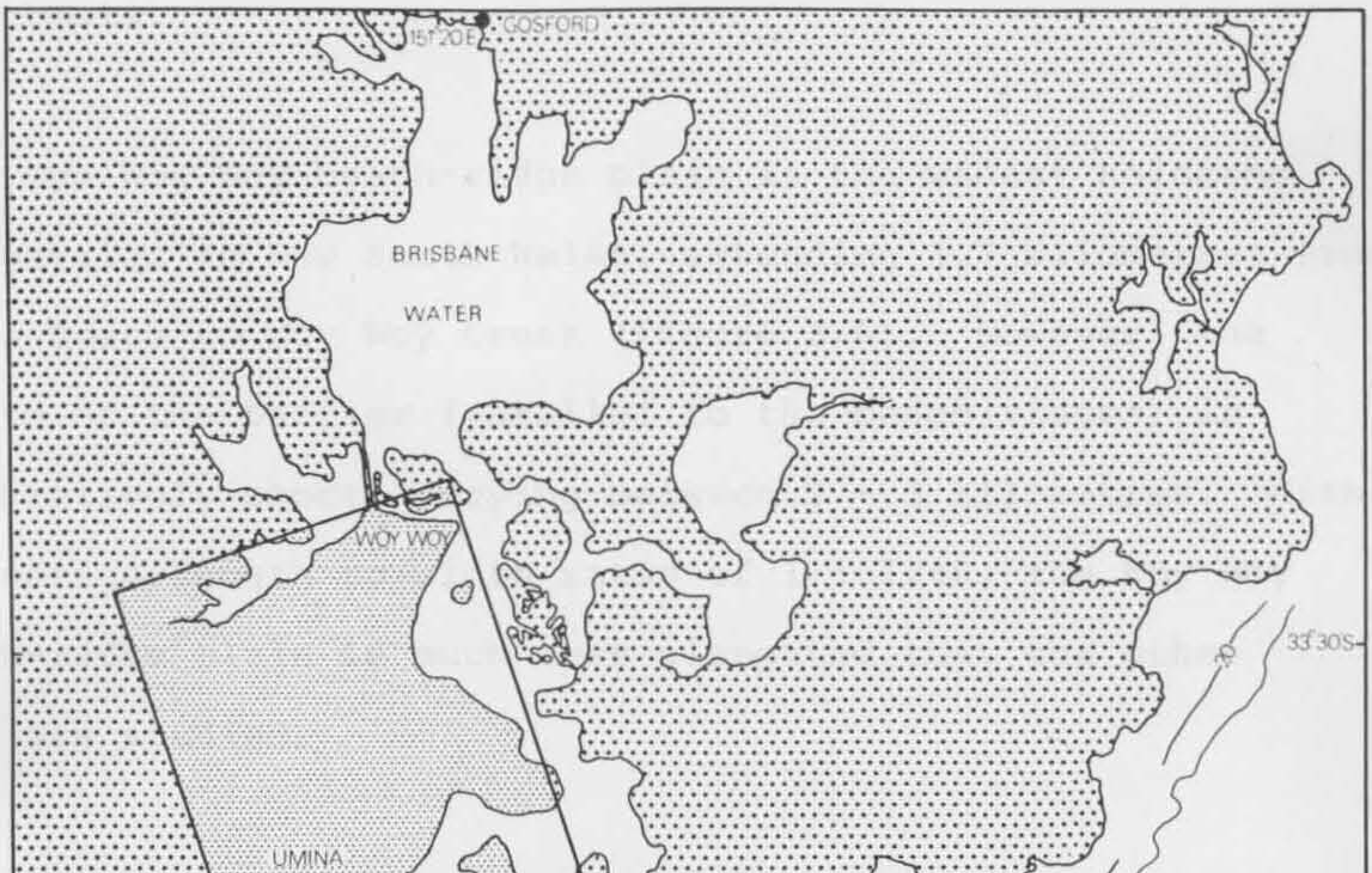

Figure 3.5 Map showing the general location of the Woy Woy-Umina beach-ridge plain in Broken Bay. The designated area is shown enlarged in Figure 3.6.

Hails (1969a, 1969b), who extended the work on the morphology and evolution of the barrier, and Thom *et al.* (1978), who revised the earlier work on the basis of radiocarbon dates obtained by the present writer. These dates, and additional unpublished radiocarbon age determinations, are included in the thesis.

The Woy Woy beach-ridge plain is the widest Holocene bay-barrier in New South Wales, extending 3.7 kilometres from Umina Beach to Woy Woy Creek (Figure 3.6). However, the length of the barrier (parallel to the beach ridges) is comparatively short, varying between 2 - 3 kilometres. With an average length to width ratio of 1 : 1.48, the Woy Woy beach-ridge plain is much less elongated that the other barriers studied.

Burges and Drover (1953) estimated the average height of the Woy Woy barrier to be 4.6 metres (15 feet) above mean sea-level, and Hails (1969a) provided an apparently accurately contoured map from which the average height was calculated, by the writer, to be 5.2 metres (17 feet) above MSL. Burges and Drover (1953) estimated the height of the ridges above the 'average height of the country' to vary from 0.92 - 3.05 metres (3-10 feet), while Hails (1969b) calculated the average swale-ridge elevation difference to be about 0.9 - 1.2 metres (3-4 feet). As Figure 3.6 indicates, the beach-ridge pattern on the Woy Woy barrier is ". . . exceptionally regular . . . [and] parallel to the present beach" (Hails, 1969b, p.1). However, virtually the entire beach-ridge plain has been affected by residential development and the micro-topography is now very difficult to discern from the ground. As well as an extensive swampy tract of land towards the northern end of the beach-ridge plain (Figure 3.6), several swales are low and swampy and have impeded drainage (Burges and Drover, 1953). At the south-western end of the barrier, Ettymalong Creek and its associated man-made canals traverse the barrier, draining small bedrock catchments (Figure 3.6). The mouth of this creek was maintained during (and subsequent to) beach-ridge progradation, but was deflected back and forth along the barrier in apparent response to changes in longshore drift direction.

The Woy Woy barrier has been extensively drilled by Hails (1969a, 1969b) and by the present writer (Thom *et al.*, 1978, 1979 in prep.). However, all of these holes were hand-drilled and did not penetrate far beyond the watertable. Thus, with the exception of the regressive facies, the stratigraphy and the age structure of the Woy Woy barrier are still largely unknown.

On morphological and pedological grounds, Hails (1969b) asserted that the inner part of the Woy Woy barrier is of Pleistocene age, and that the more extensive seaward section is of Recent (Holocene) origin. The large swampy depression (previously mentioned) which is located between these areas, Hails recognized as an interbarrier depression. However, Thom *et al.* (1978) refuted this assertion and showed, by radiocarbon dating, that the entire width of the barrier is

FIGURE 3.6

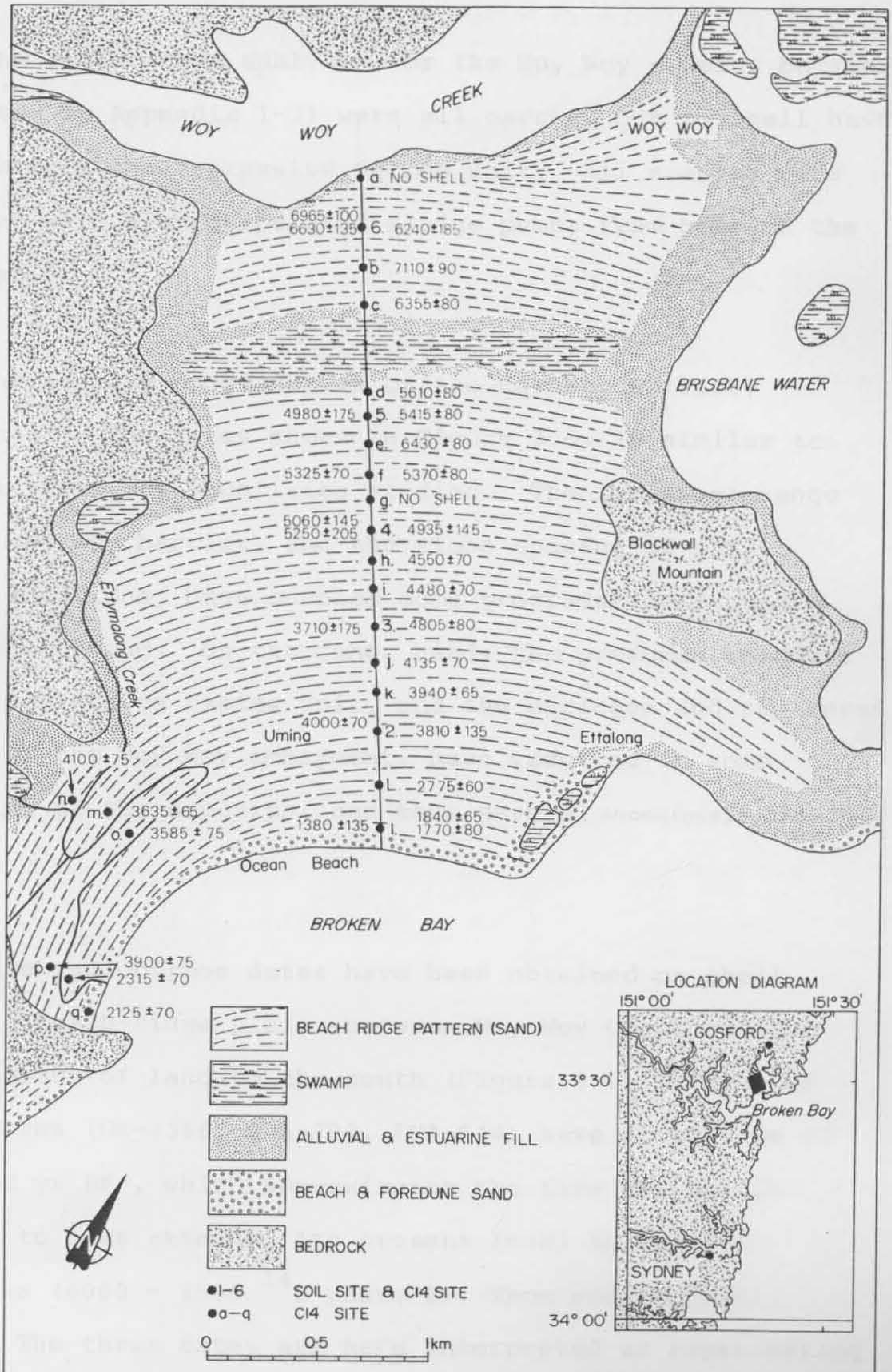

Figure 3.6 Map of the Woy Woy-Umina beach ridge plain, showing the beach-ridge pattern, transect lines, drill holes (a-r) and soil sampling sites (*1-6*). Radiocarbon ages are environmentally corrected years BP*.

of Holocene age. Additional radiocarbon dates, reported below, confirm this conclusion.

The radiocarbon analyses for the Woy Woy - Umina barrier (reported in Appendix 1-3) were all carried out on shell hash samples from the regressive facies unit. All samples were obtained with a hand-operated sludge pump, from beneath the watertable.

The seaward progradation of the Woy Woy barrier, evidenced by the dates shown in Figure 3.6, is similar to that at the other localities studied. The large age range of the Woy Woy barrier, and the close spacing of shell sample locations, have enabled some progradational phases to be recognized. On the other hand, the presumed thinness of the regressive facies unit, and the enclosed and sheltered nature of the Woy Woy embayment, have resulted in some reworking of the deposits, and thus several *anomalously old* dates.

Five radiocarbon dates have been obtained on shell from the beach-ridge plain, between Woy Woy Creek and the swampy tract of land to the south (Figure 3.6). Three of these dates (GX-4366, SUA-793, SUA-944) have a mean age of 6410 ^{14}C yr BP*, which approximates the time the sea is thought to have attained its present level in eastern Australia (6000 - 6500 ^{14}C years BP, Thom and Chappell, 1975). The three dates are here interpreted as representing an initial barrier (Woy Woy Phase I), which prograded seawards at the end of the Postglacial Marine Transgression, about 6500 - 6200 ^{14}C yr BP*. The other two dates, 7110 $\pm$ 90 ^{14}C yr BP* (SUA-792) and 6965 $\pm$ 100 ^{14}C yr BP* (SUA-942), significantly predate sea-level stabilization, and are therefore considered *anomalously old.* These dates probably were based on older shell material, which was either reworked from transgressive facies deposits and incorporated into the Phase I sediments of the regressive facies, or alternatively, was extracted *in situ* by the sludge pump from the transgressive facies unit, where the overlying regressive facies unit was particularly thin. However, the former explanation appears more likely, as the stratigraphy revealed by the drill holes did not indicate a change in facies.

The swampy tract of land towards the rear of the barrier marks a time gap in the evolution of the Woy Woy - Umina beach-ridge plain. Shell from a drill hole immediately seaward of the swamp (drill hole *d*, Figure 3.6) yielded a date of 5610 $\pm$ 80 ^{14}C yrs BP* (SUA-794), which indicates an hiatus of about 700 years in the progradation of the beach ridges.

The age structure of the beach-ridge plain seaward of the swamp is not easily interpreted, despite the large number of radiocarbon analyses of shell from this part of the barrier. Several disparate reconstructions of the geomorphic evolution of this part of the Woy Woy beach-ridge plain have been considered by the writer. However, the outline given below requires the least complex sequence of erosional/depositional events, and yet quite adequately accounts for the observed distribution of dates. Alternative reconstructions require considerable seawards progradation (and subsequent erosion) of the Phase I barrier, plus the designation of many dates in Phase II as *anomalously old*, on the basis of just one younger date. On the other hand, the following reconstruction is simple, emphasizes the mutual consistency of the majority of the dates in Phase II, and classes only one date (GX-4460, which has a large "error" term) as being of suspect accuracy.

On the basis of the obtained dates, the portion of the Woy Woy beach-ridge plain which lies between drill holes *d* and *4* (see Figure 3.6 for location) is interpreted as a discrete phase of barrier progradation (Phase II), which occurred between about 5600 and 5100 ^{14}C yr BP*. Radiocarbon dates SUA-794,-936, -796/1, -796/2, -938, -941 and GX-4459 (Appendix 1-3) define this accretionary event, given the assumptions about time gaps which were made in Section 2.2.1.2. GX-4460, as mentioned above, is regarded as being of suspect accuracy (possible calcite recrystallization?), as SUA-936 dates shell from the same bulk sample, but is perfectly consistent with all the other non-reworked Phase II dates. (See Appendix 1-3 and Figure 3.6). SUA-795 is regarded as an *anomalously old* date, probably relating to shell material reworked from Phase I sediments, which are now extant only to the north of the swamp. This interpretation of SUA-795 as *anomalously old* is also appropriate with alternative reconstructions of the geomorphic evolution of this part of the barrier. Dates SUA-796/1 and -796/2 (5370 $\pm$ 80 and 5325 $\pm$ 70 ^{14}C yr BP*) are duplicate analyses, carried out on a single sample of CO_2 gas evolved from a shell hash sample from drill hole *f* (Figure 3.6). The close correspondence of these dates indicates the analytical precision that is attainable by the dating laboratory and the suitability of marine shell for radiometric age determinations. GX-4459 (5250 $\pm$ 205 ^{14}C yr BP*), SUA-938 (4935 $\pm$ 145 ^{14}C yr BP*) and SUA-941 (5060 $\pm$ 145 ^{14}C yr BP*) are dates from a bulk sample of shell obtained from drill hole *4* (Figure 3.6). However, they do not pertain to a single CO_2 sample and hence are not strictly replicate analyses. As they coincide within one standard deviation they are here regarded as being equivalent, and a mean age of 5080 ^{14}C yr BP* has been calculated from them and used to define the end of progradational Phase II (*c.* 5100 ^{14}C yr BP*).

The next progradational episode at Woy Woy (Phase III) is indicated by an overlapping pair of dates obtained from drill holes *h* and *i* (Figure 3.6); SUA-797 (4550 $\pm$ 70 ^{14}C yr BP*) and SUA-798 (4480 $\pm$ 70 ^{14}C yr BP*), respectively. These dates have a mean age of 4515 ^{14}C yr BP*, and hence this brief beach-ridge progradational phase is assigned an age of *c.* 4500 ^{14}C yr BP*.

A somewhat wider progradational unit (Phase IV) is located to seaward of Phase III. Dates on shell samples from drillholes *3*, *j*, *k*, and *2* on the main transect line and from drillholes *m*, *n*, *o*, *p* in the vicinity of Ettymalong Creek (Figure 3.6), have been used to identify this phase. Again, reworking of shell is evident, but only one date (SUA-939) is regarded as *anomalously old*, being over 1,000 years older than another date on shell from the same bulk sample (GX-4458). The remainder of the dates from Phase IV overlap at one standard deviation to give an age range for the progradational episode of 550 years; that is, the overlapping dates extend from 4135 $\pm$ 70 ^{14}C yr BP* (SUA-799) to 3585 $\pm$ 75 ^{14}C yr BP* (SUA-804). Seaward of Phase IV it is possible to unambiguously identify only one progradational phase, on the basis of the dates obtained so far. SUA-801 (2775 $\pm$ 60), SUA-807 (2315 $\pm$ 70), SUA-806 (2125 $\pm$ 70), SUA-940 (1840 $\pm$ 65), SUA-937 (1770 $\pm$ 80) and GX-4367 (1380 $\pm$ 135) trace the evolution and termination of Phase V. The latter three dates pertain to shell from a bulk sample obtained from drill hole *1*. The two older dates are therefore assumed to represent shell which was reworked from slightly further back in this progradational phase. Therefore, Phase V probably consisted of slow, intermittent progradation, interspersed with periods of slight erosion. The age of the low, irregular foredune complex which stretches behind Ocean Beach (Figure 3.6) is not known, although it must be less than 1380 $\pm$ 135 ^{14}C yr BP* (GX-4367).

3.3.1.3 Moruya-Broulee Barrier. This bay barrier is located adjacent to the entrance of the Moruya River, on the south coast of New South Wales, approximately 250 kilometres from Sydney. See Figure 3.1 for location, and Figure 3.7 for a map of the barrier. Thom *et al.* (1978) have described the morphology of the Moruya bay barrier. It occupies a broad bedrock embayment and blocks several small drainage basins, which now contain freshwater peat swamps (e.g., Waldrons Swamp, Figure 3.7). Some of these swamps drain across the

FIGURE 3.7

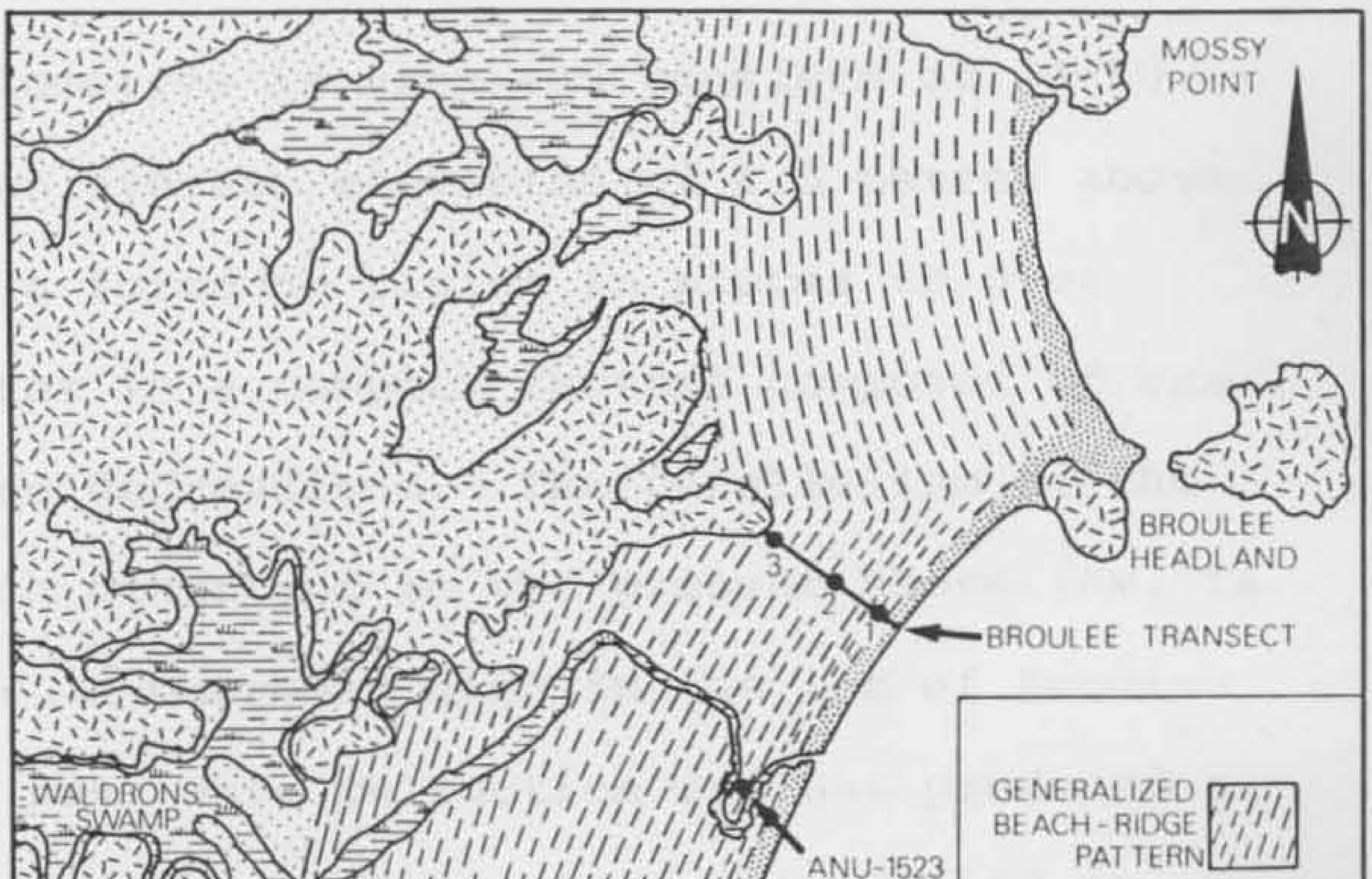

Figure 3.7 Map of the Moruya-Broulee beach-ridge plain and associated deposits. The location of both the Moruya and Broulee transect lines and soil/drill hole sites are also indicated. After Thom *et al.* (1978).

barrier as swampy creeks (e.g., Waldrons Creek).

The Moruya barrier has a maximum width of 2 kilometres and is about 9 kilometres long, stretching from the Moruya River to Mossy Point (Figure 3.7), and hence has an average length to width ratio of 1 : 0.22. The barrier is approximately 12 square kilometres in area and consists of 40-50 beach ridges, with an average elevation of 4.5 metres above mean sea-level, and a foredune rising in places to over 10 metres. The latter is a complex feature composed of small hillocks and enclosed depressions. The parallelism of the beach ridges, to each other and to the present shoreline, is pronounced. However, a basement high in the lee of Broulee Island has affected past wave refraction and has produced a confused beach-ridge pattern in this area (simplified in Figure 3.7). The height difference between ridges and swales is greater in this central area than it is to either the north or the south.

The stratigraphy and geomorphic evolution of the Moruya bay barrier have been described by Thom *et al.* (1978) and more recent investigations by the writer (Thom *et al.*, 1979, in prep.) have expanded this work.

The stratigraphy may be generalized into five lithofacies: estuarine clay; basal transgressive sand with gravel; nearshore shelly sand; well-sorted "leached" dune and beach sand; and currently mobile dune, beach and nearshore sand. These facies units, and the age structure of the sediments along the main Moruya transect, are shown in Figure 3.8.

All radiocarbon dates from the Moruya barrier, including those from the Broulee transect, are reported in Appendix 1-4. The locations of the Moruya and Broulee transect lines are shown in Figure 3.7.

The following description of the Moruya barrier lithofacies and age structure is based on that of Thom *et al.* (1978, pp.28-31).

The lowest unit in the sequence (see Figure 3.8) is a compact, dark grey organic-rich clay containing thin layers of sand. The top of this unit occurs at 30m below MSL. It appears that the unit becomes less calcareous, less sandy and more organic-rich with depth. Shells occur locally, including the two common mud in-fauna, *Nassarius sp.* and *Notospisular parva.* However, they were sampled in insufficient quantity to date. Radiocarbon ages were obtained on organic muds from this unit. It is inferred from similar environments of deposition along the New South Wales coast, that these muds were deposited in an estuarine basin, behind a seaward sand barrier. As the muds would have been in isotopic equilibrium with the terrestrial environment at the time of deposition, no environmental correction has been made (Appendix 1-4; ANU-1132, -1133). On the basis of these two dates the muds accumulated at a rate of *c.* 1 m/100 ^{14}C years. Assuming sedimentation at a constant rate, the unit accumulated until *c.* 8300 ^{14}C yr BP. A regression of about 5m is inferred from oxidized clay shown abutting bedrock in Figure 3.8. This clay forms a subsurface "scarp" facing seawards. Part of the clay unit has been removed, perhaps by marine erosion accompanying the subsequent

FIGURE 3.8

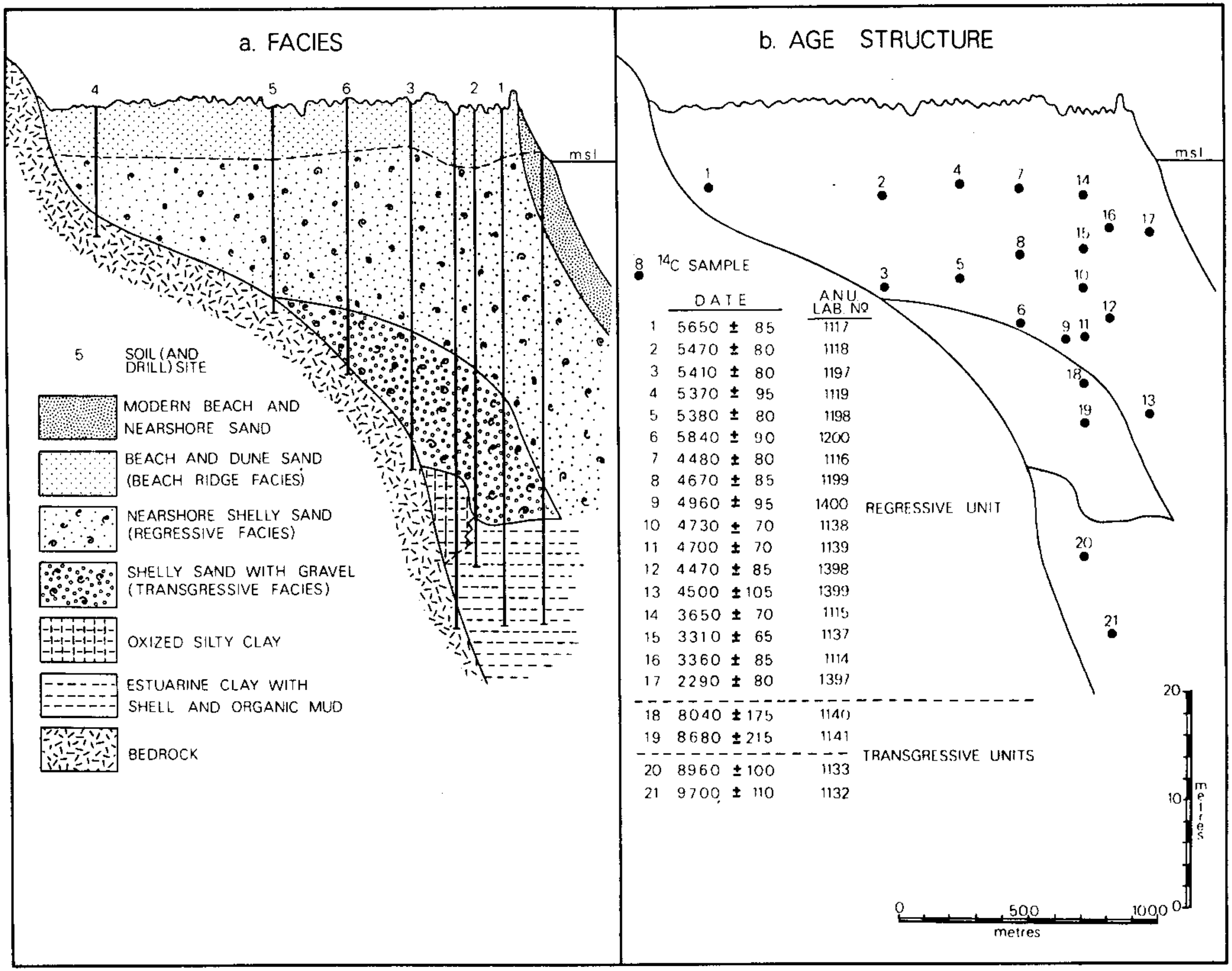

Figure 3.8 Cross-section of the Moruya beach-ridge plain along the Moruya transect (see Figure 3.7 for location), showing (a) facies and (b) ^{14}C age distribution. All dates are environmentally corrected years BP*, except numbers 20 and 21. After Thom *et al.* (1978).

marine transgression.

A gravelly sand lithofacies (Figure 3.8) overlies the basal clay and bedrock. It appears as an irregularly-shaped lens of sediment. The sand is medium-coarse, moderately well-sorted, locally rich in well-rounded pebbles (presumably reworked from Tertiary fluvial gravels), and quite calcareous. However, it is only locally enriched in large shell fragments. A nearshore-beach environment of deposition is suggested, on the basis of sediment sorting and biota. Radiocarbon dates on the carbonate sand fraction overlap those from the underlying estuarine clay facies. Some degree of reworking of nearshore shell material is implied, and this is to be expected if this was a transgressive sand sheet.

Above the transgressive sand is a wedge of very shelly sand opening out in a seaward direction. This yellow grey, medium to coarse, shelly sand becomes markedly greyer and finer with depth. Wood fragments are abundant towards the base of the unit. The sand is rich in detrital shell fragments (up to 20 percent carbonate) as well as in whole shell, especially the nearshore gastropod *Bankivia fasciata*. This shelly sand is interpreted as having been deposited in the nearshore zone, from *c.* -3 to -25m MSL, and as shown by the pattern of ^{14}C ages, it was formed as a regressive shoreface sequence associated with the progradation of the beach-ridge plain. Environments of deposition grade from foreshore beach and upper nearshore (highly fragmented shells in coarse sand), to fine organic-rich grey sand with well-preserved whole shells, typical of deeper nearshore waters (-10 to -30m).

Twenty radiocarbon dates on shell fragments have been obtained from the nearshore unit, of which seventeen are from the Moruya transect line, and three from the Broulee transect. The Moruya dates are listed in Figure 3.8, and the sample positions are also shown. The three Broulee drill hole locations match the three soil sample sites shown in Figure 3.7. The Broulee dates are listed in Appendix 1-4.

The uppermost lithofacies of the Moruya barrier forms a tabular sand sheet of uniform thickness (4-6m) which covers the underlying shelly sands. It is coarsest at the base, fining slightly upwards towards the groundsurface The sands are mostly leached of carbonate. This cover sand is attributed to the deposition of low-relief foredunes on a prograding beach face. Thus the unit is composed of sand deposited by beach processes in the backshore zone, and by aeolian processes around sand-binding dune plants.

The Holocene depositional history of the Moruya embayment may be summarized as follows:

1. Between c. 8500 and 10,000 ^{14}C years ago a low-relief barrier stood 30 to 40m below present sea-level and seaward of the present shoreline. Estuarine sediments accumulated behind this transgressing barrier. Vertical and landward growth of the barrier may have ceased between c. 8000 and 8500 ^{14}C yr BP.

2. Rapid marine transgression from 8000 to about 6000 ^{14}C yr BP took the sandy open-ocean shoreline to the head of the embayment, blocking off narrow drowned valleys in which estuarine shelly muds were rapidly accumulating.

3. From about 5700 to c. 2000 ^{14}C years ago, the shoreline prograded by the mechanism of multiple beach-ridge formation. The pattern of progradation was probably episodic, with the first phase resulting in the deposition of more than half the beach-ridge plain. The seventeen dates associated with the progradation at Moruya are listed in Figure 3.8 and their sampling locations are also indicated. These regressive facies dates form the basis for the ages assigned to the soil sample sites in Section 3.4

4. Relative shoreline stability has characterized the last 2000 ^{14}C years in this embayment, during which time a complex hummocky foredune has formed.

3.3.1.4 <u>Disaster Bay - Wonboyn Barrier</u>. The extensive Disaster Bay beach-ridge plain is located at the head of Disaster Bay, on the south coast of New South Wales, about 30 kilometres north of the Victorian border. Figures 3.9 and 3.10 show the general locality of the area, and the configuration of the beach-ridge plain, respectively.

The Disaster Bay barrier is 5.8 square kilometres in area, attaining 1.6 kilometres in width, and nearly

FIGURE 3.9

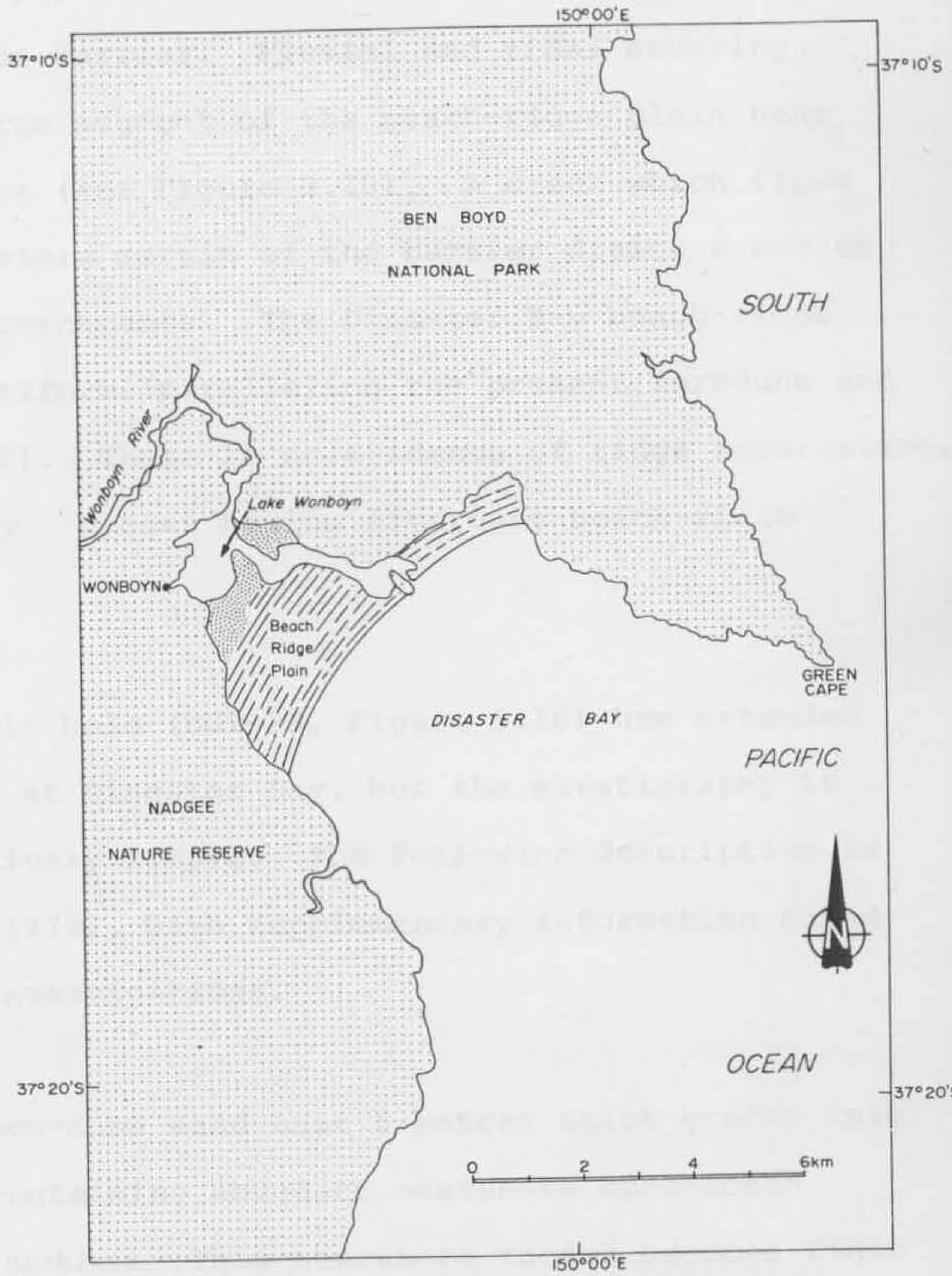

Figure 3.9 Map showing the location of the beach-ridge plain at the head of Disaster Bay, far south coast of New South Wales.

4 kilometres in length. It therefore has a length to width ratio of 1 : 0.33. It consists of about 60 beach ridges, averaging nearly 5 metres above mean sea-level, and a narrow foredune complex, rising to over 10 metres. The bay barrier blocks a drowned bedrock valley containing a large estuarine lagoon (Lake Wonboyn), which drains into the sea near the northern end of the barrier. Fluvial and tidal scouring have removed a large segment of the beach-ridge plain near the lagoon entrance (see Figure 3.10). A creek which flows along the southwestern margin of the barrier drains a series of small bedrock catchments. The Disaster Bay beach-ridge pattern is very uniform, paralleling the present foredune and beach (Figure 3.10). There is no evidence of ridge recurvature, or of accretionary phases having divergent beach-ridge orientations.

Only one drill hole (BGT-23, Figure 3.10) has extended as far as bedrock at Disaster Bay, but the stratigraphy it revealed is relatively simple. The following description is from Thom *et al.* (1978), with supplementary information based on the writer's investigations.

An upper beach-dune sand unit 6 metres thick grades into shell-rich sand containing abundant nearshore open-ocean species, such as *Bankivia*. This nearshore facies becomes finer and darker grey with depth and is underlain by a lighter grey, coarse, moderately sorted, non-carbonate sand. The lower sand is interpreted as transgressive sand and, as at Moruya, it overlies lagoonal estuarine clay. The thickness of the nearshore regressive sand facies at Disaster Bay

FIGURE 3.10

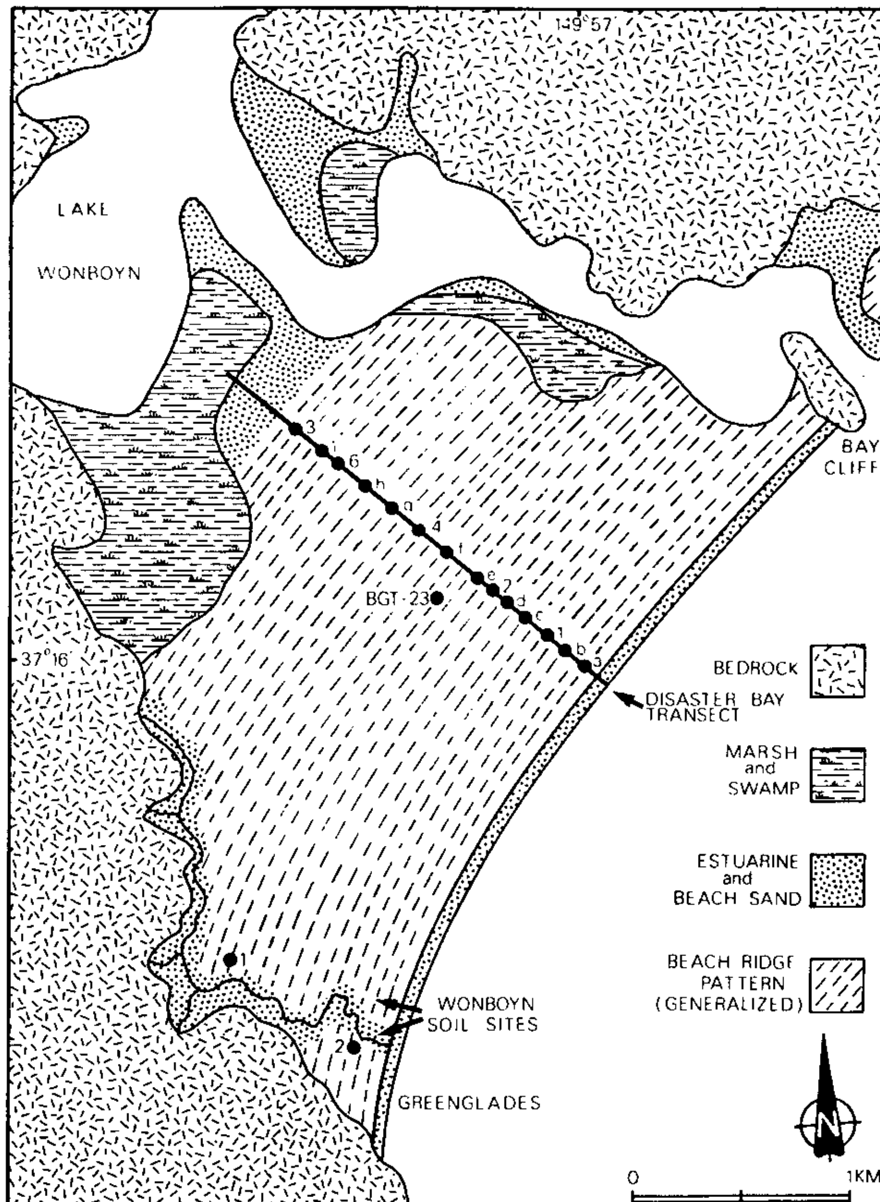

Figure 3.10 Map of the Disaster Bay-Wonboyn beach-ridge plain, showing the surveyed transect line and the location of drill holes (*a-i*) and soil sites (*1-6*).

compares with similar facies at Moruya (20 - 25m). A drill hole located on the back-barrier slope at Disaster Bay revealed interfingering barrier sand and lagoonal clays and muds, indicating a configuration similar to that at Fens.

Fifteen radiocarbon dates were obtained on shell samples from the nearshore regressive facies (see Appendix 1-5 and Figure 3.11). Two of these dates are considered *anomalously old:* GX-3635 (8650 $\pm$ 155 ^{14}C yr BP*), because it substantially predates the time sea-level reached its present position ($\pm$ 1 metre) and hence probably contains reworked transgressive facies shell; ANU-1584 (2600 $\pm$ 100 ^{14}C yr BP*) is also slightly *anomalously old* as it is out of progradational sequence. A shell sample from drill hole BGT-23 (see Figures 3.10 and 3.11), which gave an age of 3160 $\pm$ 140 ^{14}C yr BP* (ANU-1396) is <u>not</u> out of progradational sequence; it was obtained from <u>15m</u> below the groundsurface and because of this greater depth, it is still in progradational sequence with the other shallower dates.

The dates indicate that a low narrow bay barrier, consisting of reworked transgressive sand and shell, formed at the head of Disaster Bay probably at the time sea-level stabilized at its present level (6000 - 6500 ^{14}C yr BP). This initial barrier rapidly prograded seawards during an accretionary phase about 5400 ^{14}C yr BP* (ANU-1585, SUA-900, Appendix 1-5). Little progradation occurred over the next 1500 years (or alternatively it occurred and was subsequently eroded), but about 3800 ^{14}C years* ago

FIGURE 3.11

Figure 3.11 Cross-section of the Disaster Bay beach-ridge plain, showing the location of drill holes (*a-i*) and drill holes/soil sites (*1-6*). All radiocarbon dates are environmentally corrected years BP*.

(SUA-899) progradation recommenced and continued until about 1100 years* ago (SUA-892), during which time the shoreline moved some 1.5 kilometres to the southeast. It is unlikely that the accretion rate was uniform throughout this long period, hence progradational phases may have occurred. However, as the dates shown in Figure 3.11 indicate, any such phase must have been of such short duration that it is not possible to unambiguously identify it.

The age structure of the narrow, rather poorly-developed foredune complex, located seaward of the site of SUA-892 (1090 $\pm$ 60 ^{14}C yr BP*, Figure 3.11) is unknown, but the beach-ridge plain may have formerly extended further seaward. This hypothesis is supported by the exposure of organic stained (but not podzolized) sand in the face of the cliffed foredune, after recent severe beach erosion. However, because of its position in relation to SUA-892, the foredune must be less than 1100 ^{14}C years* old.

3.3.1.5 Cowley Beach - Inarlinga Barrier. As shown in Figure 3.12, the sediment filled embayment between Kurrimine and Double Point (north Queensland), contains two quite distinct beach-ridge systems. The landward beach-ridge plain has been termed an Inner Barrier, and the seaward an Outer Barrier, by Bird and Hopley (1969). The Inner Barrier was assigned a Pleistocene age by these authors, on the basis of alluvial ferruginous sandrock which outcrops near Kurrimine. Bird and Hopley maintained that indurated sands were indicative of barrier deposits of Last Interglacial

FIGURE 3.12

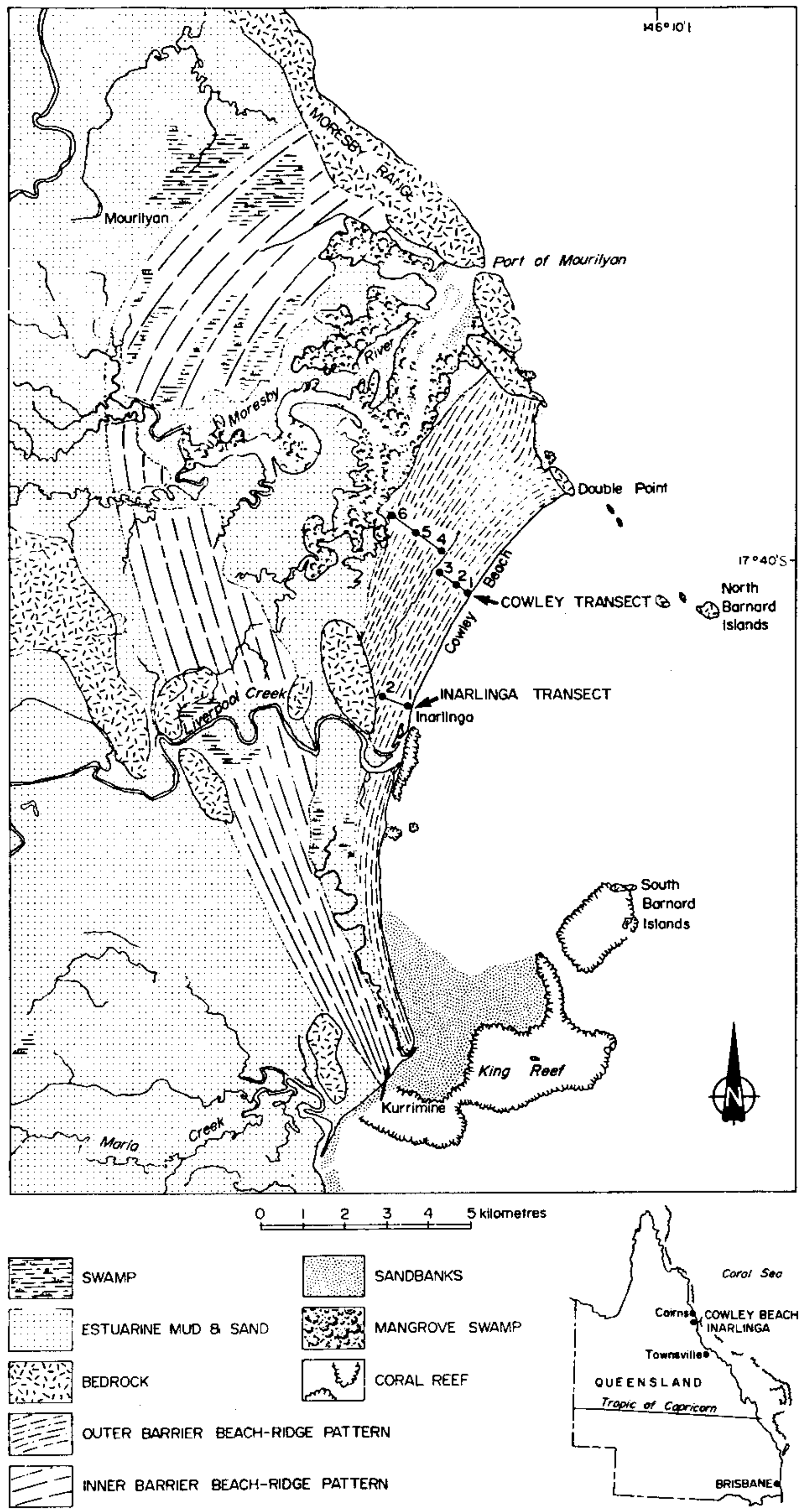

Figure 3.12 Map of the Cowley-Inarlinga barrier systems and associated deposits. The two Outer Barrier transect lines are shown, together with the soil sampling sites.

age in New South Wales, and therefore probably also in Queensland. Although not mentioned by Bird and Hopley, the subdued beach-ridge topography and the very broad spacing of the swales and ridges of the Kurrimine-Double Point Inner Barrier, support the hypothesis that it is of Pleistocene age (cf. Langford-Smith, 1969). On morphological grounds (e.g., ridge spacing, ridge-swale height differences, relief sharpness), the Outer Barrier in the Kurrimine-Double Point embayment (hereafter referred to as the Cowley Beach - Inarlinga barrier) is certainly of Holocene age, as claimed by Bird and Hopley (1969).

The Cowley Beach - Inarlinga barrier is by far the most extensive beach-ridge plain included in this study, being 21.9 square kilometres in area. Its configuration also makes the Cowley Barrier somewhat unusual, in that it infills a markedly asymmetric embayment, and consequently narrows considerably towards the south (see Figure 3.12). However, although many of the beach ridges terminate against the rear margin of the barrier, few are truncated by the present shoreline, and few appear to merge with one another. In the lee of the Double Point bedrock outlier, wave refraction has resulted in some beach-ridge pattern irregularities, but as there is no other evidence of ridge recurvature on the barrier it is unlikely that longshore spit growth (rather than shore-normal beach-ridge accretion) was the dominant process of barrier progradation.

As indicated in Figure 3.12, two transect lines were surveyed across the northern part of the Cowley Barrier; the average elevation was found to be approximately 3 metres above MSL (see Figure 3.13). Observations near Kurrimine indicated that this part of the barrier is at the same elevation. Ridge-swale height differences, over most of the beach-ridge plain, were found to be less than one metre. Foredune development is minimal along the entire length of the barrier.

At Kurrimine, the beach orientation changes sharply and truncates the Inner and Outer Barriers; both barriers here overlie a fringing coral reef (King Reef, Figure 3.12). A much smaller reef is located across the mouth of Liverpool Creek. However, this is probably a relict feature, as freshwater discharge from the creek would be unfavourable for coral growth. At present, beach erosion is minimal and longshore drift is from south to north.

Extensive drilling of the Cowley barrier by the writer, using a hand auger and sludge-pumping techniques, has not yielded datable shell or coral, presumably because any biogenic carbonate that was initially present in the sediments has by now been completely leached by the high rainfall. Consequently, the age structure and geomorphic development of the barrier have been inferred from morphological evidence and by reference to analogous radiometrically dated coastal deposits in north Queensland and New South Wales. The age framework postulated below for the Cowley Outer Barrier is therefore less reliably based than the frameworks established for the other barriers in the study. However, the Cowley age framework still permits generalized comparisons to be made

FIGURE 3.13

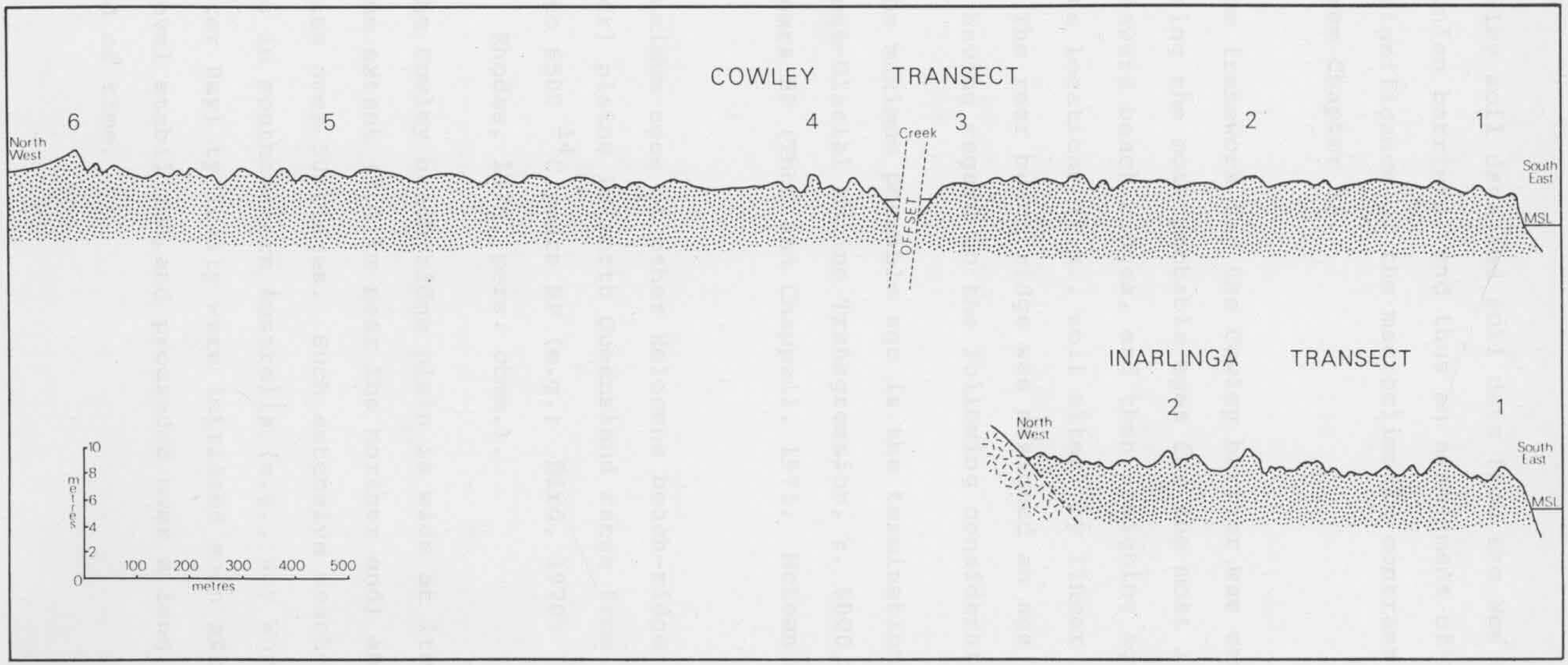

Figure 3.13 Cross-sections of the Cowley-Inarlinga Outer Barrier, showing location of soil sites. Figure 3.12 shows the location of the transect lines.

between Cowley soil data and soil data from the New South Wales/Tasmanian barriers, and thus an assessment of the pedogenic significance of the macroclimatic contrast is still possible (see Chapter 5).

The age framework for the Cowley barrier was constructed by determining the most probable ages for the most landward and most seaward beach ridges, and then assigning ages to intermediate locations (i.e., soil sites) by linear interpolation. The rear beach ridge was assigned an age of 6000 ^{14}C years, having regard to the following considerations:

1. The maximum possible age is the termination of the Post-Glacial Marine Transgression, *c.* 6000 - 6500 ^{14}C years BP (Thom and Chappell, 1975; McLean *et al.*, 1978).

2. Maximum ages of other Holocene beach-ridge (and chenier) plains in north Queensland range from about 5500 to 6500 ^{14}C years BP (e.g.; Bird, 1970; Smart, 1976; Rhodes, 1979, pers. comm.).

3. The Cowley beach-ridge plain is wide at its maximum extent (3.4 km near the norther end) and contains over 50 ridges. Such extensive beach-ridge plains in southeastern Australia (e.g., Woy Woy, Disaster Bay) typically were initiated soon after sea-level stabilized, and prograded over a long period of time.

An age of 1000 ^{14}C yrs has been assigned to the seaward side of the Cowley barrier, in the light of the three considerations listed below:

1. The beach-ridge plain is wide at the northern end and, as mentioned above, has therefore probably prograded over a considerable time period.

2. Little foredune development has occurred on the barrier, although Bird and Hopley (1969) have shown that such aeolian accretion does occur in the humid tropical coastal sector of north Queensland. The minimal foredune development at Cowley, when compared to the size of the foredunes on the dated New South Wales and Queensland barriers, supports the 1000 year age estimate.

The specific interpolated ages assigned to the various Cowley soil sites are discussed in Section 3.4.5, however, it is relevant to note here that the morphology of the Cowley Barrier (at the northern end at least) shows no evidence of major progradational phases or of erosive episodes, and therefore the age interpolative technique is probably fairly reliable. The writer is of the opinion (on the basis of comparison with the Disaster Bay and Woy Woy beach-ridge plains) that the estimated ages are accurate to within $\pm$ 400yrs. However, as mentioned earlier, the prime objective in including the north Queensland sites in the study (macroclimatic contrast) may still be achieved, despite the comparatively imprecise age estimates.

3.3.1.6 Rheban Spit. Although morphostratigraphically a prograded bay barrier of the type described by Thom *et al.* (1978), Rheban Spit is unusual in that successive phases of progradation and erosion have resulted in sets of beach ridges, each with a slightly different orientation (and sometimes different pattern) to the preceding sets. Figures 3.14 and 3.15 show the location of the barrier and its beach-ridge pattern. Jennings (1955) attributed the differences in orientation to varying exposure to dominant wave approach along the length of the spit, but Davies (1959) noted that this does not adequately explain the older beach-ridge sets, with their greater concavity in plan. Davies suggested that bathymetric changes were probably responsible for the different beach-ridge orientations. However, during all phases of beach-ridge formation at Rheban, accretion was probably in a shore-normal, rather than longshore, direction. This is apparent from the lack of ridge recurvature (see Figure 3.15), and from a comparison of 1946 and 1966 aerial photographs of the spit, which show the development of modern beach ridges (Bowden and Kirkpatrick, 1974, Figure 1).

Rheban Spit is a small barrier, with an area of only 1.58 square kilometres. It is attached to bedrock at its northwestern extremity and is aligned roughly NW-SE. The barrier blocks Earlham Lagoon and surrounding marshland on its southwestern side, and is bordered by Carrickfergus Bay and the Mercury Passage on its northwestern and eastern sides, respectively (Figure 3.15). The length of the barrier is 3.2 kilometres, and its width averages approximately 750 metres, giving it an average length to width ratio of 1 : 0.23,

FIGURE 3.14

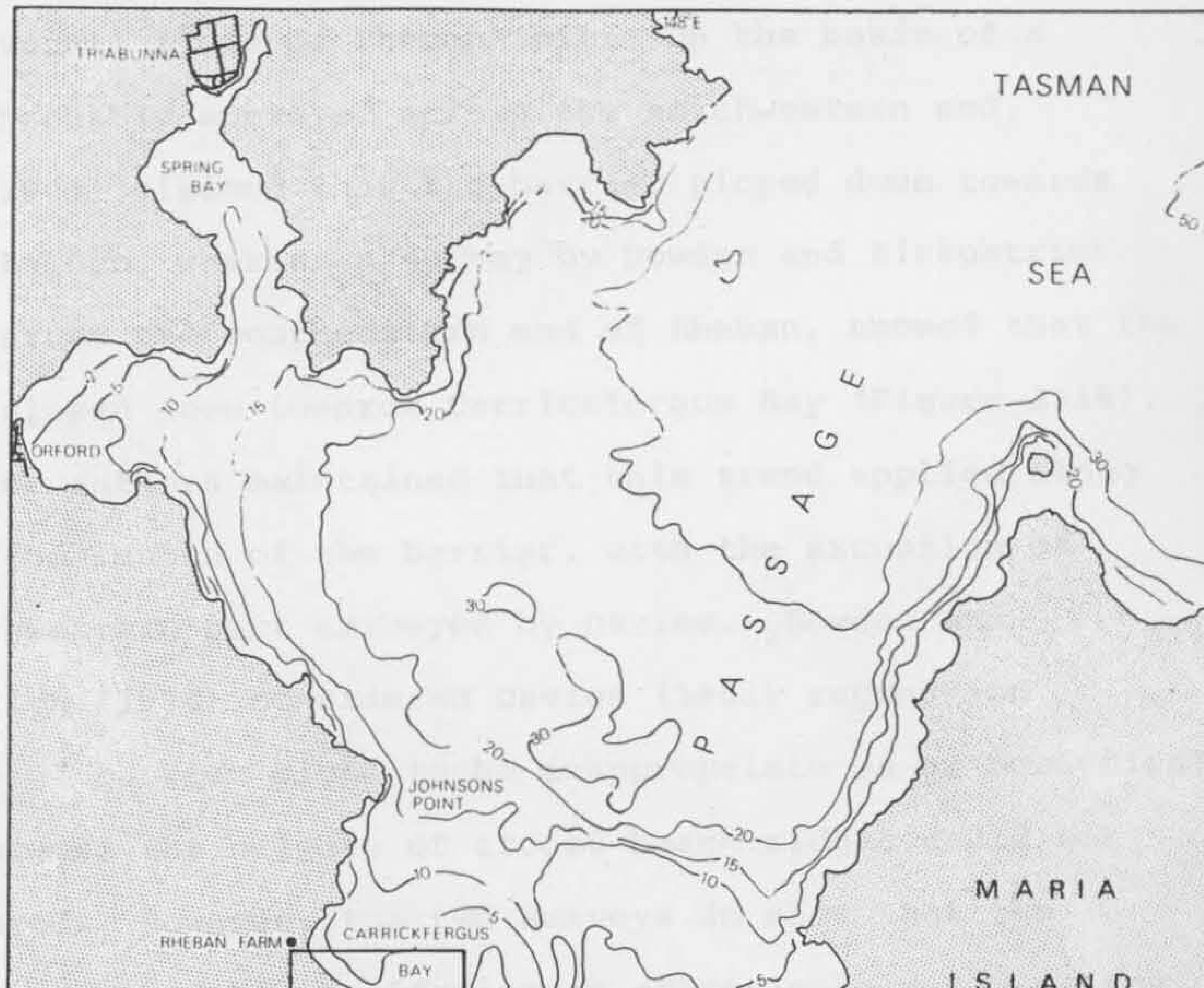

Figure 3.14 Map showing the location of Rheban Spit within the Mercury Passage, east coast of Tasmania. Designated area is shown enlarged in Figure 3.15.

which is similar to that for Moruya (1 : 0.22).

There has been some disagreement in the literature as to the overall slope of Rheban Spit. On the basis of a profile probably surveyed across the northwestern end, Davies (1961) claimed that the barrier sloped down towards Earlham Lagoon, whereas a survey by Bowden and Kirkpatrick (1974) across the southeastern end of Rheban, showed that the barrier sloped down towards Carrickfergus Bay (Figure 3.16). The latter authors maintained that this trend applied along most of the length of the barrier, with the exception of the northwestern part surveyed by Davies. Bowden and Kirkpatrick (1974) considered Davies (1961) regression analysis of barrier slope to be inappropriate as an analytical tool, because the heights of eroded beach-ridges could not be measured. However, the two surveys do show that the average elevation of the barrier is approximately 3.5 metres above MSL, and that in the southeastern section some swales are only one metre above MSL, while the frontal dunes rise to over 6 metres MSL. Ridge - swale elevation differences appear to be greater in this part of the barrier, than they are at the northwestern end.

As deep drilling of Rheban Spit was not possible, the following discussion will be confined to the evolution of the regressive (progradational) facies. Four such units, with intervening erosive phases, were inferred from the beach-ridge pattern by Bowden and Kirkpatrick (1974), whose maps and cross-sections were used as the bases for Figures 3.15 and 3.16. The writer considers that, whilst the

FIGURE 3.15

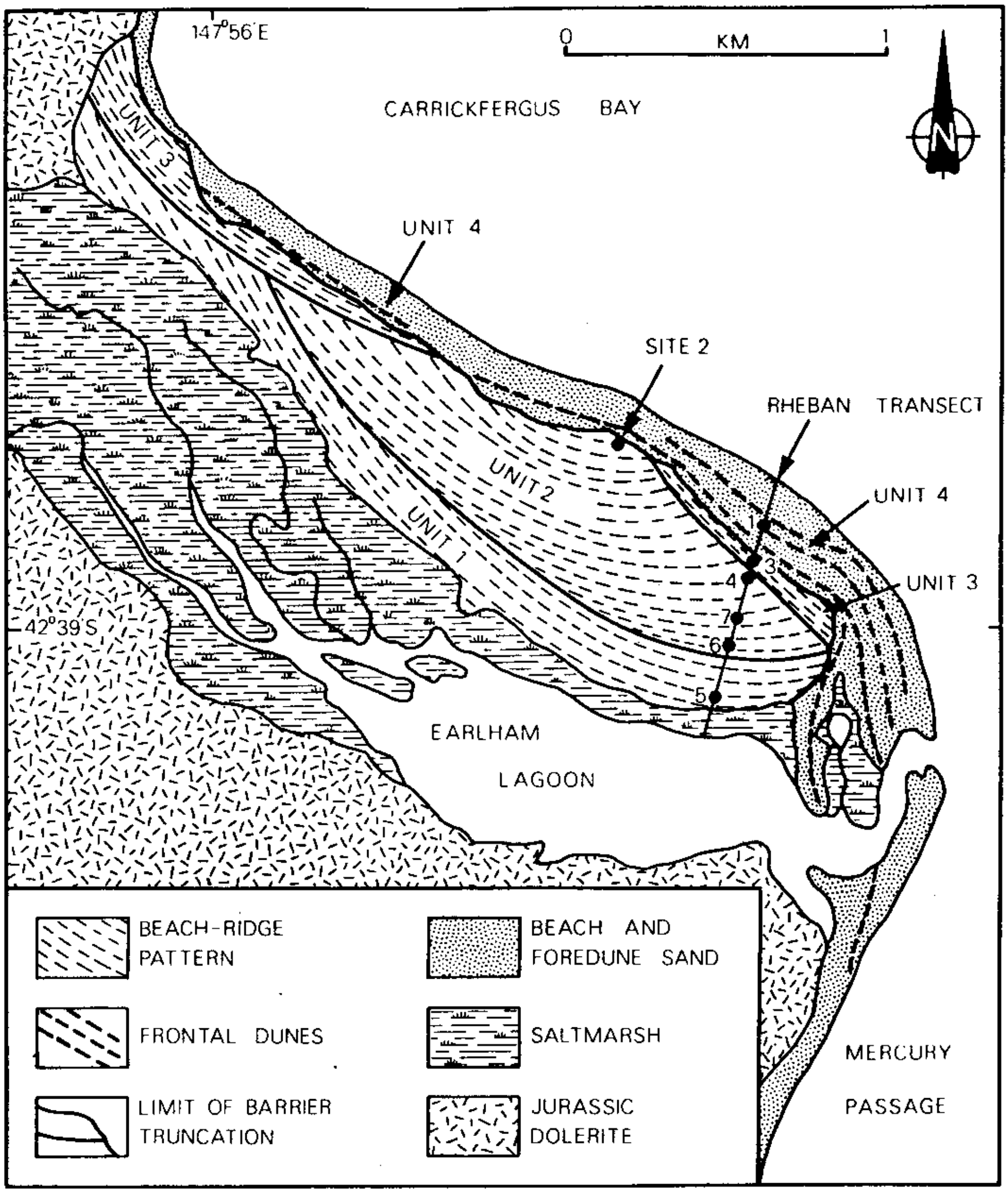

Figure 3.15 Map of Rheban Spit, showing beach-ridge and foredune patterns, progradational units, and truncation limits. The location of the surveyed transect line and the soil sites are also shown.

truncation limits of the progradational units at Rheban were adequately mapped by Bowden and Kirkpatrick (1974, Figure 1), their depiction of the beach-ridge pattern within each unit was not entirely accurate. Therefore, the beach-ridge pattern shown in Figure 3.15 (derived from large scale, vertical aerial photographs and field observations) differs slightly from that in Figure 1 in Bowden and Kirkpatrick (1974). As Figure 3.15 shows, the transect line surveyed by Bowden and Kirkpatrick intersects all four progradational units. The writer established soil (and C14) sampling sites along this line, and an additional site (Site 2, Figure 3.15) was established off the transect line, so that the full age and pedological range of progradational Unit II could be assessed.

The following reconstruction of the evolution of the Rheban regressive facies units is therefore based on beach-ridge and truncation-limit patterns (Figure 3.15), C14 ages obtained by the writer (Figure 3.16 and Appendix 1-6), and the morphological observations of Bowden and Kirkpatrick (1974) and the writer.

The initial phase of barrier progradation at Rheban resulted in a beach-ridge plain which was probably quite extensive; at least as long as the present spit, and possibly as wide. The remnant of this initial progradational unit is shown in Figure 3.15 as Unit I and consists of a narrow group of beach ridges which mark the rear of the spit, along the northern side of Earlham Lagoon. These ridges are quite distinct at the northwestern end of the spit, where they are obliquely cut by a later beach-ridge sequence.

FIGURE 3.16

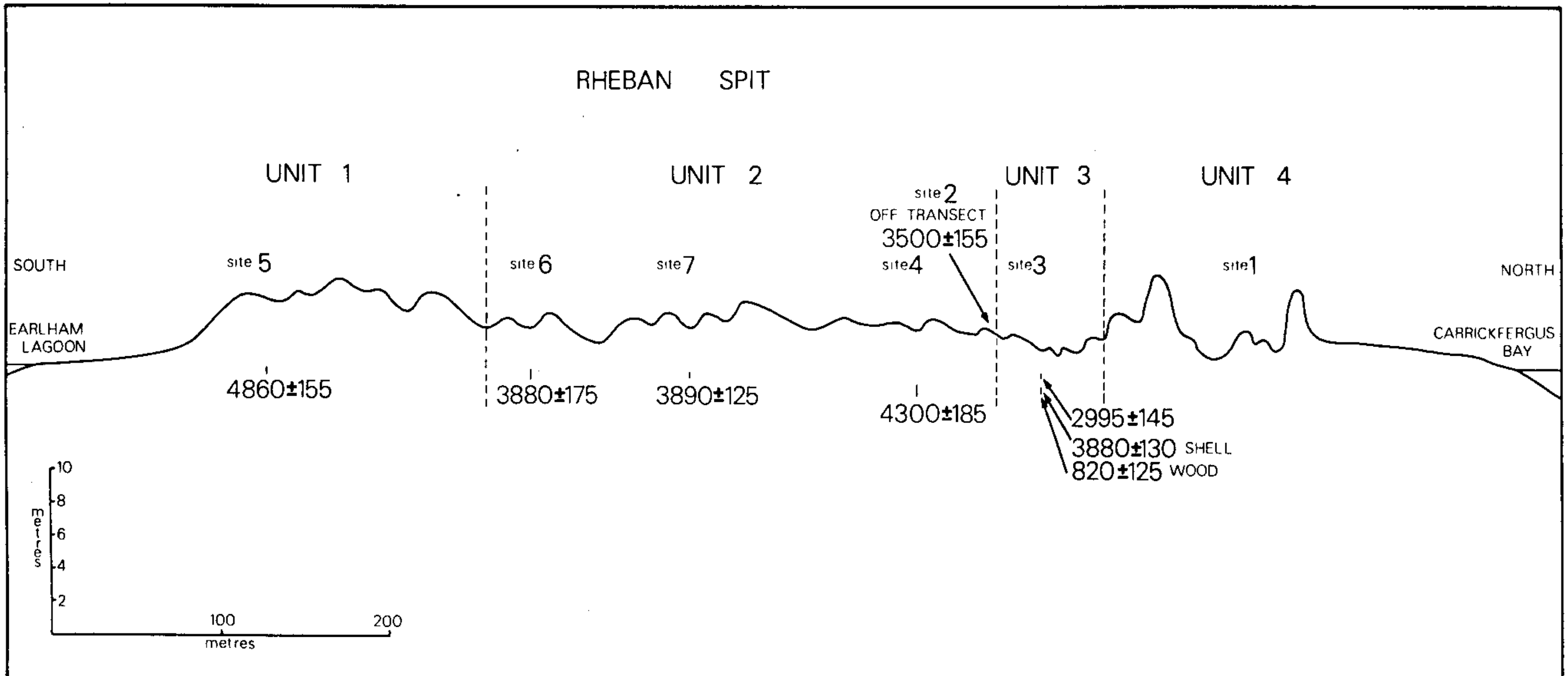

Figure 3.16 Cross-section of Rheban Spit (after Bowden and Kirkpatrick, 1974), showing the location of soil/drill hole sites, the extent of progradational units and the depths of shell samples used for ^{14}C dating. All ages are environmentally corrected years BP*, except that obtained on a wood sample from Site 3 (820 ± 125 yrs BP).

Along the rest of the barrier they tend to be less distinctive in plan, but quite distinctive in profile (Figures 3.15 and 3.16).

Only one soil/C14 site was established within progradational Unit I (Site 5). Shells from this site were dated at 4860 $\pm$ 155 ^{14}C yr BP* (GX-4022), which is somewhat younger than the initial progradation phases of the other barriers in the study.

Unit II is distinguished by the pattern of its beach ridges and truncation limits (Figure 3.15), but radiocarbon dating of incorporated shells also differentiates it from Units I and III. Unit II incorporates a larger proportion of the area of the present spit than does any other progradational unit remnant. Because of its comparatively large width, a large age range was anticipated for Unit II, and four soil/C14 sites were established within the unit - three on the transect line and one (Site 2) on the youngest ridge (see Figure 3.15). However, shells from Site 6, at the rear of Unit II (see Figure 3.16), yielded an age of 3880 $\pm$ 175 ^{14}C yr BP* (GX-4364), whilst those from Site 2 were 3500 $\pm$ 155 ^{14}C yr BP* (GX-4020). This gives an age range of only 380 radiocarbon years for Unit II. An age of 3890 $\pm$ 125 ^{14}C yr BP* (GX-4365) was obtained on shells from Site 7 (Figure 3.16), which is consistent with the age of the shells from Site 6 and Site 3 (see below), and shows that much of Unit II was deposited very soon after 3900 ^{14}C yr BP*.

Shells from Site 4, located on the transect line, well towards the northern side of Unit II (see Figure 3.15), were dated at 4300 $\pm$ 185 ^{14}C yr BP* (GX-4363). On the basis of its progradational position, this date is considered *anomalously old*, although it should be noted that when its large "error" term ($\pm 1\sigma$) and the "error" terms for GX-4364 and GX-4365 are considered, the dates are not inconsistent, the non-overlap of the "error" terms being only 100 years.

Unit III is easily distinguished on an air photo by its beach-ridge pattern, which more closely parallels the present shoreline than do the ridge patterns of Units I and II. Unit III truncates most of the beach ridges in Unit II, and is itself replaced by the Unit IV frontal dunes along part of its (former) length (see Figure 3.15). Unit III now comprises only a few beach ridges, most of which are low in elevation and rather indistinct on the ground. Where the transect line intersects Unit III, a soil/C14 site was established (Site 3), the elevation of which is only about 1 m above mean high water level.

Three radiocarbon dates have been obtained on material from Site 3. Shell hash from 1.5 m below the groundsurface yielded a date of 2995 $\pm$ 145 ^{14}C yr BP* (GX-4021), while shell hash from 2.5 m was dated at 3880 $\pm$ 130 ^{14}C yr BP* (SUA-768/1). These dates are not inconsistent with each other. Site 3 was located very close to the boundary between Units II and III (but definitely in Unit III, see Figures 3.15 and 3.16), and the date on the upper stratum shells (2995 $\pm$ 145 ^{14}C yr BP*) relates to the initiation of

Unit III. The date on the lower shells (3880 ± 130 ^{14}C yr BP*) was probably from underlying sediments deposited with Unit II. The latter date is compatible with the dates from Sites 6, 7 and 2, and therefore fits very well within the age structure of Unit II, as outlined above. A third date from Site 3 (SUA-768/2, 820 ± 125 ^{14}C yr BP) was obtained on wood fragments separated from the shell hash that was used to give SUA-768/1 (3880 ± 130 ^{14}C yr BP*). The young date is now interpreted as relating to dead *in situ* tree roots, and not to wood deposited with the sediments, as previously assumed.

The fourth progradational unit at Rheban consists of a set of frontal dunes which parallel the present shoreline. Bowden and Kirkpatrick (1974) compared 1946 and 1966 aerial photographs of Rheban and concluded that the spit had been subjected to considerable accretion at the southern end, and some erosion near the northern end, during this period. They claimed that two frontal dunes have formed near the southern end since A.D. 1946, and that the greater height of these ridges may relate to the introduction of marram grass *(Ammophila arenaria)*, which has displaced *Festuca littoralis* as the main sand-binder on the spit, the latter plant being less effective in this respect.

3.3.2 Sediments

The granulometric characteristics and average mineralogical composition of the regressive facies sediments of the study barriers are presented and compared in this section;

these sediments constitute the parent material for the podzol soils under investigation. In this section only the average values for each barrier are discussed. However, these mean values are derived from the parent material determinations for individual soil profiles, the latter being presented in Section 3.4 below.

Granulometric statistics have been computed by the *method of moments* (modified from Griffiths, 1967), the data being obtained by mechanically sieving 100 g oven-dried sediment samples through a set of 1/4 Ø sieves for 15 minutes each, and weighing the resulting size fractions to 0.01 or 0.001 g (*ibid.*, pp.61-64). None of the parent material samples yielded significant amounts (>0.001 g) of non-organic material finer than 4Ø (i.e., silt or clay).

Sediment mineral composition was determined by examining HFl-etched, sodium cobaltinitrite-stained grains, previously mounted on glass slides (Bailey and Stevens, 1960; Friedman, 1971). A binocular microscope was used to differentiate quartz, feldspar, heavy minerals, lithics (rock fragments and micas) and biogenic carbonate. Percentage composition was determined from a count of 1000 grains per slide, yielding stable and accurate estimates of mineral content (Griffiths and Rosenfeld, 1954; Chayes, 1956).

The average granulometric characteristics and mineralogical composition of the parent material at each of the study barriers is presented in Table 3.3. From this table several generalizations can be made about the characteristics of the

TABLE 3.3

GRANULOMETRIC CHARACTERISTICS AND MINERAL COMPOSITION OF PARENT MATERIAL

	FENS	WOY WOY	MORUYA	DISASTER BAY	COWLEY	RHEBAN
			GRANULOMETRY			
$\bar{x}\phi$	1.55	1.75	1.81	1.69	1.10	2.14
$\delta\phi$	0.36	0.39	0.30	0.31	0.70	0.32
			MINERALOGY			
QUARTZ %	95.3	94.2	93.2	95.5	94.1	95.6
FELDSPARS %	2.3	3.2	4.9	3.4	3.6	2.7
HEAVY MINERALS %	1.7	1.8	1.3	0.8	1.3	1.3
LITHICS %	0.7	0.3	0.7	0.3	1.0	0.1
BIOGENIC CARBONATE %	0	0.5	0.1	0.1	0	0.2

parent material:

1. Average grain size is very similar for all the New South Wales barriers (Medium Sand class of Folk, 1968).

2. Average grain size of the Cowley - Inarlinga sediments ($\bar{X}\phi$ = 1.10) is somewhat coarser than the sediments from the other barriers, but still falls within the Medium Sand class (*ibid.*).

3. Average grain size of the Rheban parent material ($\bar{X}\phi$ = 2.14) places these sediments in the Fine Sand class (*ibid.*).

4. Average size-sorting coefficients are very similar for all the New South Wales barriers and for Rheban, but the Cowley parent material sediment is much more poorly sorted.

5. The sediments are quartz-rich, with minor feldspars, low amounts of heavy minerals, and negligible amounts of lithics and biogenic carbonate.

6. The percentage composition of quartz, felspars, heavy minerals, lithics and biogenic carbonate is very consistent for all six barriers, with no apparent latitudinal trends.

7. The carbonate values might be underestimated, because of substantial dissolution of carbonate fragments during HF1 etching.

From the above observations it is apparent that the average parent material granulometric and mineralogical characteristics do not vary significantly between the four New South Wales barriers, and that even the Tasmanian and Queensland barriers have substantially the same minerology, although the granulometric characteristics differ slightly.

3.3.3 Climate

The purpose of this section is to present detailed climatic statistics for each of the barrier localities. Accordingly, Tables 3.4 to 3.9 incorporate monthly and annual climatic statistics relating to mean 9am and 3pm temperature and relative humidity, daily maximum and minimum temperatures, rainfall and raindays.

In the following discussion the more pedologically significant features of the climatic statistics for each barrier locality are outlined.

3.3.3.1 Fens. The temperature regime that is evident in the Nelson Bay data (Table 3.4) shows a seasonal pattern typical of the temperate zone of coastal eastern Australia: average summer temperatures are warm and average winter temperatures are cool. In other words, conditions are mild, because of the ameliorating influence of the Tasman Sea.

Monthly rainfall and raindays (Table 3.4) are both fairly uniformly distributed, with slight winter maxima and spring minima. Spring is also the time of lowest monthly 9am and 3pm mean relative humidity. Seasonal moisture

TABLE 3.4

CLIMATIC DATA FOR THE HAWKS NEST - FENS BARRIER

Station: NELSON BAY

Latitude 32 Deg 43 Min S Longitude 152 Deg 9 Min E Elevation 18.3 M

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
9 am Mean Temperature (C) and Mean Relative Humidity (%)													
Dry Bulb	23.7	23.9	22.1	19.2	15.2	12.8	11.5	13.5	15.4	19.3	21.0	22.7	18.4
Humidity	72	74	73	73	74	79	65	67	69	63	64	69	70
3 pm Mean Temperature (C) and Mean Relative Humidity (%)													
Dry Bulb	24.4	24.9	23.6	22.1	18.2	16.9	16.4	17.3	17.9	20.9	21.3	23.4	20.6
Humidity	70	70	67	61	64	63	51	53	62	59	64	66	63
Daily Maximum Temperature (C)													
Mean	26.8	26.8	25.6	23.9	20.1	18.3	17.6	18.8	19.8	23.4	24.5	25.8	22.6
86 Percentile	29.7	28.9	27.8	26.1	22.7	20.0	19.7	21.2	23.7	27.8	27.8	29.6	
14 Percentile	23.9	25.0	23.3	21.7	18.1	16.2	15.0	16.2	16.7	20.0	21.2	22.2	
Daily Minimum Temperature (C)													
Mean	18.7	19.0	17.4	14.7	11.5	9.5	7.6	9.1	10.3	13.8	15.4	17.3	13.7
86 Percentile	20.8	20.8	19.4	17.2	13.9	11.7	10.1	11.7	13.3	16.1	17.8	20.0	
14 Percentile	16.4	16.9	15.6	12.2	9.2	7.3	5.0	6.7	7.8	11.1	12.8	14.6	
Rainfall (mm)													
Mean	102	106	119	119	147	155	143	106	92	78	69	96	1332
Median	85	86	87	101	117	113	121	82	74	72	59	70	1293
Raindays (No)													
Mean	12	11	12	12	13	13	12	11	11	11	10	11	139

Source: Bureau of Meteorology (1975)

TABLE 3.5

CLIMATIC DATA FOR THE WOY WOY BARRIER

Station: NARARA

Latitude 33 Deg 24 Min S   Longitude 151 Deg 20 Min E   Elevation 30.5 M

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
9 am Mean Temperature (C) and Mean Relative Humidity (%)													
Dry Bulb	23.1	22.9	21.2	18.2	13.8	11.4	10.0	12.5	16.1	19.3	20.6	22.5	17.6
Humidity	68	74	76	77	80	83	79	73	64	61	60	65	72
Daily Maximum Temperature (C)													
Mean	27.1	26.8	26.0	24.0	20.1	17.6	17.4	18.7	21.2	23.9	24.7	26.6	22.8
86 Percentile	32.2	30.8	30.5	27.5	23.1	20.1	19.5	21.5	25.9	29.7	29.4	32.4	
14 Percentile	22.5	22.8	22.2	20.6	16.7	15.4	15.1	15.6	16.9	18.9	20.0	21.2	
Daily Minimum Temperature (C)													
Mean	16.3	16.9	14.8	11.3	7.6	6.2	3.9	5.4	7.2	10.8	12.8	14.7	10.7
86 Percentile	19.7	19.7	18.3	15.0	11.3	10.8	8.0	9.4	11.1	14.7	16.1	18.1	
14 Percentile	13.1	13.9	11.1	7.8	3.9	1.9	0.5	1.7	3.5	6.7	8.3	11.1	
Rainfall (mm)													
Mean	137	139	143	135	112	128	87	79	69	84	88	107	1308
Median	110	110	120	94	79	79	58	58	60	65	78	76	1249
Raindays (No)													
Mean	10	10	10	10	8	9	8	7	7	8	8	10	105

Source: Bureau of Meteorology (1975)

stress for plants, especially those on sandy soils, could result from the lower spring rainfall, rainday and relative humidity averages.

3.3.3.2 Woy Woy. The Narara temperature statistics (Table 3.5) indicate a slightly cooler temperature regime, with a slightly greater annual temperature range, than at Nelson Bay. However, average summer temperatures may still be regarded as warm, rather than hot, and average winter temperatures as cool, rather than cold. Mean 9am relative humidity shows a winter maximum, spring minimum distribution, while rainfall is greater in summer/autumn and least in spring. Raindays tend to be similarly distributed. Consequently, moisture stress during spring seems probable.

3.3.3.3 Moruya. The location of the Moruya Heads meteorological station adjacent to the sea results in a more restricted temperature range than at Narara (which is further inland), although the increased latitude causes lower temperatures overall (see Table 3.6). Rainfall is also lower at Moruya, with a summer maximum and winter minimum. Average number of raindays per month is highest in spring and summer, and lowest in winter.

3.3.3.4 Disaster Bay. Climatic data for Disaster Bay (Green Cape Lighthouse) are given in Table 3.7. Temperatures at Green Cape are slightly lower than at Moruya, but again the strong maritime influence restricts the temperature range, so that winters are cool rather than cold, and summers warm rather than hot. Rainfall at Green Cape is

TABLE 3.6

CLIMATIC DATA FOR THE MORUYA - BROULEE BARRIER

Station: MORUYA HEADS

Latitude 35 Deg 55 Min S Longitude 150 Deg 9 Min E Elevation 10.7 M

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
9 am Mean Temperature (C) and Mean Relative Humidity (%)													
Dry Bulb	20.7	20.9	19.5	16.6	12.7	10.2	9.3	11.0	13.9	16.4	18.2	19.5	15.7
Humidity	75	76	76	77	78	81	77	74	68	69	70	74	75
3 pm Mean Temperature (C) and Mean Relative Humidity (%)													
Dry Bulb	21.8	22.2	21.7	20.4	17.6	15.7	15.0	15.4	16.6	17.7	19.1	20.3	18.6
Humidity	72	74	73	67	63	64	60	61	62	67	70	73	67
Daily Maximum Temperature (C)													
Mean	23.4	23.7	23.0	21.5	18.6	16.5	15.9	16.4	18.0	19.6	21.0	22.1	20.0
86 Percentile	25.6	25.6	25.0	23.9	21.1	18.9	17.8	18.9	20.9	22.8	24.4	24.4	
14 Percentile	21.0	21.1	20.6	18.9	16.1	14.4	13.9	13.9	15.2	16.4	18.3	19.4	
Daily Minimum Temperature (C)													
Mean	15.7	16.0	14.9	12.0	8.8	6.8	5.7	6.3	8.0	10.6	12.4	14.3	11.0
86 Percentile	18.2	18.3	17.8	15.0	12.2	9.9	8.9	9.4	11.5	13.9	15.6	17.1	
14 Percentile	13.3	13.3	12.2	8.8	5.6	3.9	2.8	3.3	4.9	7.3	9.0	11.7	
Rainfall (mm)													
Mean	97	90	102	81	85	85	55	54	60	74	74	74	931
Median	82	59	70	54	54	48	35	33	44	59	60	59	885
Raindays (No)													
Mean	10	9	10	8	8	8	7	7	8	10	10	10	105

Source: Bureau of Meteorology (1975)

TABLE 3.7

CLIMATIC DATA FOR THE DISASTER BAY - WONBOYN BARRIER

Station: GREEN CAPE LIGHTHOUSE

Latitude 37 Deg 16 Min S   Longitude 150 Deg 3 Min E   Elevation 18.3 M

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
9 am Mean Temperature (C) and Mean Relative Humidity (%)													
Dry Bulb	19.2	19.7	18.4	16.8	13.4	11.5	10.5	11.2	12.6	14.7	16.0	17.6	15.1
Humidity	84	83	85	82	82	85	81	78	78	78	81	79	81
3 pm Mean Temperature (C) and Mean Relative Humidity (%)													
Dry Bulb	19.8	20.5	19.7	18.8	15.7	13.9	13.4	13.5	14.0	15.5	16.2	17.6	16.6
Humidity	83	81	82	79	75	78	73	73	75	78	84	86	79
Daily Maximum Temperature (C)													
Mean	21.4	21.8	21.0	19.9	16.7	14.9	14.3	14.7	15.7	17.3	18.3	19.6	18.0
86 Percentile	23.3	23.3	22.9	21.7	18.9	16.7	15.8	16.4	17.8	19.4	20.5	21.8	
14 Percentile	19.4	20.0	18.9	18.3	14.4	13.3	12.8	12.8	13.3	15.0	16.1	17.6	
Daily Minimum Temperature (C)													
Mean	16.3	16.6	15.6	13.8	10.9	9.1	8.2	8.4	8.5	11.4	12.4	14.1	12.1
86 Percentile	18.3	18.6	17.8	16.1	13.2	10.7	10.0	10.6	11.1	13.9	15.0	16.7	
14 Percentile	14.4	14.4	13.4	11.7	8.9	7.4	6.4	6.6	6.0	9.0	10.0	11.7	
Rainfall (mm)													
Mean	85	61	83	53	74	73	57	51	55	57	63	54	766
Median	62	42	66	40	45	46	45	45	42	47	48	44	750
Raindays (No)													
Mean	11	12	11	8	10	7	9	13	7	12	15	7	122

Source: Bureau of Meteorology (1975)

greatest in summer/autumn, and least in winter. However, this distribution is not reflected in the monthly rainday figures, which tend to be variable.

3.3.3.5 Cowley. As mentioned in Section 3.2.2.2, both temperature and rainfall are substantially higher at Cowley (Innisfail) than at the New South Wales barrier localities. The Innisfail data are given in Table 3.8, and it is apparent that the summer temperatures may be best described as hot, and winter temperatures as warm. Although in the tropics, temperature seasonality is still evident. Relative humidity tends to be highest at Innisfail during the first half of the calendar year, (Table 3.8) and rainfall is strongly seasonal, with very high average values in summer and autumn, and low values in spring. This pattern is reflected in the monthly distribution of raindays. Plant moisture stress is likely to occur in spring, but during the rest of the year ideal growing conditions prevail.

3.3.3.6 Rheban. Table 3.9 incorporates climatic data for the Orford and Rheban meteorological stations. From the table it is apparent that the temperature regime is distinctly cooler at Rheban, than at the New South Wales localities; summer temperatures are cool and winter temperatures are cold. The annual ranges of the various temperature parameters are greater at Rheban, than at the New South Wales localities, because of the lower winter temperature experienced in Tasmania. Rainfall at Rheban is low (compared to the New South Wales and Queensland barrier localities) and is fairly evenly distributed throughout the

TABLE 3.8

CLIMATIC DATA FOR THE COWLEY BEACH - INARLINGA BARRIER

Station: INNISFAIL

Latitude 17 Deg 31 Min S   Longitude 146 Deg 2 Min E   Elevation 6.7 M

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
9 am Mean Temperature (C) and Mean Relative Humidity (%)													
Dry Bulb	26.9	26.4	25.4	23.9	21.7	19.7	18.5	19.9	22.2	24.8	26.8	27.4	23.6
Humidity	81	85	86	86	86	87	85	84	77	73	73	75	82
3 pm Mean Temperature (C) and Mean Relative Humidity (%)													
Dry Bulb	28.8	28.9	27.9	26.5	24.6	23.0	22.6	23.8	25.1	26.9	28.1	28.8	26.3
Humidity	73	74	75	74	74	72	67	67	66	65	68	69	70
Daily Maximum Temperature (C)													
Mean	30.3	30.2	29.1	27.7	25.8	24.1	23.6	25.0	26.3	28.0	29.4	30.2	27.5
86 Percentile	32.2	32.2	31.1	29.4	27.6	26.1	25.6	26.7	27.8	30.0	31.1	32.2	
14 Percentile	28.3	28.2	27.2	26.1	23.9	22.2	21.7	23.2	24.6	26.3	27.7	28.3	
Daily Minimum Temperature (C)													
Mean	22.7	23.0	22.1	20.5	18.6	16.6	15.1	15.9	17.0	18.9	21.0	22.0	19.5
86 Percentile	24.0	24.2	23.6	22.2	21.1	19.4	18.3	18.4	19.3	21.0	22.8	23.8	
14 Percentile	21.6	21.7	20.6	18.9	15.8	13.3	11.2	13.1	14.4	16.7	19.1	20.3	
Rainfall (mm)													
Mean	529	606	706	473	305	191	128	114	92	82	153	265	3644
Median	494	513	643	396	264	161	104	96	67	58	111	165	3579
Raindays (No)													
Mean	16	17	19	18	16	12	11	10	8	7	9	12	155

Source: Bureau of Meteorology (1975).

TABLE 3.9

CLIMATIC DATA FOR THE RHEBAN SPIT

Station: ORFORD

Latitude 42 Deg 34 Min S   Longitude 147 Deg 52 Min E   Elevation 9.1 M

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
9 am Mean Temperature (C) and Mean Relative Humidity (%)													
Dry Bulb	17.7	18.3	16.2	13.7	9.5	6.2	6.2	7.9	10.8	13.5	14.7	16.1	12.6
Humidity	63	66	60	71	83	88	94	83	67	61	64	60	72
3 pm Mean Temperature (C) and Mean Relative Humidity (%)													
Dry Bulb	19.9	20.8	19.4	17.9	14.2	11.7	12.2	12.6	13.9	15.7	16.4	17.7	16.0
Humidity	59	61	52	56	64	69	61	64	54	56	61	58	60
Daily Maximum Temperature (C)													
Mean	22.1	22.5	21.3	19.6	15.9	13.6	13.8	14.1	15.8	17.8	18.3	20.1	17.9
86 Percentile	25.6	26.7	25.0	23.3	18.9	16.2	16.0	16.7	19.0	21.6	21.4	23.8	
14 Percentile	18.3	19.0	17.8	16.1	13.3	11.0	11.7	11.6	12.5	15.0	15.0	16.7	
Daily Minimum Temperature (C)													
Mean	11.2	12.3	10.0	8.3	5.6	3.0	2.5	3.5	4.4	6.1	8.4	9.4	7.1
86 Percentile	14.8	15.7	13.9	12.2	9.2	7.1	5.6	6.7	7.7	9.4	11.6	12.1	
14 Percentile	7.7	9.2	6.1	4.4	2.2	0.2	-0.4	0.4	1.4	2.8	5.1	6.8	
Rainfall (mm)													
Mean	43	56	45	68	72	69	62	53	49	63	61	69	710
Median	37	40	35	50	46	59	57	38	39	55	55	59	670
Raindays (No)													
Mean	8	8	8	10	12	10	12	12	11	13	13	11	128

Station: RHEBAN

Latitude 42 Deg 38 S   Longitude 147 Deg 56 E   Elevation 30 M

Rainfall (mm)

Yrs	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
32 Average	48	58	47	47	62	64	52	53	41	55	56	67	650
30 Median	42	42	41	37	47	46	46	40	37	49	39	59	590
24 Raindays	9	8	9	9	10	11	11	12	11	11	11	10	122

Source: Bureau of Meteorolody (1975).

year. However, it does tend to exhibit a slight summer deficiency, as does the annual distribution of monthly raindays. Summer moisture stress conditions would therefore probably eventuate.

3.3.4 Vegetation.

Information given below about the vegetation of the six study barriers relates to the *effective disseminule factor*, which was discussed in Chapter Two. The information consists of a general description of the vegetation distribution pattern for each beach-ridge plain (vegetation structural classification after Specht, 1970) and in some cases, a list of the most abundant species present.

3.3.4.1 Fens. Although the flora of the Myall Lakes area has been the subject of considerable attention by botanists, most of this work has been concerned with areas to the north of the Fens Embayment. Only the publications of Pidgeon (1940) and Shepherd (1970) are directly relevant to the flora of the Fens Outer Barrier. The following description is therefore based on these references, with additional observations made by the writer. The vegetation distribution pattern of the Fens Outer Barrier is depicted in Figure 3.17.

Beach erosion has not completely removed the *incipient* foredune from the Fens Outer Barrier, and consequently the vegetation of this zone is still intact. Typically, pioneer grasses such as *Festuca littoralis* and *Spinifex hirsutus* colonize this area, while at the rear of the beach *Cakile maritima* is

FIGURE 3.17

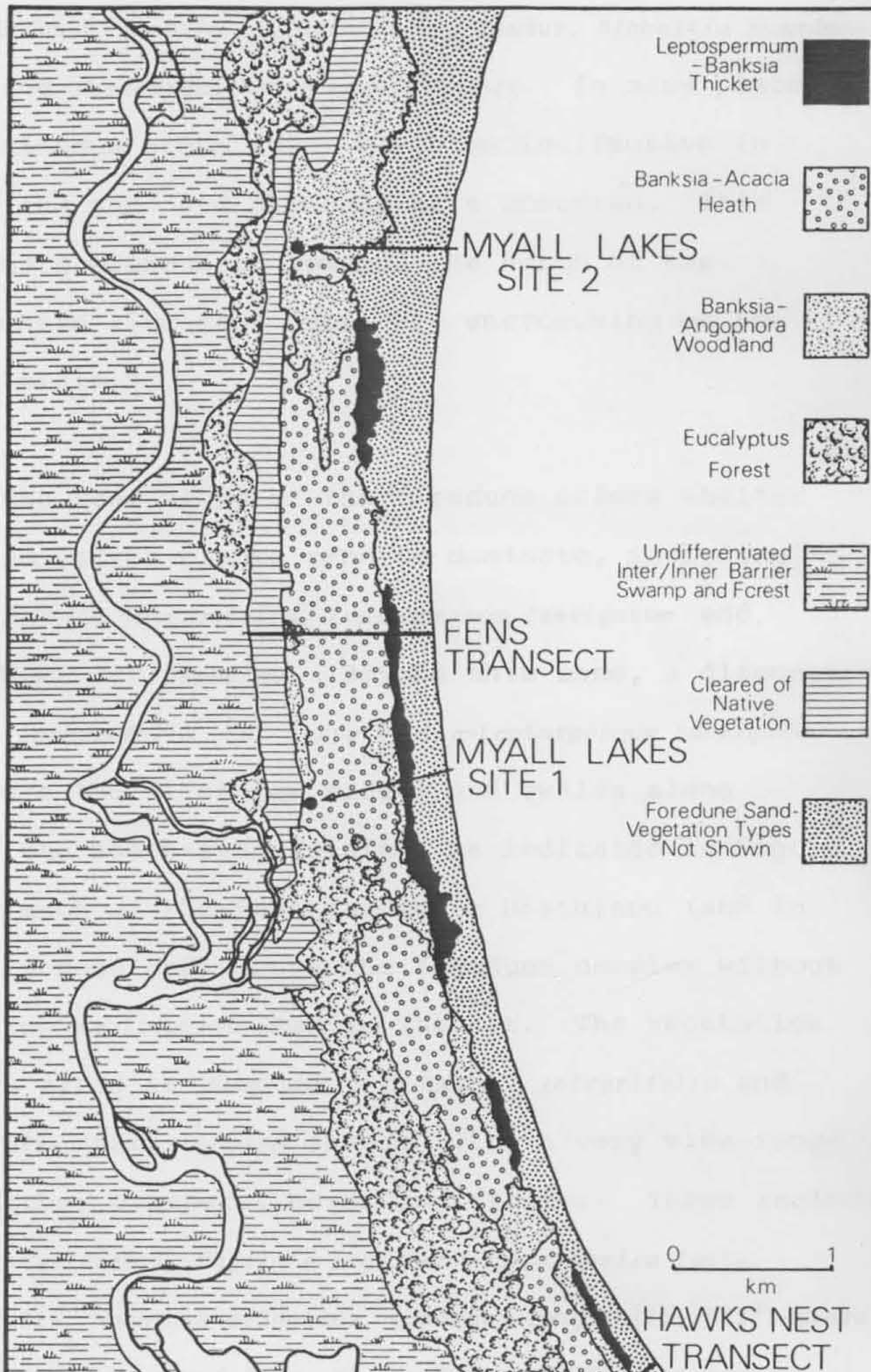

Figure 3.17 Map showing the distribution of the main vegetation types on the Fens Outer Barrier beach-ridge plain. Note that foredune vegetation types are not shown, and that the vegetation of the interbarrier depression is not differentiated.

occasionally found. The seaward face of the *established* foredune has a groundcover of mat plants and herbs, including *Scaevola candulacea, Senecio spathulatus, S. lautus, Hibbertia scandens, H. volubilis* and *Mesembryanthemum aequilaterale.* In many places this discontinuous groundcover has been ineffective in stabilizing the sand and blowouts have occurred. This erosion is more pronounced towards the north of the embayment, where live sand dunes are encroaching on the beach-ridge plain.

Where the rear slope of the foredune offers shelter from the wind, scrub plants tend to dominate, including *Correa alba, Banksia integrifolia, Leptospermum laevigatum* and *Acacia longifolia* var. *sophorae.* Beyond this zone, a discontinuous *Banksia integrifolia —B. serratifolia-Leptospermum laevigatum* Thicket covers the first few ridges and swales along sections of the beach-ridge plain. As indicated in Figure 3.17, along much of the Fens barrier a Heathland (and in some places a Woodland) abuts the foredune complex without an intervening *Leptospermum-Banksia* Thicket. The vegetation of the heath areas is composed of *Banksia integrifolia* and *Acacia longifolia* var. *sophorae* shrubs, with a very wide range of other shrubs, creepers, herbs and grasses. These include *Exocarpos cupressiformis, Phyllota phylicoides, Styphelia laeta, Acacia ulicifolia, Monotoca ellyptica, Lomandra longifolia, Billardiera scandens, Stylidium graminifolium, Persoonia lanceolata, Leucopogon ericoides, Woollsia pungens, Hibbertia fasciculata, H. obtusifolia, Olax stricta, Eriostemon lanceolatus, Actinotus helianthii, Astroloma pinifolium, Bossiaea ensata* and *Imperata cylindrica* . The Heathland is shown in Plate 3.1

PLATE 3.1

PLATE 3.2

Plate 3.1 *Banksia - Acacia* Heathland on the Fens Outer Barrier, near the Fens transect line. Note fire-effected *Acacia* in foreground and encroaching foredune drift sand in distance.

Plate 3.2 *Eucalyptus* Forest near the rear of the Fens Outer Barrier, in the vicinity of the Hawks Nest transect. Leaves on tree in foreground (right) are *Banksia integrifolia*; flowers are *Actinotus helianthii* (Flannel Flower). This area has now been mined for heavy minerals.

Where the Woodland occurs (Figure 3.17) it is dominated by *Banksia integrifolia, B. serrata* and *Angophora costata.* Sub-dominant shrubs and herbs, many the same species as those listed above for the heath areas, form a fairly open substratum. See Plate 3.3.

Along the rear part of the barrier, but in some areas extending a considerable distance seawards across the barrier (see Figure 3.17), is a *Eucalyptus* Forest dominated by *E.pilularis, E. gummifera* and *Angophora costata.* Again, the substratum is fairly open and consists of shrubs and herbs of similar species to those of the Heathland. See Plate 3.2.

On the backbarrier flats of the interbarrier depression grows a swamp forest that is dominated by *Eucalyptus robusta, Melaleuca* species, *Livistonia australis* and *Casuarina Cunninghamiana.*

It is not known to what extent the present distribution of vegetation on the Fens Outer Barrier, as depicted in Figure 3.17, reflects natural environmental conditions, and to what extent it has been effected by fire and grazing. Certainly the irregular Heathland/Woodland boundary marks a structural, rather than genetic, vegetation transition, and many Heathland areas at present appear to be developing towards a Woodland form.

3.3.4.2 Woy Woy. Although small pockets of the native vegetation of the Woy Woy - Umina beach-ridge plain still exist, it is now very difficult to gain an appreciation of the former floristic distribution and composition because of

PLATE 3.3

PLATE 3.4

Plate 3.3 *Banksia - Angophora* Woodland near the northern end of the Fens Outer Barrier. The foreground has been cleared.
Plate 3.4 Open *Banksia* Woodland on the Moruya beach-ridge plain, near Broulee Site 1. Some *Eucalyptus* dieback is evident. The bushes in foreground (at left and right) are *Casuarina littoralis*; groundcover consists mainly of *Imperata cylindrica* (Bladey Grass) and *Pteridium esculatem* (Bracken Fern).

extensive residential development. The following description is therefore largely based on the work of Burges and Drover (1953) and Hails (1969a, 1969b).

The frontal dune at Ocean Beach (Figure 3.6) was stabilized by *Festuca littoralis* and *Spinifex hirsutus*, as at most other New South Wales barrier localities. These sand binding plants merged into a cover of succulents on the front of the stabilized foredune, which included *Hydrocotyle* spp., *Hibbertia volubilis*, *H. scandens* and *Sporobolus capensis*, with *Lomandra longifolia*. Landwards of the stabilized foredune, *Leptospermum laevigatum* and *Banksia integrifolia* formed a Thicket about 100 metres wide. Beyond this Thicket, and extending as far as the swampy tract of land south of Woy Woy Creek (see Figure 3.6), there existed a fairly open forest of *Eucalyptus botryoides*, *E. gummifera* and *Angophora floribunda*, with occasional *Banksia integrifolia* and *B. serrata*. *Pteridium aquilinium*, *Lomandra longifolia*, *Persoonia lanceolata*, *Acacia longifolia*, *Imperata cylindrica* and other species, formed the rather sparse undergrowth.

To the north of the swampy tract, the composition of the Open Forest changed. *Eucalyptus pilularis* became more prominent and *Angophora floribunda* was replaced by *Angophora costata*. On the margins of the swampy areas *Casuarina littoralis* and *C. glauca* replaced the *Banksia* trees, and *Eucalyptus robusta* was found. *Melaleuca* species, *Typha*, reeds and sedges occupied the swamps.

3.3.4.3 Moruya. The following description of the vegetation of the Moruya-Broulee beach-ridge plain is based on observations by the writer.

Since 1974, periodic severe marine erosion in eastern Australia (Thom, 1978) has resulted in the removal of incipient foredunes from many barriers, and at some localities, including Moruya, even the established foredune has been breached. At Moruya-Broulee such erosion has resulted in the temporary destruction of the vegetation usually associated with the backshore zone. This vegetation consisted of scattered individuals of the strand plant *Cakile maritima*, pioneer sand-binding grasses such as *Spinifex hirsutus*, and low-growing colonies of *Senecio* and *Sonchus* species. Where the seaward-facing slope of the established foredune has not been greatly effected by erosion (i.e., in the northern and central sections of the embayment), the vegetation consists of *Spinifex hirsutus*, but succulents *Hibbertia volubilis*, *Scaevola suaveolens* and *Hydrocotyle vulgaris* are more common. Low creeping plants such as *Pelargonium australe* and *Euphorbia Sparmanii*, and tufted plants such as *Lomandra longifolia* and *Scirpus nodosus*, also occur. Low dense shrubs of *Acacia longifolia* var. *sophorae*, *Correa alba*, *Leucopogon Richei* and *Banksia integrifolia* are common in this zone.

On many east coast Holocene barriers *Leptospermum* species tend to dominate the lee of the established foredune (Pidgeon, 1940). However, at Moruya-Broulee this genus is relatively uncommon and a *Banksia* Woodland (probably fire and grazing affected) takes the place of the more usual *Leptospermum* *laevigatum* Thicket, and extends inland up to 200 metres. This Woodland consists of scattered *Banksia integrifolia*, *B. serrata* and *B. marginata*, with some areas of mixed *Banksia* and *Angophora floribunda*, *Eucalyptus botryoides*, *E. gummifera* and *E. piperita*. The Woodland has a scattered shrub layer consisting chiefly of *Ricinocarpus pimifolius*, *Persoonia lanceolata*, *Leucopogon ericoides*, *Acacia trachyphloia*, *A. mabellae* and *Eriostemon lanceolatus*. A lower stratus of *Pteridium aquilinum*, *Imperata cylindrica* , *Lomandra longifolia*, *Hibbertia volubilis*, and herbs and creepers, is fairly continuous throughout the Woodland. See Plate 3.4.

On its landward side the *Banksia* Woodland changes abruptly, but irregularly, to a sclerophyllous *Eucalyptus* Forest, which extends to the bedrock contact. The main Eucalypt species in this area is *E. pilularis*, but *E. botryoides*, *E. gummifera*, *E. maculata*, *E. piperita* and *E. racemosa* also occur. *Angophora* species are rare on the Moruya-Broulee barrier, but a few individuals of *A. costata* and *A. floribunda* are found in the Eucalypt Forest.

All three *Banksia* species found in the *Banksia* Woodland (but principally *B. serrata*) also occur as a scattered understorey in the Eucalypt Forest, along with occasional *Acacia suaveolens* and *A. trachyphloia*. *Macrozamia spiralis* forms a dense (fire induced) lower stratum, beneath which *Pteridium aquilinum* and tufted grasses, herbs and creepers cover most of the ground. The Eucalypt Forest is shown in Plate 3.5.

PLATE 3.5

PLATE 3.6

Plate 3.5 *Eucalyptus Forest* (principally *E. pilularis*) towards the rear of the Moruya-Broulee beach-ridge plain. The undergrowth is dominated by *Macrozamia spiralis.*

Plate 3.6 Regeneration of the Disaster Bay beach-ridge plain *Eucalyptus-Banksia* Forest, following the 1972 bushfire. The photograph was taken late in 1973, prior to the regrowth of *Acacia* species.

3.3.4.4 Disaster Bay. The vegetation of this beach-ridge plain was severely effected by a bushfire in December 1972. However, regeneration and regrowth has been swift and today the barrier is again densely vegetated, although probably with an altered floristic composition (Recher *et al.*, 1975).

Since 1974 beach erosion at Disaster Bay has completely removed the incipient foredune and its associated vegetation, and along most of the beach the established foredune has also been partly eroded. From the scarped foredune long, branched rhizomes of *Spinifex hirsutus* trail down onto the backshore zone, where *Cakile maritima* has started recolonization. On the crest of the established foredune the mat plants *Scaevola suaveolens*, *Hibbertia volubilis*, *Mesembryanthemum aequilaterale* and *Hydrocotyle vulgaris* form a well-developed groundcover, beneath a *Leptospermum laevigatum-Acacia longifolia* var. *sophorae-Leucopogon Richei* shrub stand. On the protected leeward side of the foredune, and extending 100 metres further inland, an extremely dense pre-bushfire *Leptospermum* Thicket is regenerating as a *Leptospermum laevigatum-Acacia longifolia* var. *sophorae* Thicket. On the landward side of the latter vegetation zone, a sharp and very regular transition occurs to an Open *Eucalyptus-Banksia* Forest, which extends to the rear of the beach-ridge plain. The main *Eucalyptus* species in this Forest are *E. pilularis*, *E. botryoides*, *E. piperita*, *E. consideniana* and *E. gummifera*, while the most common *Banksia* are *B. serrata*, *B. marginata* and *B. integrifolia*. The abundance of *Banksia*, relative to Eucalypts, declines towards the rear of the barrier. *Acacia* species (principally *A. longifolia* var. *sophorae*) formed a very dense understorey throughout most of the Eucalypt-*Banksia* Forest after the bushfire, but subsequently have substantially died off, especially across the middle of the beach-ridge plain.

On the lower parts of the barrier backslope, a *Melaleuca ericifolia-Sporobolus virginicus-Juncus maritimus* Thicket has regrown. This gives way to a *Salicornia* saltmarsh on the Lake Wonboyn lagoonal flats.

3.3.4.5 Cowley. The following description of the vegetation of the Cowley-Inarlinga Outer Barrier is based on field observations by the writer, and on information supplied by M.S.Hopkins (Hopkins and Graham, 1979, in press).

A gradational vegetation sequence of Open Forbland, Grassland, Shrubland and Dwart Closed Forest, extends from the rear of the beach, across the low stabilized foredune, and over the first few beach ridges of the Cowley barrier. The dominant tree species are wind-sheared *Acacia crassicarpa* and *Casuarina equisetifolia*, with *Spinifex hirsutus* and *Thermeda australis* the most common grasses. On its landward side, the gradational sequence merges into a Low Closed Forest dominated by *Acacia crassicarpa*, with areas of *Xanthorrphoea johnsonii* Shrubland. About 200 metres inland from the beach, the Low Closed Forest changes to a Medium Open Forest, which extends to the rear of the barrier. Overmature *Eucalyptus intermedia* and large *Acacia crassicarpa* form the canopy of the Open Forest, while the subcanopy consists of the latter species plus *Casuarina littoralis*. A widespread understorey of juvenile trees and shrubs consists of *A. crassicarpa*, *C. littoralis*, *Thryptomene loigandra*, *Canarium australianum*, *Persoonia falcata* and *Terminalia muelleri*. Groundcover is well developed and includes *Thermeda australis*, *Sorghum plumosum*, *Heteropogon triticeus* and *Coilorhachis rattboellioides*. In the deeper swales and drainage lines and along the western margin of the Outer Barrier (see Figure 3.12), *Melaleuca quinquenervia* and *Tristania suaveolens* dominate Low Closed Forest paperbark swamps, which have a sedge understorey (mainly *Lepironia articulata*).

3.3.4.6 Rheban. The vegetation of Rheban Spit has been described in detail by Bowden and Kirkpatrick (1974). The following account is therefore largely based on their work, with supplementary observations by the writer. Table 3.10 lists all vascular plant species observed on the Rheban beach ridges, and indicates their relative abundance. Figure 3.18 shows the variation in the relative abundance of the species along a transect from Carrickfergus Bay to Earlham Lagoon, that is, across the spit. The transect matches that shown in Figures 3.15 and 3.16.

Towards the southern end of Rheban Spit the foredune (Figure 3.15) is almost entirely vegetated by *Ammophila arenaria* on its crest and seaward slope, with occasional *Sonchus megalocarpus* and rare *Festuca littoralis*. On the inland slope *Ammophila* is dominant for the most part, with low shrubs of *Acacia longifolia* var. *sophorae* established in some areas. The latter species dominates the second smaller frontal dune, where *Scirpus nodosus*, *Poa poiformis* and *Hypochaeris radicata* are also quite common.

TABLE 3.10

PLANT SPECIES OF THE RHEBAN BEACH-RIDGE PLAIN

After Bowden and Kirkpatrick (1974)

SPECIES	
Dennstaedtiaceae	
Pteridium esculentum (Forst. f.) Nakai	vc
Gramineae	
+*Aira caryophyllea* L.	c
Danthonia setacea R. Br.	c
Dichelachne crinita (L.f.) Hook.f.	c
Poa poiformis (Labill.) Druce	vc
Stipa compacta D.K. Hughes	o
Cyperaceae	
Lepidosperma squamata Labill.	o
Scirpus nodosus Rottb.	o
Restionaceae	
Leptocarpus tenax (Labill.) R. Br.	r
Juncaceae	
J. pallidus R. Br.	r
Luzula campestris (L.) DC.	o
Liliaceae	
Dianella revoluta R. Br.	r
Lomandra longifolia Labill.	vc
Orchidaceae	
Corybas diemenicus (Lindl.) H.M.R. Rupp	o
Pterostylis alata (Labill.) Reichenb. f.	o
Casuarinaceae	
Casuarina littoralis Salisb.	r
Proteaceae	
Banksia marginata Cav.	c
Santalaceae	
Exocarpos cupressiformis Labill.	r
E. strictus R. Br.	o
Polygonaceae	
+*Rumex acetosella*	o
Ficoidaceae	
Carpobrotus rossii (Haw.)N.E. Br.	o
Caryophyllaceae	
Scleranthus biflorus (Forst. et Forst. f.) Hook. f.	r
Mimosaceae	
Acacia dealbata Link	vc
A. melanoxylon R. Br.	r
Papilionaceae	
Aotus ericoides (Vent.) G. Don.	o
Dillwynia glaberrima Sm.	o
Indigofera australis Willd.	r
Kennedia prostrata R. Br.	o
+*Ulex europaeus* L.	o

SPECIES	
Geraniaceae	
Geranium potentilloides Aucct., non certe Forst.f. ex Willde.	o
Oxalidaceae	
Oxalis corniculata L.	o
Euphorbiaceae	
Amperea xiphoclada (Sieb. ex Spreng.) Druce	o
Dilleniaceae	
Hibbertia acicularis (Labill.)F.Muell.	c
Violaceae	
Viola hederacea Labill.	r
Thymelaceae	
Pimelea humilis R.Br.	c
Myrtaceae	
Eucalyptus globulus Labill.	vc
E. viminalis Labill.	vc
Leptospermum scoparium Forst.et Forst. f.	r
Haloragaceae	
Haloragis tetragyna (Labill.)Hook.f.	c
Epacridaceae	
Astroloma humifusum (Cav.)R. Br.	vc
Epacris impressa Labill.	o
Leucopogon parviflorus (Andr.)Lindl.	r
Convolvulaceae	
Dichondra repens Forst.et Forst.f.	o
Scrophulariaceae	
Veronica calycina R. Br.	o
Rubiaceae	
Galium sp.	r
Campanulaceae	
Wahlenbergia sp.	o
Compositae	
+*Cirsium vulgare* (Savi) Ten.	r
Helichrysum apiculatum (Labill.)DC.	o
H. dendroideum N.A. Wakefield	r
+*Hypochaeris radicata* L.	o
+*Leontodon taraxacoides* (Vill.)Merat	o
+*Picris hieracioides* L.	o

vc = very common; c = common; o = occasional; r = rare.

FIGURE 3.18

Figure 3.18 Percentage frequency of selected plant species along the Rheban Spit transect (after Bowden and Kirkpatrick, 1974). The locations of soil sites are indicated on the cross-section; the stippled area represents the zone of podzolized

> The third and largest of the frontal dunes has a contrasting vegetation, although pedologically it is similar to the first two dunes (Bowden and Kirkpatrick, 1974, p.203).

This dune is covered with *Pteridium esculentum* with occasional *Poa poiformis*, frequent *Banksia marginata* and rare *Ammophila arenaria.*

The swales in the foredune complex are vegetated largely by a low mat of herbaceous species which includes *Schoenus nitens*, *Cotula reptans*, *Centaurium erythraea*, *Samolus repens* and *Lobelia alata.* A slightly taller, but more sparsely distributed stratum, is composed of *Poa poiformis*, *Scirpus nodosus* and *Juncus* spp. Minor *Acacia longifolia* var. *sophorae* also occurs in these swales.

> The break in soil type from the largely undifferentiated sands of the foredune complex to the weak podzol of the beach-ridge system corresponds with a dramatic change in the floristics and physiognomy of the vegetation (Bowden and Kirkpatrick, 1974, p.203).

The beach-ridge complex is covered by an Open Forest dominated by *Eucalyptus globulus*, although towards the lagoon *E. viminalis* is equally common. The trees are even-aged and rather sparsley spaced, with *Acacia dealbata* (2-3m high) forming a second stratum. A lower stratum again (c.1m) is dominated by *Pteridium esculentum*, *Poa poiformis* and *Lomandra longifolia*, and a fourth, less consistent stratum, dominated by small prostrate shrubs, consists mainly of *Astroloma humifusum* and *Hibbertia acicularis.* Plate 3.7. shows an area of *Eucalyptus globulus* Forest.

PLATE 3.7

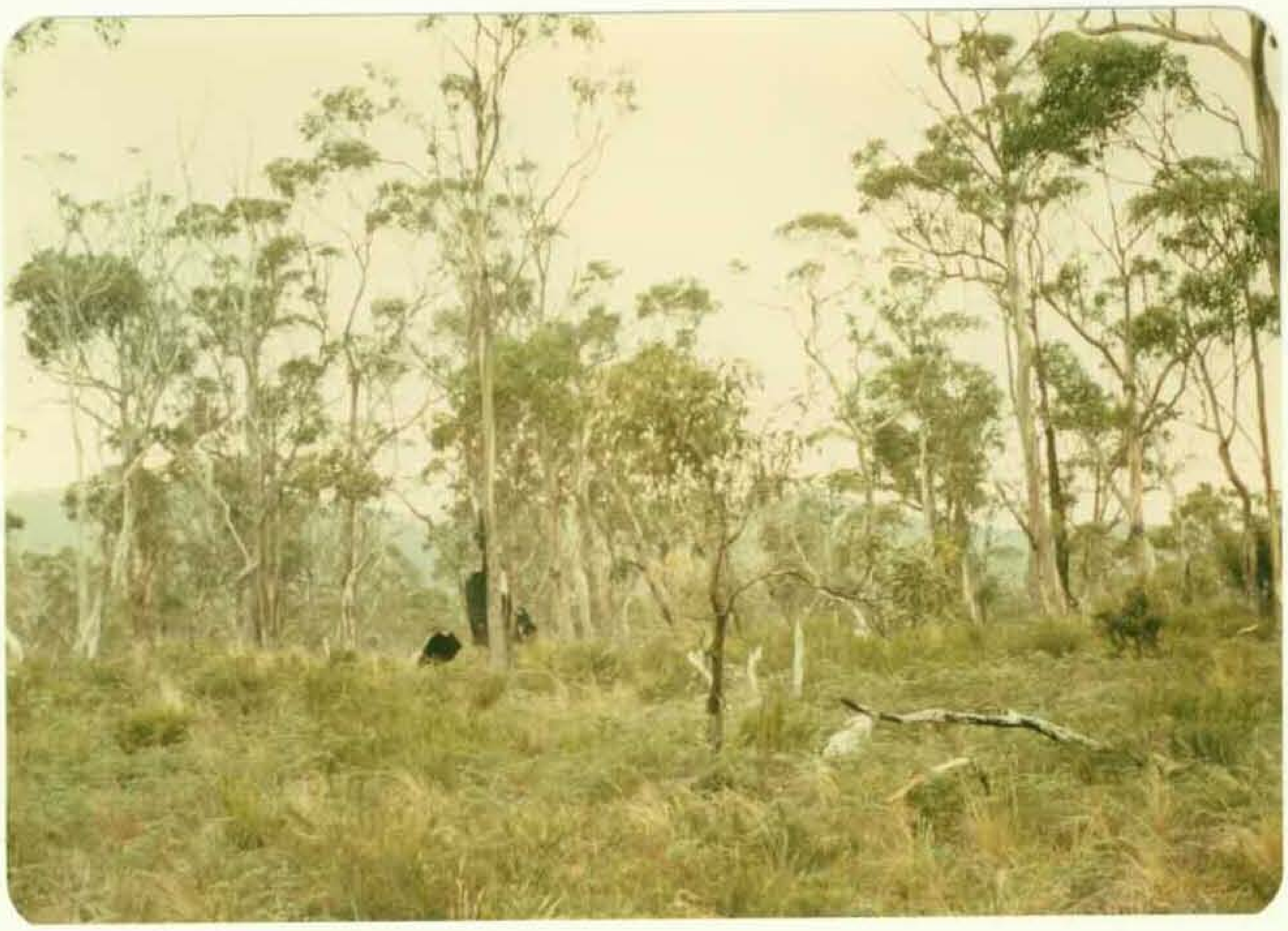

Plate 3.7 Open *Eucalyptus globulus* Forest on the Rheban Spit, in the vicinity of Site 4. The foreground may have been cleared of vegetation.

3.4 SOIL SITE PEDOGENIC FACTORS

The following discussion is concerned with the detailed pedogenic factor information that is incorporated into Tables 3.11 to 3.16 and which specifically applies to the individual soil sites that were studied.

3.4.1 Fens - Hawks Nest - Myall Lakes Soil Sites

Table 3.11 presents the pedogenic factor values for the ten soil sites located on the Fens Outer Barrier (the location of Fens, Hawks Nest and Myall Lakes sites are shown in Figures 3.2, 3.3 and 3.4). From Table 3.11 it is apparent that the soil sites range in age from 3800 to 4900 ^{14}C yrs BP*, with six of the sites being the maximum age. The latter sites are used in Chapter 5 to compare the effects of different vegetation types on the properties of soils of the same age and from similar pedogenic environments.

Both the mineral composition and grain size characteristics of the Fens parent material (the regressive facies sediments) are very uniform between soil sites. The parent material is quartz dominated (range: 93-97%), with little feldspar (1.0-4.0%) or heavy minerals (1.1-3.2%), negligible lithics (0.2-1.4%) and no recorded biogenic carbonate (although the latter mineral may have been underestimated). The parent material is Medium Sand at all sites (mean size: 1.33-1.70ø) and is Very Well-Sorted (mean sorting coefficients: 0.31-0.44ø). It does not contain a non-organic silt or clay fraction. The vertical homogeneity of the parent material sediments is demonstrated in Figure 3.19A, in which the variations with

TABLE 3.11

PEDOGENIC FACTOR VALUES FOR THE HAWKS NEST, FENS AND MYALL LAKES SOIL SITES

SOIL SITE	TIME FACTOR, SOIL AGE	PARENT MATERIAL FACTOR — MINERALOGY: QUARTZ	FELDSPARS	HEAVY MINERALS	LITHICS	BIOGENIC CARBONATE	GRANULOMETRY: MEAN GRAIN SIZE	MEAN SORTING COEFFICIENT	RELIEF FACTOR: SLOPE	TOPOGRAPHIC POSITION	WATERTABLE DEPTH	CLIMATIC FACTOR — MACRO †: AV.ANNUAL DAILY TEMP.	MEAN ANNUAL RAINFALL	AV.ANNUAL No.RAINDAYS	AV.ANNUAL RELATIVE HUMIDITY	MICRO: ANNUAL SALT FALLOUT	BIOTIC FACTOR: PLANT FACTOR
	in ^{14}C yrs BP*	%	%	%	%	%	ϕ	ϕ	degrees		metres	^{o}C	mm		%	NaCl g/m^2/yr ±1 st. dev'n.	
HAWKS NEST																	
1B	4200	96.0	2.7	1.1	0.2	0	1.48	0.36	0	SWALE	4.3	18.2	1332	139	67	106±12	*Banksia-Angophora* Woodland
2	4500	92.7	4.0	2.5	0.8	0	1.56	0.36	0	FLAT	4.6	"	"	"	"	147±12 165±12	*Banksia-Acacia* Heathland
3B	4900	94.7	3.3	1.3	0.7	0	1.65	0.44	0	SWALE	5.2	"	"	"	"	106±12	*Eucalyptus* Forest
4A	4900	95.6	1.1	2.6	0.7	0	1.70	0.35	0	SWALE	4.9	"	"	"	"	105±12	*Eucalyptus* Forest
4B	4900	94.5	1.4	3.2	0.9	0	1.56	0.34	0	SWALE	1.6	"	"	"	"	105±12	*Eucalyptus* Forest
FENS																	
1B	3800	97.2	1.0	1.5	0.3	0	1.45	0.31	0	SWALE	6.9	"	"	"	"	124±12	*Banksia-Acacia* Heathland
2B	4500	94.9	2.5	1.2	1.4	0	1.33	0.35	0	SWALE	5.3	"	"	"	"	125±12	*Banksia-Acacia* Heathland
3	4900	96.2	1.5	1.5	0.8	0	1.60	0.35	0	FLAT	7.0	"	"	"	"	93±12	*Banksia-Angophora* Woodland
MYALL LAKES																	
1	4900	95.8	2.2	1.4	0.6	0	1.57	0.38	0	FLAT	5.7	"	"	"	"	90±12	*Banksia-Acacia* Heathland
2	4900	94.8	2.5	1.8	0.9	0	1.62	0.35	0	FLAT	5.8	"	"	"	"	105±12	*Banksia-Angophora* Woodland

† Nelson Bay Meteorological Station.
Source: Bureau of Meteorology (1975).

FIGURE 3.19

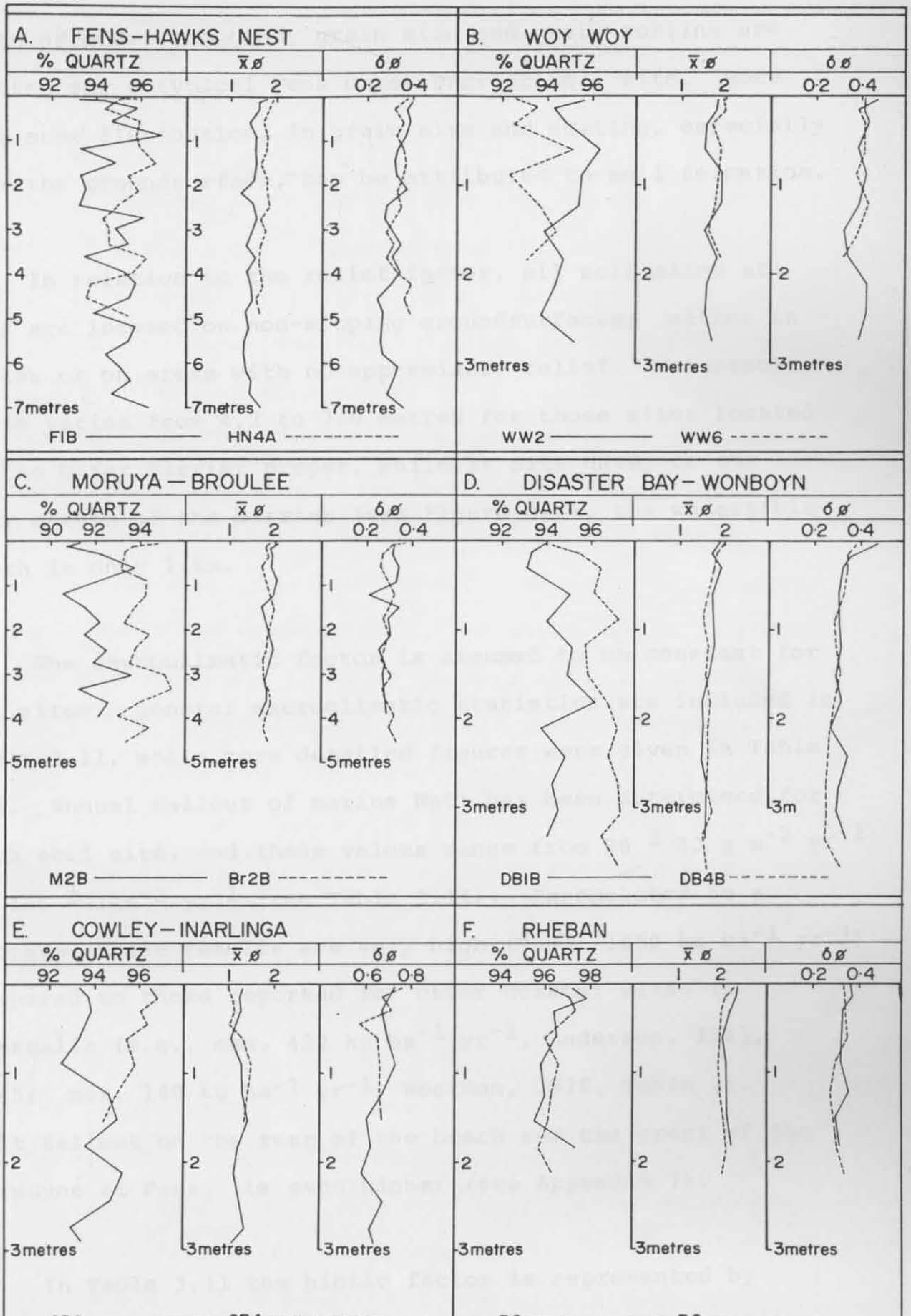

Figure 3.19 Vertical homogeneity of the barrier sediments. Depth: parameter plots show quartz composition, mean grain size ($\bar{x}\phi$) and grain sorting ($\sigma\phi$) for two representative soil profiles from each barrier.

depth of quartz content, grain size and grain sorting are plotted for a typical Fens Outer Barrier soil site. Note that some fluctuations in grain size and sorting, especially near the groundsurface, may be attributed to soil formation.

In relation to the relief factor, all soil sites at Fens are located on non-sloping groundsurfaces; either in swales or on areas with no appreciable relief. Watertable depth varies from 4.3 to 7.0 metres for those sites located on the Outer Barrier proper, while at Site HN4B, on the rear margin of the barrier (see Figure 3.4), the watertable depth is only 1.6m.

The macroclimatic factor is assumed to be constant for all sites; general macroclimatic statistics are included in Table 3.11, while more detailed figures were given in Table 3.4. Annual fallout of marine NaCl has been determined for each soil site, and these values range from 90 $\pm$ 12 g m^{-2} yr^{-1} to 165 $\pm$12gm^{-2} yr^{-1} (see Table 3.11). Exrapolated to a hectare, these results are very high (900 - 1650 kg ha^{-1} yr^{-1}) compared to those reported for other coastal sites in Australia (e.g., max. 432 kg ha^{-1} yr^{-1}, Anderson, 1941, 1945; max. 140 kg ha^{-1} yr^{-1}, Westman, 1978, Table 2). Salt fallout on the rear of the beach and the crest of the foredune at Fens, is even higher (see Appendix 7).

In Table 3.11 the biotic factor is represented by *plant factor* categories (see Section 2.1.3 for definition), the species composition of which was given in Section 3.3.4.1.

The distribution of the various vegetation types on the Fens Outer Barrier is illustrated in Figure 3.17.

3.4.2 Woy Woy Soil Sites

The pedogenic factor values for the Woy Woy sites are presented in Table 3.12. Location of the soil sites on the barrier is shown in Figure 3.6 (sites labelled 1-6). As Table 3.12 indicates, the Woy Woy sites are from 1800 to 6300 ^{14}C yrs* old, giving an age range of 4500 C14 yrs. Mineralogical composition of the parent material is very consistent for Sites 2,3,4, and 5 (95.0-95.6% quartz, 2.1-3.1% feldspar, 1.3-2.0% heavy minerals, <1% lithics and biogenic carbonate), but Sites 1 and 6 have a slightly lower quartz content, and consequently a slightly higher proportion of accessory minerals. Mean grain size shows a somewhat similar trend; Sites 1 and 6 have slightly finer parent material sediments than the other sites, with the exception of Site 4, which also has a fine-grained parent material. However, all mean grain sizes are within the Medium Sand class and a non-organic silt or clay fraction is not present. The sorting coefficients indicate Very Well-Sorted sediments, which are vertically homogenous (Figure 3.19B).

The relief factor is consistent for all the Woy Woy soil sites, in relation to both slope and topographic position, but watertable depth does vary considerably; from 5.8 metres at Site 1, to 1.2 metres at Site 5. Macroclimate is again assumed to be constant for all six sites; the microclimatic factor (salt fallout) was not assessed at Woy Woy. Finally, in Table 3.12 the plant factor is

TABLE 3.12

PEDOGENIC FACTOR VALUES FOR THE WOY WOY SOIL SITES

SOIL SITE	TIME FACTOR, SOIL AGE	PARENT MATERIAL FACTOR: MINERALOGY					PARENT MATERIAL FACTOR: GRANULOMETRY		RELIEF FACTOR			CLIMATIC FACTOR: MACRO †				MICRO	BIOTIC FACTOR
		QUARTZ	FELDSPARS	HEAVY MINERALS	LITHICS	BIOGENIC CARBONATE	MEAN GRAIN SIZE	MEAN SORTING COEFFICIENT	SLOPE	TOPOGRAPHIC POSITION	WATERTABLE DEPTH	AV.ANNUAL DAILY TEMP.	MEAN ANNUAL RAINFALL	AV.ANNUAL No.RAINDAYS	AV.ANNUAL RELATIVE HUMIDITY	ANNUAL SALT FALLOUT	PLANT FACTOR ‡
	in ^{14}C yrs BP*	%	%	%	%	%	ϕ	ϕ	degrees		metres	^{o}C	mm		%	NaCl g/m^{2}/yr ±1 st. dev'n.	
WOY WOY 1	1800	91.2	4.9	2.6	0	1.3	1.91	0.35	0	FLAT	5.8	16.8	1308	105	N.A.	N.D.	*Leptospermum-Banksia* Thicket
2	3800	95.2	2.1	1.8	0.5	0.4	1.68	0.40	0	SWALE	2.7	"	"	"	"	"	*Eucalyptus botryoides-Angophora floribunda* Open Forest
3	4100	95.0	3.2	1.3	0.4	0.1	1.55	0.36	0	SWALE	2.2	"	"	"	"	"	*E.botryoides-A.floribunda* Open Forest
4	5100	95.6	1.9	2.0	0.2	0.3	1.90	0.43	0	SWALE	1.5	"	"	"	"	"	*E.botryoides-A.floribunda* Open Forest
5	5400	95.1	3.1	1.3	0.3	0.2	1.68	0.42	0	SWALE	1.2	"	"	"	"	"	*E.botryoides-A.floribunda* Open Forest
6	6300	93.1	3.9	1.8	0.6	0.6	1.79	0.39	0	SWALE	1.7	"	"	"	"	"	*E.pilularis-A.costata* Open Forest

† Narara Meteorological Station
Source: Bureau of Meteorology (1975).

‡ Probable Pre-Urban Development Vegetation

N.A. Not Available.

N.D. Not Determined.

expressed in terms of the pre-urban development flora, the species composition of which was discussed in Section 3.3.4.2.

3.4.3 Moruya - Broulee Soil Sites

Table 3.13 gives the pedogenic factor values assigned to the nine soil sites reported for the Moruya - Broulee barrier. As shown in Figure 3.7, these sites were located on two transect lines, stretching across the centre and northern end of the beach-ridge plain.

The total age range for the Moruya - Broulee soil sites is 3700 C14 years, that is, from 5700 ^{14}C yrs BP* at Moruya Site 4B (M4B), to 2000 ^{14}C yrs BP* at Broulee Site 1B (Br1B). However, all the sites but Br1B are older than 3000 ^{14}C years*.

Parent material composition is more variable at Moruya - Broulee than at either Fens or Woy Woy; quartz content varies from 90.1 (M1B) to 96.3 percent (M3B); feldspars from 2.9 (M5B) to 7.4 percent (Br3B), heavy minerals from 0.2 (M3B) to 2.4 percent (M6B), lithics 0.2 to 1.2 percent, but biogenic carbonate is less than 0.3 percent at all sites. However, mean grain size is quite constant and within the Medium Sand class (1.67 - 1.99ϕ), and the mean sorting coefficients all consistently indicate Very Well-Sorted sediments (0.28 - 0.33ϕ). The parent material sediments are free of silt and clay, and are vertically homogenous (Figure 3.19C).

TABLE 3.13

PEDOGENIC FACTOR VALUES FOR THE MORUYA - BROULEE SOIL SITES

SOIL SITE	TIME FACTOR, SOIL AGE	PARENT MATERIAL FACTOR: MINERALOGY					PARENT MATERIAL FACTOR: GRANULOMETRY		RELIEF FACTOR			CLIMATIC FACTOR: MACRO †				CLIMATIC FACTOR: MICRO	BIOTIC FACTOR
		QUARTZ	FELDSPARS	HEAVY MINERALS	LITHICS	BIOGENIC CARBONATE	MEAN GRAIN SIZE	MEAN SORTING COEFFICIENT	SLOPE	TOPOGRAPHIC POSITION	WATERTABLE DEPTH	AV. ANNUAL DAILY TEMP.	MEAN ANNUAL RAINFALL	AV. ANNUAL No. RAINDAYS	AV. ANNUAL RELATIVE HUMIDITY	ANNUAL SALT FALLOUT	PLANT FACTOR
	in ^{14}C yrs BP*	%	%	%	%	%	ϕ	ϕ	degrees		metres	^{o}C	mm		%	NaCl $g/m^2/yr$ ±1 st. dev'n.	
MORUYA																	
1B	3300	90.1	6.5	2.2	1.2	0	1.67	0.29	0	SWALE	4.0	15.5	931	105	71	83±13	*Banksia* Woodland Dieback Area
2B	3700	91.6	7.3	0.6	0.5	0	1.79	0.30	0	SWALE	4.0	"	"	"	"	95±13	*Banksia* Woodland
3B	4500	96.3	3.3	0.2	0.2	0	1.69	0.29	0	SWALE	4.0	"	"	"	"	100±13	*Eucalyptus* Forest
4B	5700	93.5	4.7	1.6	0.2	0	1.99	0.33	0	SWALE	3.4	"	"	"	"	73±13	*Eucalyptus* Forest
5B	5400	94.1	2.9	2.0	1.0	0	1.90	0.28	0	SWALE	3.0	"	"	"	"	N.D.	*Eucalyptus* Forest
6B	5400	92.4	4.2	2.4	1.0	0	1.83	0.29	0	SWALE	3.4	"	"	"	"	66±13	*Eucalyptus* Forest
BROULEE																	
1B	2000	95.8	3.0	1.0	1.0	0.1	1.74	0.30	0	SWALE	3.7	"	"	"	"	187±13	*Banksia* Woodland
2B	3100	94.6	4.7	0.6	0.6	0.1	1.83	0.31	0	SWALE	4.6	"	"	"	"	66±13	*Eucalyptus* Forest
3B	3900	90.8	7.4	1.0	1.0	0.3	1.85	0.33	0	SWALE	4.0	"	"	"	"	49±13	*Eucalyptus* Forest

† Moruya Heads Meteorological Station.
Source: Bureau of Meteorology (1975).

N.D. Not Determined.

All the Moruya - Broulee soil sites are located on level ground (slope = 0 degrees) within swales, and the watertable is at a consistent depth (3.0 - 4.0 metres). Macroclimate is assumed constant for all sites, with the more significant parameters included in Table 3.13. The high salt fallout figure for Site Br1B (Table 3.13) probably reflects the increased exposure at this site caused by sand quarrying in the foredune. Results for the other sites indicate a general decrease in fallout away from the sea. Additional fallout data for beach and foredune locations at Moruya - Broulee are given in Appendix 7.

The plant factor varies little between the Moruya - Broulee soil sites, with only two main vegetation types present. *Banksia* Woodland occurs at M1B, M2B and Br1B, while a *Eucalyptus* Forest dominates the remaining sites. The species composition of these vegetation types was discussed in Section 3.3.4.3.

3.4.4 Disaster Bay - Wonboyn Soil Sites

The location of the Disaster Bay and Wonboyn soil sites is shown in Figure 3.10 and Table 3.14 presents the pedogenic factor values. Note that Disaster Bay Site 5 (which was not situated on the beach-ridge plain proper) is not reported in the thesis. The age range of the soil sites is from 1200 ^{14}C yrs BP* for Wonboyn Site 2, to 6000 ^{14}C yrs BP* for DB3B. Both Wonboyn site ages were inferred from the Disaster Bay age structure, on the basis of progradational position and beach-ridge pattern, and are considered reliable estimates.

TABLE 3.14

PEDOGENIC FACTOR VALUES FOR THE DISASTER BAY - WONBOYN SOIL SITES

SOIL SITE	TIME FACTOR, SOIL AGE	PARENT MATERIAL FACTOR: MINERALOGY: QUARTZ	FELDSPARS	HEAVY MINERALS	LITHICS	BIOGENIC CARBONATE	GRANULOMETRY: MEAN GRAIN SIZE	MEAN SORTING COEFFICIENT	RELIEF FACTOR: SLOPE	TOPOGRAPHIC POSITION	WATERTABLE DEPTH	CLIMATIC FACTOR: MACRO †: AV. ANNUAL DAILY TEMP.	MEAN ANNUAL RAINFALL	AV. ANNUAL No. RAINDAYS	AV. ANNUAL RELATIVE HUMIDITY	MICRO: ANNUAL SALT FALLOUT	BIOTIC FACTOR: PLANT FACTOR †
	in ^{14}C yrs BP*	%	%	%	%	%	ϕ	ϕ	degrees		metres	^{o}C	mm		%	NaCl g/m^2/yr ±1 st. dev'n.	
DISASTER BAY																	
1A	1400	95.6	3.3	0.4	0.4	0	1.61	0.33	0	RIDGE	4.3	15.1	766	122	80	70±14	*Eucalyptus-Banksia* Open Forest
1B	1400	94.5	5.1	0.2	0.2	0	1.60	0.32	0	SWALE	3.2	"	"	"	"	70±14	*Eucalyptus-Banksia* Open Forest
2B	2300	93.0	5.4	1.4	0.2	0	1.84	0.30	0	SWALE	3.4	"	"	"	"	71±14	*Eucalyptus-Banksia* Open Forest
3B	6000	95.7	1.5	1.8	1.0	0	1.65	0.32	0	SWALE	5.8	"	"	"	"	72±14	*Eucalyptus-Banksia* Open Forest
4B	3300	97.2	1.4	1.0	0.4	0	1.63	0.27	0	SWALE	3.7	"	"	"	"	65±14	*Eucalyptus-Banksia* Open Forest
6	5400	94.1	4.9	1.0	0	0	1.68	0.30	0	FLAT	4.1	"	"	"	"	76±14	*Eucalyptus-Banksia* Open Forest
WONBOYN																	
1	2500	97.8	1.6	0.3	0.1	0.3	1.72	0.36	0	FLAT	2.5	"	"	"	"	61±16	*Eucalyptus-Banksia* Open Forest
2	1200	96.1	3.6	0.2	0	0.1	1.76	0.31	0	FLAT	2.4	"	"	"	"	72±14	*Eucalyptus-Banksia* Open Forest

† Green Cape Meteorological Station
Source: Bureau of Meteorology (1975).

The parent material for the Disaster Bay - Wonboyn soils is uniformly quartzose, varying from 93 percent quartz for DB2B, to 97.8 percent for W-1. Mean grain size is very similar for all sites (1.60 - 1.84ø) and sorting is also consistent (coefficients : 0.27 - 0.36ø). Neither a silt nor clay inorganic fraction is present in the parent material sediments, the vertical homogeneity of which is illustrated in Figure 3.19D.

All sites are located on level groundsurfaces (slope = 0 degrees) in swales or flat areas, with the exception of DB1A which was situated on a ridge crest so as to facilitate investigation of the pedogenic effects of the topographic factor (see Chapter 5). Watertable depth varies from 2.4 to 5.8 metres.

Macroclimatic data, relevant to all the soil sites, are included in Table 3.14, together with marine salt fallout determinations. The latter indicate a uniform fallout distribution across the Disaster Bay - Wonboyn beach-ridge plain, although substantially higher values are reported for the foredune and beach in Appendix 7.

The plant factor, as reported in Table 3.14, relates to the pre-1972 bushfire vegetation types, and is identical for all the soil sites. That is, it consisted of a *Eucalyptus-Banksia* Open Forest, the floristic composition of which was discussed in Section 3.3.4.4.

3.4.5 Cowley - Inarlinga Soil Sites

Figures 3.12 and 3.13 show the location of the soil sampling sites on the Cowley - Inarlinga Outer Barrier, and Table 3.15 presents the pedogenic factor values for these sites.

As explained in Section 3.3.1.5, the ages of the Cowley - Inarlinga soil sites are estimates, suitable radiocarbon dating material not being available. The estimated ages range from 1000 ^{14}C yrs BP* to 6000 ^{14}C yrs BP*, with the site ages incrementing by 1000 ^{14}c yrs, except for Inarlinga Site 2 (3500 ^{14}C yrs BP*). Although not radiometrically dated, the chronological order of the sites listed in Table 3.15 is accurate, being determined by the progradational sequence evidenced in the beach-ridge pattern.

As Table 3.15 indicates, the proportion of feldspar in the parent material of both the Cowley and Inarlinga soil sites shows a distinct and consistent decrease across the barrier, from seaward to landward. In Cowley Beach Site 1 (CB1) the feldspar proportion is 5.9 percent (I-1 = 5.8%), while in CB6 the content has fallen to 0.6 percent. Two explanations seem feasible : either 1) the supply of feldspars (relative to quartz) increased as the beach-ridge plain prograded seaward, or 2) the "parent material" sediments have been subjected to leaching over time, which has resulted in the progressive dissolution of feldspar grains. The consistency of the trend in feldspar content across the barrier, together with the lack of trends in the

TABLE 3.15

PEDOGENIC VALUES FOR THE COWLEY - INARLINGA SOIL SITES

SOIL SITE	TIME FACTOR ESTIMATED SOIL AGE	PARENT MATERIAL FACTOR: MINERALOGY QUARTZ	FELDSPARS	HEAVY MINERALS	LITHICS	BIOGENIC CARBONATE	GRANULOMETRY MEAN GRAIN SIZE	MEAN SORTING COEFFICIENT	RELIEF FACTOR: SLOPE	TOPOGRAPHIC POSITION	WATERTABLE DEPTH	CLIMATIC FACTOR: MACRO † AV. ANNUAL DAILY TEMP.	MEAN ANNUAL RAINFALL	AV. ANNUAL No. RAINDAYS	AV. ANNUAL RELATIVE HUMIDITY	MICRO ANNUAL SALT FALLOUT	BIOTIC FACTOR: PLANT FACTOR
.	in ^{14}C yrsBP*	%	%	%	%	%	φ	φ	degrees		metres	°C	mm		%	NaCl g/m²/yr ±1 st. dev'n.	
COWLEY 1	1000	92.2	5.9	0.2	1.7	0	1.07	0.71	0	SLIGHT RIDGE	2.0	23.5	3644	155	76	N.D.	*Acacia crassicarpa* Low Closed Forest
2	2000	93.5	3.7	2.0	0.8	0	1.13	0.64	0	SLIGHT RIDGE	2.9	"	"	"	"	"	*Eucalyptus-Acacia* Open Forest
3	3000	94.2	3.3	1.9	0.6	0	0.98	0.87	0	SLIGHT RIDGE	1.5	"	"	"	"	"	*Eucalyptus-Acacia* Open Forest
4	4000	94.4	2.6	1.7	1.3	0	1.45	0.67	0	SLIGHT RIDGE	1.5	"	"	"	"	"	*Eucalyptus-Acacia* Open Forest
5	5000	96.1	2.4	0.5	1.0	0	0.91	0.66	0	SLIGHT RIDGE	1.1	"	"	"	"	"	*Eucalyptus-Acacia* Open Forest
6	6000	98.3	0.6	0.8	0.3	0	1.85	0.32	0	SLIGHT RIDGE	3.1	"	"	"	"	"	*Eucalyptus-Acacia* Open Forest
INARLINGA 1	1000	93.3	5.8	0.2	0.7	0	0.67	0.83	0	SLIGHT RIDGE	2.9	"	"	"	"	"	*Acacia crassicarpa* Low Closed Forest
2	3500	91.1	4.6	3.2	1.2	0	0.74	0.91	0	SLIGHT RIDGE	2.1	"	"	"	"	"	*Eucalyptus-Acacia* Open Forest

† Innisfail Meteorologcal Station
Source: Bureau of Meteorology (1975).

proportion of heavy minerals or lithics (see Table 3.15), indicate to the writer that the second explanation postulated above is the more likely. The mean grain size and size sorting of the parent material sediments seem to support this conclusion, as neither parameter show a consistent trend across the barrier. It is notable that the parent material at Site 6 (located on the landward-most beach ridge), is considerably finer than the parent material at the other soil sites, although little silt or clay is present. The finer sediment probably reflects the initial dominance of marine sediment as sea level stabilized at its present position. Subsequent progradation of the beach-ridge plain appears to have incorporated substantial amounts of coarser, more angular, fluvial sediment (see Table 3.15 and Chapter 4) and to a greater degree than in the other barriers, the sediments tend to fine upwards, as indicated in Figure 3.19E.

All the Cowley - Inarlinga soil sites are located on level ground, although as Table 3.15 indicates, the sites are situated on slight ridges, rather than in swales, because of the shallow watertable. Depth to the watertable ranges from 1.1 to 3.1 metres.

Macroclimatic statistics for Innisfail are included in Table 3.15. The extremely high annual rainfall figure and warm average annual daily temperature may have influenced the feldspar trend noted above. Determinations of marine aerosol salt fallout were not carried out on the Cowley barrier.

The eight soil sites at Cowley - Inarlinga were located beneath two vegetation types. Sites CB1 and I-1 were situated in an *Acacia* dominated Low Closed Forest, while all the other sites (located further from the sea) were in areas of *Eucalyptus-Acacia* Open Forest. The floristic composition of these vegetation types was discussed in Section 3.3.4.5.

3.4.6 Rheban Soil Sites

Table 3.16 presents the pedogenic factor values for the Rheban soil sites, the locations of which are shown in Figures 3.15 and 3.16.

As Table 3.16 indicates, six of the seven Rheban soil sites are in excess of 3000 C^{14} years in age (oldest = 4800 ^{14}C yrs BP*), while Site 1 has an age of zero radiocarbon years, dating to A.D.1950 or later. Parent material characteristics appear to reflect the age disparity between Site 1 and the rest of the soil sites. Feldspar comprises 4.1 percent of the parent material at Site 1, but only 2.0 to 3.1 percent at the other sites. Similarly, the mean grain size of the parent material is 2.33ø at Site 1, whereas the other sites range from 2.01 to 2.18ø. The silt and clay content of the parent material is negligible, and the sediments display marked vertical homogeneity (Figure 3.19F). As age trends are not apparent in any parent material parameters for Sites 2 to 7, and as heavy minerals are concentrated in the Site 1 sediments, it seems probable that the foredune ridges are comprised of more intensively reworked, less quartzose sediments than the beach ridges,

TABLE 3.16

PEDOGENIC FACTOR VALUES FOR THE RHEBAN SOIL SITES

SOIL SITE	TIME FACTOR, SOIL AGE	PARENT MATERIAL FACTOR: MINERALOGY: QUARTZ	FELDSPARS	HEAVY MINERALS	LITHICS	BIOGENIC CARBONATE	GRANULOMETRY: MEAN GRAIN SIZE	MEAN SORTING COEFFICIENT	RELIEF FACTOR: SLOPE	TOPOGRAPHIC POSITION	WATERTABLE DEPTH	CLIMATIC FACTOR: MACRO †: AV. ANNUAL DAILY TEMP.	MEAN ANNUAL RAINFALL	AV. ANNUAL No. RAINDAYS	AV. ANNUAL RELATIVE HUMIDITY	MICRO: ANNUAL SALT FALLOUT	BIOTIC FACTOR: PLANT FACTOR
	in ^{14}C yrs BP*	%	%	%	%	%	φ	φ	degrees		metres	°C	mm		%	NaCl g/m²/yr ±1 st. dev'n.	
RHEBAN 1	0	90.8	4.1	3.5	0.1	1.5	2.33	0.29	0	SWALE	3+	12.5	650	122	66	N.D.	*Ammophila-Acacia* Open Shrubland
2	3500	97.4	2.0	0.2	0.4	0	2.15	0.33	0	SWALE	1.8	"	"	"	"	"	Open *Eucalyptus* Forest
3	3000	95.6	2.7	1.5	0	0.2	2.10	0.36	0	SWALE	1.2	"	"	"	"	"	Open *Eucalyptus* Forest
4	3900	96.0	3.1	1.0	0	0	2.18	0.29	0	SWALE	2.1	"	"	"	"	"	Open *Eucalyptus* Forest
5	4800	96.8	2.0	1.1	0.1	0	2.01	0.32	0	SWALE	3.4	"	"	"	"	"	Open *Eucalyptus* Forest
6	3900	96.4	2.7	0.9	0	0	2.08	0.32	0	SWALE	2.1	"	"	"	"	"	Open *Eucalyptus* Forest
7	3900	96.5	2.5	1.0	0.1	0	2.15	0.30	0	SWALE	2.4	"	"	"	"	"	Open *Eucalyptus* Forest

† Rheban and Orford Meteorological Stations.
Source: Bureau of Meteorology (1975).
N.D. Not Determined.

and that leaching has not caused the differences in composition and grain size.

All the Rheban soil sites are located on level swale floors, with fairly shallow watertables (1.2 - 3.4 metres, Table 3.16). Macroclimatic data for Rheban and Orford indicate that both average annual rainfall and average annual daily temperature are fairly low (see Table 3.16). Marine salt fallout was not measured.

The plant factor vegetation types pertinent to the Rheban soil sites are few. Site 1, in the foredune area, has an *Ammophila-Acacia* Open Shrubland vegetation, while an Open *Eucalyptus* Forest covers all the other soil sites. Details of the floristic composition of these vegetation types were given in Section 3.3.4.6.

3.5 SUMMARY

Information has been presented in Chapter Three about the pedological environments of the podzol soils under investigation. This information relates to the regional setting of the New South Wales, Queensland and Tasmanian barriers, to the environmental and geomorphic characteristics of individual barriers, and to the pedogenic factors applicable to specific soil sites. From this information several general points arise which are of significance in the study; these are listed below.

1. The ages of the soil sites range from zero to over 6000 ^{14}C yrs*. Clustering of sites with the same age

allows assessment of the effects of climate, vegetation, relief and parent material on soil properties.

2. The sediment which comprises the parent material for the podzol soils is remarkably uniform, in both texture and mineral composition. The sediment is predominantly Medium Sand, contains no silt or clay, is very well-sorted, and consists of over 90 percent quartz, with small proportions of feldspar, heavy minerals, lithics and biogenic carbonate.

3. All soil sites are located on flat ground-surfaces, most being situated on swale floors. Where the watertable is particularly shallow, the sites are located on ridge crests. Watertable depth is the most variable aspect of the relief factor.

4. Although latitudinal trends in climate exist between the New South Wales barriers, they all may be regarded as falling within the same general climatic region; even the climate at Rheban does not differ substantially. At Cowley, however, the climate is significantly different - much wetter and considerably warmer.

5. Salt fallout data for the New South Wales barriers indicates substantial accessions at all soil sites, with very high values being recorded on the seaward side of the barriers.

6. The vegetation of the beach-ridge plains is structurally quite consistent, with a *Eucalyptus-Banksia* Forest covering a large proportion of the area of each barrier and usually a *Banksia-Leptospermum* Thicket, or *Banksia-Acacia* Woodland, occupying a comparatively narrow zone, landward of the foredune.

CHAPTER IV

PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE SOILS

4.1 INTRODUCTION

This chapter presents the data which resulted from field and laboratory observations, and measurements, of soil properties. The soil properties are: profile morphological characteristics, organic matter content, cation concentrations, sand grain surface textures and sand grain organic-mineral coatings.

The objective of the chapter is to present, describe and illustrate the data, so that they will characterize the barrier soils and will also provide a quantitative basis in Chapter Five for relating soil properties to the relevant pedogenic factors.

4.2 PROFILE MORPHOLOGY

Soil profile morphology refers to the assemblage of soil properties that can usually be described or measured in the field, and which form the basis of many general pedological studies. As soil classification is not an objective of the present investigation, the adoption of a complex, highly structured, hierarchical profile description system, such as those proposed by Northcote (1971) and the Soil Survey Staff (1960, 1967, 1975), were considered inappropriate. Instead, a less structured descriptive procedure was designed to suit the characteristics of the podzol profiles under investigation.

4.2.1 Morphological Characteristics

The morphological properties of the soil profiles which were described or measured during the study, are defined below.

Horizons – Only the "master" horizons (A_0, A_1, A_2, B and C) were distinguished in the field, as further subdivision would have anticipated the results of laboratory analyses. Also, in incipient podzol profiles it is often difficult to distinguish even the "master" horizons, and hence further subdivision is impractical. The characteristics used to distinguish the "master" horizons were: colour, mottling, visible organic matter and texture.[1]

For field identification purposes, the following definitions of the soil "master" horizons were employed:

The A_0 horizon is a thin, often discontinuous, surface horizon, relatively rich in raw and decomposing organic material, and usually dark grey in colour. It grades evenly into the underlying A_1 horizon.

The A_1 is much thicker and usually lighter in colour than the A_0, and more diffuse on its lower boundary. The A_1 is comparatively rich in decomposed organic matter, but also frequently contains abundant fine plant roots.

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1. References in the thesis to *horizon development* relate to changes in horizon properties from profile to profile. References to *horizon differentiation* refer to the distinctiveness of a particular horizon, in terms of one or more soil properties, when compared to the horizons above and/or below it. The term *profile development*, comprises both horizon development and horizon differentiation, as they relate to both the A and B horizons.

The A_2 is usually the lightest-coloured horizon; it has a low organic content, and varies considerably in thickness. Its boundary with the B horizon may be sharp or gradational; if sharp, the boundary may be even or highly irregular.

The B horizon is generally the thickest horizon and is darker in colour than the A or C horizons. It varies in colour from medium yellow to dark brownish black, and is often mottled.

The transition to the C horizon is always gradational and even; the latter horizon is lighter coloured than the B and is non-mottled. The thickness of the C horizon depends on the combined thickness of the A and B horizons, and the depth of the watertable. In a few profiles (those located in low-lying positions), the watertable is permanently (or frequently) within the B horizon, and hence the C horizon is considered to be absent.

Horizon boundaries – The characteristics of the lower boundary of each horizon were recorded (sharp or gradational, even or irregular), as well as its depth (or depth range). Horizon thicknesses were calculated from the boundary depths.

Colour – Soil colours were identified with the aid of *Revised Standard Soil Color Charts* (1970). These charts are based on the revised Munsell colour notation system (*Munsell Soil Color Charts*, 1954), although some colour names are different.

Air-dry samples were used to determine dominant horizon colour and, where variegated or mottled horizons were encountered, subdominant colours were also noted. The use of air-dry samples ensured that consistent moisture conditions applied to all colour determinations. This was particularly important for A_2 horizon colour descriptions (see Northcote, 1971, p.17).

Texture – Field determinations of horizon texture using the *bolus* method (Northcote, 1971, p.26) indicated that all the profiles studied were of the *sand* or *loamy sand* texture grades (Marshall, 1947). Laboratory mechanical analyses of soil samples confirmed the field determinations and provided more detailed information on textural variations (examples given in Chapter Three; Table 3.3 and Figure 3.19).

Structure – As the sandy texture of the soils has prevented ped development (Butler, 1955) all the profile horizons investigated were either apedal-single grain, or apedal-massive (Northcote, 1971).

Organic Matter – The occurrence of visible organic material (including root penetration) was noted in the field; more precise determinations of organic matter content were carried out later in the laboratory. The latter results are discussed in Section 4.3.

Soil Reaction – As a portable field pH meter was not available, the pH of the soil samples was measured as soon as they were received in the laboratory. A soil-water dispersion of 1:5 (weight to weight) was prepared from each sample, shaken for one hour, and the pH of the supernatant liquid was measured electrometrically with a combination glass-calomel electrode, calibrated with buffered solutions of appropriate pH.

<u>Carbonate</u> – Calcium carbonate was present in the C horizon of some soils in the form of residual marine shell debris. The presence of calcium carbonate in a sample was inferred from effervescence, following the application of 10 percent hydrochloric acid.

<u>Moisture</u> – Horizons were classed in the field as either wet, moist or dry; laboratory determinations later provided more precise information.

<u>Watertable</u> – The depth of the watertable, at the time of sampling, was noted for each soil profile. The watertable determined the maximum depth to which each profile was sampled.

<u>Orterde and Iron Nodules</u> – The occurrence in a profile of a moderately to firmly cemented, iron and humus rich, upper B horizon, was noted. The presence of iron nodules and concretions were also recorded.

<u>Special Features</u> – Unusual variations in any of the above profile characteristics, or the occurrence of other features (for example, an abundance of heavy minerals or pumice in the profile) were included in this category.

4.2.2 <u>Profile Descriptions</u>

Observations of soil profile morphological characteristics are presented in tabular form in Appendix Two. This data is summarized below to indicate the general morphological features of the soils developed in each barrier.

4.2.2.1 <u>Hawks Nest - Fens - Myall Lakes Soil Sites</u>. The locations of these soil sites on the Fens Outer Barrier beach-ridge plain are indicated in Figures 3.2, 3.3, and 3.4;

Appendices 2-1 to 2-10 present the relevant profile descriptions, in tabular form. The most significant trends that are evident in the profile descriptions are:

1. With the exception of Site HN4B, which has a shallow watertable, all the profiles are deep.
2. In terms of thickness, boundary configuration, colour, structure and soil reaction (pH), the A_1, A_2 and B horizons all range from moderately well-developed and well-differentiated on the seaward side of the barrier, to strongly developed/differentiated on the landward side. In other words, the soil profiles range from moderately to strongly developed.
3. All the soil profiles located towards the rear of the barrier (except HN4B) exhibit similar profile morphologies.
4. Neither horizon texture nor shell reaction vary within, or between, the profiles.

4.2.2.2 Woy Woy Soil Sites. Figure 3.6 shows the locations of the Woy Woy soil sites. Descriptions of these profiles are given in Appendices 2-11 to 2-16. From these descriptions several general points emerge:

1. In contrast to the soils of the Fens barrier, those from the Woy Woy beach-ridge plain are mostly shallow. At the time of sampling the watertable was in the B horizon of all profiles, except Woy Woy Site 1.
2. Horizon development and horizon differentiation both range from minimal at Woy Woy Site 1 (seaward side of barrier), to strong at Site 6 (landward side). Hence, a greater range in profile development is apparent in

PLATE 4.1

PLATE 4.2

Plate 4.1 Photograph of Moruya Profile 1B (3300 yrs*) during construction of sample pit; pit was about 0.5 metre deep at the time. Note that the colour of the A_1 horizon appears lighter grey than was the case.
Plate 4.2 Moruya Profile 3B (4500 yrs*) taken when pit was about 1 metre deep. Note pronounced A_2 and B horizons; A horizon appears lighter than in field.

PLATE 4.3

Plate 4.3 Photograph of Moruya Profile 5B (5400 yrs*). The B horizon is deeper than in Profiles 1B or 3B, but the A_2 horizon appears less distinctive. The tape is graduated in inches; the pit is about 1.5 metres deep.

the Woy Woy profiles than is evident at Fens. However, the Woy Woy profiles are more variable than the Fens sites, probably because of the effects of the high watertable.

3. Unlike most of the other barrier soil sites, shell reaction was positive in the lower parts of all the Woy Woy profiles, except Site 6.

4.2.2.3 Moruya - Broulee Soil Sites. The locations of these soil sites are shown in Figure 3.7. Appendices 2-17 to 2-25 present the profile descriptions, in which the following general features are apparent:

1. Profile development (i.e., horizon development and horizon differentiation) varies from moderate on the seaward side of the barrier, to strong on the landward side, in terms of most morphological characteristics.
2. The watertable is well below the B horizon in all profiles; it does not appear to influence profile morphology.
3. Shell reaction was positive for all watertable samples except Broulee Site 3B. A significant reaction was observed in C horizon samples from Moruya Sites 1B, 2B and 3B, and Broulee Sites 1B and 2B. The depth of the uppermost shell-bearing sample increases with distance from the sea.

4.2.2.4 Disaster Bay-Wonboyn Soil Sites. Figure 3.10 shows the locations of the Disaster Bay and Wonboyn soil sites; Appendices 2-26 to 2-33 present the profile descriptions.

PLATE 4.4

Plate 4.4 Disaster Bay Profile 1B (1400 yrs*) during pit construction. Pit is about one metre deep and is well into the incipient B horizon. The A_2 horizon is not readily apparent.

The most notable features of the Disaster Bay-Wonboyn profiles are the very thick B horizons and the lack of visible C horizons. This is not due to a shallow watertable - the watertable in the Disaster Bay profiles is over 3 metres deep at all sites - but rather to inordinately thick B horizons, which extend to depths usually occupied by the C horizon. However, apart from their exceptional thickness, the B horizons display a range in development (in terms of their other visible characteristics) which is commensurate with their age range, and is similar to that found in the soils of the other barriers.

Other features of the Disaster Bay - Wonboyn soil profiles are:

1. In terms of morphological characteristics, the profiles range in development across the barrier, from incipient profiles on the seaward side (Sites DB1A, DB1B, W-2), to strongly developed profiles on the landward side (DB3B, DB6).
2. A positive shell reaction was not observed for any soil sample.
3. The groundwater beneath the profiles varied in colour from light to dark brown.

4.2.2.5 <u>Rheban Soil Sites</u>. The locations of the seven Rheban profiles are indicated in Figure 3.15. Appendices 2-34 to 2-40 present the profile descriptions, from which the following general features have been identified:

1. A wide range in profile development is encompassed

PLATE 4.5

PLATE 4.6

Plate 4.5 Disaster Bay Profile 2B (2300 yrs*). Note: severely burnt groundsurface; thick A_1, thin A_2 and exposed upper B horizon.

Plate 4.6 Profile DB3B (6000 yrs*). Note thick dark A_1 and lighter A_2 at base of pit (0.8m deep). The B horizon is not exposed.

by the Rheban profiles; Site 1 (in the foredune area) displays no evidence of profile development, whereas Site 5 (on the Earlham Lagoon side of the barrier) exhibits a well-developed podzol profile. The most marked change occurs between Sites 1 and 3.

2. Although the watertable is shallow at Rheban, it is below the B horizon in all the sampled profiles.

3. The Rheban soil horizons are all relatively thin; this applies particularly to the B horizon.

4. Shell reaction was positive throughout Site 1, and at the watertable in Site 3; no reaction was noted for any other Rheban samples.

4.2.2.6 Cowley Beach-Inarlinga Soil Sites. The Cowley barrier map (Figure 3.12) shows the location of the soil sites and Appendices 2-41 to 2-48 present the profile descriptions. General features of the Cowley-Inarlinga profiles are as follows:

1. The youngest, seaward profiles (CB1, CB2, I-1) do not exhibit an A_2 horizon. The organic rich A_1 horizon grades directly into the darker B horizon, without a visible intervening horizon.

2. The thickness of the C horizon decreases in a landward direction across the barrier, so that in profiles CB5, CB6 and I-2, the B horizon extends to the watertable.

3. Although horizon thickness, boundary configuration, texture and shell reaction do not seem to indicate a progressive increase in profile development across the Cowley barrier (seaward to landward), dominant horizon colour, mottling, structure and soil reaction (pH) do

reveal such a trend.

4.2.2.7 Summary.

One fundamental trend is apparent from the profile descriptions: a definite gradation exists across each beach-ridge plain in the degree of profile development. On some barriers the range in development is limited (e.g., Fens), but on most it is quite substantial. The extent to which profile development relates to the individual pedogenic factors will be examined in Chapters Five and Six.

4.3 ORGANIC MATTER

Many pedogenic studies have indicated that the amount of organic material in a soil profile can be related to the age of the soil (for example: Salisbury, 1925; Burges and Drover, 1953; Crocker and Major, 1955; Olson, 1958; Franzmeier and Whiteside, 1963a, 1963b; and Franzmeier *et al.*, 1963). It was therefore decided to investigate the relationship between the organic matter content of the soils being studied and the pedogenic factors.

Organic matter was determined by the low temperature ignition method (Hesse, 1971), wherein total organic matter content is equated with the weight loss on ignition. A full description of the technique and a discussion of its accuracy and limitations are given in Appendix Three.

4.3.1 Organic Matter Distribution

Results of the determinations are incorporated into Appendices 3-1 to 3-10, while Appendices 3-11 to 3-20 present the same data in the form of isopleth cross-sections, termed *isograms*, after Ryan and McGarity (1978). The isograms illustrate the distribution of total organic matter, both within individual soil profiles and across the barriers. The abscissa on each isogram represents distance along the transect from the sea, while sample depth is plotted on the ordinate. The origin is on the right of each isogram and soil site (profile) numbers are at the top. Vertical exaggeration has been introduced to enable sample depths to be accurately plotted; the isolines have been interpolated by hand. Note that the organic matter isograms employ a dual isopleth interval so that the sharp near-surface transitions can be adequately portrayed, and yet gradual subsurface changes can also be shown. Thus, for values from 0.2 to 1.0 percent, a 0.2 percent isopleth interval has been used, whereas higher values have been contoured using a 1.0 percent isopleth interval. To indicate the change in isopleth interval, the 2.0 percent isopleth is shown as a broken line.

The general characteristics of the organic matter distribution patterns, are outlined below.

4.3.1.1 Hawks Nest-Fens-Myall Lakes Sites. Appendices 3-1 and 3-2 present the results of the organic matter determinations for the Hawks Nest, Fens and Myall Lakes sites. The isograms in Appendices 3-11 and 3-12 illustrate the distribution patterns for the Hawks Nest and Fens transects. As the Myall Lakes soil sites were not located on a transect line (see Figure 3.2), they are not shown on the isograms.

The Hawks Nest isogram (Appendix 3-11) shows a very even, but fairly sharp, decrease in organic matter content in the upper half metre of all the profiles. Near-surface organic matter content is over 6 percent at all sites, but this decreases to 0.2 - 0.4 percent in the samples from 61 centimetres. Only subtle distribution changes occur below this depth; the slight (but analytically significant) concentrations in the subsurface of Profiles 2, 3B and 4A may reflect illuviated colloidal organic matter. Such a subsurface organic matter concentration is more pronounced in the Fens isogram (Appendix 3-12), where the levels rise to over 0.8 percent. The sharp (but even) near-surface organic matter gradient in the Fens and Myall Lakes profiles (see data in Appendix 3-2) is similar to that in the Hawks Nest isogram.

4.3.1.2 Woy Woy Sites. Organic matter data for these soil sites are presented in Appendix 3-3 and the isogram distribution patterns are shown in Appendix 3-13. A sharp near-surface gradient is evident in the Woy Woy organic matter distribution pattern, but it is much less regular than the Hawks Nest or Fens patterns, particularly in Profiles 4 and 5 (see Appendix 3-13). A marked subsurface organic matter concentration is evident in the Woy Woy isogram - in Site 5 and especially in Site 6. The slight rise in organic matter values in the subsurface of Woy Woy Site 1 may have been caused by CO_2 loss during low temperature ignition, but more probably by small amounts or organic material (wood), deposited with the parent material sediments.

4.3.1.3 Moruya-Broulee Sites. Figure 4.1 shows the Moruya transect organic matter distribution pattern. The near-surface isopleth gradient is not as sharp in the Moruya or Broulee profiles (Appendices 3-14 and 3-15) as it is in the Fens or Woy Woy soils, but the gradient is even and regular. Subsurface values show little variation in the Moruya - Broulee organic matter isograms, except in the lower parts of Profiles 1B and 2B. Again, these irregularities may be due to either CO_2 loss from shell carbonate, or to wood debris in the sediment. In this case the former alternative seems the more likely, as the irregularities match high calcium concentrations reported below (Section 4.4.1.4), and hence may be related to relatively high carbonate contents. The landward-most Moruya profile (Site 4B) exhibits a pronounced illuviated organic matter concentration at a depth of about one metre.

4.3.1.4 Disaster Bay-Wonboyn Sites. Appendices 3-6 and 3-7 contain the organic matter data for the Disaster Bay and Wonboyn sites, while Appendices 3-16 and 3-17 present the relevant isograms. Both the Disaster Bay and Wonboyn isograms display quite simple and regular distribution patterns, with sharp (but even) near-surface gradients above 30 cms, and only slight variations below this depth. Low concentrations of illuviated organic matter may be recognized (at depth) in the landward soil profiles on the Disaster Bay transect (Sites 3B, 6 and 4B), and in Wonboyn Site 1.

4.3.1.5 Rheban Sites. The Rheban organic matter distribution pattern is depicted in Figure 4.2 (and Appendix 3-18); the

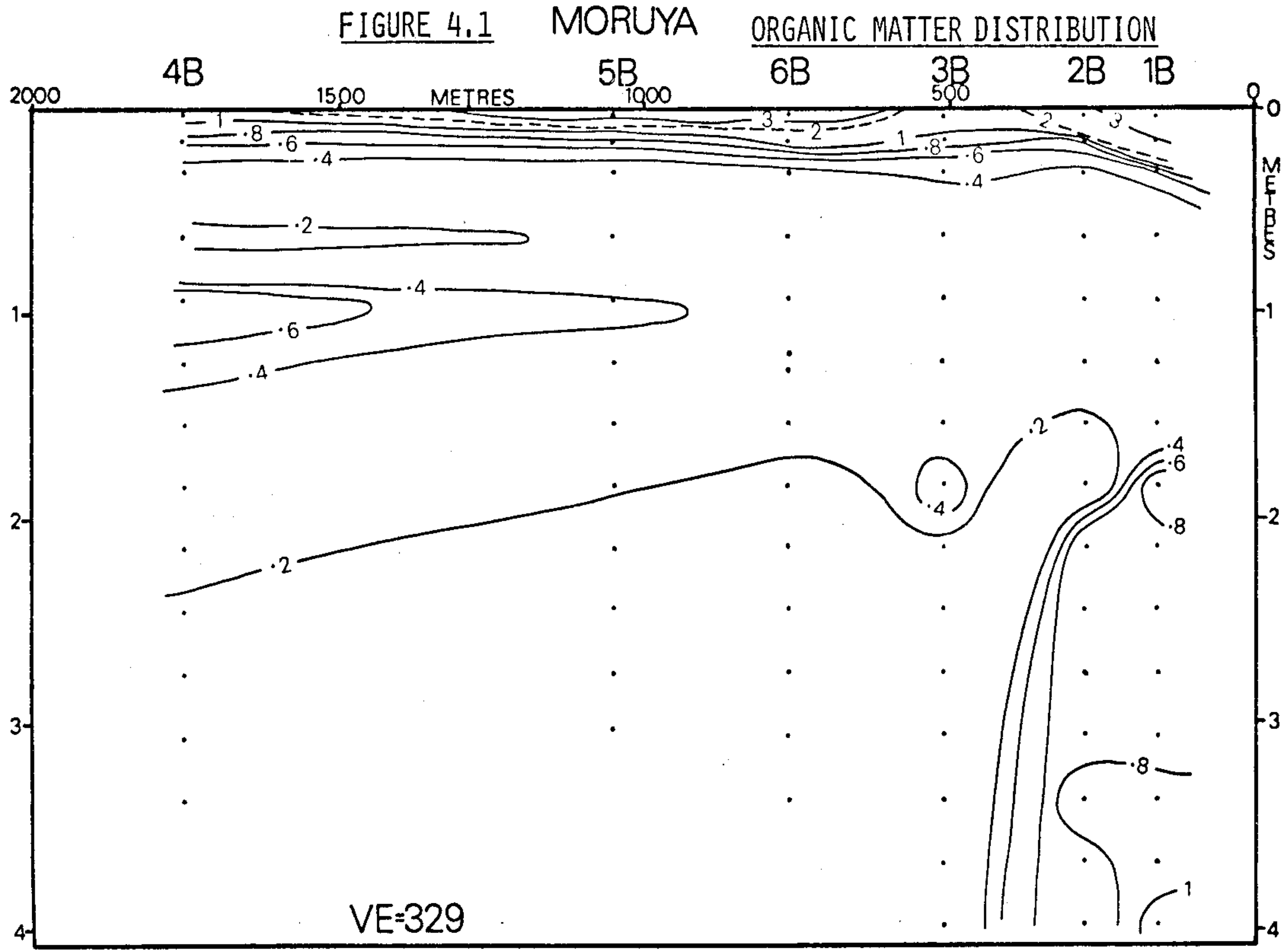
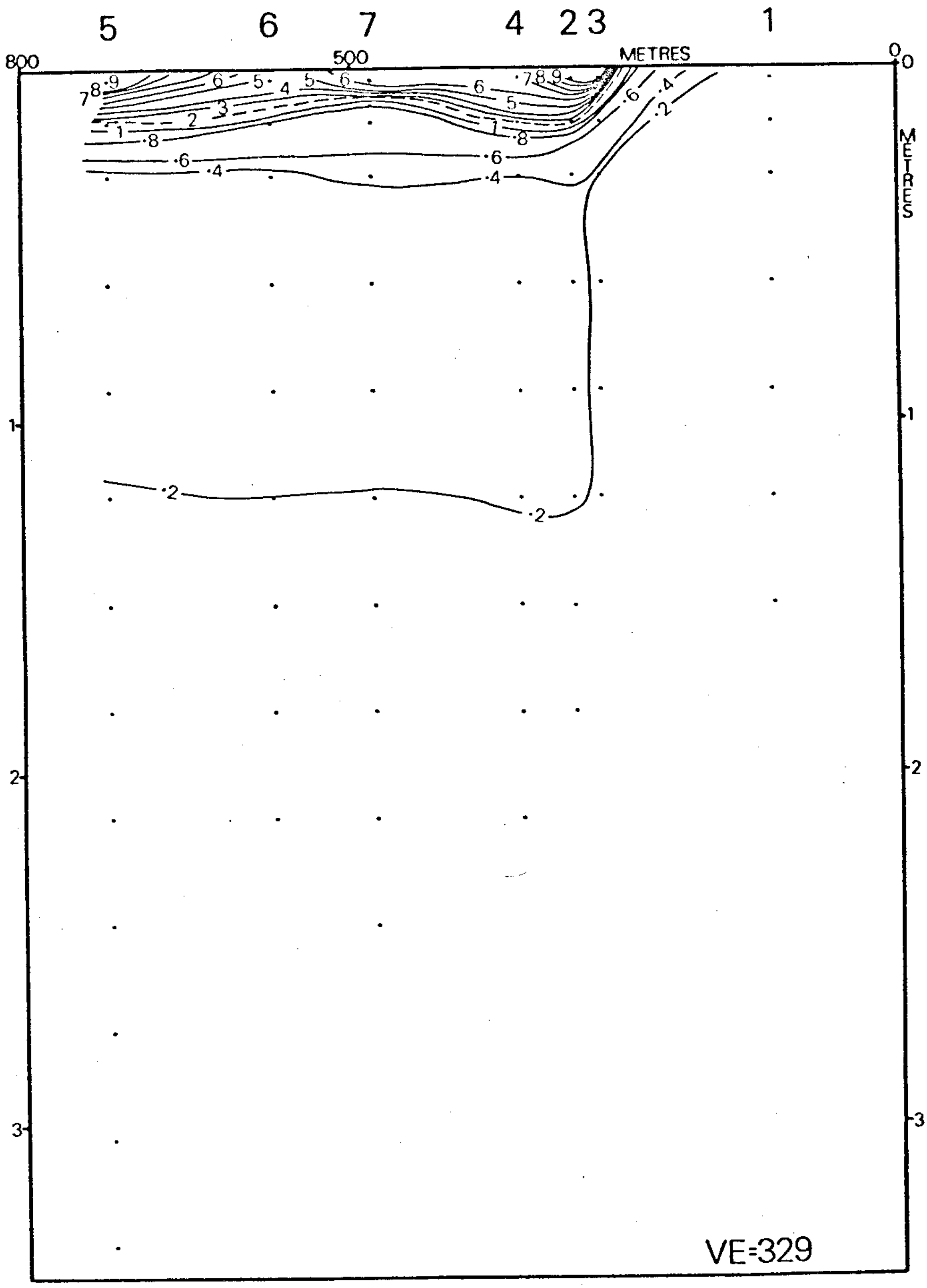


FIGURE 4.1
MORUYA
ORGANIC MATTER DISTRIBUTION
4B
5B
6B
3B
2B
1B
2000
1500
METRES
1000
500
0
METRES
VE=329

FIGURE 4.2 RHEBAN ORGANIC MATTER DISTRIBUTION



relevant organic matter data is presented in Appendix 3-8. The Rheban isogram displays a sharp and somewhat irregular near-surface organic matter gradient between Profiles 3 and 5. However, Profile 1, located within the modern foredune area, does not display the gradient, all values being less than 0.2 percent. None of the Rheban profiles exhibits a zone of illuviated organics.

4.3.1.6 Cowley Beach-Inarlinga Sites. Appendices 3-9 and 3-10 present the organic matter data for these sites and the relevant isograms are given in Appendices 3-19 and 3-20. The Cowley Beach isogram displays an irregular near-surface organic matter gradient, but a consistent increase in the depth of subsurface isopleths across the barrier, and a distinct zone of illuviated organic matter in the older, landward profiles. The Inarlinga pattern reflects these trends (i.e., increase in isopleth depths to landward and the associated development of an illuviated organic matter horizon), but unlike the Cowley isogram, the near-surface gradient is very regular and even in the Inarlinga profiles.

4.3.1.7 Summary. From the foregoing descriptions of the organic matter distribution patterns in the various barriers, several common characteristics can be recognized:

1. The highest organic matter concentrations occur near the groundsurface, with a sharp, but usually regular, organic matter gradient over the first 30 cms or so. Generally, surface values are constant across the barriers.
2. Subsurface values are low, generally less than 0.4 percent.

3. A zone of illuviated organic matter is evident in most of the older landward profiles, but is absent from the younger seaward profiles.

4. Irregularities in the lower parts of some seaward profiles may be associated with high carbonate concentrations and the consequent slight loss of CO_2 during analysis. However, some of these samples may contain small amounts of detrital organic matter.

4.4. CATION CONCENTRATIONS

The scientific literature on podzolization contains abundant evidence that cations are mobilized and translocated during pedogenesis (for example; Rode, 1937; Ponomareva, 1964; Pedro *et al.*, 1978). The evidence strongly suggests that some cations tend to concentrate in illuvial B horizons, while others are leached from the solum (Rode, 1937). For example, less reactive cations, such as Fe and Al, accumulate in the soil profile while reactive bases, such as Ca and Na, are largely removed. The cations selected for analysis in the present study are of both types; that is, some are of the "accumulative" and some of the "dissipative" type. It was thought that such a combination would be the most comprehensive and yet also the most sensitive means of chemically monitoring the development of podzol soils of different ages. Although many alternative chemical characteristics could have been measured, only cation concentration analyses meet the criteria outlined in Section 2.2.3.1. The selected cations are Fe, Mn, Al, Ca, Mg and Na.

Cation concentrations were determined by atomic absorption spectrophotometry on hydrochloric acid digested soil extracts. Details of sample preparation and analysis are given in Appendix Four, together with information on preliminary analyses, sample replication, blank determinations and the precision and accuracy of the method.

4.4.1 Cation Data

Results of the cation analyses are reported as micro*grams* per gram of oven dry sample for Fe, Mn and Al, and as micro*moles* per gram of oven dry sample for Ca, Mg and Na. Determinations have not been reported as oxides (or hydroxides) because: i) to do so would require assumptions about the compounds in which the cations are present in the soil; and ii) it is unnecessary as inter-element comparisons are not required.

Results of all cation determinations carried out on barrier soil samples are included in Appendices 4-1 to 4-48. To provide a better appreciation of the characteristics of these data, and to illustrate cation distribution trends within soil profiles and across the barriers, isograms have been drawn to correspond to the barrier transect lines. As with the organic matter isograms, the origin is on the right, with distance from the sea plotted on the abscissa, and sample depth on the ordinate. Soil site (profile) numbers are shown at the top of the isograms.

The cation distribution patterns evident in the isograms are discussed below: for each cation, the characteristic distribution pattern is outlined, one or two representative isograms are presented, and any notable exceptions to the trends are mentioned. In the discussion, references to the master soil horizons have the following connotations: A_2 - an eluvial horizon, generally with comparatively low cation concentrations; B - an illuvial horizon, generally with a higher concentration of "accumulative" cations than the A_2 horizon (see introduction to Section 4.4); C - essentially the parent material horizon, with variable cation concentrations, usually intermediate between the A_2 and B horizon values. The thickness of these horizons is usually assessed from the distribution pattern of the cation under consideration. However, in a few cases (e.g., when dealing with "dissipative" cation patterns), it has been necessary to refer to the visible boundaries of specific horizons; the latter are shown in Appendix Two.

Note that unless otherwise stated, all trends mentioned in the following discussion refer to changes along a barrier transect, in a seaward to landward direction.

4.4.1.1 Iron. The concentration of iron in the analysed soil samples is reported with the other cation data in Appendix Four; the distribution of iron in the soil profiles, and across the barriers, is depicted in the isograms in the same appendix. Some of these isograms have been reproduced as figures in this chapter.

The generalized iron distribution pattern which prevails, to a varying degree, across all of the barriers, has the following features:

1. Overall, iron concentrations range from low (<100 micrograms/g) to comparatively high values (>3000 micrograms/g), although most isogram maxima are less than 2000 micrograms/g.

2. There is a pronounced increase in iron concentration in the B horizon, across the barriers.

3. An initial sharp decrease, then much less substantial increase, occurs in iron concentrations in the A_2 horizon, across the isograms.

4. A tendency is evident towards a decrease in A_1 horizon values, with increasing distance from the sea.

5. A marked increase in A_2/B horizon differentiation occurs across the barriers.

6. A gradational A_1/A_2 transition is displayed across most barriers.

7. An initial increase, then constancy, in the thickness of the A_2 horizon is evident.

8. Progressive thickening of the B horizon is indicated by the iron distribution patterns.

9. Progressive decrease in the thickness of the C horizon is apparent.

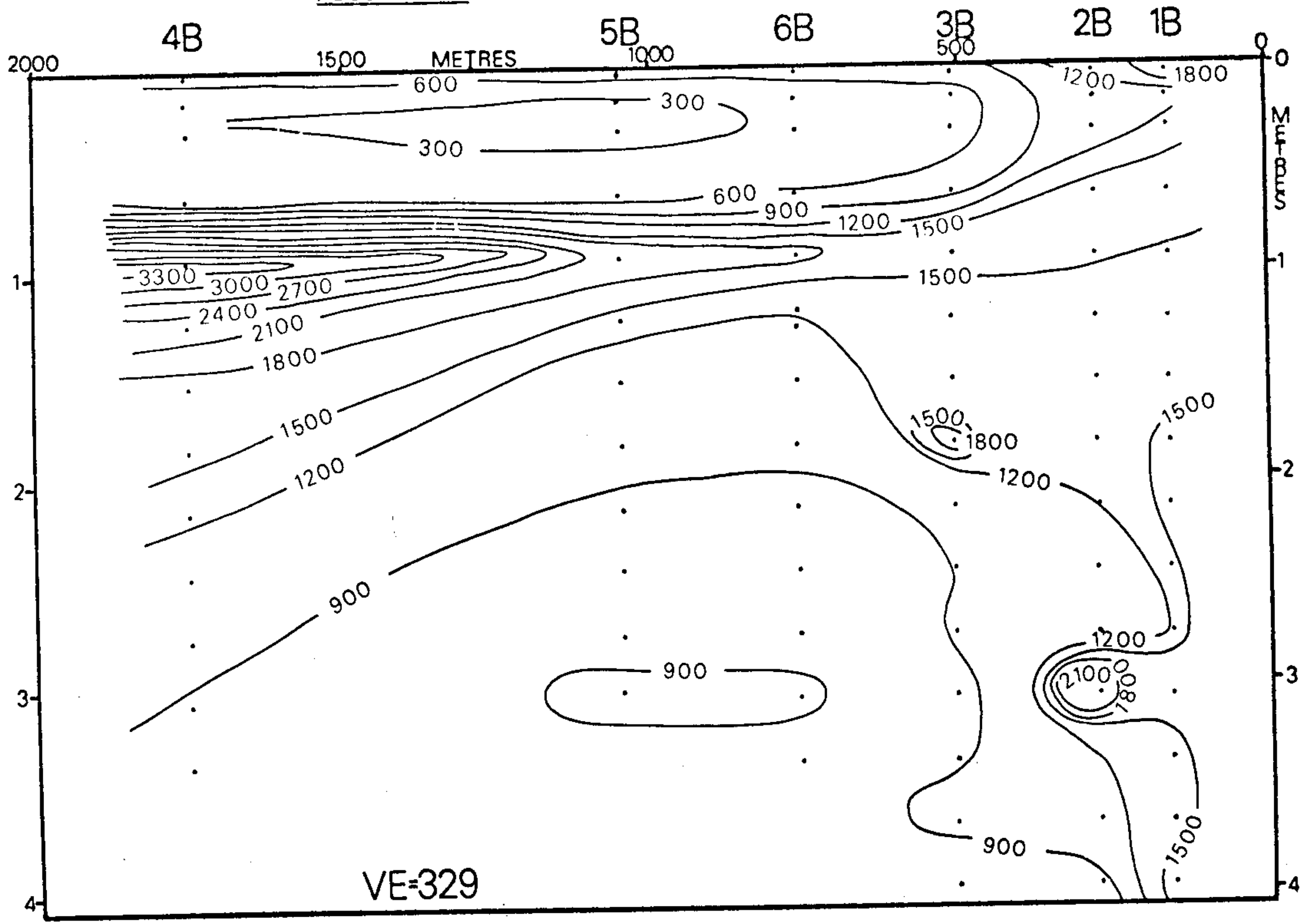
Taken together, these trends indicate a general increase in podzol profile development across the barriers, from seaward to landward.

Moruya Iron Isogram - The Moruya iron distribution pattern well-illustrates the general increase in profile development across the barrier. The Moruya iron pattern is also typical, in that it displays most of the other characteristics listed above.

The principal features of the Moruya iron isogram, shown in Figure 4.3, are as follows:

1. The distribution pattern is simple and systematic, although Profiles (Sites) 1B, 2B and 3B are somewhat irregular at depth. Lateral and vertical isopleth discontinuities are few, and those that occur are not substantial.
2. Concentrations of iron range from low to very high; the maximum value (3390 micrograms/g) occurs in the upper B horizon of Profile 4B (at the rear of the barrier), and is the highest iron concentration measured in any barrier soil sample during the study.
3. The minimum concentration of the A_2 horizon decreases from 1180 to 280 micrograms/g, between Profiles 1B and 5B, but rises slightly to 350 micrograms/g in Profile 4B, at the rear of the barrier.
4. The maximum B horizon iron concentration progressively increases across the isogram between Profiles 1B and 4B.
5. A_2/B horizon differentiation ranges from moderate in Profile 1B, to very strong in Profile 4B. The slight excess of iron in the A_2 horizon of Profile 4B, relative to Profile 5B, is more than compensated for by the higher B horizon concentrations in Profile 5B.
6. A_1/A_2 horizon differentiation is irregular and slight in Profiles 1B and 2B, and moderate in the other profiles.
7. B/C horizon differentiation is irregular and slight in Profiles 1B and 2B, but becomes progressively more

FIGURE 4.3 MORUYA IRON DISTRIBUTION



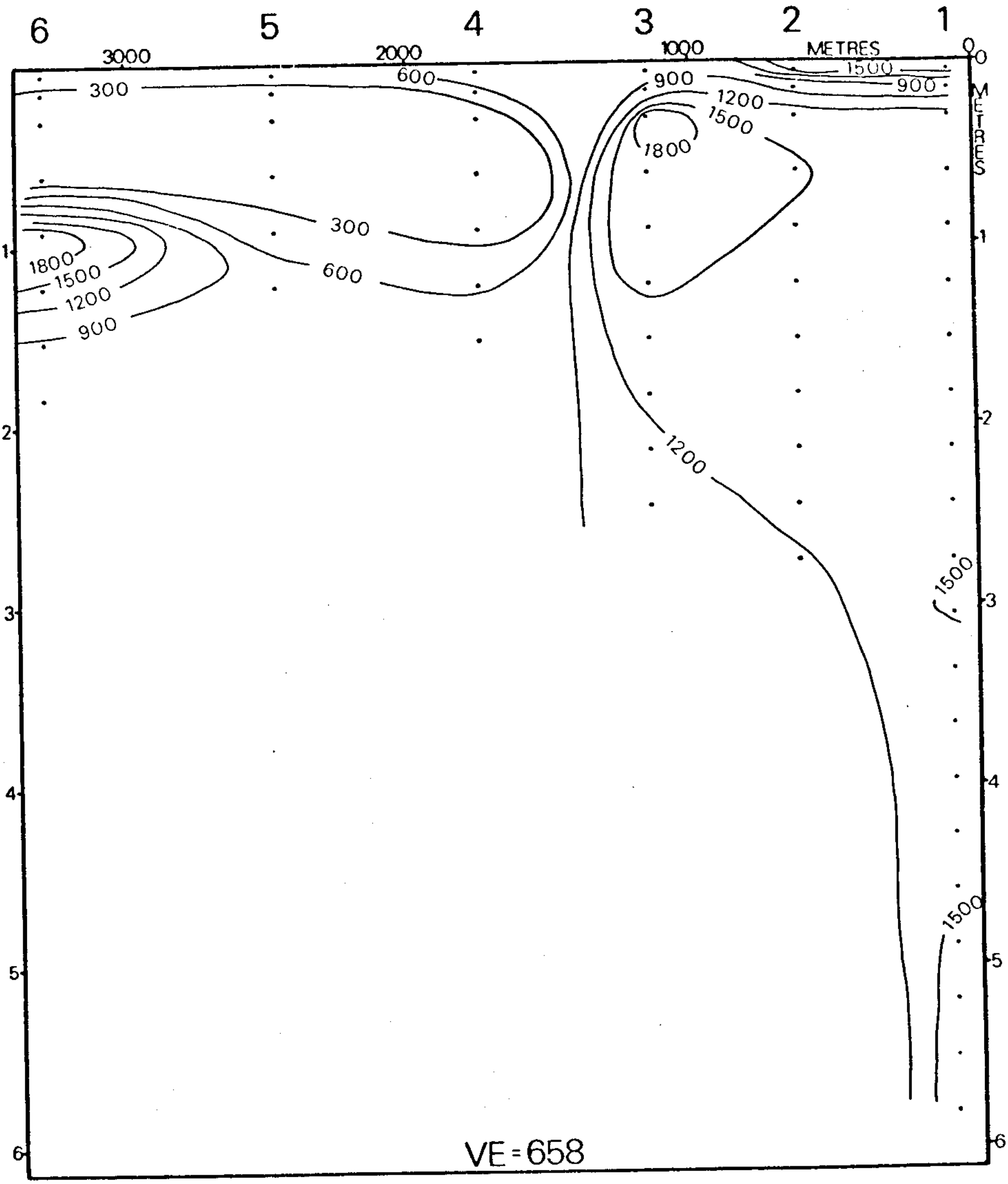
regular and more pronounced across the barrier until, in Profile 4B, it is very marked.

8. The A_1/A_2 horizon transition is not well defined, but appears to be at a constant depth across the barrier. The A_2/B horizon transition increases in depth between Profiles 1B and 3B, then remains fairly constant between Profiles 3B and 4B. The B/C transition is poorly defined in Profiles 1B to 3B, but in Profiles 4B, 5B and 6B, it becomes somewhat sharper and tends to increase in depth (see Figure 4.3).

9. Changes in the depths of horizon boundaries across the Moruya barrier (as defined by iron concentrations) result in : i) consistent thickness of the A_1 horizon; ii) increase in the thickness of the A_2 horizon between Profiles 1B and 3B, then a constant thickness across to Profile 4B; iii) increase in the thickness of the B horizon across the section, between Profiles 6B and 4B (see Figure 4.3).

Other Iron Isograms - With some variations, iron distribution across the other barriers quite closely resembles the Moruya pattern (see isograms in Appendix 4). However, one of the most significant departures from this pattern occurs in the Woy Woy Fe isogram (Figure 4.4), in which a major lateral discontinuity between Sites 3 and 4 extends from the ground-surface to the watertable. Similar pronounced discontinuities occur in both the Disaster Bay and Rheban isograms (Appendices 4-78 and 4-90, respectively), while much less severe irregularities are found in the Cowley Beach and Fens isograms (Appendices 4-96, 4-50). Such discontinuities mark abrupt changes in the degree of podzol development, and must reflect

FIGURE 4.4 WOY WOY IRON DISTRIBUTION



major differences in the balance of the pedogenic factors. Less substantial irregularities, in the thickness of horizons and in the sharpness and depth of horizon transitions, may also indicate inter-profile pedogenic factor variability. Examples of these minor irregularities may be seen in the Rheban, Hawks Nest and Cowley Beach iron isograms (Appendices 4-90, 4-50 and 4-96, respectively).

Owing to the limited number of soil sites on the Wonboyn and Inarlinga transects (and to a lesser extent the Broulee transect), the relevant isograms display more regular patterns than the isograms that represent the longer transects from the same barriers.

4.4.1.2 Manganese. Data on manganese concentrations in the soil samples are given in the tables in Appendix 4; the transect distribution patterns are shown in the relevant isograms in the same appendix. A geometric isopleth interval has been used in these diagrams. The following comments relate to the general characteristics that can be recognized in the manganese distribution patterns:

1. Manganese concentrations are substantially lower than the equivalent iron values, throughout all the profiles. Measured manganese concentrations range from less than 1 microgram/g in a leached A_2 horizon sample from Disaster Bay, to about 150 micrograms/g in a surface sample from Rheban.
2. In each isogram the manganese values tend to be of the same magnitude, although the surface concentrations are usually substantially higher.

3. The manganese distribution patterns exhibit considerably fewer common features than the iron distribution patterns, and consequently they are much more difficult to succinctly characterize. However, one trend that is detectable in most of the isograms is a general increase in the development of the A_2 and B horizons across the barriers. Three variations on this trend may be observed in the manganese isograms: the *first* involves an increase in the development of the A_2 horizon, with a concomitant decrease (or constancy) in the development of the B horizon; the *second* occurs where both the A_2 and B horizons increase in their development across the barrier; and the *third* situation is where the B horizon increases in its degree of development across the barrier but is not matched by the A_2 horizon, which is either constant, or even degrades (i.e., becomes less distinctive). Profile development here refers, not solely to changes in B horizon maxima and A_2 horizon minima, but also to the thickness and lateral extent of the horizons. Distribution irregularities may also further complicate the situation; they are common in the manganese isograms.

Woy Woy Manganese Isogram - This isogram is representative of those barriers across which the A_2 horizon shows increased development, while the B horizon tends to degrade. Such a distribution pattern would seem to indicate an increase in manganese leaching across the barrier, but it is possible that parent material variability is responsible. Broulee, Cowley Beach and Inarlinga are the other isograms with manganese distribution patterns of this type. They are illustrated in Appendices 4-73, 4-97 and 4-103, respectively.

Characteristics of the Woy Woy manganese distribution pattern, shown in Figure 4.5 (and Appendix 4-63), are as follows:

1. With the exception of the comparatively high-concentration surface samples, manganese values are quite uniform down each profile.
2. The distribution pattern is very simple and regular (note, however, the geometric isopleth interval).
3. Average *subsurface* profile concentrations progressively decrease away from the sea, with the development of a thick horizon of low manganese content (an A_2 horizon?).
4. In terms of manganese, B horizon development is minimal in all profiles.

The Broulee, Cowley Beach and Inarlinga manganese distribution patterns all agree well with the Woy Woy pattern. However, manganese concentrations in the two Queensland isograms are considerably higher than they are in the Woy Woy or Broulee isograms.

Fens Manganese Isogram - The Fens transect distribution pattern, shown in Figure 4.6, is representative of those manganese isograms which indicate a constancy, or even decrease, in A_2 horizon development across the barriers, with a concomitant increase in B horizon development. The other manganese isograms of this type - Moruya, Disaster Bay

FIGURE 4.5 WOY WOY MANGANESE DISTRIBUTION

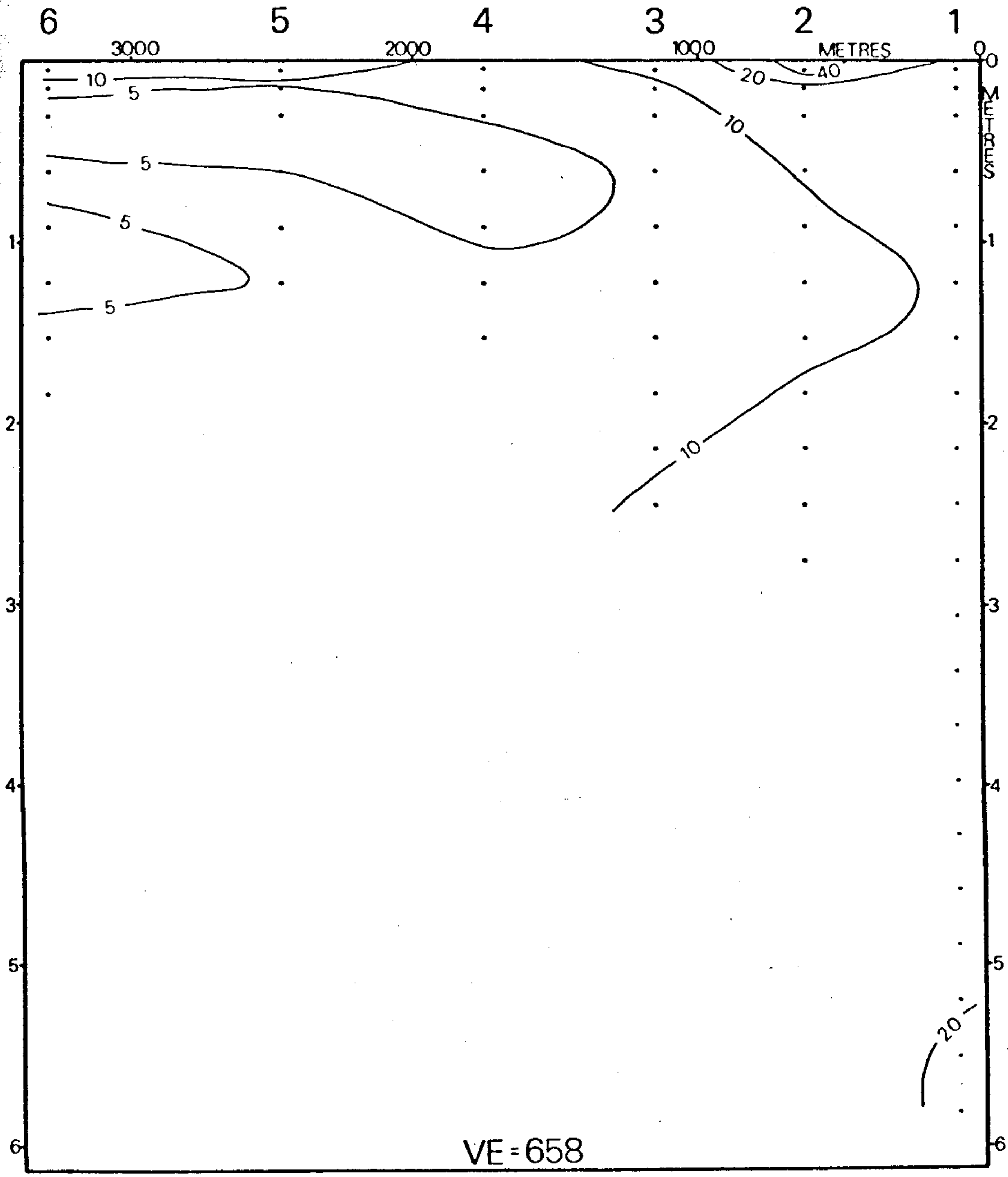


FIGURE 4.6 FENS MANGANESE DISTRIBUTION

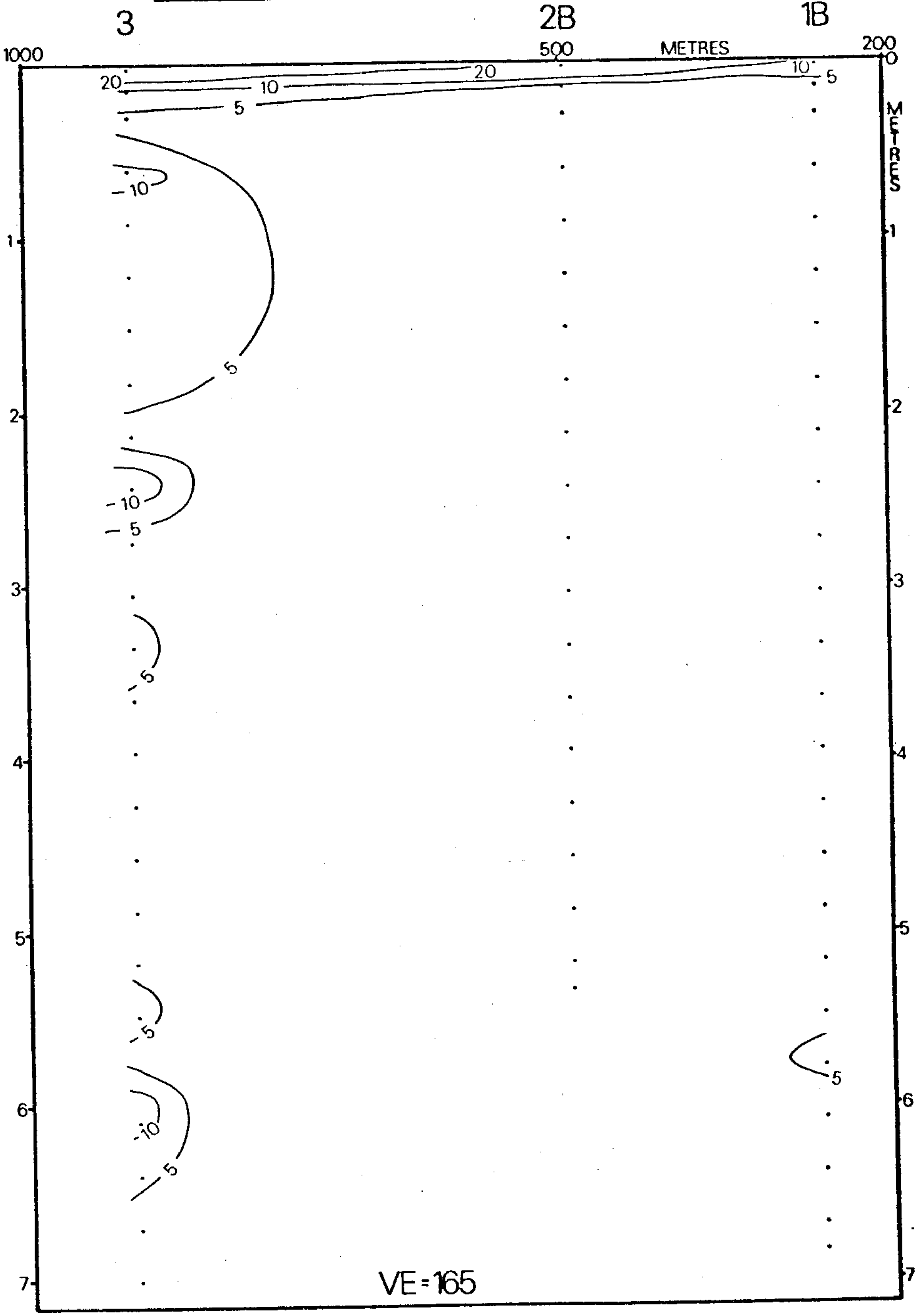


FIGURE 4.7 RHEBAN MANGANESE DISTRIBUTION

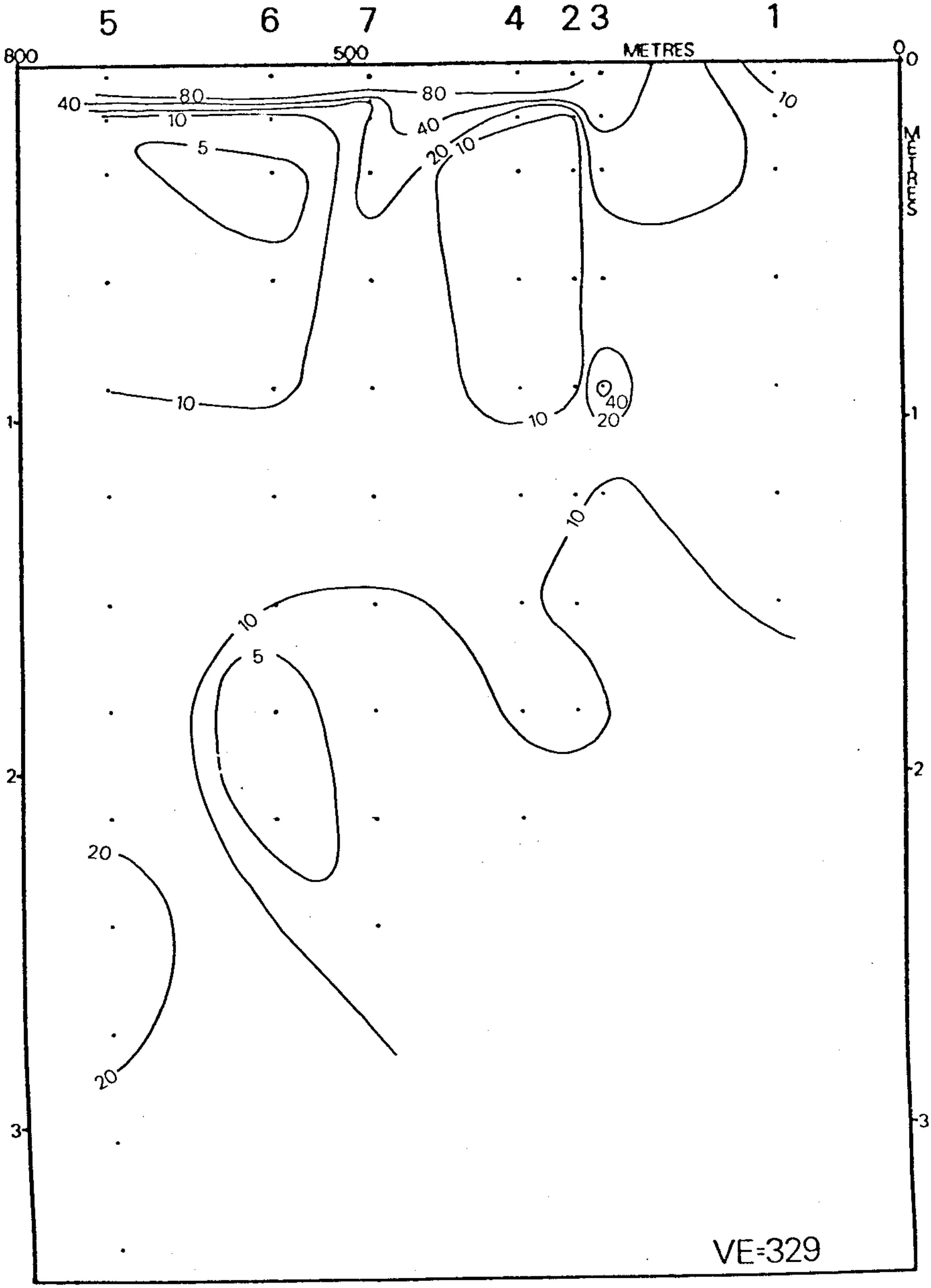
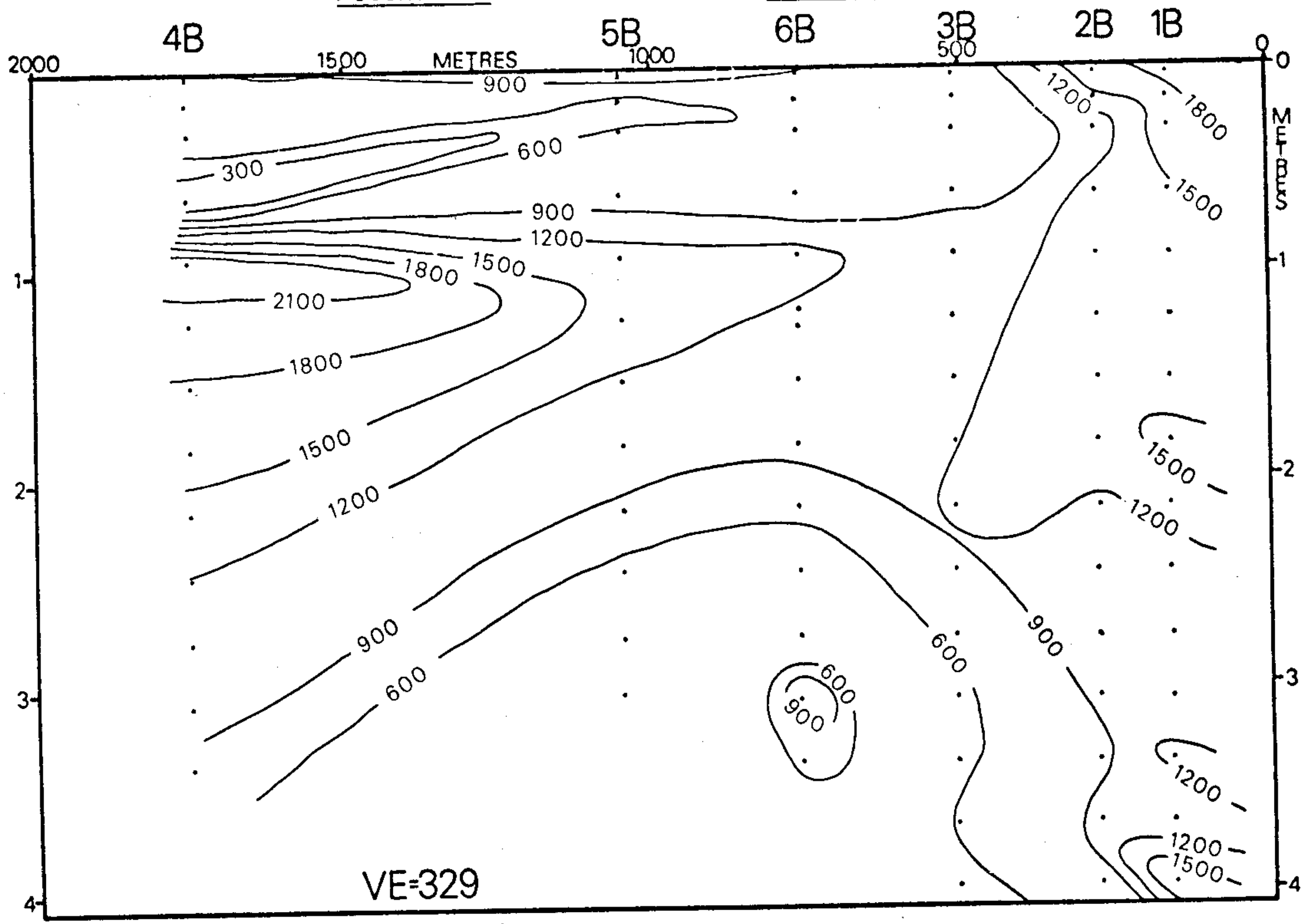


FIGURE 4.8 MORUYA ALUMINIUM DISTRIBUTION



and Hawks Nest - are illustrated in Appendices 4-67, 4-79 and 4-51, respectively.

Significant features of the Fens manganese distribution pattern include:

1. A slight increase in B horizon development across the isogram, with a slight concomitant A_2 horizon degradation.
2. Concentrations are low throughout each profile, with the highest values near the surface.
3. Profile development is minimal in Profiles (Soil Sites) 1B and 2B, and only moderate in Profile 3. Consequently, there are some minor lateral discontinuities between Profiles 2B and 3.

The Disaster Bay, Moruya and Hawks Nest manganese distribution patterns all display the slight increase in B horizon development and the slight A_2 horizon degradation that are evident in the Fens isogram, and are therefore grouped with Fens. However, they differ slightly from Fens by displaying greater variability in the subsurface concentrations and in the magnitude of lateral discontinuities.

Rheban Manganese Isogram - The third A_2 and B horizon trend mentioned above is that in which both horizons display increased development across a barrier. While this trend is typical of virtually all the iron distribution patterns, it is comparatively rare for manganese; only Rheban (Appendix 4-91) and Wonboyn (Appendix 4-85) are of this type. The main features of the Rheban manganese distribution pattern, as depicted in Figure 4.7, are:

1. A wide range in concentrations, from less than 5 to almost 150 micromoles/g, with the highest values at the surface. Presumably, manganese has been concentrated in the organic fraction, although Westman (1978) found the greatest amounts of Mn in his older (south Queensland) coastal podzols to be in the B_1 horizon.

2. A fairly complex distribution pattern with a pronounced lateral discontinuity between Profiles (sites) 2 and 3, and sharp vertical changes near the surface. This results in strong A_1/A_2 horizon differentiation in all profiles, except Profiles 1 and 3 (see Figure 4.7).

3. With the exception of the irregularities around Profiles 3 and 7, an initial increase, then constancy, is indicated in the development of the A_2 horizon, with increasing distance from the sea.

4. Although irregular in the depth of its upper and lower boundaries and in its thickness, the B horizon displays increased development across the barrier, from Profile 1 to Profile 5 (see Figure 4.7). The irregularities are due, in part, to differences in the watertable depth, and in part to variations in the depth of the A_2/B horizon boundary.

As the Wonboyn isogram contains only two soil profiles, its manganese isopleth pattern is probably less reliable than those based on more soil sites. However, the distribution pattern is very simple and regular, and shows a slight trend towards increased development of both the A_2 and B horizons, with increasing distance from the sea (see Appendix 4-85).

4.4.1.3 Aluminium. The concentration of aluminium in the analysed soil samples, and the distribution of these values across the barriers, are documented in the relevant tables and isograms in Appendix Four.

The most common characteristics of the aluminium distribution patterns are:

1. Concentrations range (overall) from less than 100 micrograms/g, to well over 6000 micrograms/g.
2. Distribution patterns are mostly very regular, but become less regular towards the watertable.
3. The A_2 horizon shows an increase in development (i.e., lower Al values; more distinct) across the barriers, from seaward to landward.
4. B horizon development also increases across the barriers (i.e., higher Al values; more distinct).
5. A_2/B horizon differentiation becomes more pronounced towards the rear of the barrier.

Collectively, these trends indicate an increase in profile development.

Moruya Aluminium Isogram - The aluminium distribution pattern shown in Figure 4.8 is typical of all the aluminium isograms; the main features of the Moruya pattern are:

1. A systematic pattern, with a few slight irregularities at depth (see Profiles 1B, 2B, 3B and 6B in Figure 4.8).

2. Aluminium concentrations range from low (90 micrograms/g) in the A_2 of Profile 4B, to moderately high (2145 micrograms/g) in the B horizon of the same profile.

3. Concentrations in the A_1 horizon decrease substantially from Profiles 1B to 3B, then are fairly constant across the rest of the barrier (see Figure 4.8).

4. A_2 horizon concentrations fall sharply between Profiles 1B and 3B, then show comparatively little decline between Profiles 6B and 5B (Figure 4.8). However, in Profile 4B, at the rear of the barrier, the minimum concentration is considerably lower.

5. B horizon aluminium values are similar in Profiles 1B and 2B, but tend to fall slightly in Profile 3B. However, in Profile 6B concentrations increase and this trend continues to the rear of the barrier (see Figure 4.8).

6. C horizon aluminium concentrations are variable.

7. A_1/A_2 horizon differentiation (in terms of Al) is not strong in Profiles 1B, 2B, 3B, 6B and 5B, but increases in Profile 4B, at the rear of the barrier.

8. A_2/B horizon differentiation is slight in Profiles 1B and 2B, moderate in Profiles 3B and 6B, strong in Profile 5B and very strong in Profile 4B (Figure 4.8).

9. B/C horizon differentiation is variable, but generally increases across the barrier, with distance from the sea.

10. The A_1/A_2 horizon boundary is not clearly defined but appears to be at a constant depth between Profiles

1B and 5B, but to increase in depth in Profile 4B. On the other hand, the A_2/B transition is at a consistent depth across the barrier. The B/C transition is gradational, but does appear to be shallower near the middle of the barrier.

Other Aluminium Isograms - Irregularities are more common in the other aluminium distribution patterns than they are in the Moruya pattern. For example, the Disaster Bay isogram (Appendix 4-80) displays a major lateral discontinuity between Profiles (Sites) 3B and 6; otherwise the pattern is very regular. Similarly, Rheban (Appendix 4-92) displays a lateral discontinuity near Profiles 2 and 3, but in this isogram minor irregularities also occur. The Hawks Nest (Appendix 4-52) and Fens (Appendix 4-58) isograms display quite regular aluminium distribution patterns and are in general agreement with each other, and with the generalized aluminium pattern previously described. Wonboyn (Appendix 4-86) also fits the general pattern, but the Broulee pattern (Appendix 4-74) is less in agreement, because of a few very high aluminium concentrations near the watertable in Profile 3B, and near the surface in Profile 1B. The Woy Woy isogram (Appendix 4-64) agrees well with the generalized aluminium pattern, except for an irregularity in the B horizon in Profile 3.

A feature of both the Cowley Beach and Inarlinga aluminium isograms (Appendices 4-98 and 4-104, respectively) that is not apparent in any of the other isograms, is the lack of an A_1 horizon near the groundsurface. Both Queensland isograms show a pronounced deepening and intensification of the A_2 horizon (lower Al values) across the barrier so that the A_2/B horizon boundary increases in depth. This trend is particularly noticeable on the Cowley Beach aluminium isogram (Appendix 4-98) in which the 6- and 21- microgram/g isopleths drop from 29 cms to 100 cms depth, and from 60 cms to 120 cms depth, respectively. In this isogram the maximum aluminium B horizon concentration occurs in Profile 5, although the B horizon in Profile 6 (with a deeper watertable) is much thicker.

4.4.1.4 Calcium. Appendix 4 includes the results of the calcium analyses and also presents isograms which show the distribution of calcium across those barrier transects for which data are available (i.e., all except Woy Woy).

The most characteristic features of the calcium isogram distribution patterns are as follows:

1. The patterns are simple and regular. (Note: a geometric isopleth interval has been used in all the calcium isograms).
2. Concentrations range from high to very low (no detectable calcium). For technical reasons, values in excess of 100 micromoles/g are not specified.
3. Almost all isograms indicate a decrease in average subsurface calcium concentration with increasing distance from the sea.
4. Most isograms have high calcium concentrations near the surface, but low subsurface values, resulting

in a sharp concentration gradient between the 3 cm and 15 cm samples. A few isograms display high concentrattions at depth in the seaward profiles, which may reflect unleached marine shell.

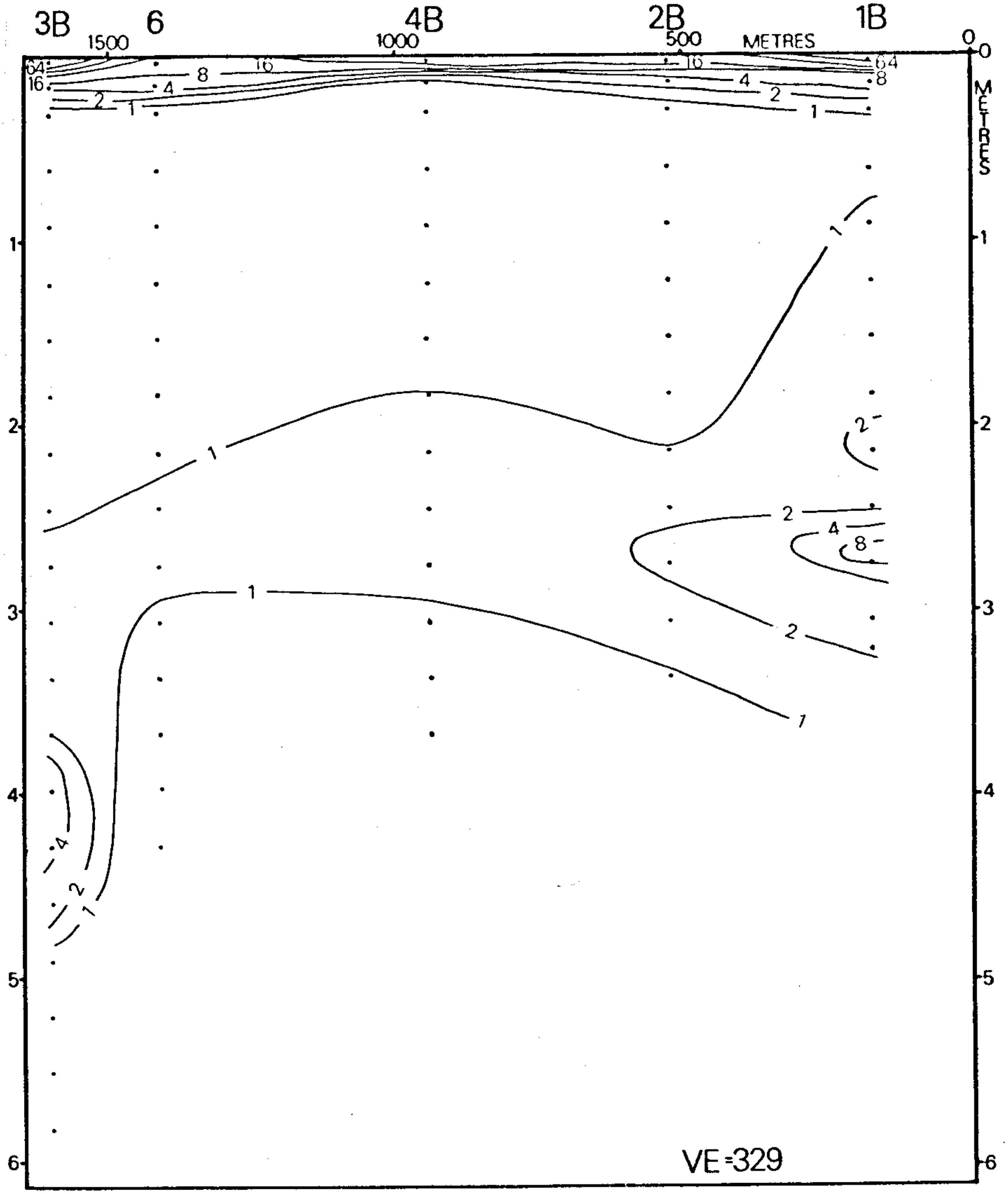
5. The A_2 horizon (as defined by the distribution of calcium) increases in thickness across most isograms. The greater thickness results from a deepening of the lower boundary of the A_2 horizon. Minimum A_2 calcium values are fairly consistent across each isogram.

6. Changes in the degree of B horizon development are not apparent across the isograms, with the possible exception of Fens.

Disaster Bay Calcium Isogram - All of the characteristics listed above are well-demonstrated by the Disaster Bay calcium isogram, which is shown in Figure 4.9. The only substantial departure from the general characteristics, is the lack of high calcium concentrations in the seaward-most soil profiles.

Other Calcium Isograms - Most of the other calcium distribution patterns are remarkably similar. However, there are a few significant departures from the Disaster Bay pattern. For example, the Fens calcium isogram (Appendix 4-59) displays an isopleth pattern near Profile 3 which seems to indicate a slight degree of B horizon development. Both the Moruya and Broulee isograms (Appendices 4-69 and 4-75, respectively) have very high concentrations at depth, in their seaward-most profiles. The sharp vertical and lateral transition to these high values becomes progressively deeper in the profiles with increasing distance from the sea. This could indicate

FIGURE 4.9 DISASTER BAY CALCIUM DISTRIBUTION



a trend towards deeper leaching away from the sea, and/or a change in the calcium content of the parent material. The Cowley Beach isogram (Appendix 4-99) displays a deeply developed A_2 (leached) horizon on its landward side, with the complete absence of a B horizon (in terms of calcium distribution). Although this isogram therefore differs somewhat from the Moruya pattern in this respect, overall it is still quite similar.

4.4.1.5 Magnesium. Concentrations of magnesium in the soil samples are listed in the tables in Appendix 4 and the distribution patterns for these transects for which magnesium data are available, are shown in the isograms in the same appendix. Magnesium concentrations are not available for the Woy Woy and Inarlinga transects, nor for part of the Cowley Beach transect.

In general terms, the magnesium distribution patterns display the following characteristics:

1. Concentrations are low to very low throughout all the isograms, with the highest values occurring near the surface.
2. The distribution patterns are simple, even allowing for the effects of the geometric isopleth interval that was used in the construction of the isograms.
3. Average profile concentration tends to decrease across the barriers.
4. A distinct A_2 (leached) horizon is present in all isograms, but not usually on the seaward side.

5. The B horizon shows little development in most of the isograms.

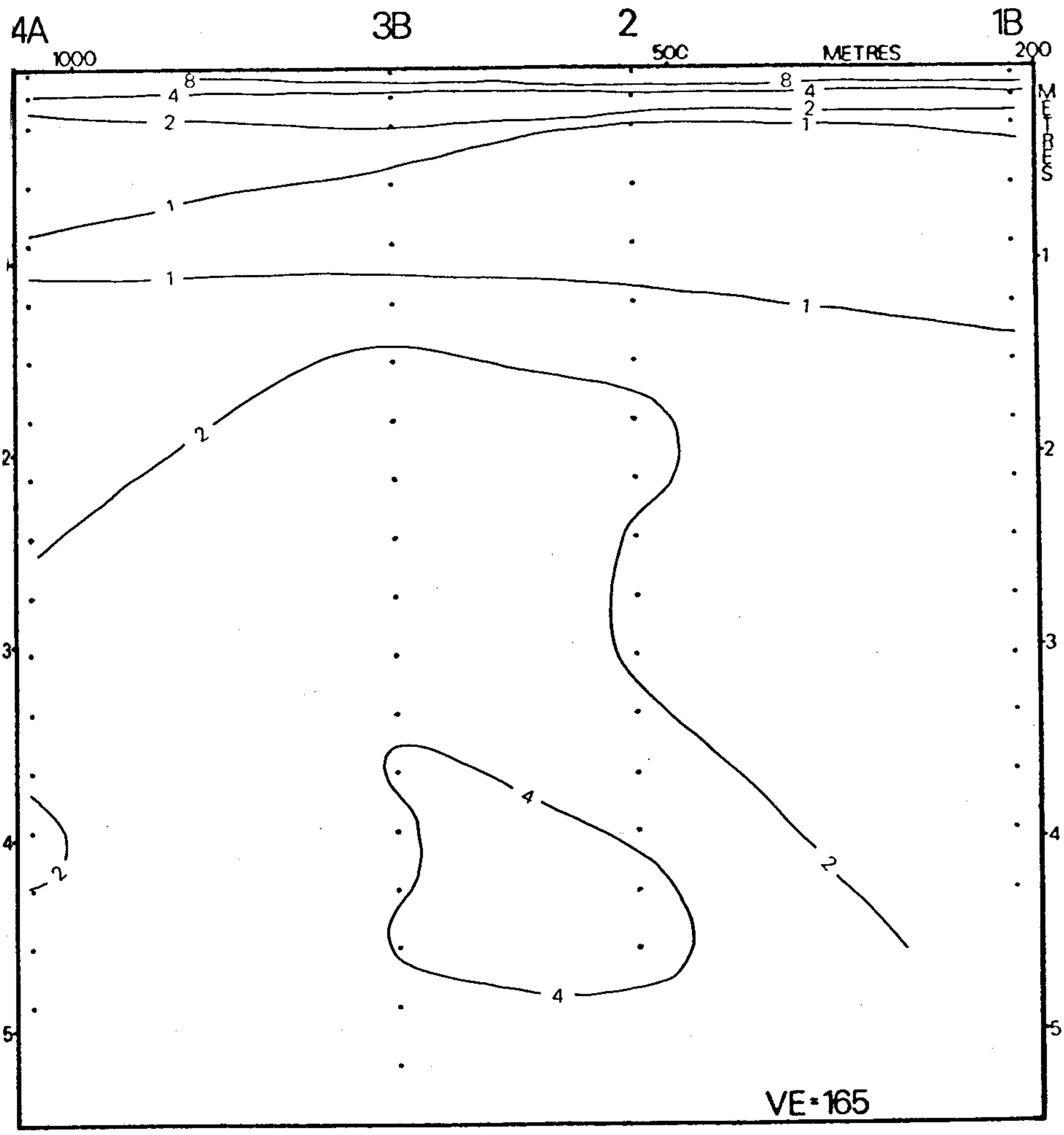
6. The A_1 horizon is generally of consistent thickness across the isograms.

Hawks Nest Magnesium Isogram - This isogram is shown in Figure 4.10. It displays most of the characteristics listed above and therefore is representative of the general magnesium distribution pattern. However, the Hawks Nest distribution does differ from the general pattern in two minor respects. First, average profile concentrations do not show a general decrease away from the sea. In fact, a slight increase occurs across Profiles 1B, 2 and 3B, with a decrease to Profile 4A (at the rear). Second, a *slight* change in the degree of development of the B horizon is suggested by the isopleth pattern, whereas this is not the general trend.

Other Magnesium Isograms - Apart from irregularities in the thickness of the A_2 horizon in the Rheban isogram (see Appendix 4-94), and a lateral discontinuity on the landward side of the Disaster Bay isogram (see Appendix 4-82), all the other isograms for which magnesium data are available appear to be well represented by the Hawks Nest distribution pattern, and by the generalized characteristics previously described.

4.4.1.6 Sodium. Concentrations of sodium in the soil samples are reported in the tables in Appendix 4, together with isograms which show the transect distribution patterns.

FIGURE 4.10 HAWKS NEST MAGNESIUM DISTRIBUTION



Although these patterns display few obvious similarities, the two common characteristics which may be discerned are:

1. Concentrations are very low throughout all the isograms, with few values above 2 micromoles/g and none in excess of 10 micromoles/g.

2. A trend that can be recognized in about half the isograms (Fens, Woy Woy, Rheban, Broulee and Wonboyn), involves a decrease in the average upper profile sodium concentration across the isogram, with a corresponding slight increase in the development of the A_2 (leached) horizon.

Fens Sodium Isograms - The Fens isogram is one that displays both of the above characteristics (see Figure 4.11). Other significant features of the Fens sodium distribution pattern are:

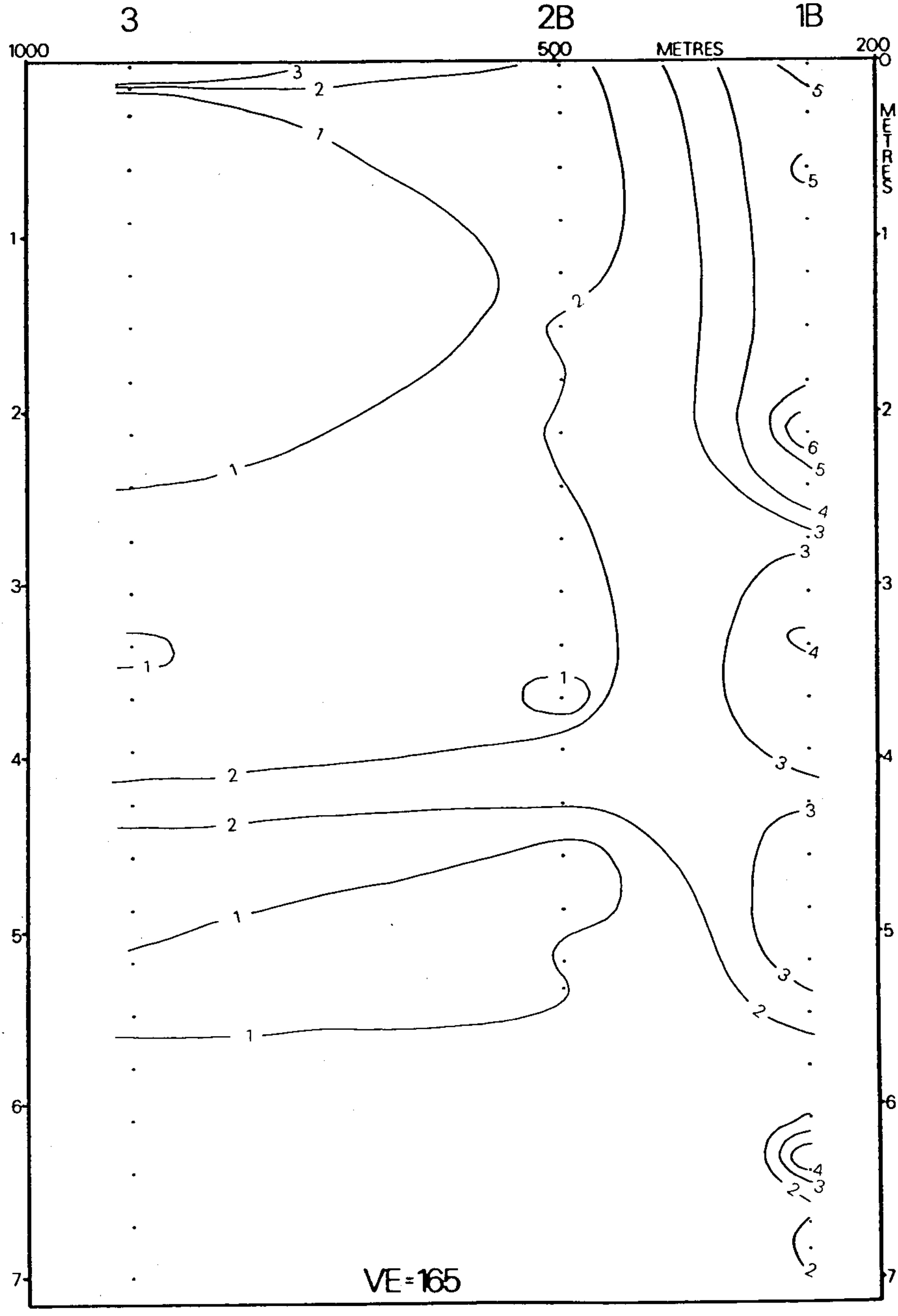
1. An irregular and complex isopleth pattern, particularly in Profile 1B, and to a lesser extent in Profile 2B.

2. A distinct decrease in average profile concentration of sodium across the barrier, from Profile 1B to Profile 3.

3. The progressive development of an A_2 horizon across the barrier.

Other Sodium Isograms - Those isograms across which a decrease in average profile concentration of sodium is not evident (i.e., Disaster Bay, Moruya, Hawks Nest, Cowley Beach and Inarlinga), all display varied isopleth configurations, some being very complex (e.g., Moruya; see Appendix 4-71), and others quite simple (e.g., Disaster Bay; Appendix 4-83).

FIGURE 4.11 FENS SODIUM DISTRIBUTION



4.4.1.7 Summary. In Section 4.4 the results of the cation analyses have been reported and the distributions of the cations, within the soil profiles and across the study barriers, have been described and illustrated. From the descriptions it is apparent that:

1. Most of the investigated cations are distributed within the barrier soils in a regular, systematic manner.
2. The distribution patterns of some cations exhibit a typical podzol horizon sequence (A_1, A_2, B, C), whereas others do not. Iron, aluminium and to a lesser extent manganese, display such a sequence.
3. The distributions of the "dissipative" cations, calcium, magnesium and sodium, do not exhibit the A_1-A_2-B-C horizon sequence.
4. Trends are evident across the barrier transects in the degree of horizon development and differentiation. The distributions of iron, aluminium and manganese display increased horizon development and differentiation across the barriers, while the calcium, magnesium and sodium isogram patterns indicate progressive leaching of these cations.

4.5 GRAIN SURFACE TEXTURES

4.5.1 Introduction

Scanning electron microscopy (SEM) was used by the writer to assess the effects of podzol development on quartz sand grain surface textures, within the factorial pedological framework outlined in Chapter Two. The specific objectives of this aspect of the study are:

1. To determine whether podzol development has affected the surface textures of quartz sand grains.

2. If such an effect is observed, to quantify it and to investigate how it relates to the relevant pedogenic factors, in particular, to the ages of the soil profiles.

When the SEM work was commenced in 1974 no pedological studies were available on the effects of soil development on quartz sand grain textures, with the exception of a few descriptive papers dealing with grains from high intensity, tropical weathering environments (e.g., Doornkamp and Krinsley, 1971). Subsequently, a few articles employing SEM techniques have appeared in the pedological literature. However, these studies have not examined podzol development in a factorial context and generally they bear very little resemblance to the present study. For example, the paper by Little *et al.* (1978), dealing with the textural effects of pedogenesis on Fraser Island (Queensland), is superficially similar to the present study. However, Little *et al.* were concerned only with gross grain surface morphology (not specific textural features, as investigated herein) and they recognized only four morphological types. Of these, only three could be differentiated under the SEM and consequently a petrographic microscope, rather than a SEM, was used by Little *et al.* to quantify their textural observations. In addition, Little *et al.* (1978) dealt with pedogenesis on a completely different time scale to that used in the present study. All the soil profiles they examined were over 15,000 years old, some being in excess of 400,000 years old; the sand barrier soils of the present study are all less than 6,500 years old. Finally, as Little *et al.* did not employ a factorial approach it is not possible to assess to what extent climatic or vegetative change, parent material differences or topographic variations have affected their observations.

4.5.2 The S.E.M. and Grain Surface Texture Investigations

The scanning electron microscope came into general sedimentological use in the late 1960's, largely replacing the transmission electron microscope (TEM). Advantages of the SEM, over the TEM, are that it does not require the production of replicas (the specimen is viewed directly) and it is capable of lower magnifications, thereby allowing the entire upper surface of a sand grain to be covered in a single field of view. In addition, SEM micrographs give a simulated three-dimensional view of a specimen, and are therefore much easier to interpret than TEM micrographs.

Many papers have been published on the application of the SEM to quartz sand grain surface texture identification. Generally, these papers have been of two types; those which define specific grain surface textural features and attempt to relate them to environmental processes (e.g., Margolis and Krinsley, 1974; Barbaraux *et al.*, 1972; Gees, 1969; Baker, 1976; Marzolf, 1976); and those papers which try to deduce the environmental history of sedimentary deposits from observations of grain surface textures (e.g., Waugh, 1970; Margolis and Kennett 1971; Smalley *et al.* 1973). However, a few workers have urged caution in associating specific surface textural features with particular environmental processes (e.g., Setlow and Karpovich, 1972; Brown, 1973; Manker and Ponder, 1978), although most writers seem to be of the opinion that, if appropriate precautions are taken, the problems can be avoided (e.g., Krinsley and Donahue, 1968; Baker, 1976). Also, the publication by Krinsley and Doornkamp (1973) of an *Atlas of Quartz Sand Surface Textures* has helped overcome many problems of textural recognition and identification, and it remains a most useful and comprehensive aid.

4.5.3 Quartz Sand Grain Textural Features

Diagnostic features on quartz sand grain surfaces can be regarded as of either mechanical or chemical origin (Ly, 1978). Although mechanically formed surface features were common on virtually all the sand grains examined by the writer, they are not directly relevant to the present study, concerned as it is with the *chemical* effects of podzol development on surface textures.[1]

A fundamental problem which is inherent in most textural investigations is the persistence of features from previous sedimentary environments. To a large extent this problem has been obviated in the present study by the exclusion of features of mechanical origin, and by discounting those features of chemical origin that were recognized as inherited. Any

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1. For details of mechanical features see, for example, Margolis and Krinsley (1971), Krinsley and Doornkamp (1973), or Ly (1978).

inherited chemical features that have been unavoidably included in the data have been treated as "noise", to be filtered from the target data during analysis (see Chapter Five).

In the present study, no attempt is made to identify new textural features of chemical origin, as to do so would introduce the possibility of a circular argument. That is, new textural features would be recognized on the basis of their occurrence in well-developed soil horizons, and their absence from poorly-developed horizons. However, if the occurrence of these same features was then used to monitor degree of soil development, the validity of the reasoning could be seriously questioned. All the textural features described below have been recognized by Krinsley and Doornkamp (1973) in the *Atlas* , as being of chemical origin. However, an attempt is made here to place the features into a more systematic morphogenetic framework.

The morphogenetic classification used below distinguishes between textures formed primarily by the dissolution of silica (*solution features*), and those formed by its precipitation (*precipitation features*). Table 4.1 outlines the classification scheme and refers to the relevant micrograph illustrations in Appendix Five.

4.5.3.1 Silica Solution Features. Two types of solution features are recognized - those that are localized and those that are extensively developed.

TABLE 4.1

CLASSIFICATION OF QUARTZ SAND GRAIN SURFACE TEXTURES OF CHEMICAL ORIGIN

MORPHOGENETIC TYPES	APPENDICES
1. SILICA SOLUTION FEATURES	
A. Localized Solution Features	
i. Solution pits	5- 1
ii. Solution crevasses	5- 2
iii. Oriented 'V' forms (etch triangles)	5- 3
iv. Oriented solution channels	5- 4
v. Etched surface cracks	5- 5
B. Extensive Solution Features	
i. Extensive chemical decomposition surfaces	5- 6
ii. Deep dissolution surfaces	5- 7
iii. Scaling and flaking	5- 8
2. SILICA PRECIPITATION FEATURES	
i. Silica plastering	5- 9
ii. Smooth/undulating silica precipitation surfaces	5-10
iii. Precipitated upturned silica plates	5-11
iv. Silica precipitation on surface projections	5-12

Localized Solution Features - Generally, these are small, discrete textural features, although they sometimes occur in groups; they have been counted individually. The various types are defined below.

Solution Pits occur in a variety of forms but are usually comparatively deep, steep-sided cavities in the grain surface. Typically, the surface expression of the pit is circular or subcircular, although the shapes of some pits appear to reflect the trigonal symmetry of quartz. Observed pit diameters range from about 2 to 10 microns, with depths of approximately the same magnitude. Usually the larger pits are less circular, tending to be elongated parallel to the principal cleavage direction. The micrographs in Appendix 5-1 illustrate the range of solution pits observed by the writer.

Solution crevasses are parallel or subparallel, elongated steep-sided cavities, each of which decreases in width and depth towards the ends. They usually occur in groups along structural weaknesses in the sand grain, with the crevasses normal to the structural trend, but parallel to the main cleavage direction. Solution crevasses are not nearly as common as solution pits and were only observed on grains with well-developed solution morphologies. It is possible that they originate as a line of subcircular solution cavities, which become elongated by the dissolution of silica from between parallel cleavage plates. Crevasses tend to be of a constant size, most being about 5 to 6 microns long, and less than 2 microns wide. The thin, backward-peeling crevasse margins described by Krinsley and Doornkamp (1973, p.18), were not observed by the writer.

Solution crevasses are illustrated in Appendix 5-2.

Oriented 'V' forms of chemical origin (otherwise known as *etch triangles*) have been carefully distinguished from 'V'-shaped pits of mechanical impact origin by Krinsley and Doornkamp (1973, p.14-15). Chemical 'V'-shaped pits are triangular in form, often contain diminishing 'V' forms, and are extremely regular, with no evidence of mechanical breakage. They occur in strongly oriented sets, with individual pits ranging in length from less than one micron to over 100 microns. While the distribution (but not the orientation) of the pits appears to be random on some grain surfaces, on others they coincide with lines of apparent structural weakness. Appendix 5-3 presents examples of these forms.

Oriented solution channels result from the dissolution of quartz along structural weaknesses in a sand grain; that is, along either cleavage or fracture planes. It seems likely that an oriented solution channel could result from the merging of oriented, etched 'V' forms, where the latter were originally aligned along a plane of structural weakness. Oriented solution channels are illustrated in Appendix 5-4.

Etched surface cracks are unoriented and somewhat irregular linear features, which have resulted from either active dissolution of a grain along a former mechanical fracture, or from the irregular coalescence of aligned primary solution features. Etched surface cracks are shown in Appendix 5-5.

Extensive Solution Features - These textural features exhibit less well-defined morphologies than the localized solution features, but as they cover larger areas they are still relatively easy to recognize. To permit quantification, it has been necessary to count each contiguous area of extensive textural features as one unit. This should be remembered when comparing or combining the counts of localized and extensive textural features. The three main types of extensive solution features are discussed below.

Extensive chemical decomposition surfaces are regarded by Krinsley and Doornkamp (1973, p.18) as the most prominent surface feature to result from high-energy chemical environments, being "...so distinctive that it alone probably would be sufficient to categorise the high-energy chemical environment" (*op.cit.*). Such decomposition surfaces are extensively etched, resulting in a highly irregular texture and considerable surface debris. Usually, most of the localized solution features discussed above are also found on these grains; these have been counted separately. In the present study only the Queensland soil samples yielded quartz grains with surfaces as chemically decomposed as those illustrated in the *Atlas* (from tropical areas). However, many New South Wales (and even some Tasmanian) sand grains display extensive, but less severe, development of chemical decomposition surfaces. It is probable that grains with this surface texture are equivalent to those termed "saccharoidal" or "microcrystalline" by Little *et al.* (1978). Examples of extensive chemical decomposition surfaces are shown in Appendix 5-6.

Deep dissolution surfaces are distinguished from extensive chemical decomposition surfaces by the greater depth of the solution morphology and the general lack of surficial debris. They probably represent a more advanced form of chemical decomposition, requiring longer and/or more intensive chemical dissolution. Deep dissolution surface textures are also similar to the microcrystalline or saccharoidal textures described by Little *et al.* (1978). Deep dissolution surfaces are illustrated in Appendix 5-7.

Scaling and flaking of small silica platelets from the surfaces of quartz grains subjected to intense chemical solution has been reported by Krinsley and Doornkamp (1973). This phenomenon was found to be of only limited occurrence in the present study, being mainly confined to sand grains from the north Queensland barrier. However, some New South Wales sand grains exhibit limited silica flaking in surface depressions. The micrographs in Appendix 5-8 illustrate scaling and flaking textures.

4.5.3.2 Silica Precipitation Features. Four types are recognized; they are defined below.

Silica plastering is considered by Krinsley and Doornkamp (1973, p.38) to result from rapid localized precipitation of silica. It occurs in discrete masses, usually within large shallow surface depressions. Typically, the silica is amorphous, with no apparent crystallographic orientation. Although the silica masses usually thin towards the edges, they are sharply differentiated from the underlying grain topography, when examined in the emissive mode. Appendix 5-9 shows examples of silica plastering.

Smooth/undulating silica precipitation surfaces probably develop when silica is precipitated at a slower rate than that which results in silica plastering (Krinsley and Doornkamp, 1973, p.11). The undulating precipitation surface masks the underlying grain topography and is usually free of projections. It may cover a grain completely, but is usually much more restricted in its extent. Examples are depicted in Appendix 5-10.

Precipitated upturned silica plates probably result from slower silica precipitation than either of the two precipitation features discussed above (Krinsley and Doornkamp, 1973, p.11). The newly precipitated plates develop on pre-existing plates, or sometimes on cleavage traces, usually resulting in strongly oriented features. Individual upturned precipitation plates are very thin and are usually small in size (less than 5 microns in length). Appendix 5-11 presents examples.

Silica precipitation on surface projections occurs as a result of extemely slow silica precipitation (Krinsley and Doornkamp, 1973, p.11). Rarely, this precipitation takes the form of quartz crystal terminations; more commonly, the precipitated silica occurs as small rounded projections which cap the higher points of a grain surface, previously made irregular by chemical or mechanical processes. Examples are shown in Appendix 5-12.

4.5.4 Texture Observations

Table 4.2 shows the results of the quartz sand grain texture counts. To reduce the texture data to a manageable amount, only aggregate counts for 1) localized solution features, 2) extensive solution features, and 3) precipitation features, are reported in the table (plus the sum of the three counts). Although the data in Table 4.2 appear

TABLE 4.2

GRAIN TEXTURE OBSERVATIONS (30 GRAIN SAMPLES)

TRANSECT	PROFILE (SITE)	SAMPLE	HORIZON	SOLUTION FEATURES TOTAL No. LOCALIZED FEATURES	TOTAL No. EXTENSIVE FEATURES	PRECIPITATION FEATURES TOTAL No. FEATURES	TOTAL No. FEATURES
HAWKS NEST	1B	2	A_1	19	6	21	46
		4	A_2	56	8	43	107
		7	B	21	5	39	65
		14	C	25	2	45	72
	2	2	A_1	34	0	24	58
		4	A_2	55	10	52	117
		8	B	38	1	45	84
		14	C	23	6	26	55
	3B	2	A_1	51	15	35	101
		5	A_2	62	7	59	128
		8	B	43	4	72	119
		17	C	31	2	32	65
	4A	2	A_1	62	5	13	80
		5	A_2	66	25	48	139
		8	B	58	13	55	126
		15	C	33	5	17	55
	4B	2	A_1	51	14	27	92
		5	A_2	48	11	39	98
		7	B	29	25	82	136
FENS	3	2	A_1	31	6	44	81
		4	A_2	28	17	64	109
		9	B	43	15	51	109
		23	C	19	6	17	42
-	ML1	2	A_1	36	5	33	74
		5	A_2	31	18	45	94
		9	B	22	15	68	105
		19	C	11	9	29	49
-	ML2	2	A_1	36	29	28	93
		5	A_2	37	11	54	102
		10	B	43	12	36	91
		19	C	16	5	35	56
WOY WOY	1	1	A_1	17	3	9	29
		2	A_2	17	2	28	47
		4	B	12	2	22	36
		15	C	16	0	7	23
	2	1	A_1	23	7	24	54
		2	A_2	41	8	29	78
		6	B	27	6	36	69
	3	1	A_1	53	2	19	74
		2	A_2	50	7	30	87
		5	B	54	5	19	78

TABLE 4.2 CONTINUED

	4	2	A_1	48	9	26	83
		5	A_2	22	7	36	65
		6	B	30	8	55	93
	5	1	A_1	51	13	21	85
		3	A_2	63	14	59	136
		5	B	34	12	36	82
	6	1	A_1	64	11	27	102
		4	A_2	73	14	76	163
		5	B	35	7	73	115
MORUYA	1B	1	A_1	35	2	31	68
		2	A_2	80	6	58	144
		3	B	36	3	28	67
		12	C	26	3	18	47
	2B	1	A_1	29	3	28	60
		3	A_2	63	8	49	120
		4	B	65	17	40	122
		12	C	16	2	15	33
	3B	1	A_1	44	10	29	83
		3	A_2	60	14	52	126
		5	B	44	7	48	99
		12	C	34	3	25	62
	6B	1	A_1	59	8	44	111
		3	A_2	69	14	59	142
		5	B	18	12	55	85
		11	C	30	3	23	56
	5B	1	A_1	33	16	40	89
		3	A_2	67	18	68	153
		6	B	40	9	49	98
		10	C	34	6	29	69
	4B	1	A_1	65	15	47	127
		3	A_2	56	19	85	160
		5	B	44	14	58	116
		9	C	40	6	35	81
DISASTER BAY	1B	1	A_1	44	10	21	75
		3	A_2	21	5	14	40
		5	B	9	2	18	29
	1A	1	A_1	24	5	26	55
		2	A_2	30	8	29	67
		5	B	11	6	23	40
	2B	1	A_1	31	7	30	68
		3	A_2	37	8	46	91
		7	B	27	6	21	54
	4B	1	A_1	42	10	36	88
		3	A_2	47	13	52	112
		9	B	33	8	47	88
	6	1	A_1	60	11	57	128
		3	A_2	69	10	73	152
		7	B	38	14	45	97

TABLE 4.2 CONTINUED

	3B	1	A_1	60	10	55	125
		3	A_2	68	18	80	166
		10	B	58	11	87	156
RHEBAN	1	2	-	17	0	4	21
	3	1	A_1	41	3	27	71
		2	A_2	23	10	52	85
		3	B	36	5	12	53
		5	C	13	6	19	38
	2	1	A_1	45	4	39	88
		2	A_2	39	12	40	91
		4	B	31	7	34	72
		7	C	16	4	17	37
	4	1	A_1	41	4	23	68
		2	A_2	43	17	40	100
		4	B	36	7	51	94
		8	C	12	4	14	30
	7	1	A_1	37	26	49	112
		2	A_2	49	22	63	134
		4	B	38	12	32	82
		8	C	11	8	23	42
	6	1	A_1	24	12	25	61
		2	A_2	47	18	73	138
		4	B	38	12	45	95
		8	C	20	3	9	32
	5	1	A_1	34	13	53	100
		2	A_2	55	39	78	172
		4	B	41	18	56	115
		10	C	26	2	18	46
COWLEY	1	1	A_1	27	22	30	79
		3	B	31	15	42	88
		8	C	18	5	11	34
	2	1	A_1	42	13	27	82
		4	B	49	17	57	123
		9	C	33	19	19	71
	3	1	A_1	48	17	56	121
		2B	A_2	60	24	78	162
		3B	B	41	24	34	99
		6	C	26	12	20	58
	4	1	A_1	65	31	61	157
		2	A_2	34	46	45	125
		3B	B	63	15	61	139
		6	C	47	14	29	90
	5	1	A_1	49	44	67	160
		3	A_2	52	26	73	151
		4B	B	48	21	85	154
	6	1	A_1	75	52	54	181
		3	A_2	63	33	86	182
		8	B	41	36	92	169

to be highly variable, a number of general features and some consistent trends are discernible across the barrier transects (seaward to landward).

4.5.4.1 Localized Solution Features. Overall, the occurrence of localized solution features is greater than the occurrence of either of the other two types of textural features.

1. In the A_1 horizons a general increase in localized solution features is evident across the transects.
2. In the A_2 and B horizons, localized solution feature counts are variable, with the only trend being apparent in the Disaster Bay data (both A_2 and B horizon counts increase across the transect).
3. C horizon values are comparatively low and constant, with no apparent trends.

4.5.4.2 Extensive Solution Features. Much lower counts were recorded for these larger composite features than were noted for the other two texture types.

1. A_1 horizon counts of extensive solution features are variable across all transects, with no evident trends.
2. A slight general increase in the A_2 horizon counts is apparent across the Moruya, Disaster Bay and Rheban transects. The A_1 and A_2 extensive solution feature counts are roughly equivalent for most samples.
3. B horizon counts are variable, with slight increases evident only across the Disaster Bay and Rheban transects.

4. The incidence of extensive solution features is lowest in the C horizon samples, with no systematic trends across the transects.

4.5.4.3 Precipitation Features. These are comparatively abundant on the observed sand grains.

1. A_1 horizon counts of precipitation features are generally variable, with an apparent increase across the Disaster Bay transect, and a less systematic increase across Cowley Beach.

2. In the A_2 horizon, strong increases are observable in the precipitation feature count across the Woy Woy and Disaster Bay transects, an initial decrease than increase is evident across both the Moruya and Rheban transects, and no definite trends are apparent across the other transects.

3. Most B horizon trends are quite definite, with general increases in the precipitation feature count across the Hawks Nest, Moruya, Disaster Bay and Cowley Beach transects. Woy Woy exhibits a less regular, but still appreciable increase, while across the Rheban transect the increase is slight and somewhat erratic.

4. Precipitation features are less common in the C horizon samples than in samples from the other horizons. The C horizon counts are irregular, with only slight trends (increases) evident across the Moruya and Cowley Beach transects.

4.5.4.4 Total Textural Features. Table 4.2 also includes the total count for the three texture types in each horizon sample; these figures are less variable than the individual texture counts, and the trends are generally more pronounced.

1. Across both the Woy Woy and Cowley transects the total texture counts for the A_1 horizon show a definite increase, with a very high incidence of textural features for all Cowley profiles. In the Hawks Nest, Moruya and Disaster Bay A_1 horizons there is a similar, but less regular, increase in total feature counts across the transects. Rheban is the only transect in which an A_1 horizon trend is not apparent.

2. Both the A_2 and B horizon texture counts increase consistently across the Hawks Nest, Woy Woy, Disaster Bay and Rheban transects. At Moruya, the A_2 and B horizon counts initially fall, then increase, but the trends are not marked. At Cowley Beach, the A_2 counts are variable, but the B horizon values increase across the transect (except in Profile 3).

3. C horizon values are comparatively low in all profiles, with no apparent trends.

4.5.5 <u>Summary</u>

The most significant features of the distribution of the textural count data are:

1. The data are quite variable, even when aggregated into the three basic classes.

2. Across most barrier transects, trends are evident in the occurrence of textural features in the A_1, A_2 and B horizons.

3. The most common trend across the transects is for

an increase in the occurrence of the textural features, seaward to landward.

4. Trends are most pronounced in the total textural feature count, especially in the A_2 and B horizons.

4.6 GRAIN COATINGS

4.6.1 Introduction

Sand grain samples from many of the soil profiles were systematically examined by scanning electron microscopy in an attempt to determine the extent to which the composition and occurrence of organic-mineral grain coatings relate to the ages of the podzol profiles. It was not possible to look at the effects of the other pedogenic factors, nor to sample all soil profiles, because of restricted access to the microprobe facilities.

In some respects the grain coating investigation is similar to that which dealt with grain surface textures, but it differs significantly in that the textural study was concerned only with grains that had been thoroughly cleaned with hydrochloric acid, whereas the sand grains discussed here had not been cleaned of any organic-mineral coating.

For SEM observation purposes, organic-mineral coatings were defined as any organically derived material adhering to grain surfaces, whether amorphous, or of obvious biogenic form.

The same soil samples that were selected to represent the profile horizons in the texture study were subsampled for

TABLE 4.3

GRAIN COATING OBSERVATIONS (50 GRAIN SAMPLES)

TRANSECT	PROFILE (SITE)	SAMPLE	HORIZON	CLEAN GRAINS No. GRAINS	PARTIAL COATINGS No. GRAINS	EXTENSIVE COATINGS No. GRAINS	RELATIVE Fe CONCENTRATION IN COATINGS	RELATIVE Al CONCENTRATION IN COATINGS
HAWKS NEST	1B	2	A_1	10	34	6	M	M
		4	A_2	21	26	3	L	L
		7	B	15	20	15	M	L
		14	C	39	11	0	L	L
	2	2	A_1	19	19	12	M	M
		4	A_2	27	21	2	L	L
		8	B	7	21	22	M	H
		14	C	42	8	0	L	L
	3B	2	A_1	13	27	10	M	M
		5	A_2	29	16	5	L	L
		8	B	2	15	33	H	M
		17	C	44	6	0	L	M
	4A	2	A_1	8	28	14	M	M
		5	A_2	34	13	3	L	L
		8	B	6	5	39	H	H
		15	C	46	3	1	L	M
WOY WOY	1	1	A_1	24	23	3	M	M
		2	A_2	19	31	0	L	L
		4	B	27	21	2	L	M
		15	C	44	6	0	L	L
	2	1	A_1	14	31	5	M	M
		2	A_2	28	18	4	M	L
		6	B	12	29	9	M	L
	3	1	A_1	2	34	14	M	M
		2	A_2	17	27	6	L	L
		5	B	8	23	19	H	H
	4	2	A_1	6	25	19	M	M
		5	A_2	26	13	11	L	L
		6	B	1	14	35	H	H
	5	1	A_1	1	43	6	L	L
		3	A_2	24	19	7	L	L
		5	B	3	16	31	H	H
	6	1	A_1	3	39	8	L	M
		4	A_2	30	7	13	L	L
		5	B	0	6	44	H	H
MORUYA	1B	1	A_1	22	25	3	H	M
		2	A_2	25	21	4	M	L
		3	B	18	28	4	M	M
		12	C	39	11	0	L	L

TABLE 4.3 CONTINUED

	2B	1	A_1	13	28	9	H	H
		3	A_2	27	18	5	L	M
		4	B	12	35	3	M	M
		12	C	44	6	0	L	L
	3B	1	A_1	16	22	12	M	M
		3	A_2	23	17	10	L	M
		5	B	14	21	15	M	M
		12	C	47	3	0	L	M
	6B	1	A_1	7	25	18	L	M
		3	A_2	25	22	3	L	L
		5	B	6	7	37	M	H
		11	C	46	4	0	L	L
	5B	1	A_1	11	33	6	M	M
		3	A_2	30	16	4	L	M
		6	B	0	8	42	H	H
		10	C	48	2	0	M	L
	4B	1	A_1	5	29	16	M	L
		3	A_2	36	14	0	L	L
		5	B	4	11	35	H	H
		9	C	43	5	2	L	M
DISASTER BAY	1B	1	A_1	35	13	2	L	M
		3	A_2	26	24	0	L	L
		5	B	17	25	8	M	L
	1A	1	A_1	21	25	4	L	L
		2	A_2	29	21	0	L	L
		5	B	17	30	3	L	L
	2B	1	A_1	17	27	6	M	M
		3	A_2	21	29	0	L	L
		7	B	13	21	16	L	M
	4B	1	A_1	19	22	9	L	M
		3	A_2	11	37	2	L	L
		9	B	7	12	31	M	M
	6	1	A_1	4	35	11	M	M
		3	A_2	28	13	9	L	L
		7	B	1	9	40	H	H
	3B	1	A_1	4	23	23	L	H
		3	A_2	37	10	3	L	L
		10	B	0	0	50	H	H
RHEBAN	1	2	-	48	2	0	L	L
	3	1	A_1	23	18	9	M	M
		2	A_2	18	31	1	M	M
		3	B	30	9	11	H	M
		5	C	35	9	6	M	M
	2	1	A_1	21	19	10	M	M
		2	A_2	26	20	4	L	L
		4	B	8	32	10	H	M
		7	C	47	1	2	L	L

TABLE 4.3 CONTINUED

	4	1	A_1	11	22	17	M	M
		2	A_2	27	18	5	L	L
		4	B	10	13	27	H	M
		8	C	40	10	0	M	L
	7	1	A_1	11	26	13	M	M
		2	A_2	27	15	8	L	L
		4	B	4	7	39	M	M
		8	C	42	8	0	L	L
	6	1	A_1	14	21	15	M	M
		2	A_2	29	17	4	L	L
		4	B	4	9	37	H	M
		8	C	45	4	1	M	L
	5	1	A_1	5	30	15	M	M
		2	A_2	36	10	4	L	L
		4	B	1	5	44	H	H
		10	C	37	10	3	M	L
COWLEY	1	1	A_1	20	30	0	M	L
		3	B	15	26	9	H	H
		8	C	37	11	2	M	M
	2	1	A_1	4	37	9	M	L
		4	B	5	24	21	H	H
		9	C	39	7	4	M	M
	3	1	A_1	5	25	20	M	L
		2B	A_2	31	19	0	M	M
		3B	B	0	14	36	H	H
		6	C	35	10	5	M	M
	4	1	A_1	0	32	18	M	M
		2	A_2	27	15	8	M	L
		3B	B	0	7	43	H	H
		6	C	30	12	8	M	M
	5	1	A_1	0	25	25	M	M
		3	A_2	38	7	5	L	L
		4B	B	0	4	46	H	H
	6	1	A_1	0	23	27	L	L
		3	A_2	41	6	3	L	L
		8	B	0	0	50	H	H

the grain coating observations. Information about specimen preparation and observation techniques, and about the SEM equipment that was used, is included in Appendix Six, together with all the micrographs, X-ray maps and EDAX spectra that are referred to in the following discussion.

4.6.2 Coating Observations

A simple three way classification of grain coatings was used to quantify the SEM observations. Coatings were classed as either extensive (at lease 50 percent of upper grain surface covered by organic-mineral coating), partial (up to about 50 percent covered), or essentially without coatings ("clean"). In addition, qualitative assessment was made (by EDAX/WDS) of the comparative concentrations of iron and aluminium in the grain coatings of each sample (low, moderate or high). Results of the observations and determinations are given in Table 4.3.

4.6.2.1 Clean Sand Grains. Appendix 6-1 presents micrographs, X-ray maps and EDAX data for a representative selection of sand grains without organic-mineral coatings. Such clean sand grains were found to be of common occurrence in the barrier sediments, especially in the C horizons.

Beach sediments - To investigate whether the soil parent material sediments were originally coated with organic-mineral material, as would seem possible from the marine organic carbon studies of Wilson (1959), Blanchard (1968), and Menzel and Ryther (1970), beach sand from the various barriers was examined (in addition to C horizon samples).

No organic coatings were found on any of the beach grains; iron and aluminium X-ray distribution maps and microprobe analyses, indicated evenly dispersed low levels of these (and most other) elements on the grain surfaces. However, sodium was found to be abundant on the grains, frequently in crystalline form (NaCl). Plates 1 to 6 in Appendix 6-1 illustrate typical clean beach sand grains.

Soil horizons - As is evident from Table 4.3, the occurrence of clean sand grains varies between soil horizons. In the A_1 and B horizons, there is a trend towards a decrease in the proportion of clean grains with increasing distance from the sea, while in the A_2 horizon the opposite trend is evident. The proportion of clean grains in the C horizon samples is comparatively high, and is uniform between profiles. Plates 7 to 12 in Appendix 6-1, show typical clean sand grains from the various soil horizons.

4.6.2.2 Partial Grain Coatings. Appendix 6-2 contains the micrographs and other data relating to those grains with partial coatings. In all cases, iron and aluminium levels were higher in the coating than on the exposed grain surfaces. Partially coated grains dominate the A_1 horizon (see Table 4.3), but in both the A_2 and B horizons the proportion of partially coated grains decreases with increasing distance from the sea, while the occurrence of these grains is low, but constant, throughout the C horizon. Partially coated grains in the A_1 horizon are covered by less-decomposed organic material than those in the A_2 or B horizons, where the coating is more amorphous and usually richer in iron and aluminium. As distance from the sea increases, the amorphous coatings (especially on B horizon grains) tend to become more diffuse and contain higher concentrations of iron and aluminium. The plates in Appendix 6-2 illustrate these features.

4.6.2.3 Extensive Grain Coatings. Examples of extensive organic mineral grain coatings are presented in Appendix 6-3, in which variations in the morphology and composition of these coatings are also illustrated.

From Table 4.3 it is evident that, compared with the proportions of clean and partially coated grains, those grains with extensive coatings are in a minority in all samples except those from the B horizon. It is also evident from Table 4.3, that the proportion of extensively coated grains in the B horizon, increases with increasing distance from the sea. From the illustrations and comments in Appendix 6-3, it is apparent that the iron and aluminium concentrations in the extensive grain coatings also increase across the barriers in the same direction (seaward to landward).

4.6.3 Summary

Although the grain coating data contain much "noise", some significant points emerge from the observations.

1. The development of organic-mineral grain coatings increases across the barriers in the B horizon, and to a lesser extent in the A_1 horizon. Such grain coatings are rare on beach and C horizon sediments.

2. Coatings are rich in iron and aluminium, relative to the exposed grain surfaces, and relative to beach and C horizon sediments.

3. The concentration of iron and aluminium in the organic-mineral coatings increases with increasing distance from the sea. The extent to which this trend is associated with the actual ages of soil profiles is examined in Chapter Six.

4.7 SUMMARY

In Chapter Four the soil data that resulted from the investigation have been introduced and have been presented mainly in the form of appendices. Soil profile morphological characteristics, organic matter content, cation concentrations, grain surface textures and grain coatings have all been discussed. The analytical techniques that were used to obtain the data have been described and the most significant distribution trends, both within the soil profiles and across the barrier transects, have been identified. In the following chapters the soil data are analysed in more detail.

CHAPTER V

ROLE OF THE PEDOGENIC FACTORS OTHER THAN TIME

5.1 INTRODUCTION

The present chapter attempts to evaluate, by means of selected examples, the extent to which variations in the individual pedogenic factors (excluding time) effect the properties of the podzol soils under investigation. This is accomplished by comparing the physical and chemical characteristics of profiles from pedogenic environments that are essentially identical in relation to all but one pedogenic factor. Differences in the profile characteristics may therefore be attributed to the varying influence of the single pedogenic factor.

The requirements of pedogenic factor constancy limit the number of soil profiles in the study that are suitable for assessing the role of the non-temporal pedogenic factors. Consequently, although it has not been possible to include very many soils in this aspect of the study, those that are used do provide relevant and typical examples of the influence of the individual pedogenic factors (except time) on soil properties. However, not all the investigated soil properties are discussed below, in relation to the role of each factor. Generally, only those properties found to be effected by a factor are discussed, although where the lack of a relationship is of interest, the property is also included in the discussion.

In the discussion that follows the role of each pedogenic factor (but time) is examined in turn: the role of the plant factor is assessed by a comparison of the properties of five soil sites on the Fens barrier (Section 5.2); the effects of macroclimatic variation are examined in Section 5.3, by comparing the average characteristics of the north Queensland, New South Wales and Tasmanian soil profiles; the influence of micro-climatic variation (Section 5.4), which relates solely to aerosol salt fallout, is assessed for selected New South Wales soil sites; the role of relief is examined by comparing two pairs of New South Wales barrier soils (Section 5.5); and the influence of the parent material factor is demonstrated by comparing the properties of selected Moruya and Disaster Bay profiles (Section 5.6).

5.2 ROLE OF THE PLANT FACTOR

5.2.1 Introduction

The Hawks Nest-Fens Outer Barrier provides a rare opportunity to examine the impact on soil characteristics of several diverse vegetation types, within an otherwise homogenous pedogenic environment. The soil sites used for this comparison are Hawks Nest 4A, Hawks Nest 3B, Fens 3 and Myall Lakes 1 and 2 (Figure 3.2). On the basis of radiocarbon dating and morphostratigraphic position, these profiles were assigned an age of 4900 ^{14}C yrs* in Chapter Three. All the profiles have formed from parent material of very consistent mineralogical composition and texture (Table 3.11 and Figure 3.19), and all experience the same macroclimatic conditions. Approximately the same annual input of marine aerosol fallout is received by the five sites (Table 3.11). In addition, the relief factor is essentially constant (slight swales or flat ground-surface areas). Thus, only the plant factor varies substantially between the five soil sites. Localized pedogenic effects, caused by individual plant specimens (Enright, 1978; Zinke, 1962; Zinke and Crocker, 1962), have been minimized, or probably even negated, by the compound soil sampling procedures that were employed (see Section 2.2.2.3).

Eucalyptus pilularis Forest occurs at both Hawks Nest sites, *Banksia integrifolia - B. serrata - Angophora costata* Woodland at Myall Lakes 2 and Fens 3, and *Banksia integrifolia - Acacia longifolia* var. *sophorae* Heathland at Myall Lakes 1. The subdominant species are mentioned in Section 3.3.4.1. It is not known how long the present vegetation distribution pattern has existed on the Fens Outer Barrier, but fire has probably effected most of the vegetation at some time in the past, as it probably has on all eastern Australian barriers. However, there is no reason to presume that the vegetation composition at the five soil sites has ever been homogenous, and it seems much more probably that appreciable, and even substantial, vegetation differences have always existed.

Several characteristics of the soils at each of the sites were evaluated, in order to determine if the different plant types have had an impact on the development of the profiles.

5.2.2 Profile Morphology

Appendix 2-4 and Appendices 2-6 to 2-10 inclusive, provide information about the morphological characteristics of the profiles under consideration. An examination of these Appendices indicates that the five profiles are morphologically very similar. To substantiate this claim the most significant characteristics of the soil profiles are examined below in turn.

Horizon Thickness - Table 5.1 gives the thickness of the horizons in each soil profile. It is apparent that the A_0 horizon is of a consistent thickness in all profiles (coefficient of variation = 14 percent), as is the A_1 horizon (c.v. = 29 percent) in all profiles but F3, where it is substantially thinner. The A_2 horizon varies from 91 to 122 cms in thickness and is therefore also quite consistent (c.v. = 11 percent). The B horizon is much thicker than the A_2 and ranges from 218 to 274 cms. However, with a coefficient of variation of only 9 percent, the B horizon may also be regarded as being of a consistent thickness. On the other hand the C horizon, as would be expected with profiles of varying watertable depth, has a coefficient of variation of 50 percent, and ranges in thickness from 911 to 290 cms.

From these figues it can be seen that the five profiles differ substantially in horizon thickness only in the C horizon. The latter may be regarded as a non-genetic horizon, which in deep, freely drained sands occupies the interval between the base of the B horizon and the watertable.

Dominant Horizon Colour - The method of assessing dominant horizon colour was outlined in Section 4.2.1 and the resulting data for the five profiles are included in Appendix Two. Table 5.2 summarizes these data. It is apparent from the table that, in relation to dominant horizon colour, all five

TABLE 5.1

COMPARISON OF HORIZON THICKNESSES

HORIZON	SOIL PROFILE					COEFFICIENT OF VARIATION
	HN3B cms	HN4A cms	F3 cms	ML1 cms	ML2 cms	%
A_0	3	3	4	3	3	14
A_1	46	46	20	46	46	29
A_2	91	102	117	107	122	11
B	274	218	274	259	274	9
C	107	91	290	168	137	50

TABLE 5.2

COMPARISON OF DOMINANT HORIZON COLOURS

HORIZON	SOIL PROFILE				
	HN3B	HN4A	F3	ML1	ML2
A_1	10YR 5/1	10YR 6/1	10YR 5/1	10YR 5/1	10YR 5/1
A_2	7.5YR 7/1	10YR 7/1	10YR 7/1	10YR 7/1	10YR 7/1
B	10YR 5/4	10YR 5/4	10YR 4/3	10YR 5/4	10YR 5/4
C	10YR 7/2	10YR 7/2	10YR 7/3	10YR 7/3	10YR 7/2

TABLE 5.3

COMPARISON OF AVERAGE HORIZON pH VALUES

HORIZON	STATISTIC	SOIL PROFILE				
		HN3B	HN4A	F3	ML1	ML2
A_1	$\bar{x}$	4.7	4.7	4.8	4.7	5.1
	S.E.	0.26	0.33	0.30	0.32	0.48
A_2	$\bar{x}$	4.7	4.4	5.0	4.8	5.2
	S.E.	0.23	0.03	0.31	0.30	0.23
B	$\bar{x}$	5.8	5.8	5.8	5.9	6.2
	S.E.	0.11	0.13	0.09	0.13	0.12
C	$\bar{x}$	6.4	6.2	6.5	6.4	6.3
	S.E.	0.12	0.11	0.20	0.13	0.12

profiles are extremely similar, with only two minor departures from the "norm" in the A_1, A_2 and B horizons, and a range of only one colour *value* unit between the five C horizons.

Horizon Texture - Texture is sandy throughout all five profiles, with insufficient clay to allow any horizon to be classed as a loamy sand (Marshall 1947). No gravel was found in the profiles above the watertable. See relevant appendices.

Horizon Structure - Apedal throughout all profiles; mostly apedal single grain, but consistently apedal massive in at lease part of the B horizon.

Shell $CaCO_3$ Reaction - Nil reaction for all horizon and watertable samples. These 4900 year* old profiles have been completely leached of any shell carbonate they may once have contained.

Soil Reaction (pH) - Table 5.3 presents the mean and standard error of the pH values for the samples from each horizon in the five profiles. The full pH data for each profile are plotted in Appendix Four. An examination of Table 5.3 indicates that the pH values are mutually consistent across the five profiles in all horizons, with the A_2 being the most variable.

Therefore, although Profiles HN3B, HN4A, F3, ML1 and ML2 support diverse flora, in terms of their morphological characteristics they are indeed very similar soils.

5.2.3 Organic Matter

In Figure 5.1 the percentage organic matter (O.M.) for

FIGURE 5.1

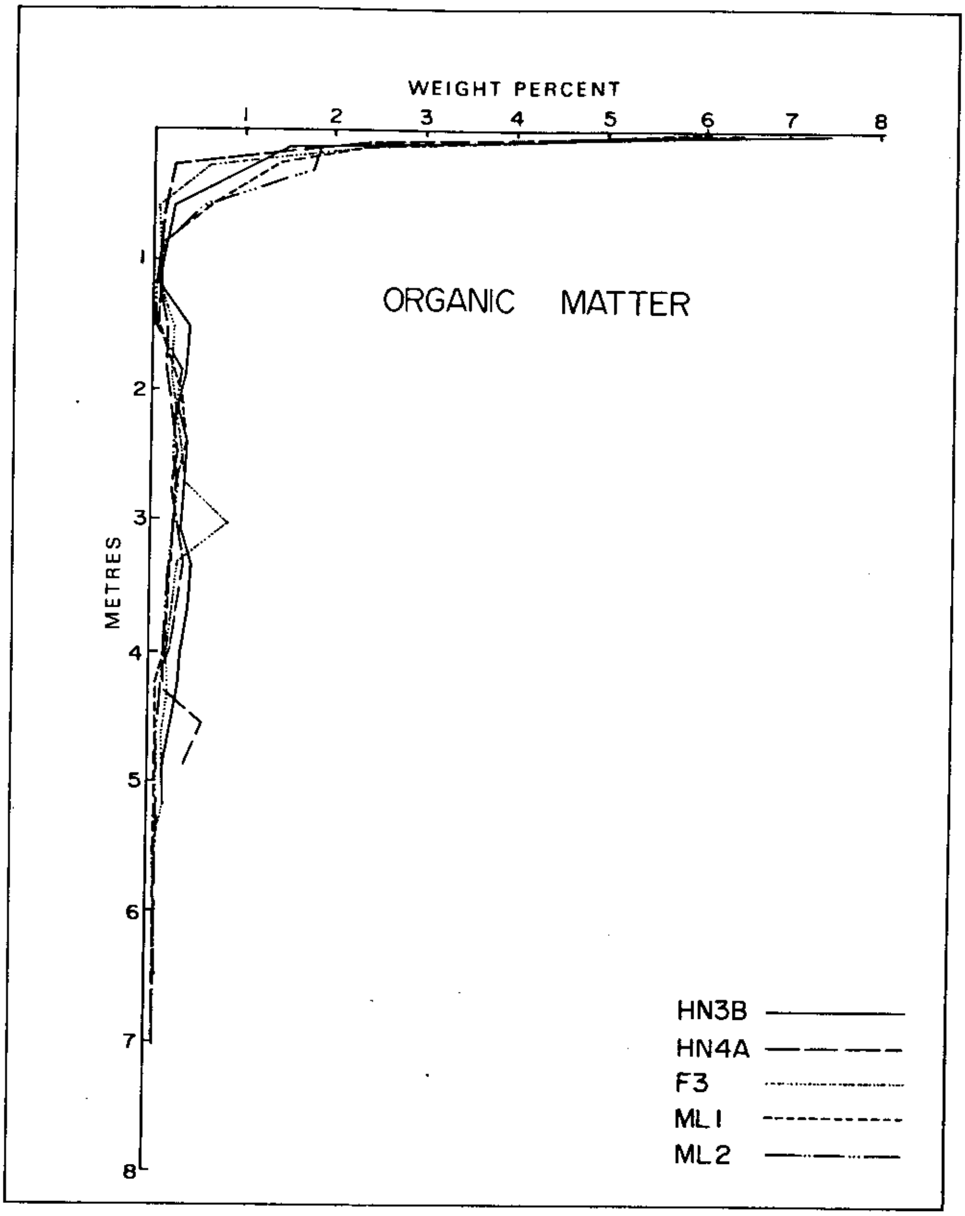

Figure 5.1 Organic matter distribution in Profiles HN3B, HN4A, F3, ML1 and ML2.

each soil sample is plotted at the appropriate depth. Comparison of these depth-organic matter graphs shows a very strong similarity between them, with relatively high nearsurface values which rapidly decrease down the profiles; the similarity of the graphs below 1 metre depth is partricularly marked. To measure the degree of association a distribution-free statistic, Kendall's Correlation Coefficient Tau (τ), was calculated for each pair of graphs in turn. O.M. values were paired (by depth) as far as possible down the profiles and τ was calculated by the method of Hammond and McCullagh (1974), corrected for tied values. To test the significance of the determined coefficient a z-value was calculated and referred to a probability table.[1]

Results of the tau calculations are given as a correlation matrix in Table 5.4, wherein both the value of the correlation coefficient (τ) and the association probability (p) are reported in each cell. The table shows high correlation coefficients for the correlation of ML1/ML2 and HN3B/F3, and moderate coefficients for the other correlations. Thus, the analysis supports the observation made above, that the organic matter distribution pattern is very similar in all profiles, despite the differing site vegetation types.

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1. NOTE: This procedure was followed for all calculations of τ mentioned in the thesis. In addition, the null hypothesis associated with the τ statistic is always assumed to be that no relationship exists between the correlated parameters; the alternative hypothesis is always assumed to be that a relationship does exist. The rejection level for Ho is 95 percent confidence (i.e., $\alpha = 0.05$) in most tests.

TABLE 5.4

KENDALL'S TAU CORRELATION MATRIX FOR THE DISTRIBUTION OF ORGANIC MATTER IN SELECTED PROFILES FROM THE FENS OUTER BARRIER

		HN4A	HN3B	F3	ML1	ML2
HN4A	τ	1.0000	0.3721	0.4120	0.2162	0.1589
	p		0.0154	0.0084	0.1056	0.1788
HN3B	τ		1.0000	0.6509	0.4629	0.5074
	p			<0.0001	0.0028	0.0012
F3	τ			1.0000	0.4976	0.5749
	p				0.0008	<0.0001
ML1	τ				1.0000	0.7341
	p					<0.0001
ML2	τ					1.0000

H_0: no relationship exists between the two O.M. depth distribution patterns.

H_1: a relationship does exist between the two O.M. depth distributions.

The blocked cells indicate that H_0 may be rejected with 95% confidence, and H_1 accepted.

5.2.4 Cation Concentrations

Depth-concentration graphs for iron, manganese, aluminium, calcium, magnesium and sodium are given in Figures 5.2 to 5.7. The consistency of each set of curves is discussed below.

Iron - All the depth-concentration graphs showing iron distribution down-the-profile (Figure 5.2) exhibit marked A_1 - A_2 - B - C horizon differentiation. Although B horizon values tend to be variable, reflecting large scale mottling patterns (see Appendix 2), this variability may be regarded as a common characteristic of the profiles. Iron distribution in the five profiles does, therefore, tend to show a consistent depth-concentration pattern. This is supported by the correlation coefficients given in Table 5.5 (Kendall's Tau, calculated using procedures discussed above for O.M.), which indicate that a significant association exists between all iron distribution patterns, with the exception of HN4A/F3, for which it is not possible to reject the null hypothesis with 95 percent confidence (see Table 5.5).[1]

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1. Fens Profile 3 is the deepest of the five soil profiles under consideration (see Appendix 2). As values are paired from the surface downwards in the calculation of τ, it follows that a substantial proportion of the F3 values (those towards the base of the profile) are not included in the correlation. This depth anomaly has caused the low τ values for the F3 iron and aluminium correlations.

FIGURE 5.2

FIGURE 5.3

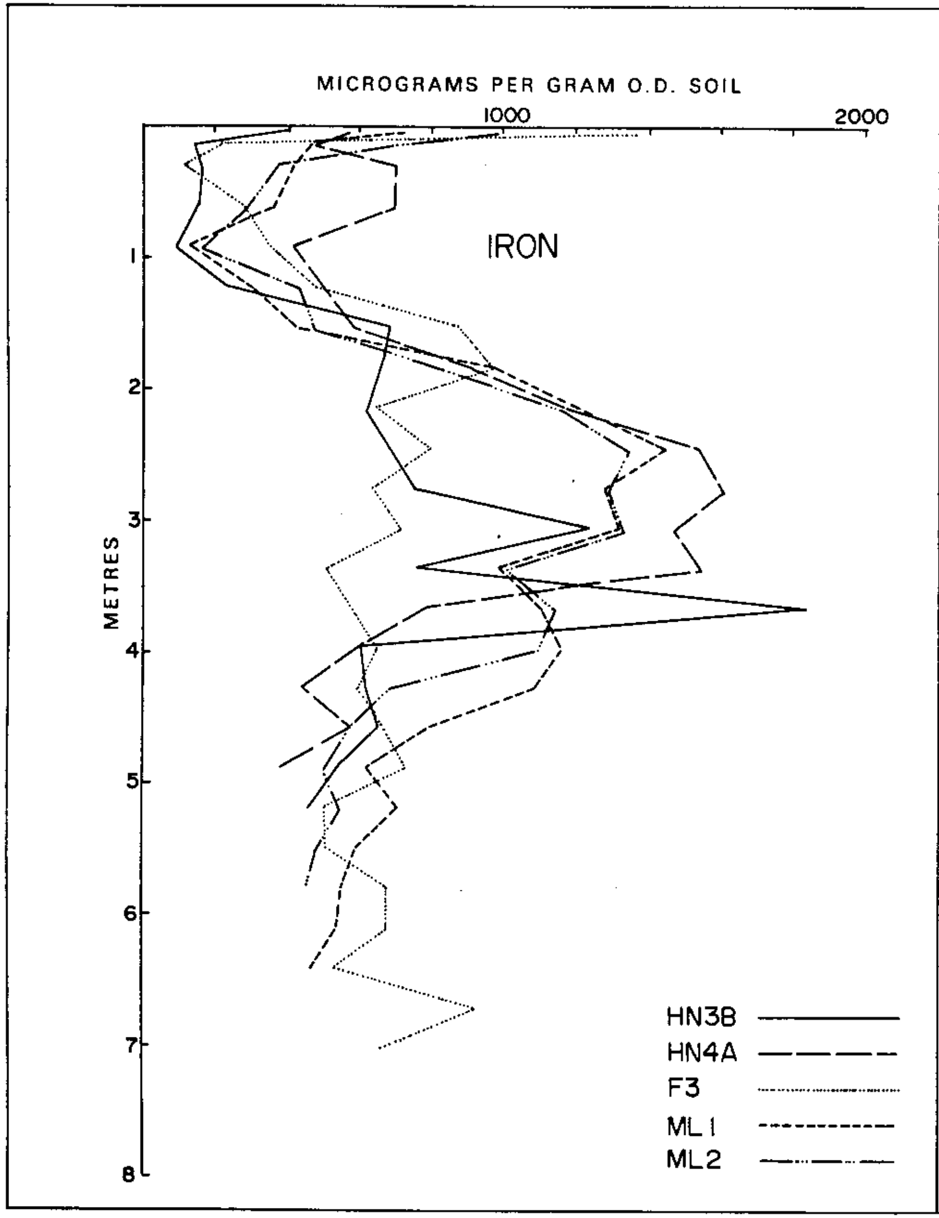

Figure 5.2 Iron distribution in Profiles HN3B, HN4A, F3, ML1 and ML2.

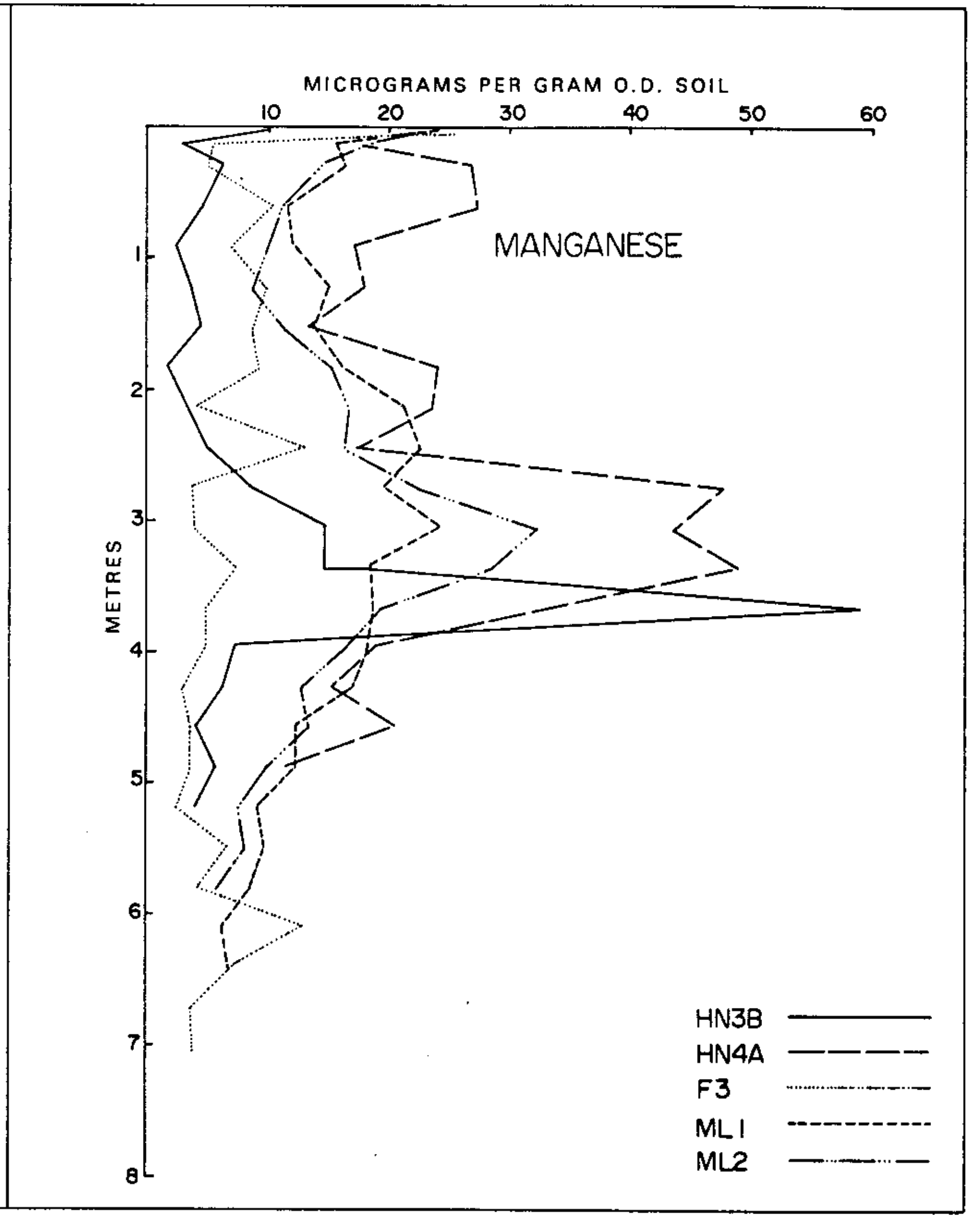

Figure 5.3 Manganese distribution in Profiles HN3B, HN4A, F3, ML1 and ML2.

TABLE 5.5

KENDALL'S TAU CORRELATION MATRIX FOR THE DISTRIBUTION OF IRON IN SELECTED PROFILES FROM THE FENS OUTER BARRIER

		HN4A	HN3B	F3	ML1	ML2
HN4A	τ	1.0000	0.4636	0.0656	0.4984	0.4967
	p		0.0036	0.3520	0.0020	0.0020
HN3B	τ		1.0000	0.3363	0.5487	0.5723
	p			0.0222	0.0005	0.0003
F3	τ			1.0000	0.3493	0.3287
	p				0.0139	0.0139
ML1	τ				1.0000	0.8693
	p					<0.0001
ML2	τ					1.0000

H_0: no relationship exists between the two iron depth distribution patterns.

H_1: a relationship does exist between the two iron depth distribution patterns.

The blocked cells indicate that H_0 may be rejected with 95% confidence, and H_1 accepted.

TABLE 5.6

KENDALL'S TAU CORRELATION MATRIX FOR THE DISTRIBUTION OF ALUMINIUM IN SELECTED PROFILES FROM THE FENS OUTER BARRIER

		HN4A	HN3B	F3	ML1	ML2
HN4A	τ	1.0000	0.7657	0.4868	0.6471	0.5490
	p		<0.0001	0.0024	<0.0001	0.0007
HN3B	τ		1.0000	0.2695	0.5148	0.4307
	p			0.0533	0.0010	0.0049
F3	τ			1.0000	0.5037	0.5251
	p				0.0007	0.0002
ML1	τ				1.0000	0.7828
	p					<0.0001
ML2	τ					1.0000

H_0: no relationship exists between the two aluminium depth distribution patterns.

H_1: a relationship does exist between the two aluminium depth distribution patterns.

The blocked cells indicate that H_0 may be rejected with 95% confidence, and H_1 accepted.

Manganese - Although the manganese graphs (Figure 5.3) appear to be less mutually consistent than those for iron, the Mn concentrations are all very low (see abscissa scale), and hence absolute differences between graphs are substantially less than for iron. Correlation coefficients have not been calculated for the manganese profile distributions (nor for Ca, Mg or Na) because ranking the predominantly low values would be of doubtful validity, given the very high proportion of tied values and the precision of the data.

Aluminium - The five aluminium distributions (Figure 5.4) show the same A_1 - A_2 - B - C horizon contrasts as iron, but are more mutually consistent, especially in the A_2 horizon. Kendall's Correlation Coefficients were calculated for the aluminium distributions, and nine of the ten values of τ may be accepted as statistically significant at the 95 percent level of confidence (see Table 5.6). The values of the coefficient indicate that aluminium distribution in the five soil profiles is very similar.

Calcium - It can be seen from Figure 5.5 that all five depth-concentration graphs are mutually consistent, with relatively high near-surface calcium concentrations (probably associated with decaying organic matter) and very low values further down the profile. A slight increase in concentration is associated with the B horizon in each profile.

Magnesium - As indicated in Figure 5.6, the magnesium depth-concentration graphs for the five profiles are in good agreement.

Sodium - Concentrations are consistently very low, down all the profiles (see Figure 5.7), and thus differences between the curves are minimal.

FIGURE 5.4

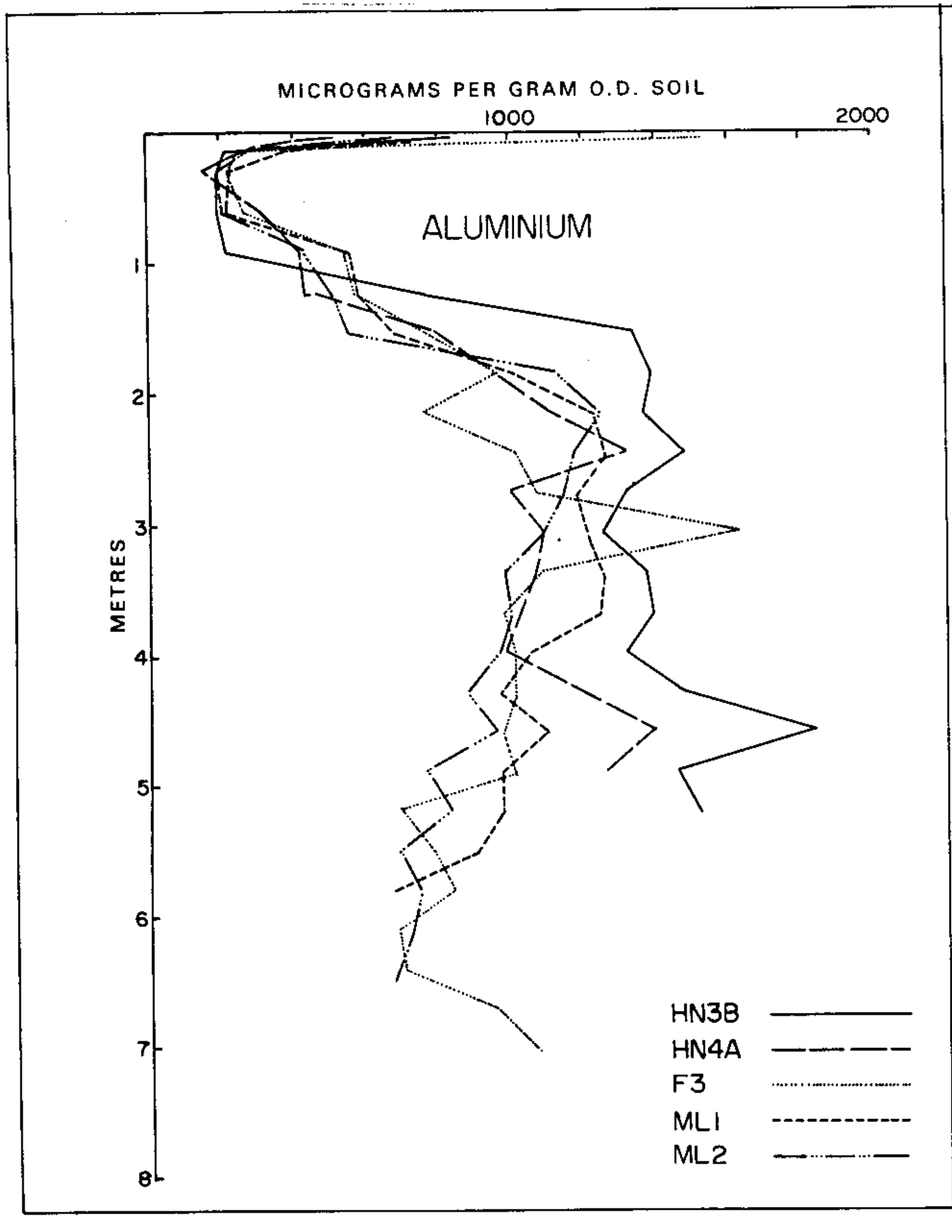

Figure 5.4 Aluminium distribution in Profiles HN3B, HN4A, F3, ML1 and ML2.

FIGURE 5.5

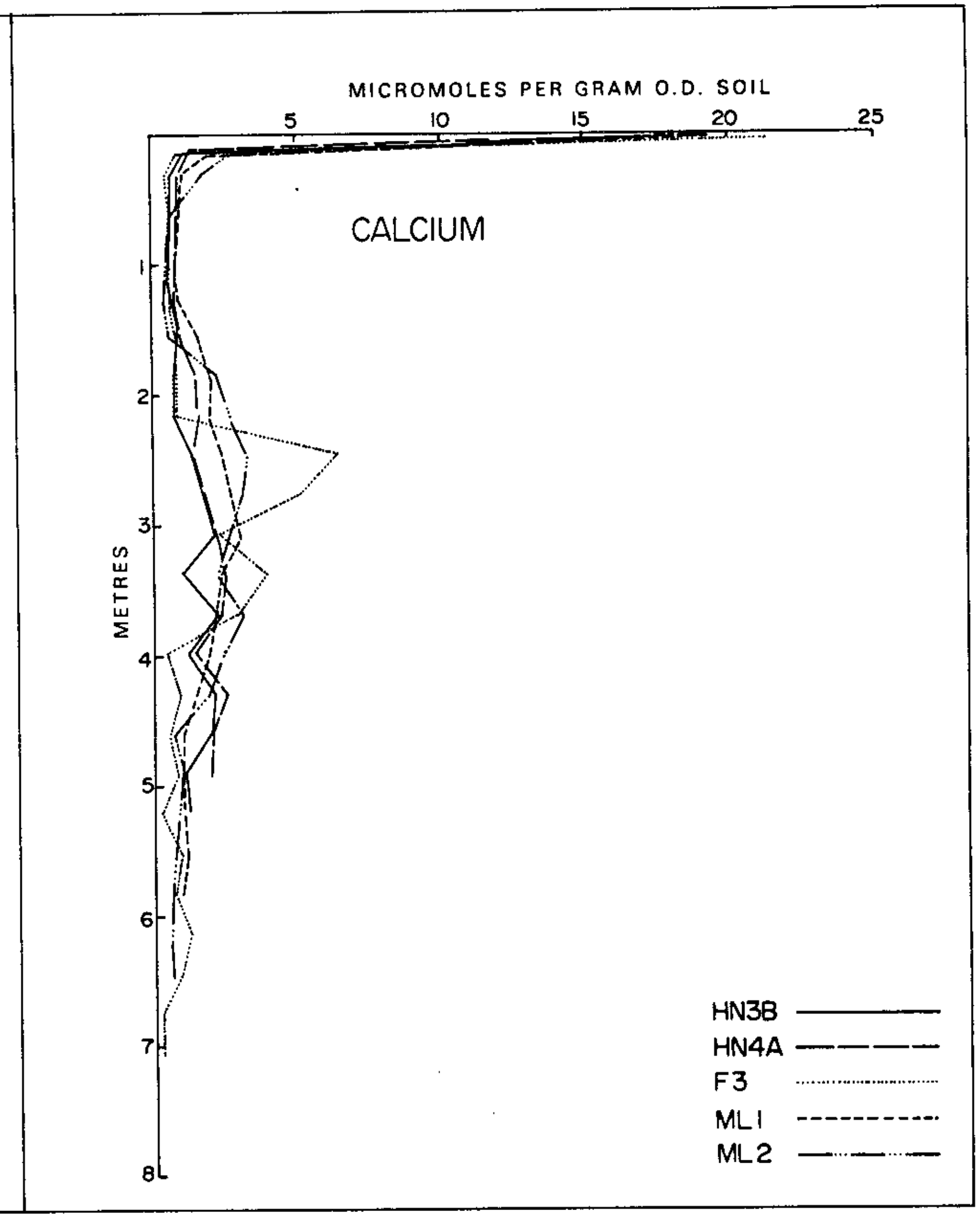

Figure 5.5 Calcium distribution in Profiles HN3B, HN4A, F3, ML1 and ML2.

FIGURE 5.6

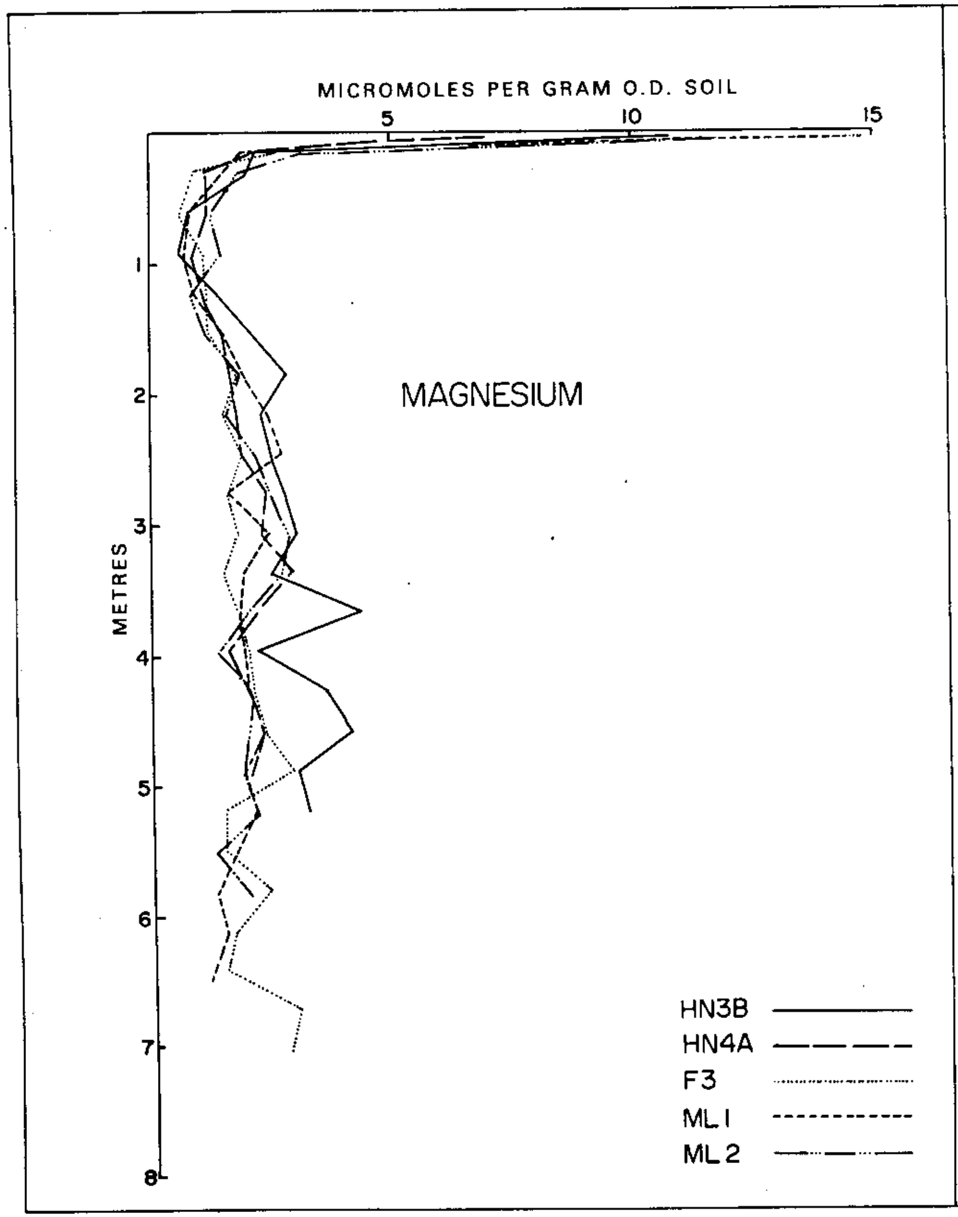

Figure 5.6 Magnesium distribution in Profiles HN3B, HN4A, F3, ML1 and ML2.

FIGURE 5.7

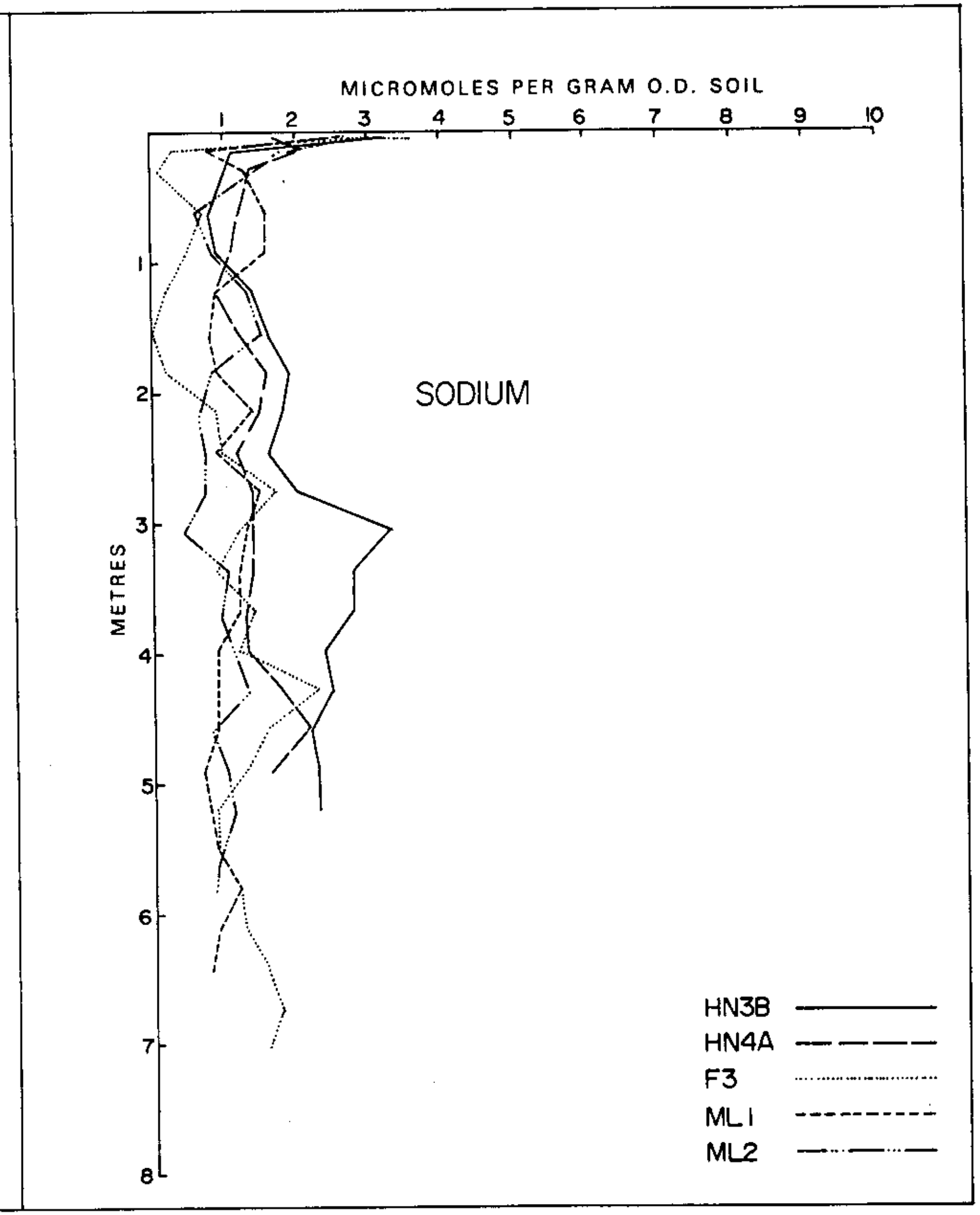

Figure 5.7 Sodium distribution in Profiles HN3B, HN4A, F3, ML1 and ML2.

Overall, the cation data strongly indicate that differences between the five profiles are minimal, despite the contrasting vegetation assemblages at the soil sites.

5.2.5 Grain Surface Textures

Table 5.7 presents data derived from SEM counts of surface features on quartz sand grains from the five profiles under consideration. The data are reported as the total number of textural features on a thirty grain sample from each horizon, in each soil profile. A mean, standard deviation and coefficient of variation have been calculated for the counts for each profile horizon, plus a χ^2 statistic, for which the expected frequencies were equated with the horizon means. However, it has not been possible to apply a suitable rigorous test of statistical significance to the determined χ^2 values, because the required formulation of the null hypothesis is that observed and expected frequencies do not differ significantly. If χ^2 does not reach the predetermined critical value, Ho cannot be rejected, *but it also cannot be accepted* (as we would wish in this case) and judgement should be suspended (W. Rieger, pers. comm., 1978).

Therefore, although chi square is not a suitably rigorous inferential statistic for the present purpose,[1] the values in Table 5.7 have been tested for statistical significance, on

---

1. Other non-parametric statistics are no more satisfactory than chi square, as all are effected by the same logical difficulties associated with the formulation of an appropriate Ho for the present objective (viz,to show the similarity of the counts in each horizon). The nature of the data precludes the use of parametric statistics, as normalization procedures would be of doubtful validity.

TABLE 5.7

TOTAL GRAIN SURFACE TEXTURES
IN SELECTED FENS OUTER BARRIER SOIL PROFILES

HORIZON	PROFILE					STATISTIC				
	HN3B	HN4A	F3	ML1	ML2	$\bar{x}$	s	Coefficicient of Variation. Percent	χ^2	Reject H_0 with 95% Confidence?
A_1	101	80	81	74	93	85.8	10.9	12.8	5.58	NO
A_2	128	139	109	94	102	114.4	18.6	16.3	12.14	YES
B	129	126	109	105	91	110.0	13.5	12.2	6.58	NO
C	65	55	42	49	56	53.4	8.6	16.0	5.49	NO

H_0: within a horizon, no significant difference exists between the profiles in the number of total texture counts.

H_1: a significant difference does exist between profiles in the number of total texture counts.

the premise that a weak test of significance is preferable to no test. In the A_1, B and C horizons the χ^2 values do not allow Ho to be rejected; they therefore weakly support the proposition that throughout each horizon (but the A_2), the number of total texture counts is very similar.

A subjective assessment of all the statistics in Table 5.7 indicates to the writer that the total textural counts for each horizon are very consistent across the five profiles.

5.2.6 Summary

This section of the chapter has examined the influence of diverse barrier vegetation types on soils from an otherwise homogenous pedogenic environment. All the soil properties assessed were found to be quite consistent across the five profiles, indicating that the differing vegetation types have had relatively little impact on the soil profile characteristics. This conclusion contrasts with the numerous reports in the literature about strong vegetation-soil interrelationships. Generally, these reports relate to either: i) distinctive localized profile irregularities caused by individual plant specimens (e.g., Zinke and Crocker, 1962; Gersper and Hollowaychuk, 1970a, 1970b, 1971; Ryan and McGarity, 1978); or ii) extensively developed soil differences related to differing vegetation associations (e.g., Ovington, 1953, 1956, 1958a, 1958b; Dickson and Crocker, 1954; Crocker and Major, 1955; Olson, 1958; Crocker, 1960; Viereck 1966; Messenger *et al.*, 1972; Messenger, 1975). However, few of the latter group of studies have been effective in negating the influence of the non-vegetative pedogenic factors: frequently the vegetation differences are actually age-vegetation differences (see for example, Dickson and Crocker, 1954). This problem has been carefully avoided in the design of the present study, so that only vegetation differences are being considered. As well, the compound soil sampling scheme that was adopted has minimized soil irregularities that may have been caused by individual plant specimens.

Therefore, within the limits of the vegetation types found on the Fens Outer Barrier, the conclusion that vegetation differences do not significantly influence the characteristics of the older soils, appears to be appropriate.

5.3 ROLE OF MACROCLIMATIC VARIATION

5.3.1 Introduction

In Chapter Three (Section 3.2.1.2) latitudinal trends were recognized in some macroclimatic statistics for the New South Wales barrier localities. However, such differences were found to be minimal for all parameters but annual precipitation, which decreases along the coast with increasing latitude (Table 3.1, columns 6 and 7).

Although the overall range in average annual precipitation is appreciable for the four New South Wales barriers (1332 to 766 mm), it is small compared with the substantial differences between the average New South Wales barrier precipitation (1084 mm), and that for Rheban (650 mm) and Cowley Beach (3644 mm; Table 5.8). Differences between the

TABLE 5.8

MACROCLIMATIC STATISTICS FOR THE NORTH QUEENSLAND, NEW SOUTH WALES AND TASMANIAN BARRIER LOCALITIES

LOCALITY	CLIMATE	AVERAGE DAILY TEMPERATURE °C	AVERAGE ANNUAL PRECIPITATION mm	AVERAGE ANNUAL RAINDAYS No.	RELATIVE HUMIDITY %
COWLEY BEACH, NORTH QUEENSLAND.	WET HUMID TROPICAL	23.5	3644	155	76
NEW SOUTH WALES BARRIERS[1]	WARM TEMPERATE	16.4 ± 0.70	1084±141	118 ± 8	73 ± 3.4
RHEBAN SPIT, TASMANIA	COOL TEMPERATE	12.5	650	122	66

1. New South Wales values are expressed as the mean ± one standard deviation, calculated from the figures for the four barriers.

other climatic statistics are also much more substantial between the New South Wales, Tasmanian and Queensland localities, than they are between the individual New South Wales barriers (see Table 5.8). The role of macroclimatic variation is therefore assessed in relation to the three regions, rather than by reference to the comparatively small New South Wales climatic range. The intention is not to exhaustively define or quantify the relationship between the macroclimatic pedogenic factor and the soil characteristics (this would require very many pedogenically "controlled" soil sites), but rather to indicate the type and magnitude of pedological differences which may be attributed to the macroclimatic differences. Profile morphology, organic matter content, and cation concentrations are examined below for this purpose.

5.3.2 Profile Morphology

The information discussed below in relation to the morphological characteristics of the soil profiles is derived from the data in Appendix 2.

Horizon Thickness - The thickness of the A_1, A_2 and B horizons of the barrier soils from the three regions of eastern Australia, are plotted against age in Figure 5.8. From this figure it is apparent that the thickness of the A_1, A_2 and B horizons is generally greatest in the New South Wales profiles, although horizon thickness variability is also greatest in the latter profiles (probably because of the more diverse pedogenic factor mix represented by the New South Wales soils). In general, the thickness of the A_1 and B horizons is greater in the Queensland soils than

FIGURE 5.8

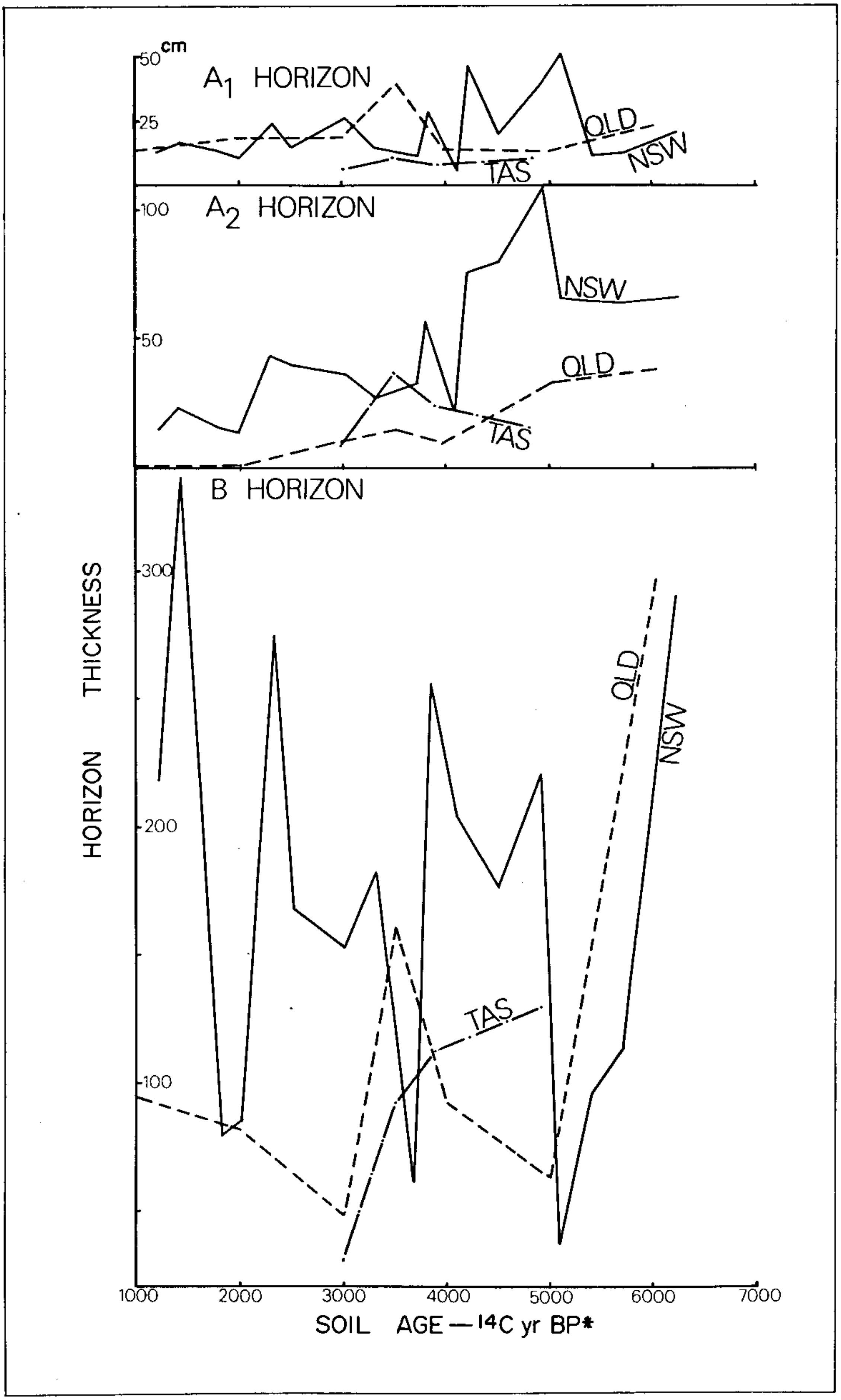

Figure 5.8 Average thickness of A_1, A_2 and B horizons in the New South Wales, north Queensland and Tasmanian soils.

the Tasmanian soils, while the reverse is the case for the A_2 horizon.

From these observations it is possible to conclude that the thickness of the A_1, A_2 and B horizons tends to be maximized under moderate climatic conditions; where precipitation or temperatures tend towards either extreme, the thickness of the horizons diminishes.

Dominant Horizon Colour - Table 5.9 lists the dominant Munsell colours most often found in the A_1, A_2, B and C horizons of the New South Wales, Queensland and Tasmanian soil profiles. It is evident that the colour of the A_1 horizon ranges from *light gray*[1] to *light brownish gray* and *dark gray*, but that approximately the same colour range occurs in all three areas. In contrast, the A_2 horizon is much more consistent, with *light gray* dominating this horizon in the New South Wales, Queensland and Tasmanian profiles. The B horizon is more variable; colours range from *very pale brown* to *pale brown*, and from *light yellowish brown* to *dark yellowish brown*. However, the range is again common to the three regions, and probably reflects age differences in the soils. The C horizon is consistently *very pale brown* in the three regions, reflecting the homongeneity of the quartzose parent material of which these barriers are composed. Therefore, dominant horizon colours do not distinguish the soils of the three areas, notwithstanding the substantial differences in macroclimate.

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1. Munsell colour names and spellings are used; most colours incorporate several colour notations.

TABLE 5 .9

DOMINANT MUNSELL COLOURS OF THE A1, A2, B AND C HORIZONS OF THE NEW SOUTH WALES, TASMANIAN AND QUEENSLAND SOILS

HORIZON	NEW SOUTH WALES PROFILES		TASMANIAN PROFILES		QUEENSLAND PROFILES	
A1	10YR6/1	light gray	10YR6/2	light brownish gray	10YR6/2	light brownish gray
	10YR6/2	light brownish gray	10YR6/1	light gray	10YR6/1	light gray
	10YR5/1	gray	10YR4/1	dark gray	10YR5/1	gray
	10YR5/2	grayish brown	2.5Y5/1	-	10YR4/1	dark gray
					10YR4/2	dark grayish brown
A2	10YR7/1	light gray	10YR7/2	light gray	10YR7/1	light gray
	10YR7/2	light gray	10YR6/1	light gray	10YR6/2	light brownish gray
	10YR6/1	light gray	7.5YR6/1	-	10YR6/1	light gray
B	10YR4/3	brown	10YR7/4	very pale brown	10YR6/3	pale brown
	10YR4/4	dark yellowish brown	10YR6/4	light yellowish brown	10YR5/4	yellowish brown
	10YR5/3	brown	10YR6/5	light yellowish brown	10YR4/4	dark yellowish brown
	10YR5/4	yellowish brown			10YR3/3	-
	10YR6/3	pale brown				
	10YR6/4	light yellowish brown				
C	10YR7/3	very pale brown	10YR7/3	very pale brown	10YR7/3	very pale brown
	10YR7/4	very pale brown	10YR7/4	very pale brown		
	10YR8/3	very pale brown	10YR8/4	very pale brown		
	10YR8/4	very pale brown	10YR8/4	very pale brown		
			2.5Y7/3	-		
			2.5Y7/4	pale yellow		

Horizon Texture - The field texture gradings reported for the New South Wales, Queensland and Tasmanian soil sites in Appendices 2.1 to 2.48 indicate that with one exception,[1] all the horizons in all the profiles studied have a *sand texture.* Laboratory analyses of selected horizon samples confirmed the lack of a non-organic silt or clay fraction (see Chapter Three). Thus, the development of podzol soils in the Holocene sand barriers of eastern Australia has not yet resulted in significant textural alteration to the original sediments in any of the three climatic regions, even in tropical north Queensland.

Horizon Structure - All the mineral horizons of the soils studied were classed as having an *apedal* structure (see Appendix 2), and in this respect no distinction was found between the New South Wales, Queensland and Tasmanian soils. However, the older soils in all three states exhibited an *apedal massive* structure in part (or all) of the B horizon, whereas the A_1 and A_2 horizons were *apedal single grain* throughout. The thickness of the apedal massive B horizons does not vary appreciably with macroclimatic conditions, but does seem to be related to soil age. Therefore, horizon structure is not a good monitor of the macroclimatic differences between the three study areas.

Soil Reaction (pH) - Table 5.10 presents the average pH values for samples from the A_1, A_2, B and C horizons of the New South Wales, Tasmanian and north Queensland soils.

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1. Broulee Site 3B; C horizon. This is classed as a loamy sand, because of its clay content. It shows the influence of underlying clay-rich Tertiary deposits.

TABLE 5.10

AVERAGE HORIZON pH VALUES FOR THE NEW SOUTH WALES, TASMANIAN AND NORTH QUEENSLAND SOILS

HORIZON	STATISTIC	NEW SOUTH WALES PROFILES	NORTH QUEENSLAND PROFILES	TASMANIAN PROFILES
A_1	$\bar{x}$	5.81	5.64	6.50
	s	0.83	0.62	0.50
A_2	$\bar{x}$	5.23	5.06[1]	5.31
	s	0.82	0.08	0.49
B	$\bar{x}$	6.05	5.30	5.85
	s	0.54	0.12	0.43
C	$\bar{x}$	6.45	5.28[1]	6.30
	s	0.77	0.08	0.73

[1] This horizon is of limited occurrence.

From the table it is apparent that in the A_2, B and C horizons, the differences between the New South Wales and Tasmanian values, are substantially less than the differences between the New South Wales and Queensland averages. In the A_1 horizon the reverse is true. Application of *t*-test statistics to the values in the table, indicates that the New South Wales and Tasmanian values, in all horizons but the A_1, are not significantly different (at the 95 percent confidence level). The New South Wales and Queensland A_1 and A_2 horizon values, are also not significantly different (at the 95 percent confidence level), but the B and C horizon values do differ significantly. The Tasmanian and Queensland values are significantly different in all horizons except the A_2 (at the 95 percent confidence level).

From the above results it is possible to conclude that the considerable macroclimatic differences between the Tasmanian and Queensland soil sites are strongly reflected in the average pH values of the A_1, B and C horizons. The hot, wet climate of north Queensland results in (on average) lower pH values than the cool, dry climate of the east coast of Tasmania. The less substantial climatic contrasts between New South Wales and the other two areas, are not so strongly reflected in the pH averages.

<u>Shell ($CaCO_3$) Reaction</u> - A positive shell (or coral) reaction was not observed for any of the north Queensland soil samples, although positive results were frequently obtained for samples from the lower parts of the younger New South Wales and Tasmanian profiles. Assuming that some detrital

carbonate was originally contained in the Cowley-Inarlinga sediments (shell or coral - both were observed on the present beach), and assuming that the age structure proposed for the barrier in Chapter Three (Section 3.3.1.5) is even very approximately correct, then leaching of carbonate from the Queensland profiles has been very much more intense than in the New South Wales or Tasmanian soils, reflecting the climatic contrasts between the areas. The data do not permit reliable comparisons to be made between the New South Wales and Tasmanian sites.

Summary - It is apparent from the foregoing discussion that most morphological characteristics of the soil profiles do not strongly reflect the macroclimatic differences between the three study areas. However, some general trends are evident in horizon thickness, soil reaction (pH) and shell reaction. This finding contrasts with the results of many overseas studies which have found that a wide range of soil properties are related to macroclimatic conditions (see summaries in Jenny, 1941; Birkeland, 1974).

5.3.3 Organic Matter

In Figure 5.9A mean percentage organic matter content has been plotted against depth for the New South Wales, Queensland and Tasmanian soils, while in Figure 5.9B the two graphs for each locality indicate one standard deviation above and below the mean organic matter values.

From Figure 5.9A, it is apparent that the average near-surface organic matter content is greatest in the Tasmanian

FIGURE 5.9

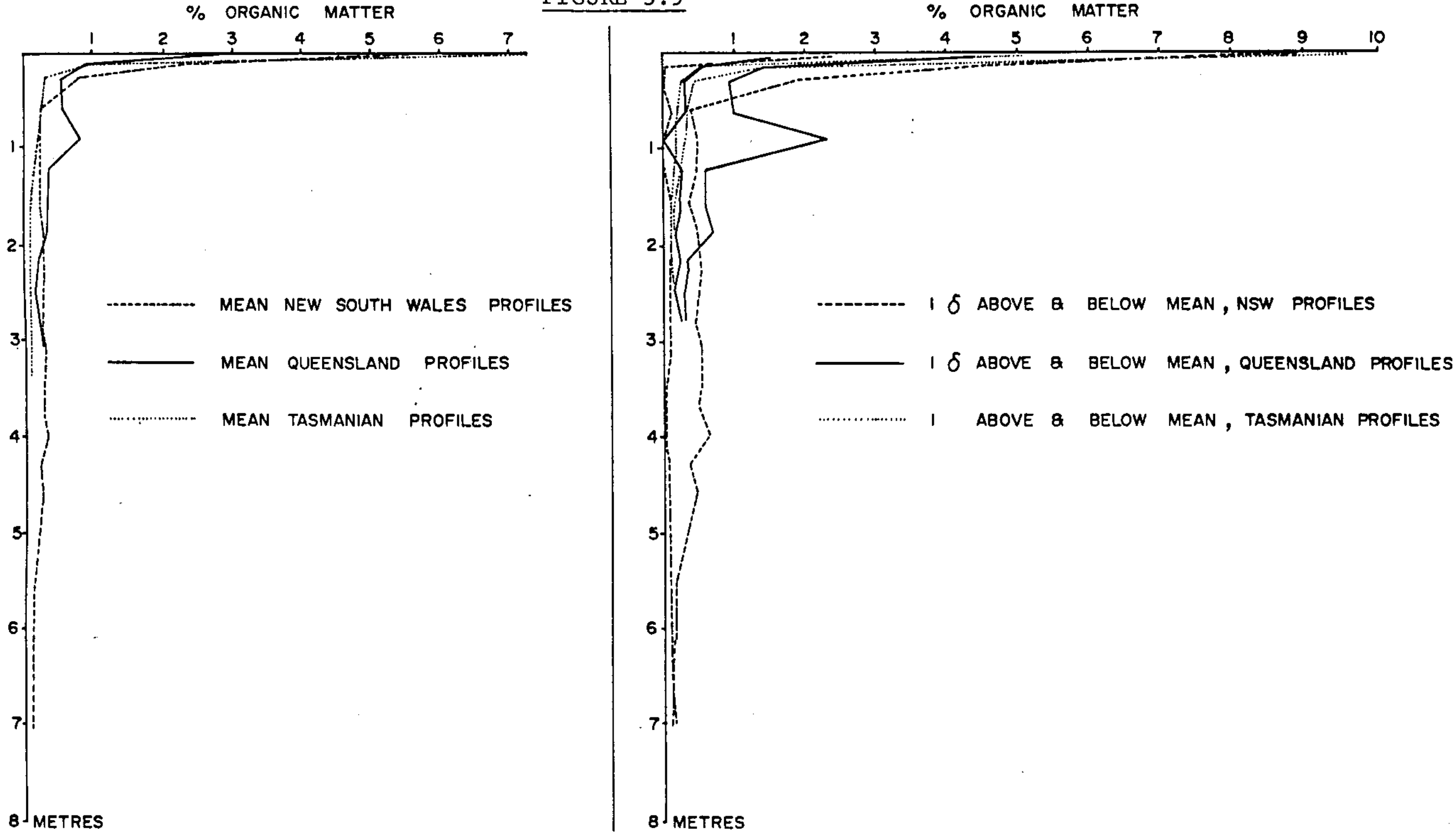

Figure 5.9 Organic matter distribution in the New South Wales; Queensland and Tasmanian soil profiles. Figures show mean values, and ±1 standard deviation, for each state.

soils and least in the Queensland sites. However, the decrease in average organic matter content with depth is least in the New South Wales soils, except between 61 and 183 cms, where the average organic content of the Queensland profiles is highest. Below 183 cms the New South Wales and Queensland averages are approximately equal, and the Tasmanian values somewhat less.

As shown in Figure 5.9B, the New South Wales organic matter averages have larger standard deviations than either the Tasmanian or Queensland values. This may be attributed to the more diverse pedogenic factor mix represented by the New South Wales soil sites. The overlap of the standard deviations indicates that while the differences between the organic matter-depth graphs for the three areas may be real, they are most probably not statistically significant. Thus, the macroclimatic contrast is not unambiguously reflected in the organic matter values except in relation to the near-surface O.M. content, which is highest in the relatively cool, dry Tasmanian climate, and lowest in the hot, wet north Queensland climate. This relationship agrees with that established by Jenny *et al.* (1949) only if the limiting effects of the higher temperatures at Cowley more than outweigh the O.M. promoting effects of the higher rainfall.

5.3.4 Cation Concentrations

In Table 5.11 mean horizon concentrations (and standard deviations) of Fe, Mn, Al, Ca, Mg and Na are presented for each of the three study areas (NSW, Queensland, Tasmania).

TABLE 5.11

EXTRACTABLE CATION CONTENT OF NEW SOUTH WALES, QUEENSLAND AND TASMANIAN SOILS

HORIZON	NEW SOUTH WALES SOILS				NORTH QUEENSLAND SOILS				TASMANIAN SOILS			
	$\bar{x}$	s	n	B/A_2	$\bar{x}$	s	n	B/A_2	$\bar{x}$	s	n	B/A_2
		IRON				IRON				IRON		
A_1	558	425	58		608	519	14		1263	366	6	
A_2	341	259	75		598	363	7		898	442	9	
B	865	498	218	2.54	1658	322	35	2.77	1482	236	19	1.65
C	825	328	111		1532	144	24		1296	345	18	
		ALUMINIUM				ALUMINIUM				ALUMINIUM		
A_1	860	554	59		940	741	14		1268	580	6	
A_2	556	347	74		866	781	7		751	303	9	
B	1060	507	216	1.91	3214	1072	35	3.71	1300	372	20	1.73
C	975	320	111		2871	518	24		1237	208	19	
		MANGANESE				MANGANESE				MANGANESE		
A_1	18.0	17.8	58		22.6	21.5	14		110	35.6	6	
A_2	6.2	7.2	75		24.1	12.3	7		14.9	12.1	9	
B	7.4	8.4	214	1.19	31.1	22.2	35	1.29	11.5	5.8	21	0.77
C	7.8	5.2	113		26.0	8.4	24		13.8	10.1	19	
		CALCIUM				CALCIUM				CALCIUM		
A_1	16.9	25.1	58		6.1	4.5	10		60.1	20.7	6	
A_2	1.3	1.4	63		0.5	0.3	6		9.0	3.1	9	
B	1.9	2.9	194	1.46	2.0	2.4	24	4.0	11.7	3.3	21	1.30
C	18.4	31.9	114		2.9	1.2	17		14.3	3.5	19	
		MAGNESIUM				MAGNESIUM				MAGNESIUM		
A_1	7.3	4.9	46		3.2	1.6	6		13.0	3.8	6	
A_2	1.6	1.3	63		1.6	-	1		7.8	3.7	9	
B	2.5	1.6	192	1.56	5.9	1.6	10	3.69	9.4	2.4	21	1.21
C	3.5	2.5	115		6.8	0.9	15		9.3	2.5	19	
		SODIUM				SODIUM				SODIUM		
A_1	2.1	1.3	59		2.0	2.2	14		4.1	1.7	6	
A_2	1.5	1.1	73		1.1	1.1	7		3.0	0.9	9	
B	1.4	1.0	217	0.93	1.2	0.8	35	1.09	3.8	1.2	21	1.27
C	2.0	1.2	113		1.4	0.7	24		4.2	1.5	19	

$\bar{x}$ and s values for iron, aluminium and manganese are MICROGRAMS PER GRAM O.D. SOIL

$\bar{x}$ and s values for calcium, magnesium and sodium are MICROMOLES PER GRAM O.D. SOIL

The relatively large standard deviations reflect not only cation variability within the bulk of each horizon, but have also been influenced by the gradational concentrations that usually occur towards the upper and lower boundaries of each horizon. As well, horizons were defined (as previously) on several criteria (some of which are visual), and hence horizon boundaries often do not coincide with marked changes in the concentration of individual cations. Such discrepancies have enlarged the standard deviations for many horizons.

From Table 5.11 the following points emerge:

1. For all cations with the exception of sodium, the Queensland sites have the highest average B horizon/A_2 horizon ratios. In other words, the A_2 and B horizons of the Queensland soils are (on average) much more strongly differentiated in terms of cation distribution, than either the New South Wales or Tasmanian soils. This must be attributed to the hot, wet climate at Cowley.

2. With the exception of sodium, the Tasmanian soils all have the lowest average B horizon/A_2 horizon ratios; that is, the A_2 and B horizons are, on average, less well differentiated than those in New South Wales and Queensland, presumably because of the lower rainfall and cooler temperatures.

3. With respect to sodium, the Tasmanian soils have a higher average B/A_2 horizon ratio than the Queensland soils, while the New South Wales average ratio is the lowest of the three.

4. Mean cation concentrations in the A_1 horizon are, in order of magnitude, New South Wales<Queensland<Tasmania for iron, aluminium and manganese, and in the order Queensland<New South Wales<Tasmania for calcium, magnesium and sodium. In other words, the hotter and wetter the climate, the more severely the "dissipative" cations are leached from the A_1 horizon.

5. Mean cation concentrations in the A_2 horizon are, in order of magniture, New South Wales<Queensland<Tasmania for iron; New South Wales<Tasmania<Queensland for aluminium and manganese; and in the order Queensland<New South Wales<Tasmania for calcium, magnesium and sodium.

6. In the B horizon, mean cation concentrations take the order New South Wales<Tasmania<Queensland for iron, aluminium and manganese; New South Wales<Queensland< Tasmania for calcium and magnesium; and Queensland< New South Wales<Tasmania for sodium.

7. The above observations reflect the basic distinction between those cations that are largely translocated within a soil profile as it develops (e.g., Fe, Al, Mn), and those that tend to be leached from the soil (e.g., Fe, Al, Mn), and those that tend to be leached from the soil (e.g., Ca, Mg, Na). In the A_2 horizon, where mobilization of cations is most intense, the New South Wales soils have the lowest average concentrations of iron, aluminium and manganese, while the Queensland soils have the lowest values for the more easily leached bases calcium, magnesium and sodium.

However, in the B horizon where iron, aluminium and manganese tend to concentrate, Queensland has the highest concentrations of these cations. B horizon concentrations of calcium, magnesium and sodium are highest in the Tasmanian soils, presumably because of less effective leaching by the cooler, drier climate.

8. Although the above observations do not take into account the large standard deviations associated with most of the mean horizon concentrations, it is considered that the trends on the whole are real, reflecting gross differences in the climatic environments of the three study areas.

5.3.5 Grain Surface Textures

Table 5.12 records the average number of total grain surface textural features (per 30 grain sample) for each horizon in each of the study areas. It is evident from the table that in the A_1, A_2 and B horizons the average number of features in the New South Wales and Tasmanian soils are approximately equal, with the north Queensland average substantially higher in each horizon. In the C horizon a similar pattern emerges, but there is a larger difference between the New South Wales and Tasmanian figures than there is between the New South Wales and north Queensland averages.

Overall, the horizon averages for total textural features for each locality do consistently relate to the macroclimatic differences between the areas, with the highest number of counts associated with the hot,

TABLE 5.12

NUMBER OF TOTAL TEXTURAL FEATURES IN THE A_1, A_2, B AND C HORIZONS OF THE NEW SOUTH WALES, NORTH QUEENSLAND AND TASMANIAN SOILS

LOCALITY	STATISTIC[1]	HORIZON			
		A_1	A_2	B	C
NEW SOUTH WALES	$\bar{x}$	80	115	90	53
	s	25	37	30	15
	n	26	26	26	14
NORTH QUEENSLAND	$\bar{x}$	130	155	136	63
	s	43	24	35	24
	n	6	4	6	4
TASMANIA	$\bar{x}$	83	120	85	34
	s	20	34	21	11
	n	6	6	6	7

[1] The values of the mean and standard deviation have been rounded to whole numbers.

wet north Queensland climate, and the lowest number with the cool, dry Tasmanian climate. The New South Wales averages are intermediate in all horizons, reflecting the milder climate of that area.

5.3.6 Summary

From the foregoing discussion it is apparent that a range of soil properties are functionally related to macro-climatic variation. Horizon thickness, soil reaction (pH) and shell reaction are the profile morphological characteristics that exhibit differences between the three localities. Similarly, the organic matter content of the A_1 horizon, the distribution of certain cations in the profiles, and the occurrence of grain surface textural features, also display associations with the macroclimatic difference between the areas.

5.4 ROLE OF MICROCLIMATIC VARIATION

5.4.1 Introduction

On the basis of data presented in Appendix 7, it is argued here that marine aerosol accession to the barrier soils can not be as important in differentially retarding podzol development as some writers have suggested (e.g., Downes, 1954; Shepherd, 1970). Aerosol fallout was found to be uniformly distributed across most of the beach-ridge plains investigated, although considerably higher levels were measured on the foredune crests and at the rear of the beach (see Appendix 7).

The following discussion centres on:

1. Association (or lack of it) between sodium chloride aerosol distribution across the New South Wales barriers and sodium chloride distribution in near-surface soil samples; and

2. Effects (if any) of sodium chloride accessions to newly initiated podzols, which are developing in restored heavy mineral mining areas.

5.4.2 Sodium Chloride Distribution

In Figure 5.10 the sodium chloride content of the near-surface soil sample from each aerosol fallout site has been plotted against the annual sodium chloride accession determined for that site. The fallout data are listed in Appendix 7; where two aerosol values were available for a single soil site they have been averaged. Soil sodium chloride values are derived from the hydrochloric acid extract data presented in Appendix 4, with the sodium concentrations recalculated to give sodium chloride. As sodium released from the organic fraction is included in the reported concentrations, the very low values reported for the soil samples in Figure 5.10 should be regarded as maximum values for aerosol derived sodium chloride, although they probably are close approximations of the actual concentrations.

From Figure 5.10 it can be seen that there is little, if any, degree of association between the two variables. However, to check this observation Kendall's Correlation

FIGURE 5.10

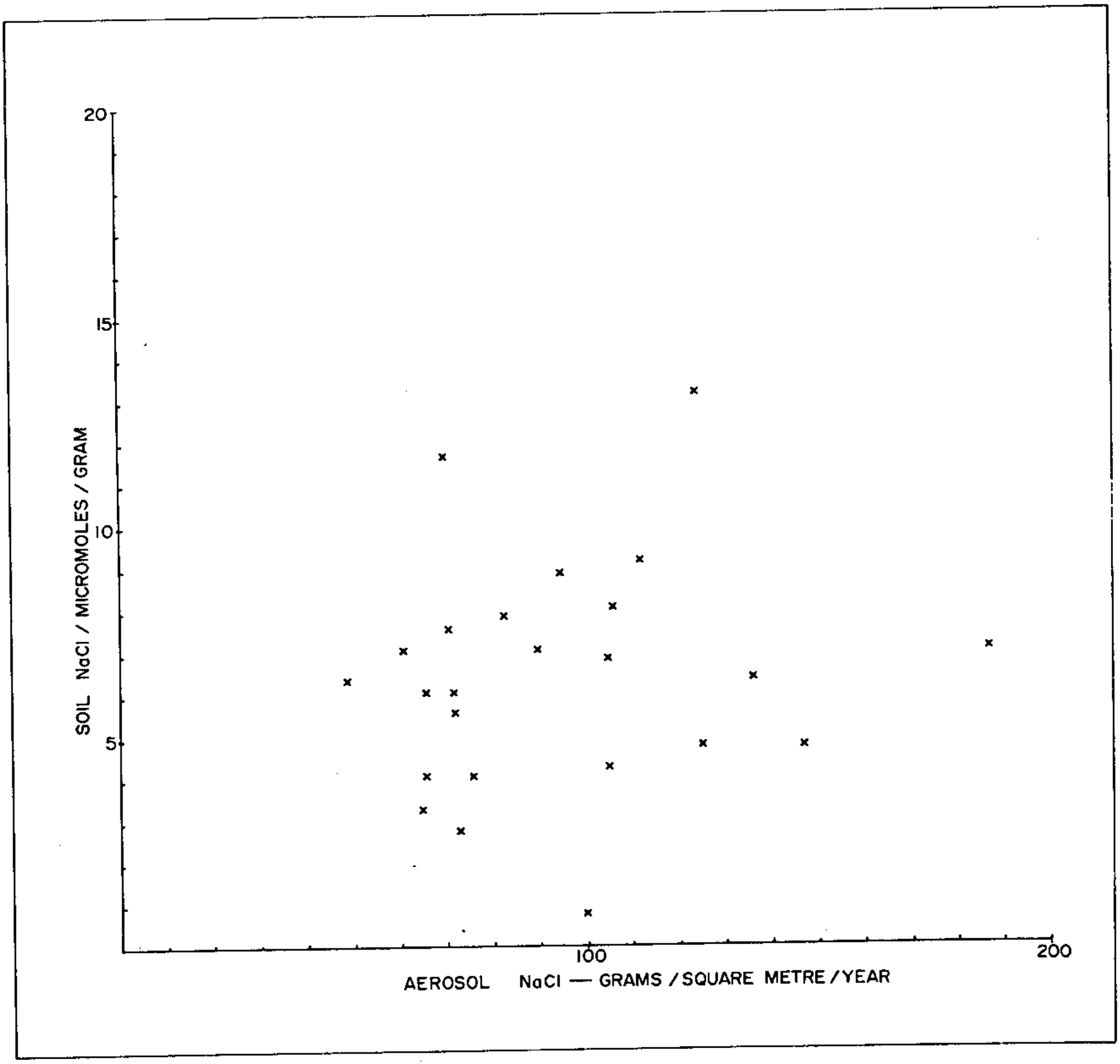

Figure 5.10 Plot of near-surface sodium chloride content against annual aerosol sodium chloride accessions for selected New South Wales soil sites.

Coefficient (τ) was determined for the data by the method of Hammond and McCullough (1974) and was found to be 0.144, after correcting for tied values. In this case the occurrence of tied values is not excessive and the precision of the data is considered adequate for the calculation of tau.

As a descriptive statistic the low value of tau supports the observation that the two sets of sodium chloride values are only weakly associated. When τ is tested for statistical significance, it is not possible to reject the null hypothesis (that no relationship exists between the two data sets) with 95 percent confidence, and hence a significant relationship is not indicated.

5.4.3 Sodium Chloride Accessions and "Mined" Soils

In an article reporting the rapid onset of podzolization in areas of the Fens Outer Barrier which were "restored" after heavy mineral mining, the writer noted that iron mobilization was apparent just four to five years after restoration, and that the intensity of the process increases with age (Paton *et al.*, 1976). After nine years, a 1 to 2 cms thick bleached horizon had formed in homogenized sand below the replaced topsoil, with scattered, roughly circular bleached pipes extending a further 45 centimetres downwards. These features are illustrated in Plates 5.1, 5.2 and 5.3.

The significance of the above-mentioned observations for the present discussion is that the podzolization processes which were initiated after restoration, progressed rapidly

PLATE 5.1

Plate 5.1 Thin bleached horizon within homogenized sand, beneath contact with replaced topsoil. Pit is located towards the northern end of the Fens Outer Barrier. The area was "restored" about five years before the photograph was taken.

PLATE 5.2

Plate 5.2 Bleached horizon (about 2-3cms thick) with scattered, circular pipes extending down a further 30-40cms. The site is in one of the earliest areas mined on the Fens Outer Barrier (to the south of Fens Transect); the age of the "soil" when the photograph was taken, was about eight years.

PLATE 5.3

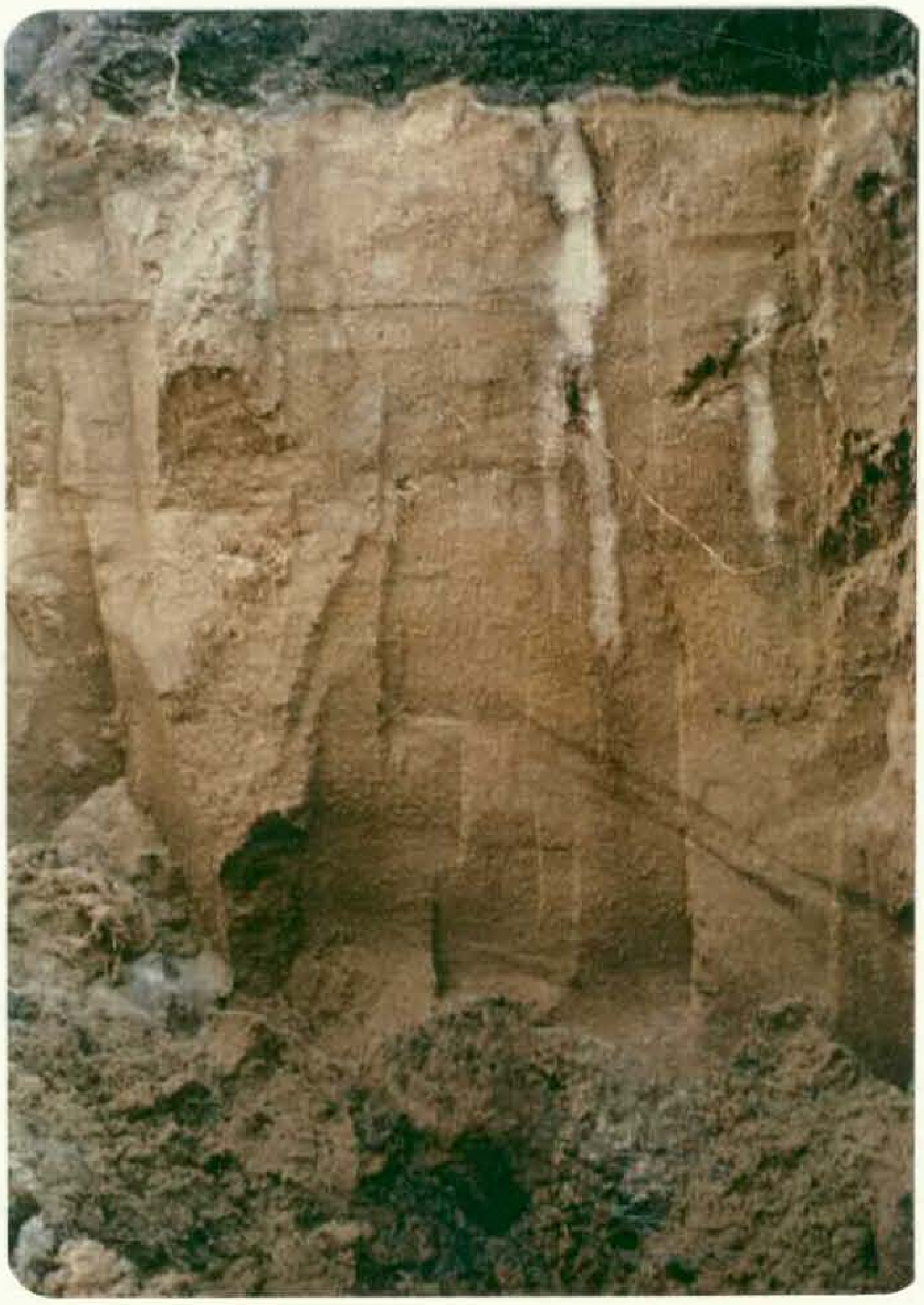

Plate 5.3 Close-up of bleached pipe extending about 15cms below bleached horizon. Same soil pit as illustrated in Plate 5.2.

despite very heavy (but uniform) sodium chloride salt accessions, (about $100/m^2/yr$; see Appendix 7).

5.4.4 Summary

It has been demonstrated above that podzolization can (and does) proceed despite high levels of marine salt fallout, and also that the distribution of sodium chloride fallout on the barriers and the distribution of sodium chloride in the near-surface of the barrier soils are poorly correlated. In addition, the very low values of sodium reported in all soils in Appendix 4, indicates that this cation is rapidly leached from the podzol profiles (also see Rogers and Westman, 1977).

The conclusion that sodium chloride is not a significant influence on podzol development in the New South Wales barriers is strongly supported by the above-mentioned observations and it is reasonable that this conclusion can be extended to the Queensland and Tasmanian barrier soils.

5.5 ROLE OF THE RELIEF FACTOR

5.5.1 Introduction

Three main elements of the relief factor were recognized in Chapter Two: i) the average *slope* of the groundsurface above a soil profile; ii) the *topographic position* of the profile; and iii) *depth of the watertable.* The slope element has been kept constant throughout the study, as all soil profiles have been located beneath completely flat groundsurfaces. Therefore, the pedogenic effect of slope variations will not be considered further. In coastal sand barriers the depth of the watertable is closely related to topographic position (Shepherd, 1970), so these aspects of the relief factor are examined jointly below.

Topographic position on a beach-ridge plain may vary between the extremes of ridge crest and swale floor. Again, virtually all soil profiles reported in the study were located beneath swales, but a few ridge crest profiles were examined so that comparisons with the swale soil profiles could be made.

Figure 5.11 illustrates the relative topographic positions and horizon configuration of Hawks Nest profiles 4A and 4B, and Disaster Bay profiles 1A and 1B. More data on the profiles are given in Appendices 2-4, 2-5, 2-26 and 2-27. It should be noted that HN4B has been included in the study because it provides an extreme example of a podzol profile with the watertable permanently at shallow depth. As such, it is somewhat atypical of beach-ridge plain soil profiles. HN4A is not strictly a "ridge" profile, but was located in a shallow swale, close to the rear of the barrier and adjacent to HN4B (Figure 5.11). Hence, in relation to Site 4B, Site 4A may be regarded as an adjacent "ridge" profile.

For both the Disaster Bay and the Hawks Nest profiles, the only pedogenic factor difference between the ridge and swale sites is in relation to topographic position. Consequently, for both sets of profiles, ridge-swale soil differences

FIGURE 5.11

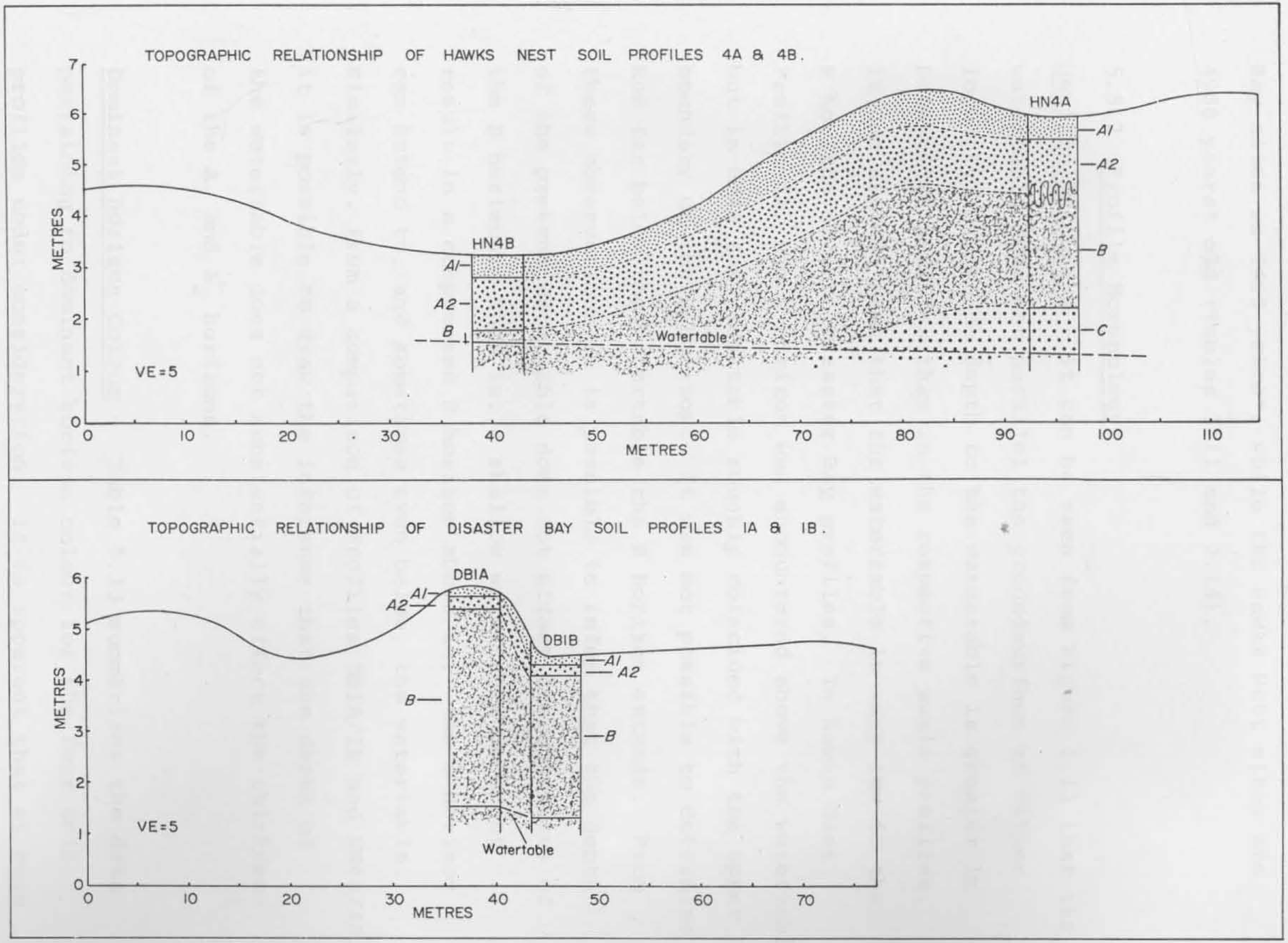

Figure 5.11 Topographic position and horizon configuration of selected Hawks Nest and Disaster Bay ridge and swale profiles.

may be attributed to the topographic aspect of the relief factor. It should be noted that the age of the Disaster Bay sites is 1400 years*, while the Hawks Nest sites are 4900 years* old (Tables 3.11 and 3.14).

5.5.2 Profile Morphology

Horizon Thickness - It can be seen from Figure 5.11 that the watertable does not parallel the groundsurface at either locality, and hence depth to the watertable is greater in both ridge profiles than in the respective swale profiles. It can also be seen that the watertable is very low in the B horizon of both Disaster Bay profiles. In Hawks Nest Profile 4A, the C horizon was encountered above the watertable, but in HN4B the watertable roughly coincided with the upper boundary of the B horizon. It was not possible to determine how far below the watertable the B horizon extends. From these observations it is possible to infer that the depth of the present watertable does not effect the thickness of the B horizon. That is, a shallow watertable does not result in a compressed B horizon above it; the B horizon can extend to, and sometimes even below, the watertable. Similarly, from a comparison of Profiles DB1A/1B and HN4A/4B, it is possible to draw the inference that the depth of the watertable does not substantially effect the thickness of the A_1 and A_2 horizons.

Dominant Horizon Colour - Table 5.13 summarizes the data pertaining to dominant horizon colour for the four soil profiles under consideration. It is apparent that at both Hawks Nest and Disaster Bay, the A_1 horizon in the swale

TABLE 5.13

DOMINANT HORIZON COLOURS IN HAWKS NEST PROFILES 4A AND 4B, AND DISASTER BAY PROFILES 1A AND 1B

HORIZON	HAWKS NEST		DISASTER BAY	
	SITE HN4A *	SITE HN4B SWALE	SITE DB1A RIDGE	SITE DB1B SWALE
A_1	10YR6/1 light gray	10YR4/1 dark gray	10YR5/1 gray	10YR4/1 dark gray
A_2	10YR7/1 light gray	7.5YR7/1** light brown-ish gray	10YR7/2 light gray	10YR7/2 light gray
B	10YR5/4 yellowish brown	7.5YR3/2 dark brown	10YR7/3 very pale brown	10YR7/3 very pale brown
C	10YR7/2 light gray	N.A.	N.A.	N.A.

* ridge equivalent

** 7.5YR7/1 - there is no Munsell equivalent; *light brownish gray* is the *Standard Soil Color Chart* (Takehara, 1967) colour classification.

N.A.- Not applicable; the horizon was not encountered above the watertable.

profile is darker than that in the equivalent ridge profile, reflecting the higher organic matter content. Although the A_2 horizon shows little colour variability between ridge and swale profiles, the B horizon differs considerably (in hue, value and chroma) between the Hawks Nest sites, but is the same dominant colour in both Disaster Bay profiles. Presumably, the age difference between the two sets of profiles (3,500 ^{14}C yrs) accounts for the discrepancy. It therefore seems probable that the dominant colour of the A_1 horizon reflects extreme topographic differences in both young and relatively old profiles, and that the dominant B horizon colour does likewise, but only in older soils.

Horizon Structure - All horizons have apedal structure. However, the Disaster Bay soils are *apedal single grain* throughout, whereas the Hawks Nest profiles are *apedal massive* in at least part of the B horizon (See Appendices 2-4 and 2-5). The difference in B horizon structure is probably associated with the 3,500 year difference in the ages of the two sets of soil sites.

Soil Reaction (pH) - Table 5.14 presents the average pH values for each horizon in each of the four profiles. From the table it is evident that the Hawks Nest and Disaster Bay A_1 horizon averages differ considerably, again presumably because of the substantial age difference. However, the A_1 ridge and swale values are very consistent within each set of profiles. On the other hand, the A_2 horizon averages differ substantially between the two Hawks Nest sites but the A_2 values are higher, with little variation between sites, at Disaster Bay. B horizon averages are identical in

TABLE 5.14

AVERAGE HORIZON pH VALUES OF SELECTED HAWKS NEST AND DISASTER BAY SOIL PROFILES

HORIZON	STATISTIC	HAWKS NEST		DISASTER BAY	
		SITE 4A *	SITE 4B swale	SITE 1A ridge	SITE 1B swale
A_1	$\bar{x}$	4.7	4.7	6.5	6.6
	s	0.60	0.63	-	0.49
	n	3	3	1	2
A_2	$\bar{x}$	4.4	3.6	5.4	5.3
	s	0.06	0.39	0.14	-
	n	3	3	2	1
B	$\bar{x}$	5.8	6.0	6.4	6.4
	s	0.38	-	0.46	0.39
	n	7	1	13	10
C	$\bar{x}$	6.2	-	-	-
	s	0.17	-	-	-
	n	4	0	0	0

* ridge equivalent

Disaster Bay 1A and 1B, and differ only slightly between the two Hawks Nest profiles. Therefore, average horizon pH appears to reflect topographic relief differences only in the A_2 horizon of relatively old soils.

Summary - A comparison of the morphological characteristics of two sets of ridge and swale soil profiles (one set old, the other comparatively young) indicates that the thickness, texture, structure and shell reaction of the A_1, A_2 and B horizons are independent of topographic position (watertable depth). In contrast, the dominant colour of the A_1 and B horizons, and the average pH of the A_2 horizon, do seem to relate to topographic position (watertable depth), although the relationship is best developed in the older profiles.

5.5.3 Organic Matter

In Figures 5.12 the depth-organic matter graphs for Profiles HN4A/H4B and DB1A/DB1B are shown. These graphs are based on data presented in Appendices 3-1 and 3-6. From the graphs it is apparent that near-surface organic matter content differs substantially between ridge and swale profiles at both Hawks Nest and Disaster Bay. A_2 horizon values are comparable in all profiles and B horizon values also appear to be consistent, with little evidence of illuviated O.M. However, in HN4B little of the B horizon is above the watertable, making comparisons difficult. Overall, only the organic matter content of the A_1 horizon seems to reflect ridge/swale topographic differences; this is in complete agreement with the findings of Russell and Rhoades (1956) for sandy soils in Nebraska.

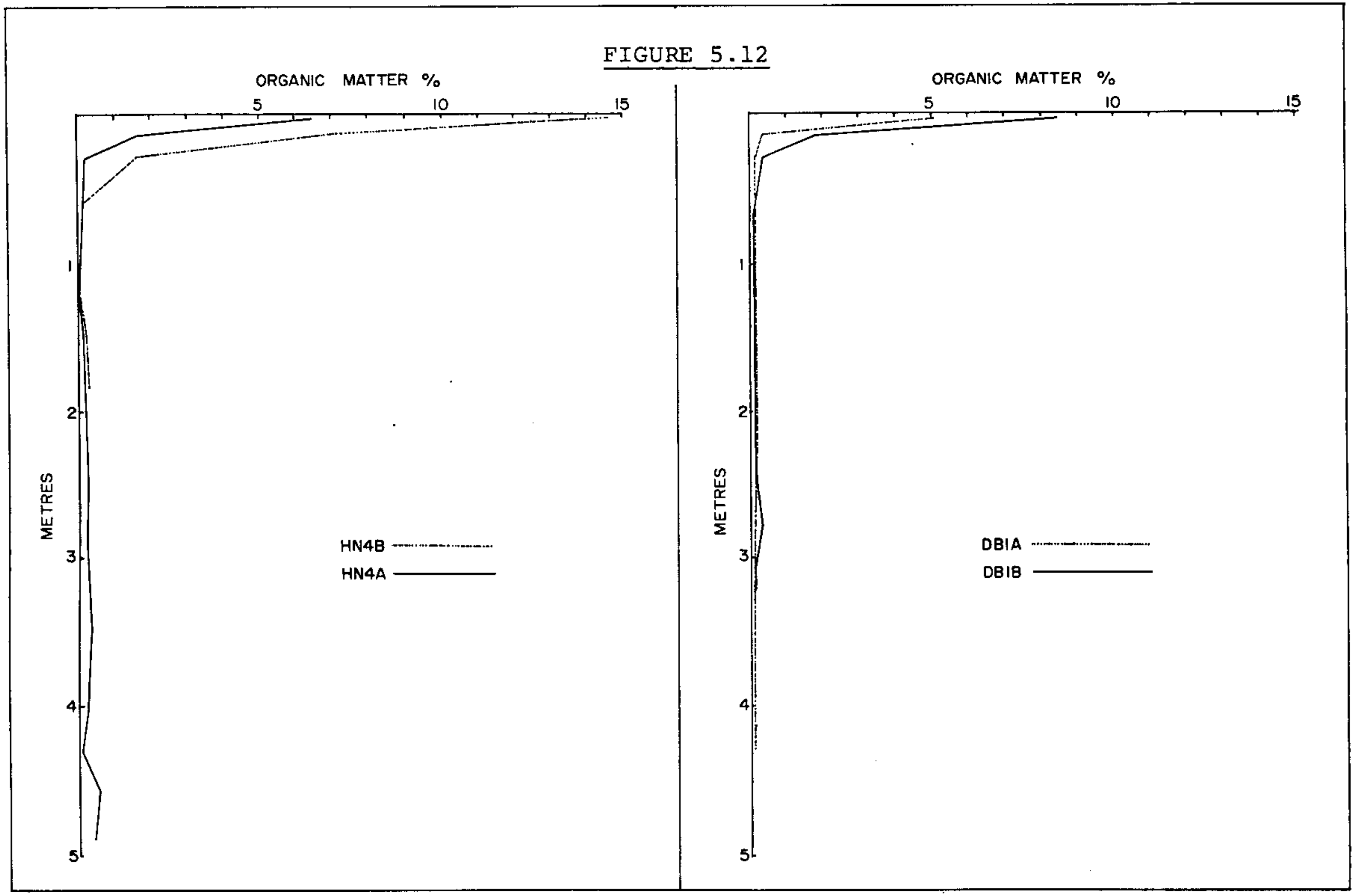

Figure 5.12 Distribution of organic matter in Hawks Nest Profiles 4A and 4B, and Disaster Bay Profiles 1A and 1B.

5.5.4 Cation Concentrations

Depth-concentration graphs for iron, aluminium, calcium and sodium are presented in Figure 5.13 for the two Hawks Nest profiles, and in Figure 5.14 for the Disaster Bay profiles. In addition, Kendall's Correlation Coefficient has been calculated for each pair of graphs and the value of τ is shown, together with an indication of whether τ can be accepted as statistically significant at the 90 percent confidence level, to reject H_0 and H_1. H_0 was formulated as: that no relationship exists between the two cation concentration depth distributions being compared; and H1: that a relationship does exist between the two cation depth distributions.

From Figure 5.13 it is apparent that the distributions of iron and aluminium over comparable depth ranges, do not correlate significantly between Profiles HN4A and HN4B, and hence the null hypothesis cannot be rejected (at $\alpha = 0.10$). This result probably reflects the topographic disparity between the two sites, but could also have been influenced by the exclusion of most of the B horizon values from the analyses, as these were at a greater depth than the shallow watertable in HN4B. On the other hand, the correlation of the calcium and sodium distributions in these profiles do yield higher values of τ, so that it is possible to reject H_0 and accept H_1, at the 90 percent confidence level. Hence, it can be maintained that HN4A and HN4B exhibit similar distribution patterns of Ca and Na, despite their topographic differences. The patterns are probably similar because of

FIGURE 5.13

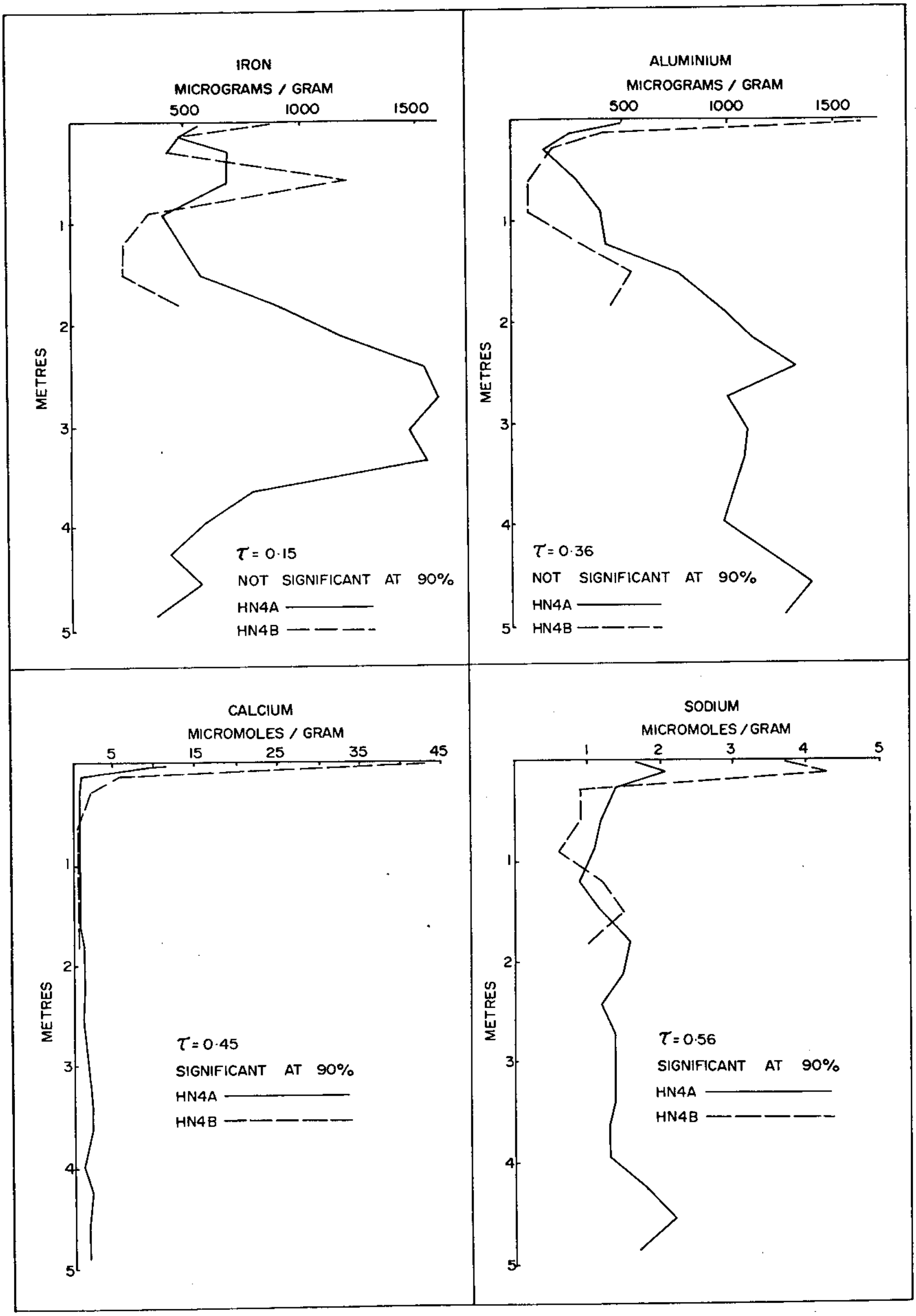

Figure 5.13 Distribution of Iron, Aluminium, Calcium and Sodium in Hawks Nest Profiles 4A and 4B.

FIGURE 5.14

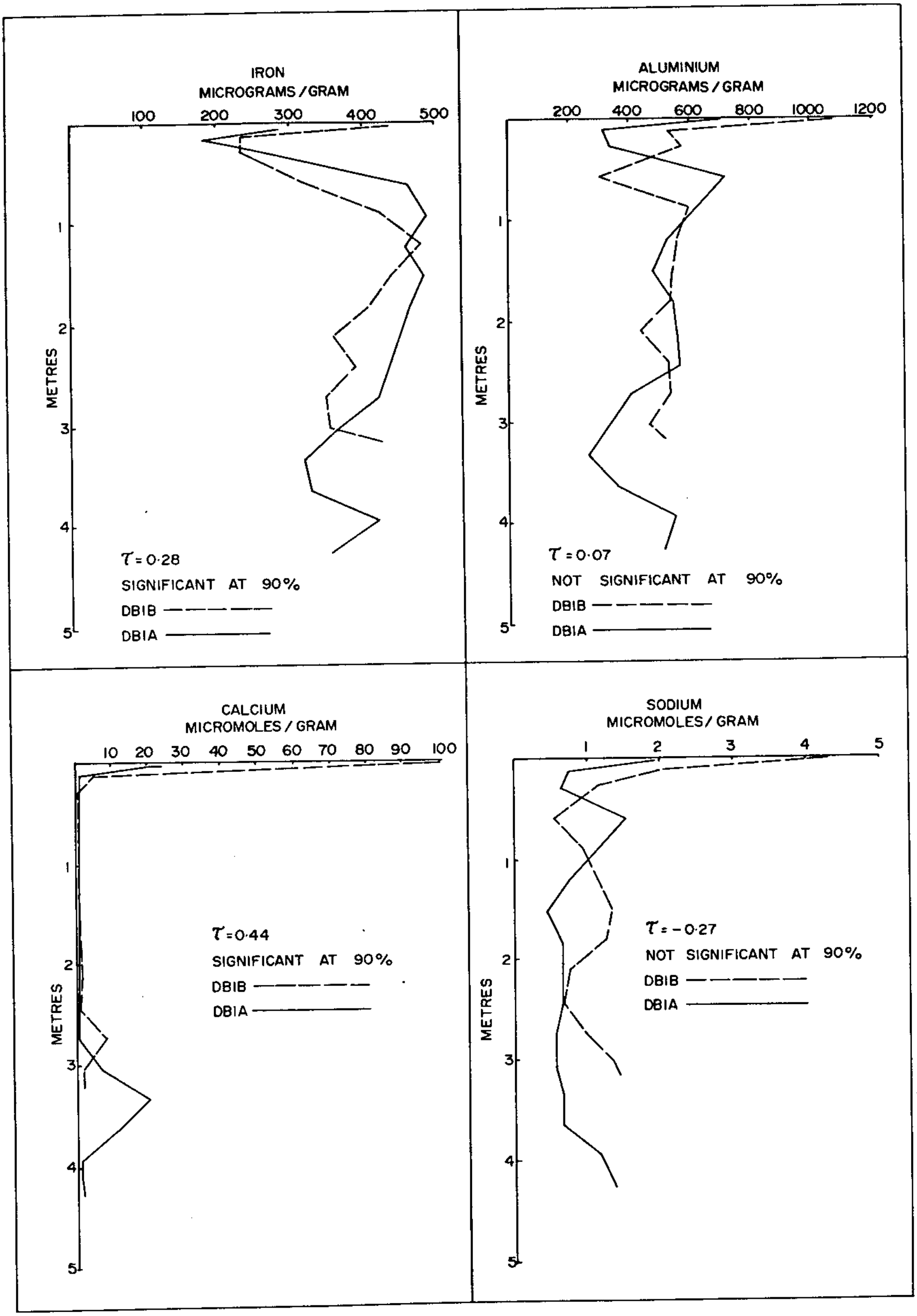

Figure 5.14 Distribution of Iron, Aluminium, Calcium and Sodium in Disaster Bay Profiles 1A and 1B.

the uniform and almose complete leaching of these bases from the old profiles.

The depth distributions of iron, aluminium, calcium and sodium in Profiles DB1A and DB1B are illustrated in Figure 5.14. The associated values of τ for iron and calcium are both significant at the 90 percent confidence level, indicating that a relationship does exist between these depth distributions (H_1). However, the lower values of τ calculated for aluminium and sodium are not significant at the 90 percent level, and do not allow H_0 to be rejected. Therefore, the topographic relief factor differences have not resulted in significant differences between DB1A and DB1B in relation to the distribution of iron and calcium, but may have, with respect to the distribution of aluminium and sodium.

Table 5.15 presents average cation values (by horizon) for both HN4A and HN4B, as well as the ratio of B and A_2 horizon values, which is a measure of the degree of profile differentiation. It can be observed that for iron, manganese, calcium and magnesium, the average HN4A ratio considerably exceeds the corresponding HN4B ratio, whereas for aluminium and sodium the converse applies. Hence, in relation to iron, manganese, calcium and magnesium, profile differentiation is greater in HN4A than in HN4B, but differentiation is less in terms of aluminium and sodium. Again, these differences probably reflect the topographic disparity, but it should be noted that little of the B horizon of HN4B was sampled and that the comparisons take no account of the standard deviations.

TABLE 5.15

AVERAGE ACID-EXTRACTABLE CATION CONTENT OF HORIZONS IN HAWKS NEST PROFILES 4A AND 4B

HORIZON		IRON		ALUMINIUM		MANGANESE		CALCIUM		MAGNESIUM		SODIUM	
		HN4A	HN4B	HN4A	HN4B	HN4A	HN4B	HN4A	HN4B	HN4A	HN4B	HN4A	HN4B
A_1	$\bar{x}$	580	673	310	1015	21.3	23.1	4.5	24.2	3.5	11.2	1.7	4.0
	s	110	272	187	841	4.87	7.92	6.21	26.45	3.10	2.83	0.35	0.42
A_2	$\bar{x}$	533	593	390	157	20.8	25.7	0.7	0.6	1.1	1.2	1.1	0.9
	s	143	533	70	133	5.7	21.66	0.06	0.10	0.15	0.61	0.15	0.30
B	$\bar{x}$	1261	355	1050	518	31.3	16.7	1.6	0.7	2.1	1.3	1.4	1.3
	s	390	177	163	67	15.06	9.69	0.54	0.21	0.49	0.07	0.15	0.35
C	$\bar{x}$	532	-	1192	-	18.4	-	1.9	-	2.0	-	1.8	-
	s	84	-	205	-	2.62	-	0.55	-	0.35	-	0.45	-
RATIO $\frac{B\bar{x}}{A_2\bar{x}}$		2.37	0.60	2.69	3.30	1.50	0.65	2.29	1.17	1.91	1.08	1.27	1.44

associated with each mean. Mechanisms by which topographic differences could effect cation horizon differentiation include subsurface lateral flow from ridges to swales, surface movement of sediment, organic matter and moisture, and more efficient nutrient recycling in swales compared to ridges because of the higher watertable.

Average horizon cation concentrations for DB1A and DB1B, and average B/A_2 horizon ratios, are given in Table 5.16. For the Disaster Bay soils, the ratios for iron, aluminium, magnesium and sodium are quite consistent, indicating similar degrees of profile differentiation within the two soils. This argument does not extent to magnesium and calcium, which show substantial differences in the magnitude of the average B/A_2 ratios between the two soil sites.

It is therefore reasonable to conclude, that in soils as young as the Disaster Bay profiles (1400 years*) ridge/swale topographic differences are reflected to only a limited extent in the cation distributions, but that in relatively old profiles, such as HN4A and HN4B (4900 years*), the cation distributions may be considerably influenced by topographic position. The most logical reason for the disparity is that in the young soils differences have not had sufficient time to develop, whereas in the older soils they have had enough time. Mechanisms which would promote such differences are not well-documented, but the more obvious were suggested above.

TABLE 5.16

AVERAGE ACID-EXTRACTABLE CATION CONTENT OF HORIZONS IN DISASTER BAY PROFILES 1A AND 1B

HORIZON		IRON		ALUMINIUM		MANGANESE		CALCIUM		MAGNESIUM		SODIUM	
		DB1A	DB1B	DB1A	DB1B	DB1A	DB1B	DB1A	DB1B	DB1A	DB1B	DB1A	DB1B
		μg/g		μg/g		μg/g		μmoles/g		μmoles/g		μmoles/g	
A_1	$\bar{x}$	285	338	695	798	6.1	7.9	24.1	52 *	9.4	9.4	1.9	3.3
	s	-	145	-	392	-	9.26	-	-	-	6.58	-	1.84
A_2	$\bar{x}$	238	235	318	290	1.0	0.2	0.9	1.1	1.3	1.6	0.7	1.1
	s	74	-	18	-	1.41	-	0.14	-	0.07	-	0.07	-
B	$\bar{x}$	425	396	485	490	2.0	1.3	4.0	2.2	2.1	2.1	0.7	1.0
	s	58	49	130	83	0.89	0.77	6.03	2.23	0.26	0.44	0.33	0.32
RATIO $\frac{B\ \bar{x}}{A_2 \bar{x}}$		1.79	1.69	1.53	1.69	2.00	6.50	4.44	2.00	1.62	1.31	1.00	0.91

* approximate value

5.5.5 Grain Surface Textures

Counts of total grain features in the A_1, A_2 and B horizon samples of Profiles HN4A, HN4B, DB1A and DB1B, are given in Table 5.17. It is at once apparent from the table, that for each horizon, the textural counts for the Hawks Nest profiles considerably exceed those for the Disaster Bay profiles, although an equal number of grains (30) were examined in each sample.

χ^2 statistics were calculated for the two pairs of profiles and χ^2 was used to test the following hypotheses:
H_0: that the distribution of total sand grain surface textural features between horizons does not differ significantly between the ridge and swale sites under consideration.
H_1: that the distribution of textural features between horizons in the ridge and swale soils is so different that it is unlikely to have resulted from "chance" variations. The rejection level was set at $\alpha = 0.05$. The calculated χ^2 statistic for both the Hawks Nest and the Disaster Bay sites was found to exceed the critical value of χ^2 (5.99), and hence H_0 could be rejected and H_1 accepted, in both cases. Thus the distribution of total grain surface textural features by horizons is significantly different in the ridge and swale soil profiles under consideration, at both Hawks Nest and Disaster Bay; again, this difference most probably reflects the topographic dissimilarity of the ridge and swale sites as the other pedogenic factors were all held constant. As a descriptive statistic the values of χ^2 (21.47 for Hawks Nest, 10.62 for Disaster Bay) indicate that the HN4A and HN4B textural distributions are less well

TABLE 5.17

TOTAL TEXTURAL FEATURES ON SAND GRAINS FROM THE A_1, A_2 AND B HORIZONS OF PROFILES HN4A, HN4B, DB1A AND DB1B

PROFILE	HORIZON			χ^2
	A_1	A_2	B	
HN4A	80	139	126	7.78
HN4B	92	98	136	
DB1A	55	67	40	10.62
DB1B	75	40	29	

associated than are the DB1A and DB1B distributions. This divergence may indicate that the influence of the topographic factor increases with increasing profile age.

The same mechanisms that are probably responsible for the cation distribution disparities (Righi and De Coninck, 1977), probably also promote the formation of grain surface textural features by effecting the moisture regime, organic matter content, O.M. decomposition rates, soil reaction (pH), nutrient turnover rates and general ionic activity of the swale profiles.

5.6 ROLE OF PARENT MATERIAL

5.6.1 Introduction

In Chapter Two several aspects of the parent material factor were identified; viz, granulometry, mineralogy, acid-extractable cations and grain surface textural features. However, both granulometry and mineralogy were shown in Section 3.3.2 to be essentially constant within the parent material of each barrier, and also to vary only marginally between the barriers (especially in New South Wales - Tasmania). As a consequence of this homogeneity it has not been possible to examine the pedogenic influence of the granulometric and mineralogical aspects of the parent material factor. On the other hand, this situation is a reminder that the homogenous nature of east Australian Holocene sand barrier sediments is ideal for factorial pedogenic studies in which these parent material characteristics are to be kept constant.

In Chapter Four it was demonstrated that both the concentration of cations and the occurrence of grain surface textural features in the parent material sediments, do vary appreciably within the barriers and, more particularly, between them. The following discussion examines the effect on horizon properties of variations in cation concentrations and textural features in the parent material. Moruya Profiles 5B and 6B, and Disaster Bay Profile 6B, were selected for this purpose because they are the same age (5400 years*) and have very similar pedogenic environments. Unfortunately, the lack of factorially comparable profiles (especially profiles of the same age) obviated the selection of additional examples. Information about the pedogenic environments of M5B, M6B and DB6 is provided in Tables 3.13 and 3.14. Table 5.18 summarizes data on the parent material characteristics of the profiles. The data were derived from C horizon samples for M5B and M6B, but in the case of DB6, where the C horizon lies below the watertable, the three deepest B horizon samples were used to obtain an estimate. In relation to granulometry and mineralogy, this procedure should not cause inaccuracy. However, the values obtained for both extracted cations and grain surface textural features could have been slightly increased by B horizon development. Such inaccuracy is here assumed to be minimal; the values represent the best parent material estimates available.

From Table 5.18 it is apparent that, for both granulometric and mineralogic parent material characteristics, all three profiles are very similar, thereby typifying the intra- and inter-barrier parent material homogeneity referred to above. In relation to the extractable cation content of the

TABLE 5.18

PARENT MATERIAL CHARACTERISTICS OF MORUYA PROFILES 5B AND 6B AND DISASTER BAY PROFILE 6

	M5B	M6B	DB6
GRANULOMETRIC CHARACTERISTICS	PHI	PHI	PHI
Mean Grain Size	1.90	1.83	1.68
Mean Sorting Coefficient (s)	0.28	0.29	0.33
MINERALOGY	PERCENT COUNT	PERCENT COUNT	PERCENT COUNT
Quartz	94.1	92.4	94.1
Feldspars	2.9	4.2	4.9
Heavy Minerals	2.0	2.4	1.0
Rock Fragments & Micas	1.0	1.0	-
Shell Carbonate	-	-	-
AVERAGE EXTRACTABLE CATION CONTENT	MICROGRAMS PER GRAM	MICROGRAMS PER GRAM	MICROGRAMS PER GRAM
Iron	856	863	332
Aluminium	613	656	813
Manganese	5.9	4.8	1.9
	MICROMOLES PER GRAM	MICROMOLES PER GRAM	MICROMOLES PER GRAM
Calcium	1.4	1.4	0.6
Magnesium	1.7	1.6	1.9
Sodium	1.4	2.0	0.8
GRAIN SURFACE TEXTURES	NUMBER	NUMBER	NUMBER
Total Features on 30 grains	69	56	54
ORGANIC CONTENT	WEIGHT PERCENT	WEIGHT PERCENT	WEIGHT PERCENT
Organic matter	0.05	0.11	0.22

parent material, it can be seen from the table that M5B and M6B are in close agreement with each other for all cations. In comparison, the parent material concentrations for DB6 are considerably lower for iron, manganese, calcium and sodium, and higher for aluminium and magnesium. The total grain surface texture count is very similar for the parent material of M6B and DB6, but for M5B the figure is somewhat higher.

5.6.2 Horizon Cation Concentrations

Data pertaining to average horizon cation concentrations and B/A_2 horizon cation ratios are given in Table 5.19. Two trends are apparent from the data:

1. Average $A_1 + A_2 + B$ horizon concentrations are higher for both M5B and M6B than DB6, for all cations except magnesium. This pattern agrees with the relative magnitude of the parent material concentrations that were given in Table 5.18, except for aluminium, where the estimated parent material concentration for DB6 (813μg/g) is greater than the parent material values for M5B and M6B.
2. In relation to the B/A_2 horizon differentiation ratios, those for M5B are higher than those for M6B and DB6, for all cations except iron (see Table 5.19). For aluminium, the DB6 ratio is intermediate between the other two ratios, and for manganese and sodium the M5B and DB6 ratios are equal.

The implications of these trends are: firstly, that the average $A_1 + A_2 + B$ horizon cation concentrations in older

TABLE 5.19

AVERAGE ACID-EXTRACTABLE CATION CONTENT OF HORIZONS IN SOIL PROFILES M5B, M6B and DB6

HORIZON	IRON			ALUMINIUM			MANGANESE			CALCIUM			MAGNESIUM			SODIUM		
	M5B	M6B	DB6	M5B	M6B	DB6	M5B	M6B	DB6	M5B	M6B	DB6	M5B	M6B	DB6	M5B	M6B	DB6
	micrograms/gram			micrograms/gram			micrograms/gram			micromoles/gram			micromoles/gram			micromoles/gram		
A_1	615	635	278	975	810	813	46.9	42.3	3.3	8.6	6.8	9.0	3.4	3.4	9.6	4.8	1.6	1.9
A_2	328	512	95	680	755	455	3.0	2.6	2.0	1.0	1.0	0.6	1.0	1.2	1.7	2.1	3.2	1.0
B	1339	1198	487	1249	1047	772	5.9	3.9	3.0	1.5	1.5	0.8	2.2	2.0	1.7	2.8	2.3	0.7
MEAN A_1,A_2,B	869	907	407	1001	923	735	10.0	7.7	2.9	2.2	1.9	1.9	1.9	1.9	2.7	2.8	2.5	0.9
RATIO B/A_2	4.08	2.34	5.13	1.84	1.39	1.70	1.97	1.50	1.50	1.50	1.50	1.33	2.20	1.67	1.00	1.33	0.72	0.70

soils do seem to reflect substantial differences in parent material cation concentrations; and secondly, that average B/A_2 ratios, which are a measure of horizon differentiation, do not seem to reflect the basic differences in parent material cation content.

Table 5.20 presents matrices containing values of Kendall's Tau, obtained by correlating the depth-distributions of iron, aluminium, manganese, calcium, magnesium and sodium, in Profiles M5B, M6B and DB6. The technique used was the same as that discussed previously (Hammond and McCullagh, 1974). The values of p shown in the matrices indicate the probability that the calculated values of tau were obtained by chance. Where $p<0.1$, the null hypothesis (that no relationship exists between the two cation depth-distributions) may be rejected, and the alternative hypothesis (that a relationship does exist) may be accepted.

The results show, that for the statistically significant values of τ, higher coefficients were obtained for the correlation of M5B with M6B, than for the correlation of either M5B with DB6, or M6B with DB6. From this it is possible to infer that differences in the parent material concentrations of acid extractable iron, aluminium, calcium and magnesium are reflected in the degree of association between the cation depth-distribution curves for these soils. The implication is that initial parent material cation concentrations influence soil profile development. This statement is in accord with the findings of many pedological studies which have established

TABLE 5.20

KENDALL'S τ CORRELATION MATRICES FOR CATION DISTRIBUTIONS IN MORUYA PROFILES 5B AND 6B AND DISASTER BAY PROFILE 6

IRON

		M5B	M6B	DB6
M5B	τ	1.00	0.91	0.45
	P	-	0.000	0.020
M6B	τ		1.00	0.42
	P		-	0.029
DB6	τ			1.00

ALUMINIUM

		M5B	M6B	DB6
M5B	τ	1.00	0.64	0.29
	P	-	0.002	0.096
M6B	τ		1.00	0.02
	P		-	0.464
DB6	τ			1.00

MANGANESE

		M5B	M6B	DB6
M5B	τ	1.00	0.40	0.52
	P	-	0.036	0.009
M6B	τ		1.00	0.51
	P		-	0.011
DB6	τ			1.00

CALCIUM

		M5B	M6B	DB6
M5B	τ	1.00	0.56	-0.02
	P	-	0.006	0.464
M6B	τ		1.00	-0.02
	P		-	0.464
DB6	τ			1.00

MAGNESIUM

		M5B	M6B	DB6
M5B	τ	1.00	0.69	0.17
	P	-	0.001	0.221
M6B	τ		1.00	0.14
	P		-	0.264
DB6	τ			1.00

SODIUM

		M5B	M6B	DB6
M5B	τ	1.00	0.08	0.26
	P	-	0.359	0.121
M6B	τ		1.00	0.00
	P		-	0.500
DB6	τ			1.00

H_0: no relationship exists between the two depth distribution patterns.

H_1: a relationship does exist between the two depth distribution patterns.

The blocked cells indicate that H_0 may be rejected with 90% confidence, and H_1 accepted.

TABLE 5.21

TOTAL TEXTURAL FEATURES ON SAND GRAINS FROM THE PARENT MATERIAL AND THE A_1, A_2 AND B HORIZONS OF PROFILES M5B, M6B AND DB6

	M5B	M6B	DB6
PARENT MATERIAL*	69	56	54
A_1 HORIZON	89	111	128
A_2 HORIZON	153	142	152
B HORIZON	98	85	97
$\bar{x}$ (A_1, A_2, B)	113	112	126

* For M5B and M6B C horizon material used. Lack of C horizon in DB6 so lower B horizon sediments used - See Section 4.5.

causal relationships between the chemical content of parent material, and the concentration and distribution of elements in the soil profiles developed from it (e.g., Jenny, 1931; Marshall and Jeffries 1946; Brewer, 1955, 1956; Khan, 1959; Gamble and Daniels, 1974; Targulian *et al.*, 1974).

5.6.3 Grain Surface Textures

Table 5.21 shows that the distribution of grain surface textural features in the parent material of Profiles M5B, M6B and DB6 is not reflected in the distribution of either A_1, A_2 or B horizon total textural counts, nor in the pattern of average counts for the three horizons. Thus, an association between the number of parent material textural features and the number of such features in the various soil horizons, is not evident in these profiles.

5.7 SUMMARY

Other than general comments on the importance of siliceous, freely drained sediments in the genesis of the intrazonal podzol soils of the east Australian barriers (e.g., Hallsworth, *et al.*, 1975), little has been published about the influence of specific non-temporal pedogenic factors on the development of these soils. The present chapter has been concerned with this problem, and has attempted to demonstrate the influence of the individual factors on soil properties, by means of selected examples. In other words, soil sites were carefully chosen so as to minimize variation in all pedogenic factors but the one under consideration, and significant differences in soil properties between the sites were ascribed to the differential impact of the variable pedogenic factor. In the case of macro- and micro- climate, the same principle was applied, but in a slightly different manner.

From the analysis, the following general conclusions may be drawn:

1. In terms of the soil properties examined during the study, and given the soil sampling techniques employed, the influence of variations in the plant factor on the older soils is minimal. The influence of different vegetation types on younger soils was not investigated, but the magnitude of such effects should decrease with age.

2. Macroclimatic variation was found to have a significant association with only a few aspects of soil profile morphology (horizon thickness, soil reaction and shell reaction), to be reflected in near-surface organic matter content, and to be strongly related to the distribution and concentration of certain cations, and to the occurrence of grain surface textures.

3. The role of microclimatic variation, which for the barrier soils relates primarily to the influx of marine salts, was not found to be associated with the content of sodium chloride in the surface of the soil profiles, nor to effect the rapid development of newly initiated podzols. Its influence was therefore considered to be negligible.

4. A comparison of the properties of ridge and swale soils indicated that only some morphological characteristics

of the profiles are related to topographic position (A_1 and B horizon dominant colour, A_2 horizon pH), and that the relationship is best established in older profiles. Organic matter content of the A_1 horizon, the distribution of certain cations in the profiles, and the occurrence of grain surface textures, were also found to be significantly associated with topographic position. In the case of cation distribution, the association was best developed in the older profiles.

5. Although the granulometric and mineralogical aspects of the parent material factor are essentially constant, both within and between the barriers, it was possible to examine the influence of slight differences in cation concentration and grain surface texture occurrence in the soil parent material. The concentration and distribution of cations in the older soil profiles does appear to be related to the presence of those cations in the parent material (as would be expected), but the occurrence in the soils of grain surface textural features was not found to be significantly related to their occurrence in the parent material.

With the limits imposed by the overall pedogenic environment of the east Australian coastal barriers, individual pedogenic factors were found to have some influence on particular soil properties. The influence of many of the factors seem to be time-dependent.

CHAPTER VI

ROLE OF THE TIME FACTOR

6.1 INTRODUCTION

The objective of the present chapter is to assess the contribution of the time factor to the development of the barrier soils, by examining the temporal trends evident in the soil data obtained during the course of the study. However, as shown in Chapter Five, some of these data incorporate a degree of "interference" or "noise", caused by (slight) variations in pedogenic factors other than time. As far as practicable this has been minimized by restricting the data to that obtained from the New South Wales barrier soils. Thus, the macroclimatic factor has been substantially negated, and variations in the parent material and vegetation factors considerably reduced. Although a minimal amount of extraneous factor interference remains in the data, this can not be eliminated without drastically curtailing the general applicability of the study. As the theoretical model and conceptual framework discussed in Chapter Two permit "imprecise" data to be used in chronsequence investigations, the problem becomes one of recognizing general trends within the fluctuations of the data - trends that are not always very pronounced.

The problem of recognizing trends has been tackled by the use of correlation and regression analysis. All soil data have been correlated with soil age[1] and linear, exponential, logarithmic and power functions have been used to identify and quantify temporal trends within the data; a coefficient of determination has been used to decide which equation best "explains" (in the statistical sense) variations in each soil parameter. In line with the main objective of the chapter (to examine temporal trends in soil properties), soil age has been designated as the independent variable in all regression equations; the resulting regression lines may be used to estimate soil parameter values from soil age, but not vice versa. A separate set of regression lines is required for the estimation of soil age; for clarity these are not shown on the graphs.

Following the examination of temporal trends in the soil data, the main findings of the study are summarized in tabular form in Section 6.7. In Section 6.8 the implications of the findings for pedogenic-geomorphic research are assessed.

6.2 PROFILE MORPHOLOGY

All data analysed in this section have been obtained from field observations which are reported in the soil profile descriptions in Appendix 2.

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1. Product Moment Correlation has been used for all but the grain surface texture and grain coating data. Significance has been determined by the use of the *t* statistic.

TABLE 6.1

AGE-HORIZON THICKNESS CORRELATION COEFFICIENTS,
COEFFICIENTS OF DETERMINATION, AND STATISTICAL SIGNIFICANCE

HORIZON THICKNESS PARAMETERS	CORRELATION COEFFICIENT (LINEAR)	COEFFICIENT OF DETERMINATION (LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?	MAXIMUM CORRELATION COEFFICIENT (NON-LINEAR)	MAXIMUM COEFFICIENT OF DETERMINATION (NON-LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?
A_1 THICKNESS	0.343	0.117	YES	0.278 (Exponential)	0.077	NO
A_2 THICKNESS	0.642	0.413	YES	0.720 (Exponential)	0.518	YES
B THICKNESS	0.062	0.004	NO	0.056 (Exponential)	0.003	NO
A_2:A_1 RATIO	0.518	0.268	YES	0.626 (Exponential)	0.392	YES
B :A_1 RATIO	0.165	0.027	NO	0.238 (Power)	0.057	NO
B :A_2 RATIO	0.687	0.473	YES	0.730 (Power)	0.533	YES
A_1+A_2 THICKNESS	0.585	0.342	YES	0.655 (Exponential)	0.430	YES
A_1+A_2+B THICKNESS	0.258	0.067	NO	0.250 (Exponential)	0.062	NO

6.2.1 Horizon Thickness and Horizon Boundary Configuration

A number of parameters relating to horizon thickness in the New South Wales soils have been correlated with soil age. Table 6.1 lists the parameters and gives a correlation coefficient and linear coefficient of determination (r^2) for each, together with the maximum coefficient of determination derived from an exponential, logarithmic or power curve fit. The latter are hereafter collectively referred to as *non-linear* coefficients of determination.

In Figures 6.1 to 6.4, A_2 horizon thickness, A_2/A_1 thickness ratio, B/A_2 thickness ratio, and A_1+A_2 thickness are plotted against soil age[1] and the relevant regression curves and correlation coefficients (r) are shown. From both the table and the figures, the following points emerge:

1. For both the linear and non-linear age-parameter correlations, the highest correlation coefficients (and hence highest coefficients of determination) are obtained for B/A_2 horizon thickness ratios, followed in decreasing order by A_2 thickness, A_1+A_2 thickness, A_2/A_1 thickness ratios and A_1 thickness. All these parameters yield correlation coefficients which are significant at the 95 percent confidence level or better. The remaining parameters shown on Table 6.1

---

1. A_1 horizon thickness is equivalent to the depth of the upper boundary of the A_2 horizon; A_1+A_2 thickness is equivalent to the depth of the upper boundary of the B horizon; and A_1+A_2+B horizon thickness equals the total thickness of the solum.

FIGURE 6.1

PLOT OF A_2 HORIZON THICKNESS FOR NEW SOUTH WALES AGAINST SOIL AGE

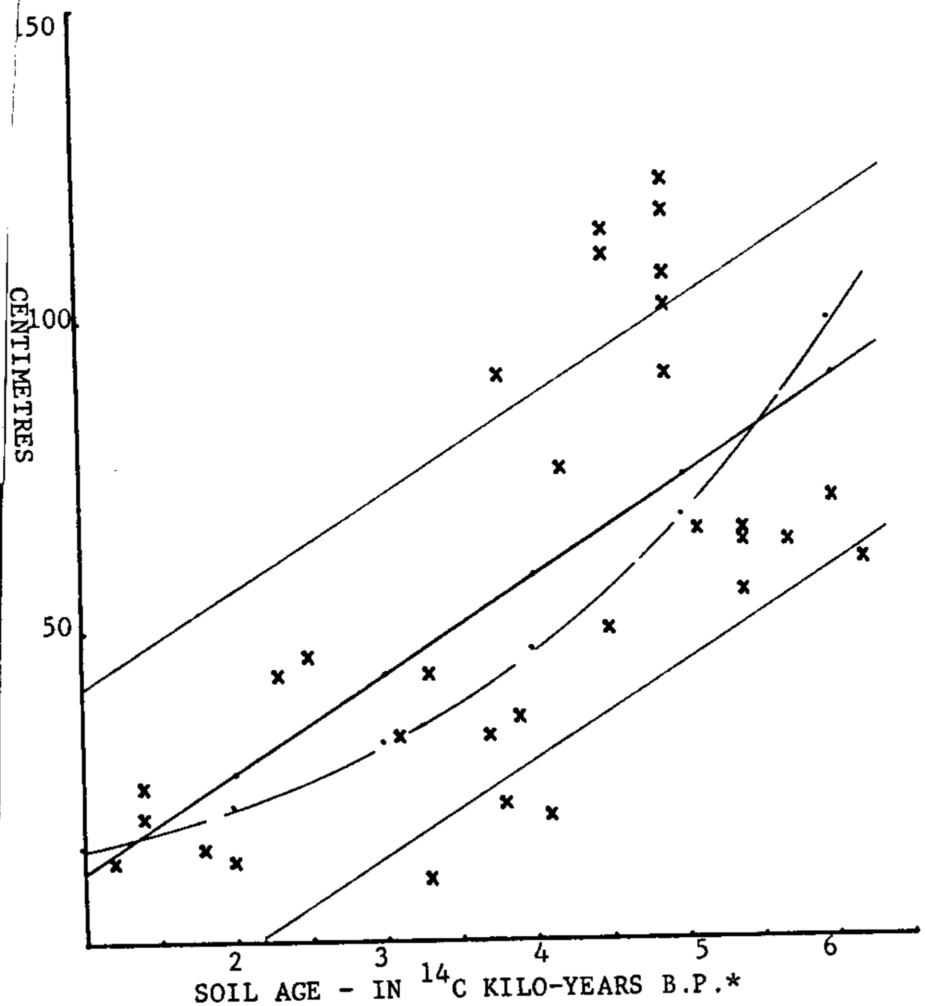


FIGURE 6.2

PLOT OF A_2/A_1 HORIZON THICKNESS RATIOS FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

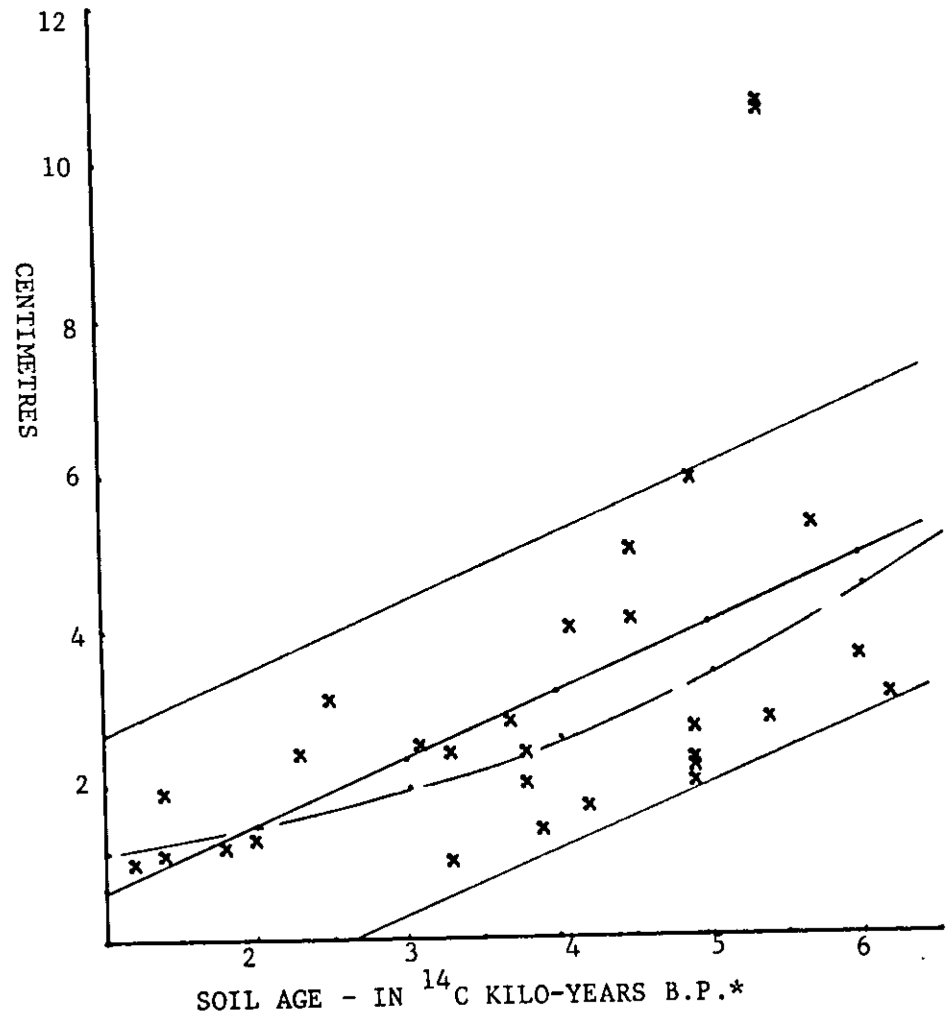


FIGURE 6.3

PLOT OF B/A_2 HORIZON THICKNESS RATIOS FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

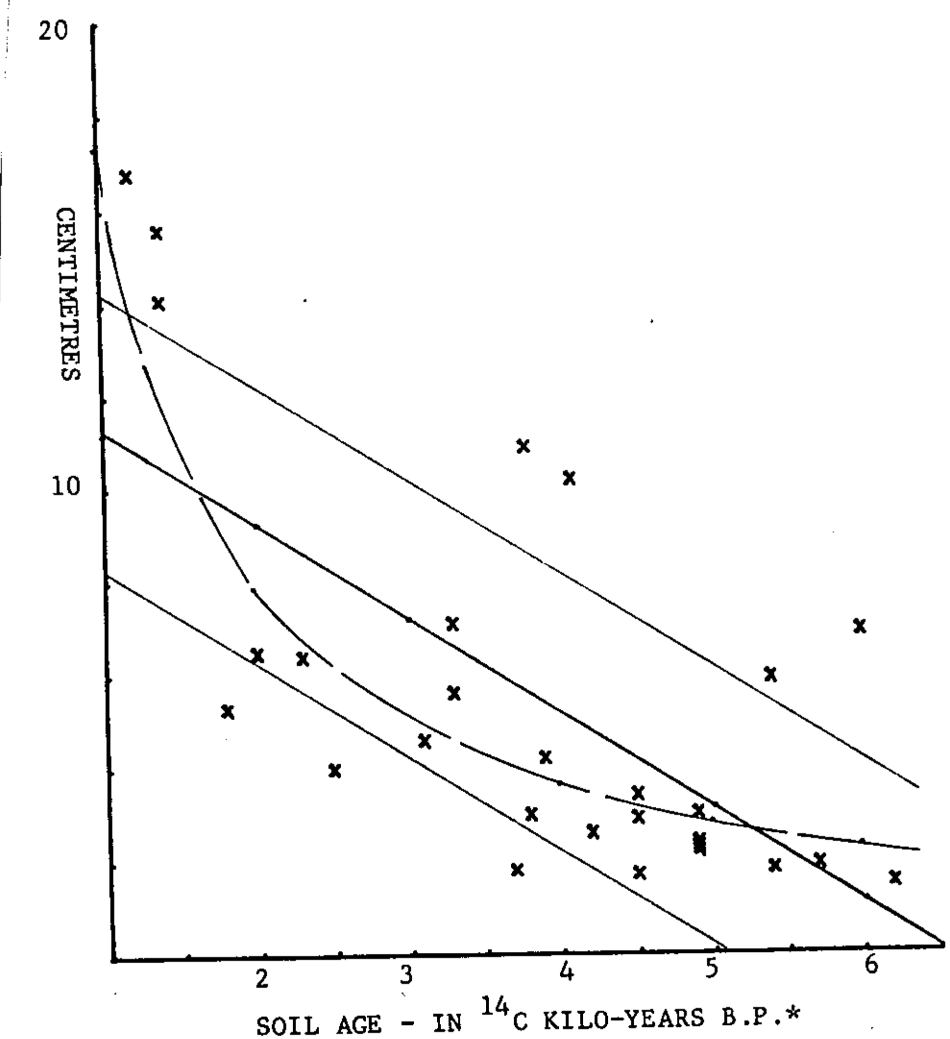
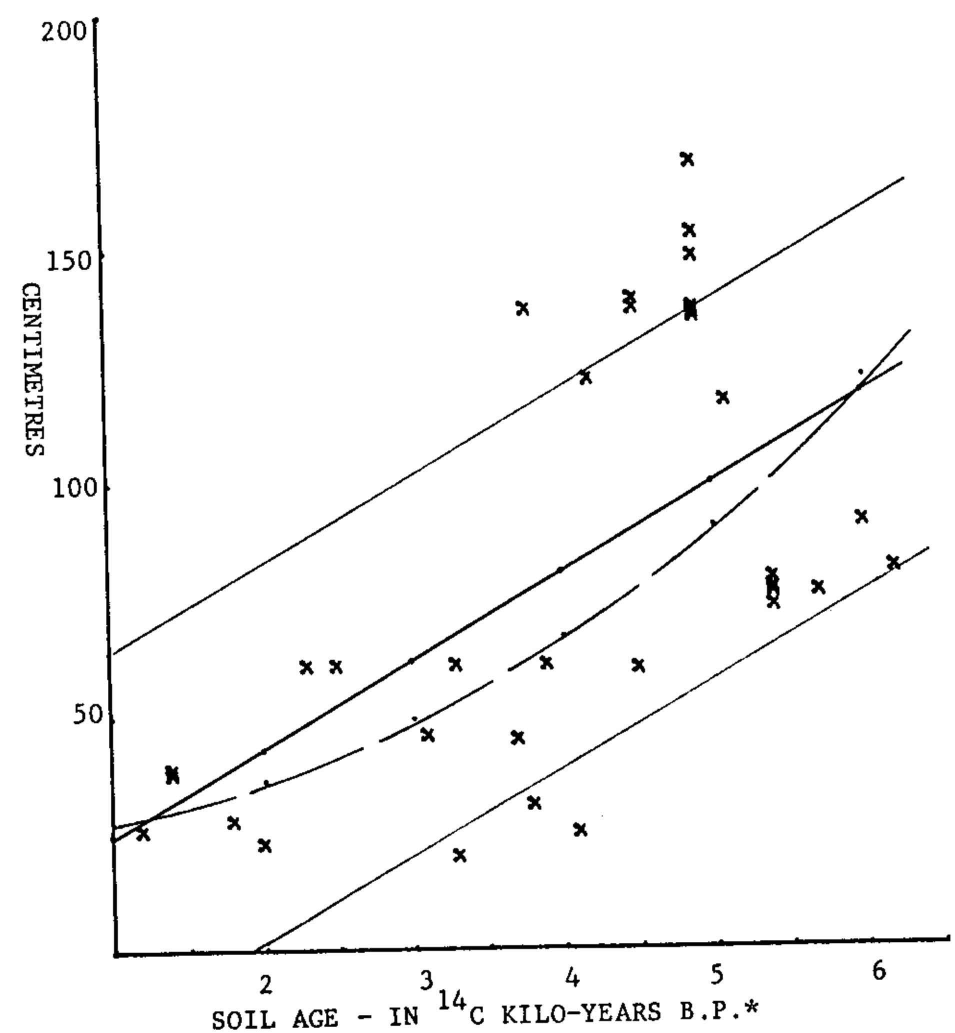


FIGURE 6.4

PLOT OF TOTAL A_1 PLUS A_2 HORIZON THICKNESS FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE



yield low correlation coefficients, which are not statistically significant at the 95 percent confidence level.

2. The trends (for significant correlations) indicated by the regression lines are (with increasing age): an increase in the individual and combined thickness of the A_1 and A_2 horizons; an increase in the A_2/A_1 thickness ratio; and a decrease in the B/A_2 thickness ratio. The thickness of the B horizon increases with age, but the correlation coefficient is low (r=0.062) and the trend is not significant at the 90% confidence level.

3. For six of the eight parameters reported, the maximum non-linear coefficient of determination exceeds the linear r^2 value. In other words, for most of the horizon thickness parameters, non-linear regressions best explain the data variations.

4. Although the regression trends illustrated on the graphs are all statistically significant, the widely spaced confidence limits indicate that, in statistical terms, their predictive reliability is not great.

Using data from Appendix 2, a list was drawn up showing A_1/A_2 and A_2/B horizon boundary characteristics in chronological order. From this list the following observations were made:

1. In relation to the A_2/B horizon boundary, a clear distinction can be drawn between those profiles younger than 4500 ^{14}C yrs BP*, and those that are older. The former profiles display only *gradational-even* boundaries,

while the latter have either *sharp-even*, *sharp-irregular* or *gradational-irregular* boundaries, and may be highly convoluted (Paton *et al.*, 1976; Stace *et al.*, 1968). Definitions of these boundary configurations were given in Chapter Four.

2. With the exception of Disaster Bay Profile 2B and Rheban Profile 3, all profiles display a *gradational-even* A_1/A_2 boundary, regardless of profile age.

6.2.2 Dominant Horizon Colour

The Munsell colour notations relating to dominant horizon colour (see Appendix 2) were analysed for temporal trends by projecting their three colour components, *hue*, *value* and *chroma*, as a three dimensional matrix (cubic colour solid), so that an individual colour notation is located at a unique point in relation to the three axes. To facilitate calculations, a cubic (rather than the more usual cylindrical) solid was used, in which 2.5 *hue* units were equal to one axis unit, and one *value* and one *chroma* unit were also equal to one axis unit.

For each New South Wales soil profile, differences in dominant colour between the A_2 and B horizons, and the B and C horizons, were calculated as *colour distances* within the colour solid, using only axis-parallel distances to join the points by the shortest route.

The calculated distances for the A_2/B colour contrasts and the B/C colour contrasts were correlated with soil age (results in Table 6.2) and plotted against soil age in Figures 6.5 and 6.6. A linear regression line is shown in both figures, together with a power regression curve in Figure 6.5, as this function yielded the highest coefficient of determination for the A_2/B horizon colour contrast.

Temporal trends in soil horizon colour contrasts can be recognized in the figures. For the A_2/B colour contrast, the data variation is best explained by a power curve ($y=0.0006x^{1.041}$) where the correlation coefficient (r) is 0.744 (55 percent of colour data variation is explained). This curve indicates an increase in colour contrast between the A_2 and B horizons, with increasing soil age; the estimated colour differences is 0.84 units in a 1000 year old soil, which rises to 5.4 units in a 6000 year old soil. In relation to the B/C colour contrast (Figure 6.6) the highest coefficient of determination ($r^2=0.474$) was obtained for a linear regression ($y=0.001x^{-1.471}$). The indicated trend is towards an increase in colour contrast between the B and C horizons as profile age increases, with a 2000 year old soil exhibiting a B/C colour difference of only 0.56 units, and a 6000 year soil a difference of 4.63 units. Thus, in terms of these temporal trends, a greater colour contrast should develop between the A_2 and B horizons of a barrier soil, than between the B and C horizons, as it gets older.

6.2.3 Horizon Texture

A temporal trend was not evident in the field texture determinations as all A_1, A_2 and B horizons were classed as

TABLE 6.2

AGE-DOMINANT HORIZON COLOUR DIFFERENCE CORRELATION COEFFICIENTS, COEFFICIENTS OF DETERMINATION, AND STATISTICAL SIGNIFICANCE

HORIZON RATIO	CORRELATION COEFFICIENT	COEFFICIENT OF DETERMINATION (LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?	MAXIMUM CORRELATION COEFFICIENT (NON-LINEAR)	MAXIMUM COEFFICIENT OF DETERMINATION (NON-LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?
A_2/B	0.678	0.460	YES	0.745 (Power)	0.554	YES
B/C	0.688	0.474	YES	0.653 (Exponential)	0.426	YES

FIGURE 6.5

PLOT OF A_2/B HORIZON DOMINANT COLOUR CONTRAST FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

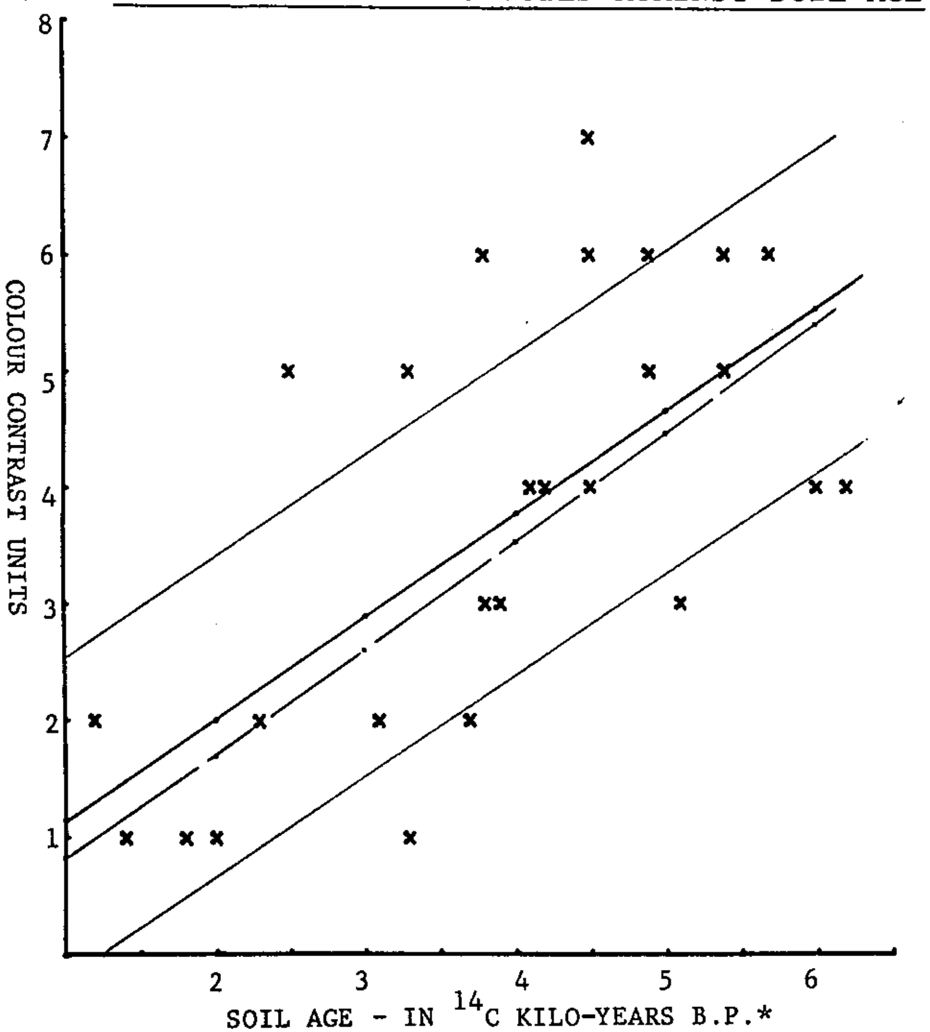
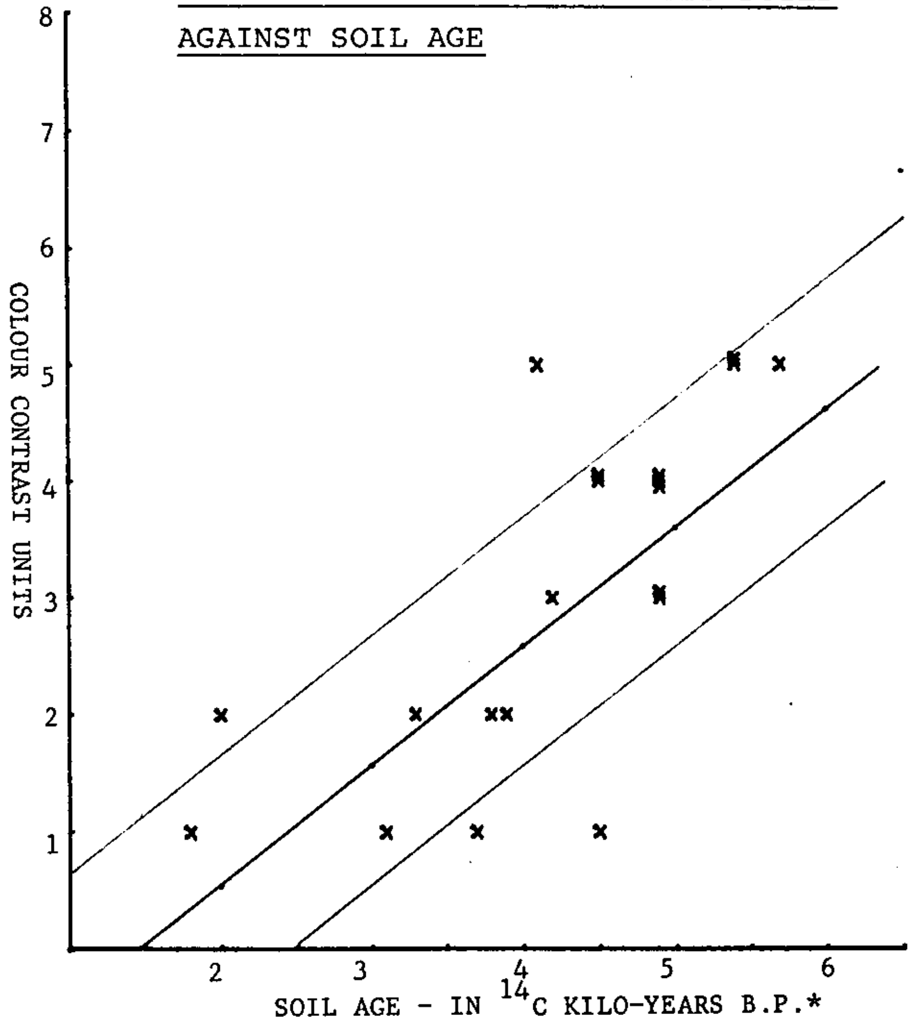


FIGURE 6.6

PLOT OF B/C HORIZON DOMINANT COLOUR CONTRAST FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE



having a *sand* texture (see Appendix 2). Mechanical analyses indicated that the non-organic silt and clay fraction in the soils was generally non-existent (see Chapter Three).

6.2.4 Horizon Structure

All soil horizons examined were classed as *apedal* (see Appendix 2), with all A_1, A_2 and C horizons classed as *apedal single grain.* On the other hand, the New South Wales B horizons were categorized as either *apedal single grain* or *apedal massive,* the latter term applying to any B horizon showing evidence of appreciable consolidation by intergranular material. From an examination of Appendix 2 it is evident that all soil profiles younger than 4500 ^{14}C yrs* are classed as having apedal single grain B horizons, while nearly all profiles older than 4500 ^{14}C yrs* have apedal massive B horizons (at least in part). The exceptions to the trend are Moruya 3B, which is 4500 yrs* old and is therefore a marginal case, and Woy Woy 5, in which most of the B horizon was beneath the shallow watertable, and therefore not observed.

6.2.5 Shell $CaCO_3$ Reaction

The results of the field tests for the presence of residual marine shell in the soil profiles are included with the profile descriptions in Appendix 2. No general temporal trends are evident in these results, in fact, only soil samples from the Woy Woy and Moruya barrier systems yielded positive results to the test. However, within the latter profiles, the depth to shell-bearing sediment does increase with increasing soil age, as is indicated by a comparison of Appendices 2-11 to 2-14, and 2-17 to 2-19. The lack of shell in the other barrier profiles, together with the increase in the depth to shell with soil age, would seem to indicate that progressive leaching of shell from the soils occurs with time, and that the amount of residual shell at any depth probably depends on i) the initial concentration, and ii) the age of the deposit. In the present study, the method of shell detection, the age of the soils, and/or the initial shell concentration in the sediments, have resulted in too few data to permit reliable shell leaching rates to be determined.

6.2.6 Soil Reaction (pH)

Average pH values for the A_1, A_2, B and C horizons of the New South Wales profiles have been correlated with soil age and regression functions calculated. Both linear and non-linear regressions were used (results in Table 6.3), but as the former yielded the highest coefficients of determination, only the linear regression lines and associated coefficients are shown on the scattergrams in Figures 6.7 to 6.10. In these figures, the regression lines explain differing proportions of the pH data variation, ranging from 35 to 84 percent. However, the regression lines indicate that the same general age - pH trend may be recognized in each horizon, namely, that average horizon pH decreases with increasing soil age. In other words, each horizon (and consequently the soil profile as a whole) becomes more acidic as it becomes older: average A_1, A_2 and B horizon pH values in 1000 and 6000 ^{14}C year-old soils differ by about 2 pH units,

TABLE 6.3

AGE-HORIZON pH CORRELATION COEFFICIENTS, COEFFICIENTS OF DETERMINATION, AND STATISTICAL SIGNIFICANCE

HORIZON	CORRELATION COEFFICIENT	COEFFICIENT OF DETERMINATION	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?	MAXIMUM CORRELATION COEFFICIENT (NON-LINEAR)	MAXIMUM COEFFICIENT OF DETERMINATION (NON-LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?
A_1	0.594	0.353	YES	0.576 (Power)	0.332	YES
A_2	0.622	0.387	YES	0.570 (Power)	0.325	YES
B	0.721	0.519	YES	0.666 (Power)	0.443	YES
C	0.915	0.838	YES	0.877 (Power)	0.768	YES

FIGURE 6.7

PLOT OF AVERAGE A_1 HORIZON SOIL REACTION VALUES (pH) FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

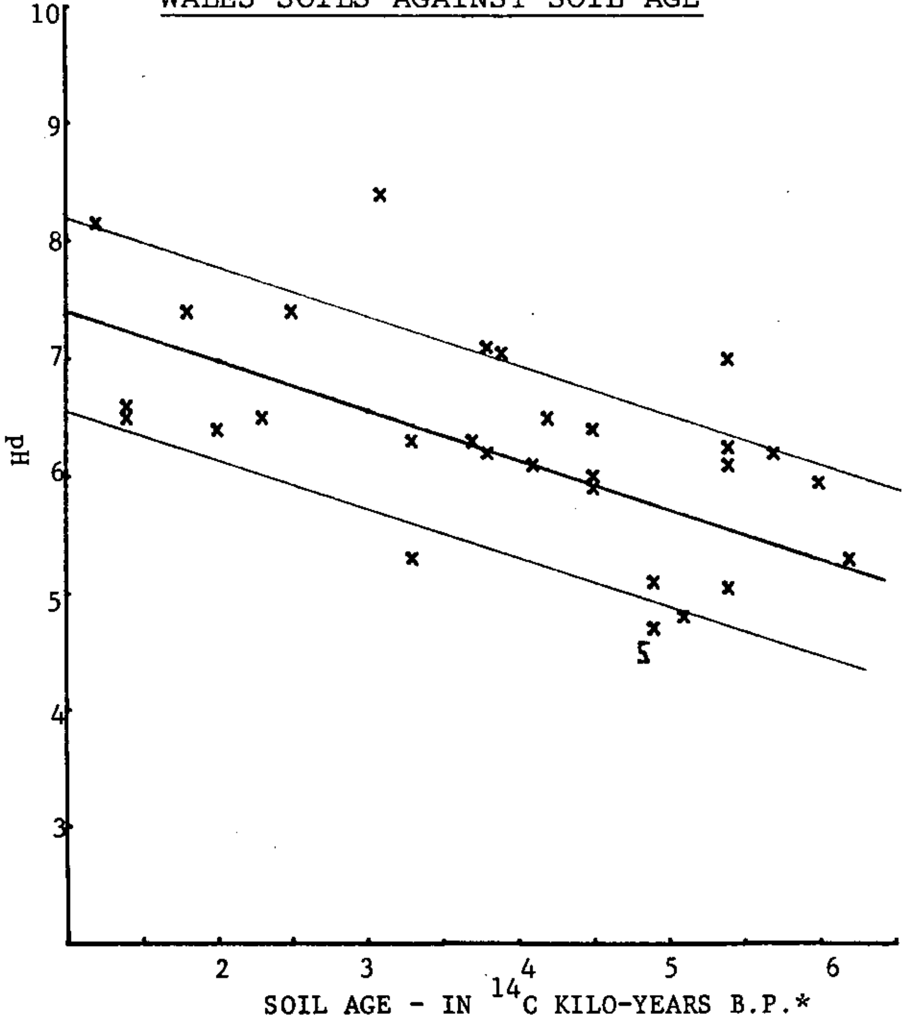


FIGURE 6.8

PLOT OF AVERAGE A_2 HORIZON SOIL REACTION VALUES (pH) FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

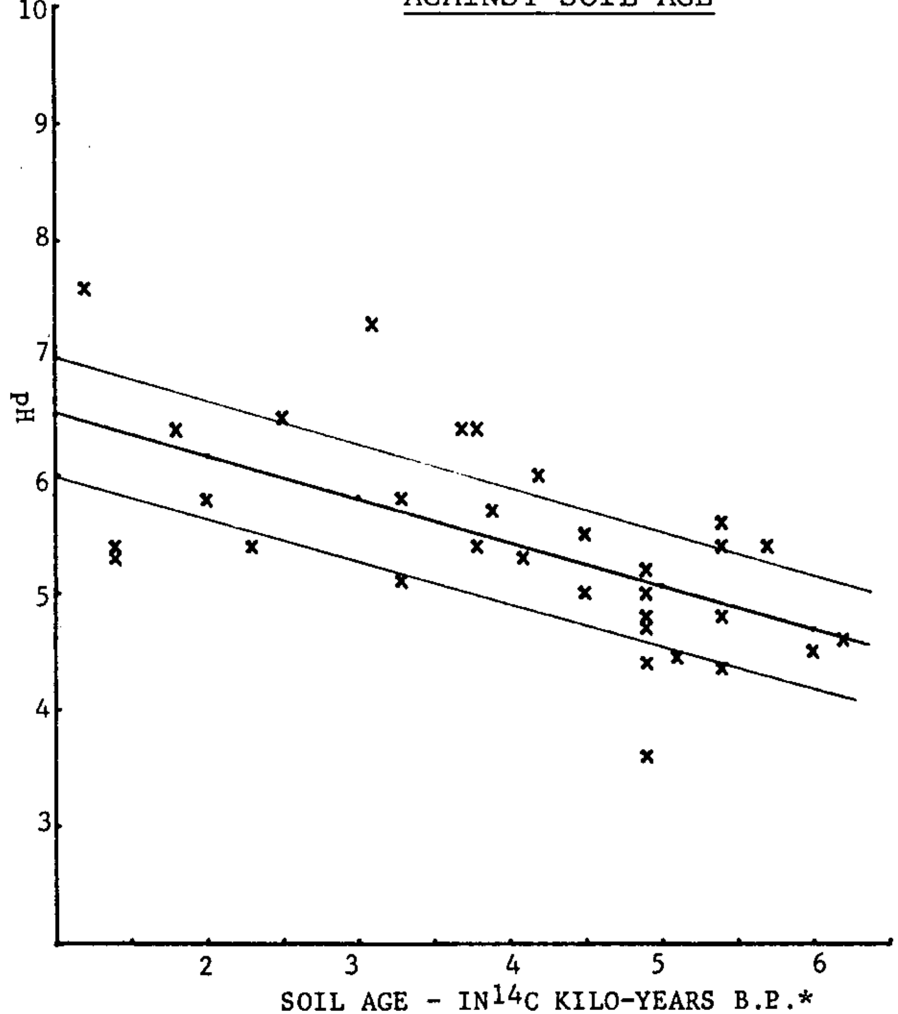


FIGURE 6.9

PLOT OF AVERAGE B HORIZON SOIL REACTION VALUES (pH) FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

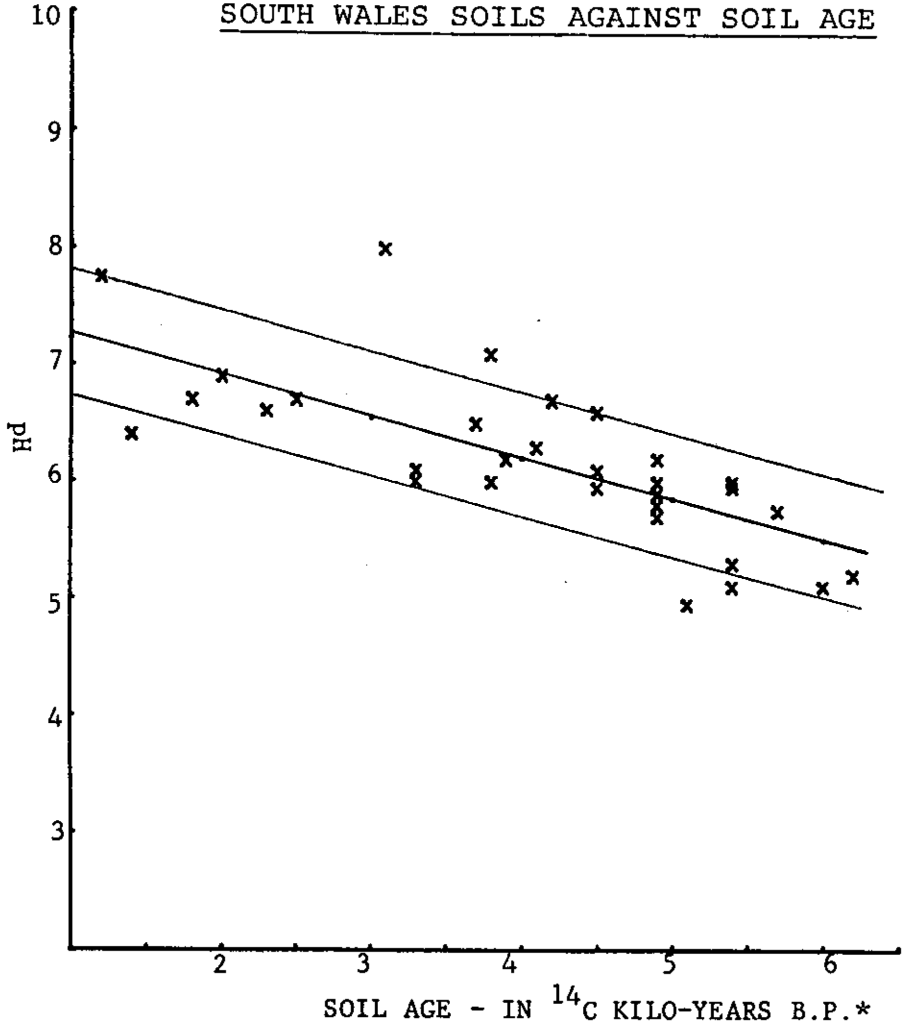
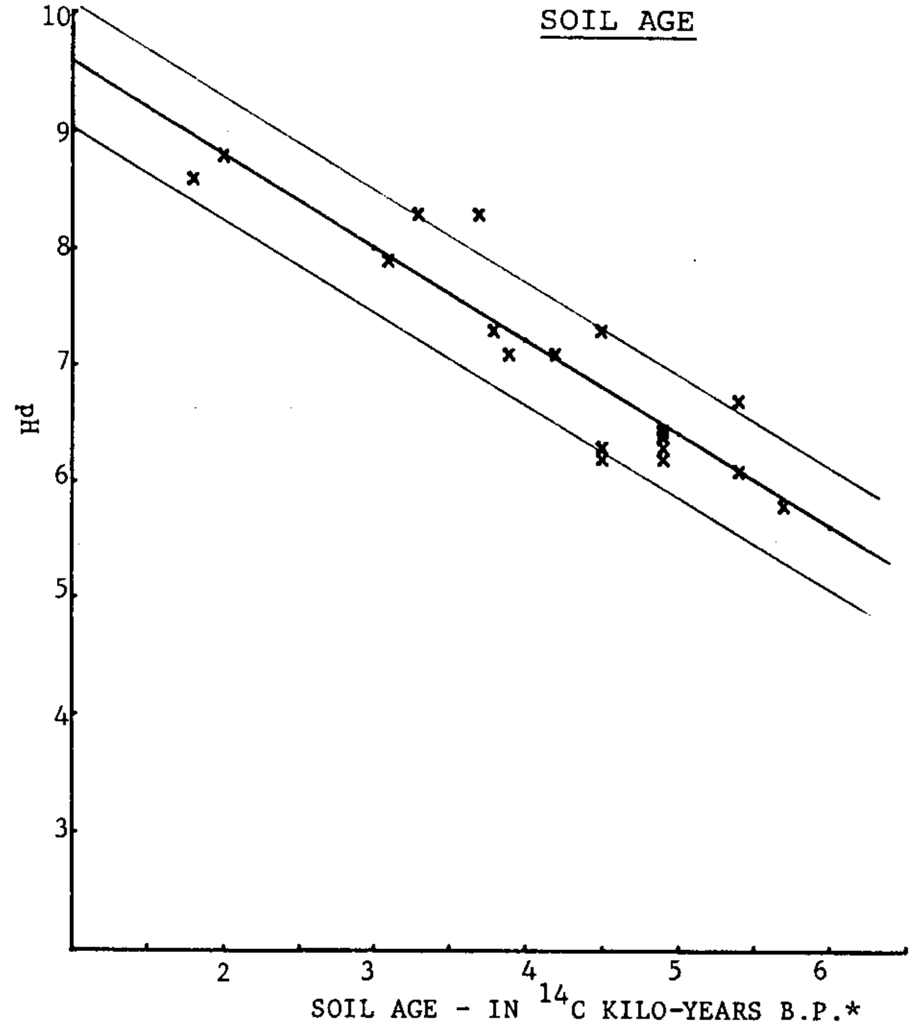


FIGURE 6.10

PLOT OF AVERAGE C HORIZON SOIL REACTION VALUES (pH) FOR NEW SOUTH WALES AGAINST SOIL AGE



and C horizon values differ by about 4 pH units. However, pH differences between horizons are maintained in profiles of all ages (compare Figures 6.7, 6.8, 6.9 and 6.10).

6.3 ORGANIC MATTER

Four aspects of the organic matter content of the New South Wales barrier soils were examined for temporal trends. These O.M. parameters are: content of the near-surface soil sample, average content of the three shallowest soil samples, average of the three highest B horizon contents, and the average content of the entire soil profile. Each parameter was correlated with soil age (results given in Table 6.4) and regression functions were determined. These are shown in Figures 6.11, 6.12, 6.13 and 6.14.

From an examination of Table 6.4 and the scattergrams, it is possible to conclude that temporal trends are not evident in the organic matter parameters, with the exception of the B horizon content, which increases directly with soil age. This trend reflects the higher levels of illuviated organics in the B horizons of the older profiles, and supports the findings of other investigators (e.g., Franzmeier, Whiteside and Mortland, 1963; Dickson and Crocker, 1954; Syers, Adams and Walker, 1970).

6.4 CATION CONCENTRATIONS

A range of parameters have been calculated from the New South Wales cation data (in Appendix 4) and correlated with soil age. Linear and non-linear regression functions have also been determined. For each cation (Fe, Mn, Al, Ca,

TABLE 6.4

AGE-ORGANIC MATTER CONTENT CORRELATION COEFFICIENTS, COEFFICIENTS OF DETERMINATION, AND STATISTICAL SIGNIFICANCE

SOIL SAMPLES	CORRELATION COEFFICIENT	COEFFICIENT OF DETERMINATION (LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL	MAXIMUM CORRELATION COEFFICIENT (NON-LINEAR)	MAXIMUM COEFFICIENT OF DETERMINATION (NON-LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?
SURFACE	0.011	0.0001	NO	0.086 (Power)	0.007	NO
AVERAGE OF SHALLOWEST THREE	0.197	0.039	NO	0.117 (Exponential)	0.014	NO
B HORIZON AVERAGE HIGHEST THREE VALUES	0.687	0.4725	YES	0.752 (Power)	0.565	YES
AVERAGE WHOLE PROFILE	0.164	0.027	NO	0.168 (Exponential)	0.028	NO

FIGURE 6.11

PLOT OF NEAR-SURFACE ORGANIC MATTER CONTENT FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

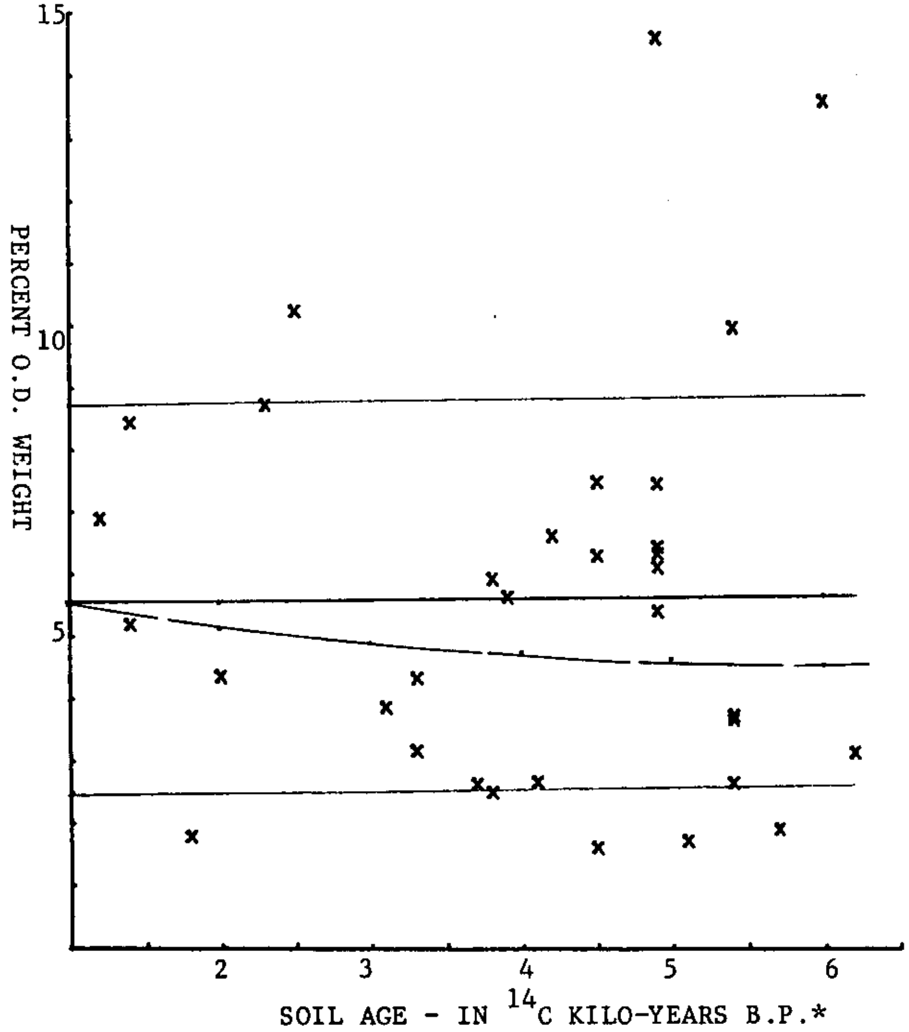


FIGURE 6.12

PLOT OF AVERAGE A_1 HORIZON ORGANIC MATTER CONTENT FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

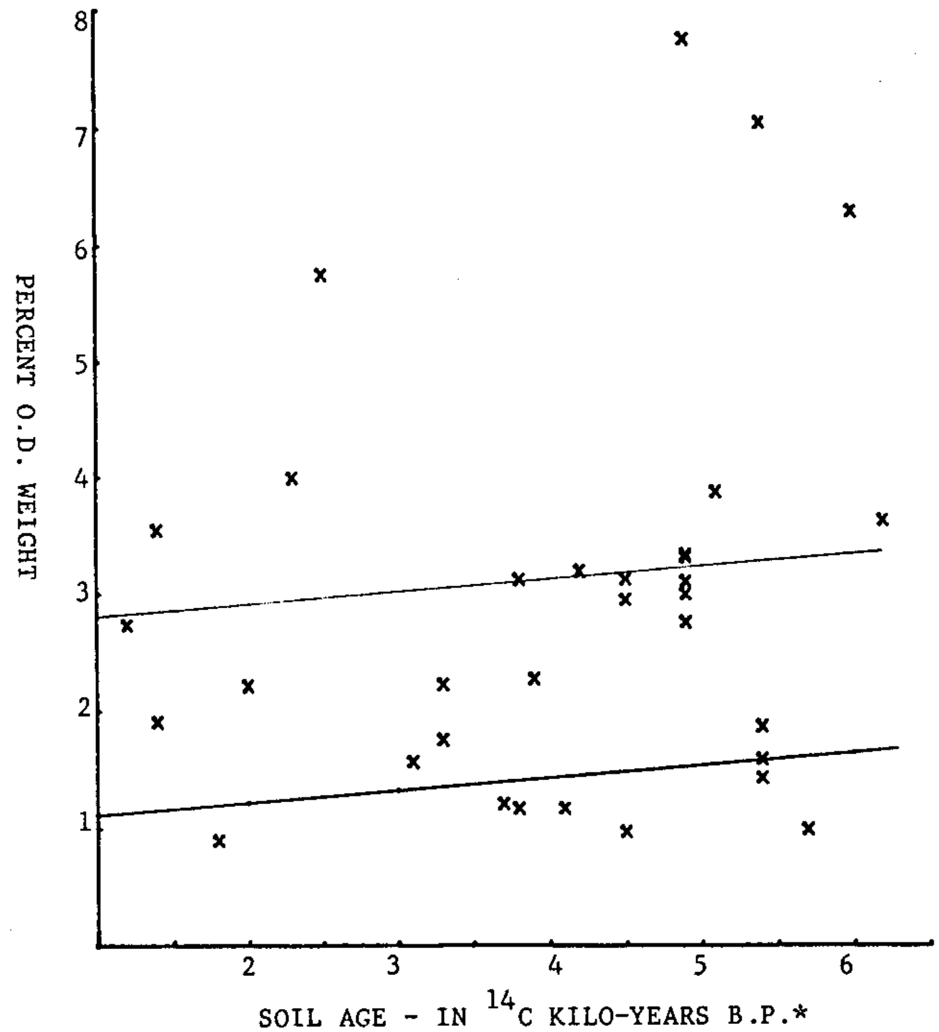


FIGURE 6.13

PLOT OF B HORIZON ORGANIC MATTER CONTENT FOR NEW SOUTH WALES AGAINST SOIL AGE

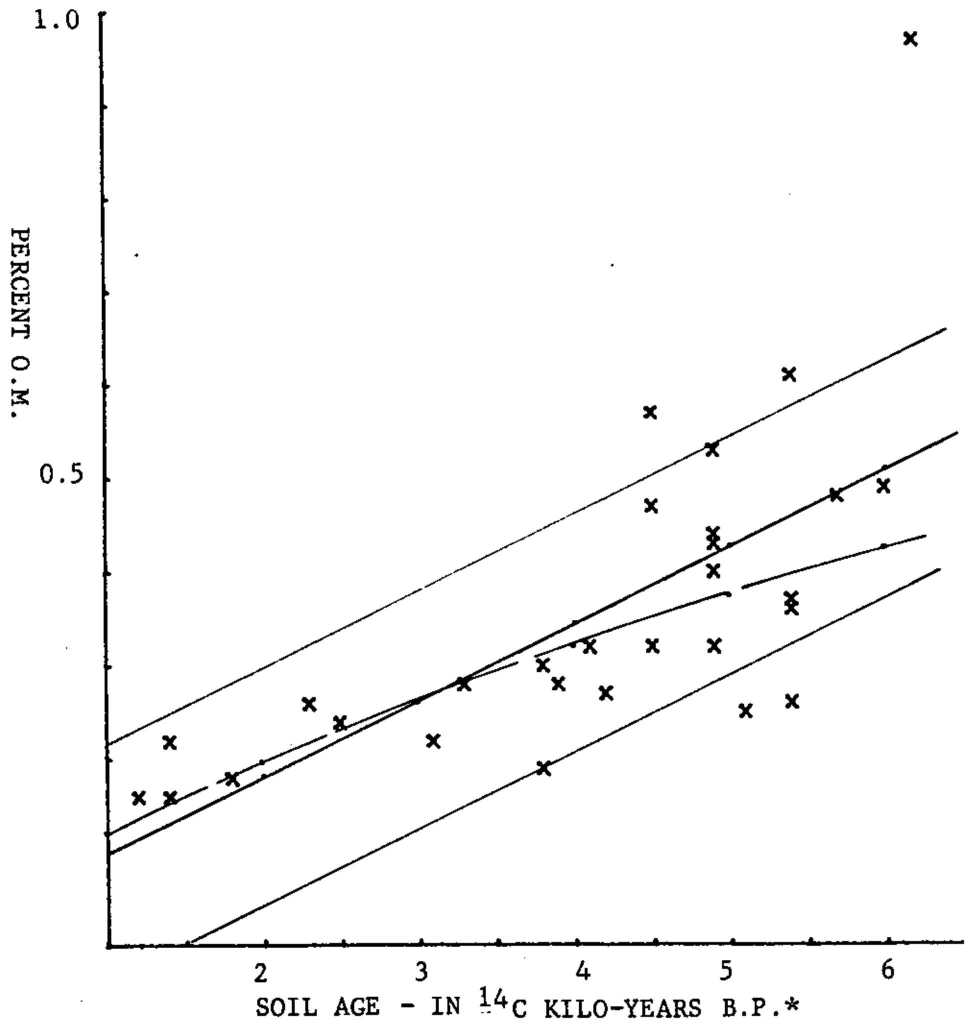
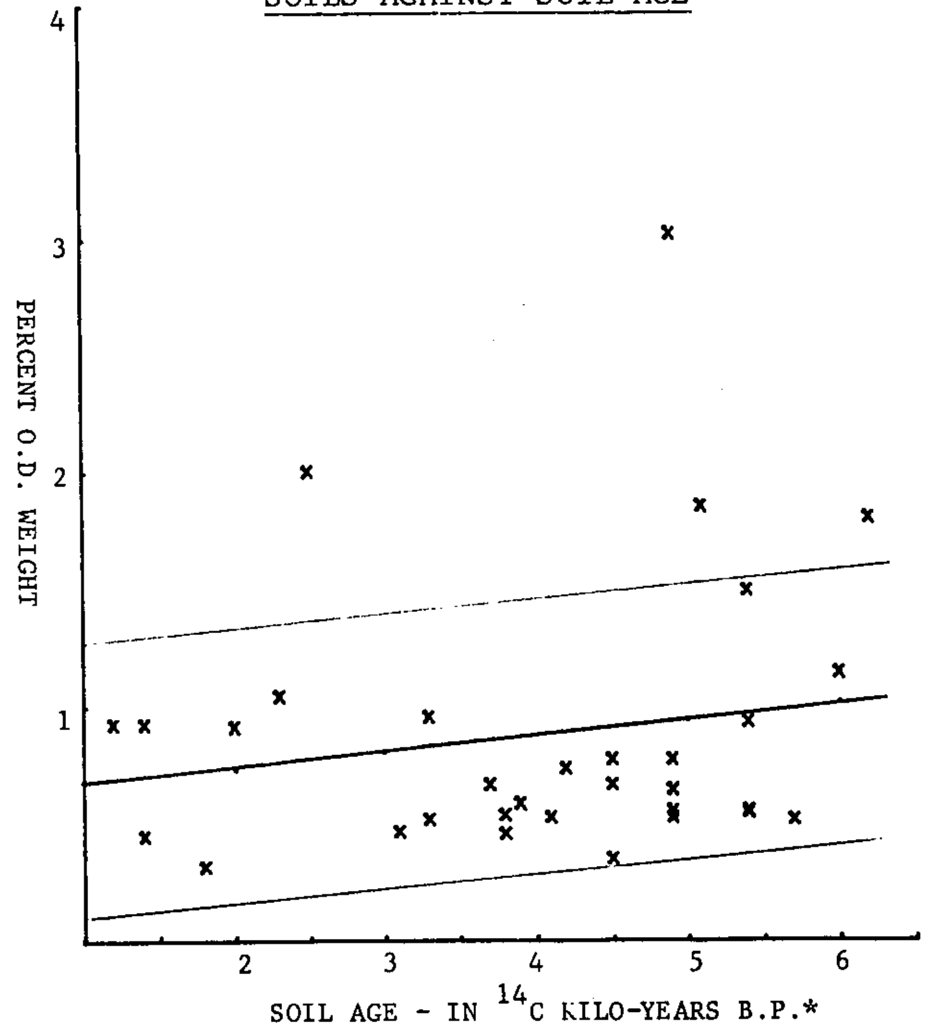


FIGURE 6.14

PLOT OF AVERAGE PROFILE ORGANIC MATTER CONTENT FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE



Mg, Na) the following parameters were derived:

1. Average cation concentration in the A_1, A_2 and B horizons.

2. Ratio of average A_1 horizon cation concentration to average A_2 horizon concentration.

3. Ratio of average B horizon concentration to average A_2 horizon concentration.

4. Sum of the A_1/A_2 and B/A_2 ratios.

The parameters are therefore capable of monitoring both changes in the cation content of each horizon, and the degree of cation differentiation between the A_1, A_2 and B horizons. Results of the age regressions for each cation are discussed below.

6.4.1 Iron

Table 6.5 presents the statistics calculated from the various iron parameter-soil age correlations and regressions. From the table it is apparent that all the correlation coefficients are low, with little of the parameter variation explained by the regression lines, either linear and non-linear. The B/A_2 iron ratio gives the highest coefficient of determination for both linear and non-linear regressions (r^2=0.268). The scattergram for this parameter is shown in Figure 6.15; age trends indicated by both the linear and power regressions are for increased B/A_2 horizon differentiation of iron, with increasing soil age.

6.4.2 Manganese.

The results of the manganese parameter-age correlations

TABLE 6.5

SOIL AGE-IRON CONCENTRATION CORRELATION COEFFICIENTS, COEFFICIENTS OF DETERMINATION, AND STATISTICAL SIGNIFICANCE

IRON CONCENTRATION PARAMETER	CORRELATION COEFFICIENT	COEFFICIENT OF DETERMINATION (LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?	MAXIMUM CORRELATION COEFFICIENT (NON LINEAR)	MAXIMUM COEFFICIENT OF DETERMINATION (NON-LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?
AVERAGE A_1 HORIZON CONCENTRATION	0.245	0.060	NO	0.071 (Power)	0.005	NO
AVERAGE A_2 HORIZON CONCENTRATION	0.224	0.050	NO	0.045 (Exponential)	0.002	NO
AVERAGE B HORIZON CONCENTRATION	0.357	0.128	YES	0.373 (Power)	0.139	YES
A_1/A_2 RATIO	0.009	0.00009	NO	0.014 (Exponential)	0.0002	NO
B/A_2 RATIO	0.497	0.247	YES	0.518 (Power)	0.268	YES
$A_1/A_2+B/A_2$ RATIO	0.356	0.127	YES	0.390 (Power)	0.152	YES

FIGURE 6.15

PLOT OF IRON B/A_2 RATIOS FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

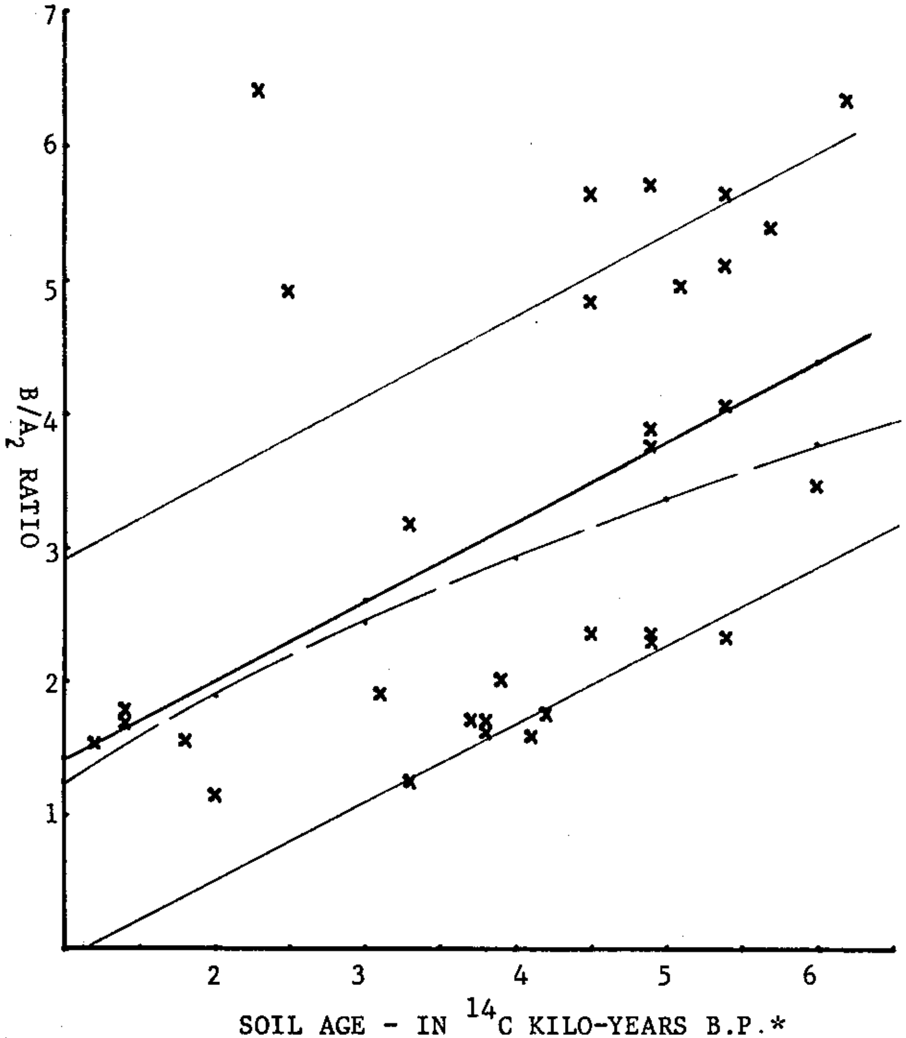


FIGURE 6.16

PLOT OF AVERAGE MANGANESE CONTENT OF B HORIZONS FOR NEW SOUTH WALES AGAINST SOIL AGE

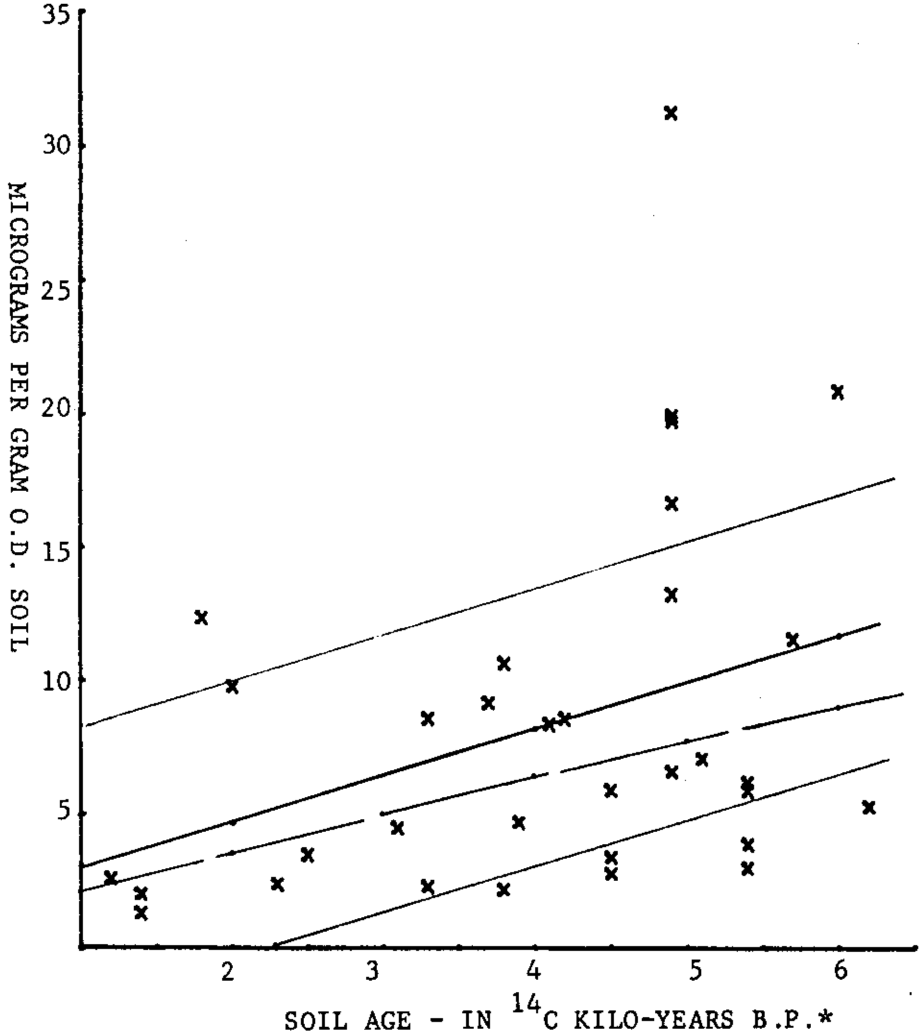


TABLE 6.6

SOIL AGE-MANGANESE CONCENTRATION CORRELATION COEFFICIENTS, COEFFICIENTS OF DETERMINATION, AND STATISTICAL SIGNIFICANCE

MANGANESE CONCENTRATION PARAMETER	CORRELATION COEFFICIENT	COEFFICIENT OF DETERMINATION (LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?	MAXIMUM CORRELATION COEFFICIENT (NON-LINEAR)	MAXIMUM COEFFICIENT OF DETERMINATION (NON-LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?
AVERAGE A_1 HORIZON CONCENTRATION	0.055	0.003	NO	0.152 (Power)	0.023	NO
AVERAGE A_2 HORIZON CONCENTRATION	0.130	0.017	NO	0.374 (Power)	0.140	YES
AVERAGE B HORIZON CONCENTRATION	0.365	0.133	YES	0.471 (Power)	0.222	YES
A_1/A_2 RATIO	0.385	0.148	YES	0.249 (Power)	0.062	NO
B/A_2 RATIO	0.045	0.002	NO	0.045 (Exponential)	0.002	NO
A_1/A_2+B/A_2 RATIO	0.257	0.066	NO	0.205 (Power)	0.042	NO

and regressions are given in Table 6.6. All correlation coefficients and coefficients of determination are low to very low, indicating that little of the variation in the manganese parameters is explained by the fitted curves. However, the trends indicated by the regression curves are for an increase in manganese concentration in the A_1, A_2 and B horizons, and a decrease in the A_1/A_2, B/A_2 and $A_1/A_2+B/A_2$ concentration ratios, as soil age increases. The highest coefficient of determination (r^2=0.222) was obtained for a power curve fitted to the average B horizon concentration data. Figure 6.16 presents the scattergram of this age:parameter plot, with the power regression curve showing an increase in manganese concentration in the B horizon, with increasing soil age.

6.4.3 Aluminium

The results of the aluminium parameter correlations and regressions are given in Table 6.7, and Figures 6.17, 6.18 and 6.19 show the scattergrams and regression lines for the three parameters with the highest coefficients of determination; viz, average B horizon concentration (power regression; r^2=0.329), A_1/A_2 concentration ratio (linear; r^2=0.247) and B/A_2 concentration ratio (power; r^2=0.247). Although these coefficients are still low, they do indicate a more significant trend in the concentration and segregation of this cation over time, than was apparent in the data for either iron or manganese. The regression lines indicate that the average aluminium concentrations in the A_1 and A_2 horizons decrease over time, while the B horizon

TABLE 6.7

SOIL AGE-ALUMINIUM CONCENTRATION CORRELATION COEFFICIENTS, COEFFICIENTS OF DETERMINATION, AND STATISTICAL SIGNIFICANCE

ALUMINIUM CONCENTRATION PARAMETER	CORRELATION COEFFICIENT	COEFFICIENT OF DETERMINATION (LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?	MAXIMUM CORRELATION COEFFICIENT (NON-LINEAR)	MAXIMUM COEFFICIENT OF DETERMINATION (NON-LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?
AVERAGE A_1 HORIZON CONCENTRATION	0.375	0.141	YES	0.313 (Power)	0.098	NO
AVERAGE A_2 HORIZON CONCENTRATION	0.176	0.031	NO	0.022 (Power)	0.001	NO
AVERAGE B HORIZON CONCENTRATION	0.559	0.313	YES	0.574 (Power)	0.329	YES
A_1/A_2 RATIO	0.485	0.235	YES	0.310 (Exponential)	0.096	NO
B/A_2 RATIO	.0.455	0.207	YES	0.497 (Power)	0.247	YES
$A_1/A_2+B/A_2$ RATIO	0.205	0.042	NO	0.195 (Exponential)	0.038	NO

FIGURE 6.17

PLOT OF AVERAGE ALUMINIUM CONTENT OF B HORIZONS FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

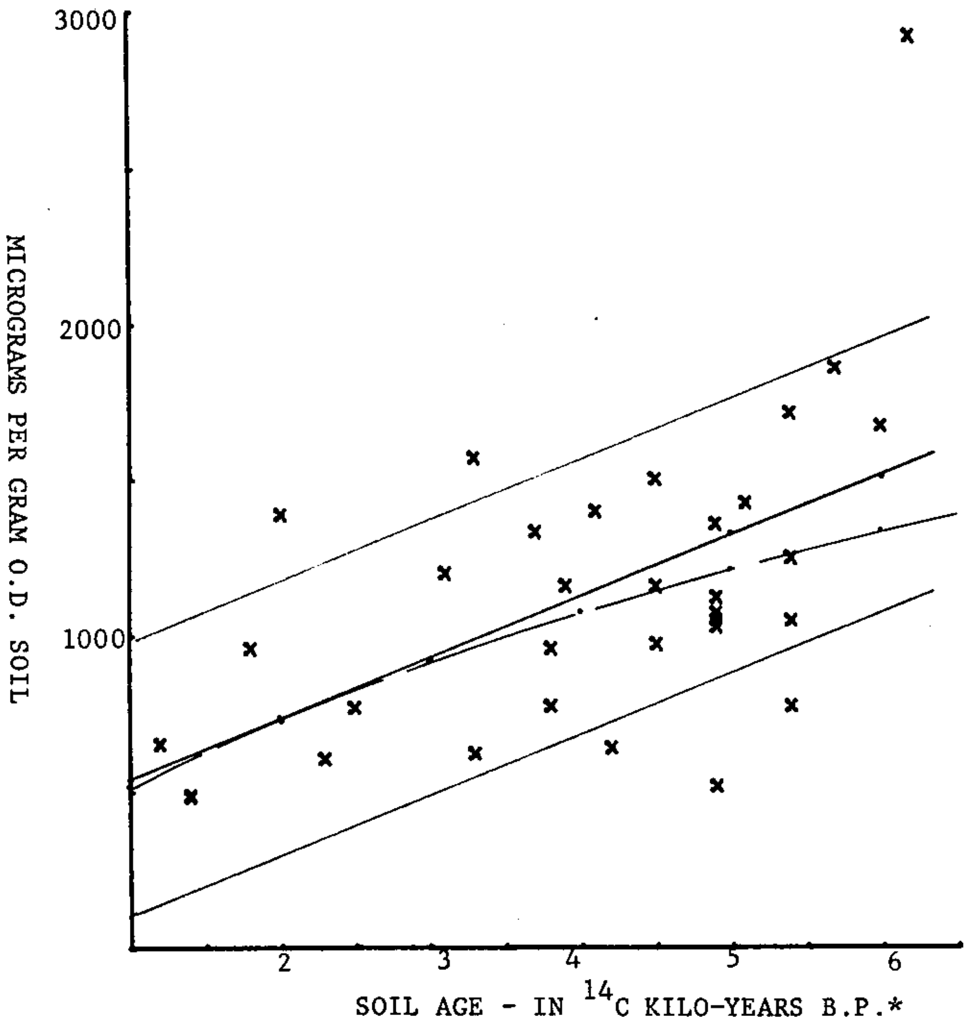


FIGURE 6.18

PLOT OF AVERAGE ALUMINIUM A_1/A_2 RATIOS FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

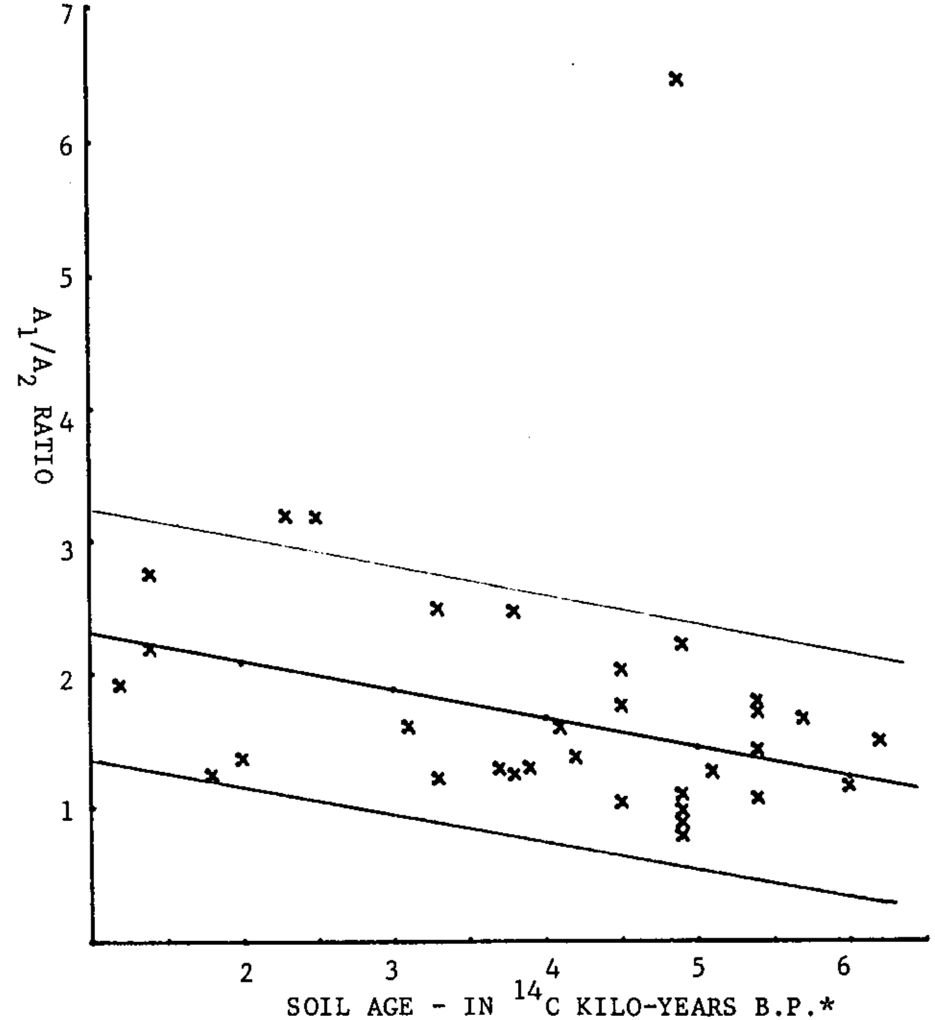
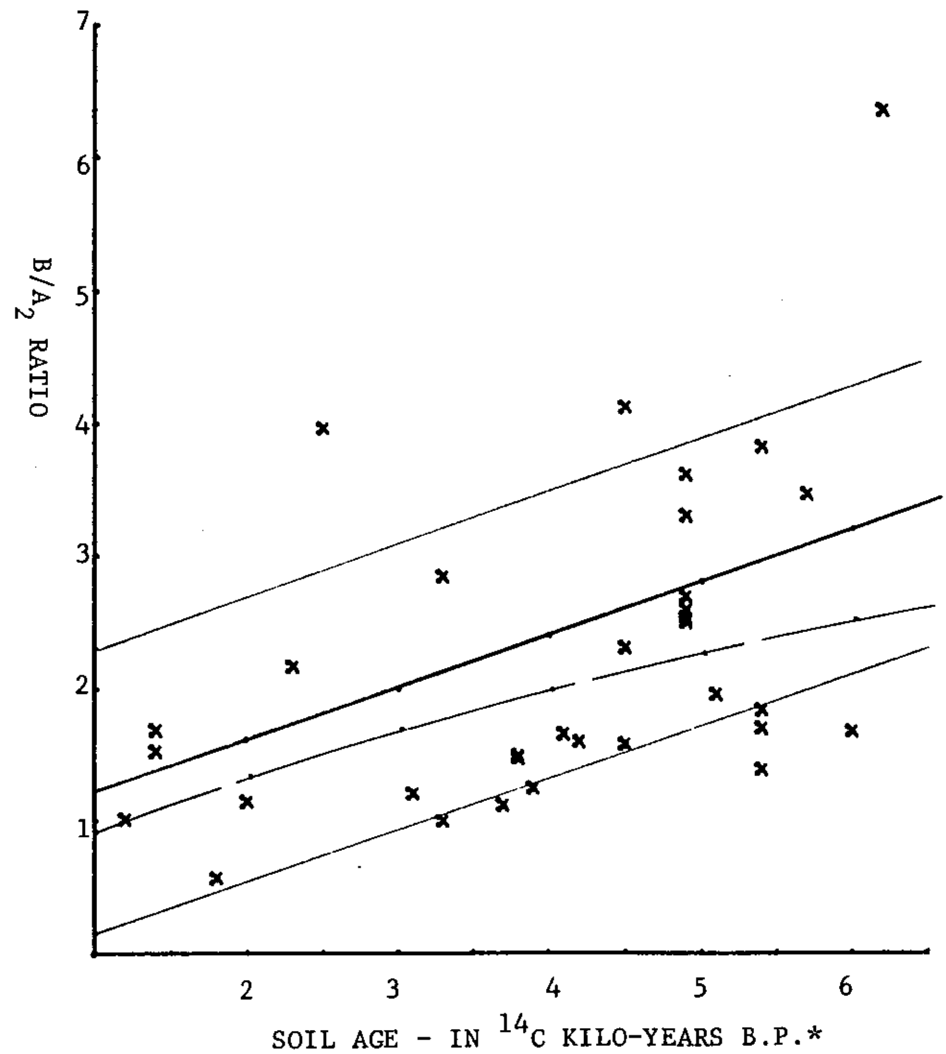


FIGURE 6.19

PLOT OF ALUMINIUM B/A_2 RATIOS FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE



concentrations increase. The A_1/A_2 concentration ratio falls, and the B/A_2 and $A_1/A_2+B/A_2$ ratios both increase, with increasing soil age.

6.4.4 Calcium

Table 6.8 presents the results of the calcium parameter correlation and regression analyses. In this case the A_1 horizon concentration, and the $A_1/A_2+B/A_2$ parameter, both yielded appreciable coefficients of determination (correlation coefficient significant at 95%) and are plotted against soil age in Figures 6.20 and 6.21. The age trend indicated by the calculated regression equations (including those shown in Figures 6.20 and 6.21) is for a decrease in calcium horizon concentrations and horizon differentiation, with increasing profile age. Such a pattern would result from progressive leaching of this base with increasing soil age, as was postulated in Chapter Four.

6.4.5 Magnesium

The correlation coefficients calculated for the magnesium parameter-age correlations are low to moderate. As indicated in Table 6.9, the highest coefficient of determination was obtained for the A_1 concentration data, but this still only explains 23 percent of the variation in that parameter (see age plot for A_1 horizon concentrations in Figure 6.22). However, as with the calcium parameters, all regression equations indicate a general decrease in horizon concentrations and horizon differentiation, with increasing soil age. Again this trend probably reflects progressive leaching of bases from the profiles.

TABLE 6.8

SOIL AGE-CALCIUM CONCENTRATION CORRELATION COEFFICIENTS, COEFFICIENTS OF DETERMINATION, AND STATISTICAL SIGNIFICANCE

CALCIUM CONCENTRATION PARAMETER	CORRELATION COEFFICIENT	COEFFICIENT OF DETERMINATION (LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?	MAXIMUM CORRELATION COEFFICIENT (NON-LINEAR)	MAXIMUM COEFFICIENT OF DETERMINATION (NON-LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?
AVERAGE A_1 HORIZON CONCENTRATION	0.483	0.233	YES	0.592 (Power)	0.350	YES
AVERAGE A_2 HORIZON CONCENTRATION	0.363	0.132	NO	0.274 (Exponential)	0.075	NO
AVERAGE B HORIZON CONCENTRATION	0.348	0.121	NO	0.283 (Power)	0.080	NO
A_1/A_2 RATIO	0.020	0.0004	NO	0.243 (Exponential)	0.059	NO
B/A_2 RATIO	- 0.063	0.004	NO	0.063 (Power)	0.004	NO
$A_1/A_2+B/A_2$ RATIO	0.493	0.243	YES	0.228 (Logarithmic)	0.052	NO

FIGURE 6.20

PLOT OF AVERAGE CALCIUM CONTENT OF A_1 HORIZONS FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

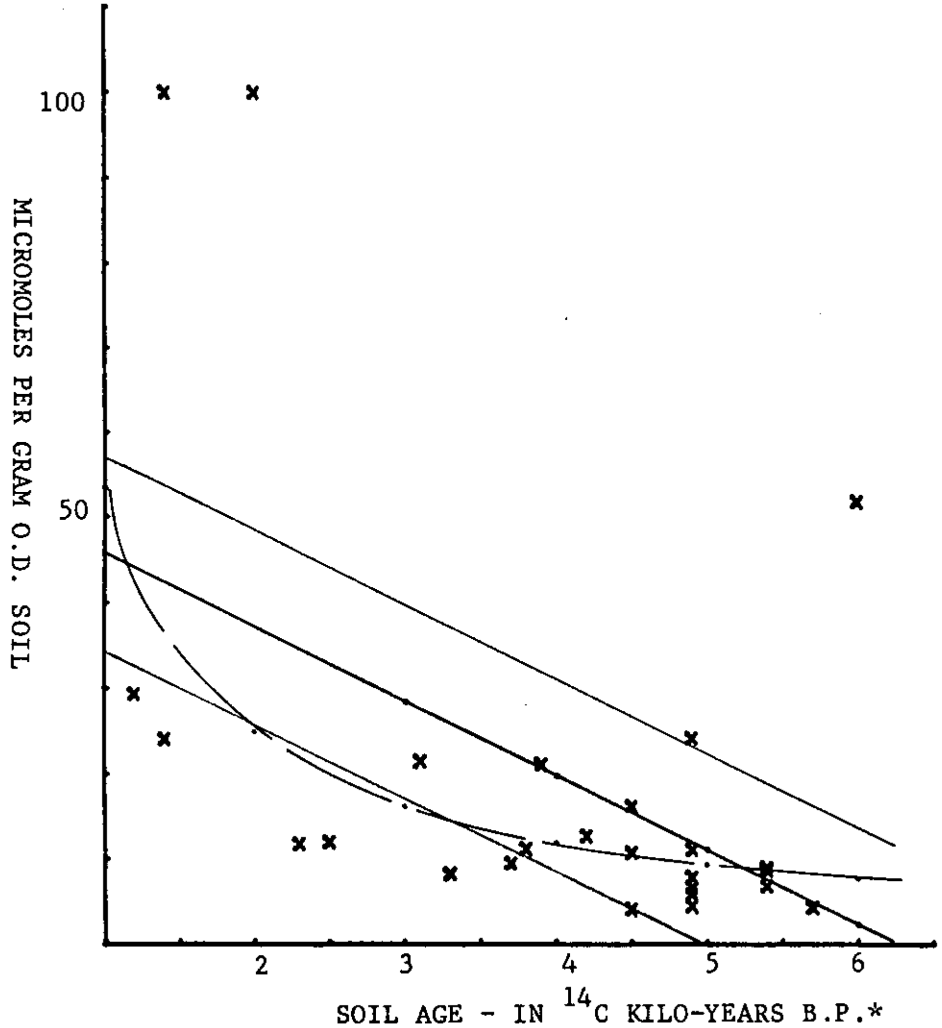


FIGURE 6.21

PLOT OF CALCIUM B/A_2 + A_1/A_2 RATIOS FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

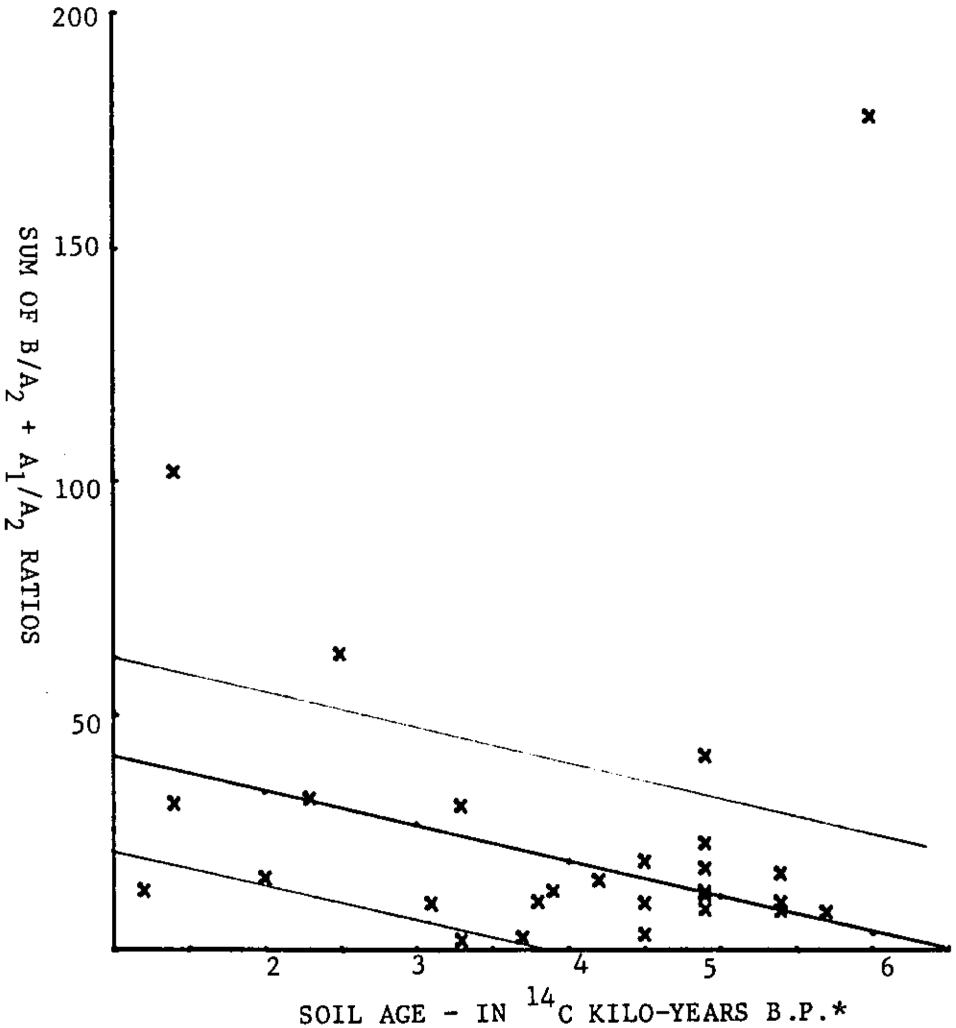


TABLE 6.9

SOIL AGE-MAGNESIUM CONCENTRATION CORRELATION COEFFICIENTS, COEFFICIENTS OF DETERMINATION, AND STATISTICAL SIGNIFICANCE

MAGNESIUM CONCENTRATION PARAMETER	CORRELATION COEFFICIENT	COEFFICIENT OF DETERMINATION (LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?	MAXIMUM CORRELATION COEFFICIENT (NON-LINEAR)	MAXIMUM COEFFICIENT OF DETERMINATION (NON-LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?
AVERAGE A_1 HORIZON CONCENTRATION	0.456	0.208	YES	0.480 (Power)	0.230	YES
AVERAGE A_2 HORIZON CONCENTRATION	0.318	0.101	NO	0.307 (Power)	0.094	NO
AVERAGE B HORIZON CONCENTRATION	0.184	0.034	NO	0.089 (Exponential)	0.008	NO
A_1/A_2 RATIO	0.110	0.012	NO	0.118 (Exponential)	0.014	NO
B/A_2 RATIO	0.387	0.150	YES	0.400 (Power)	0.160	YES
$A_1/A_2+B/A_2$ RATIO	0.022	0.001	NO	0.032 (Power)	0.001	NO

FIGURE 6.22

PLOT OF AVERAGE MAGNESIUM CONTENT OF A_1 HORIZONS FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

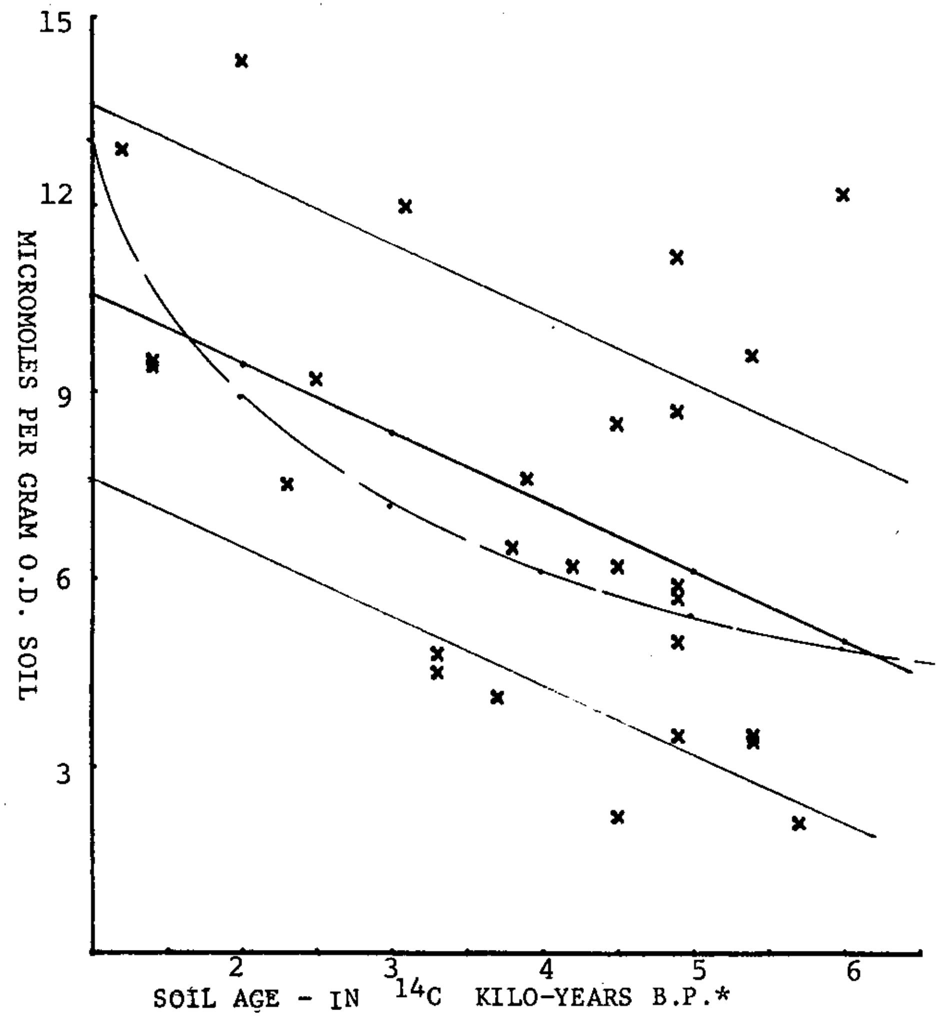


FIGURE 6.23

PLOT OF AVERAGE SODIUM CONTENT OF A_1 HORIZONS FOR NEW SOUTH WALES SOILS AGAINST SOIL AGE

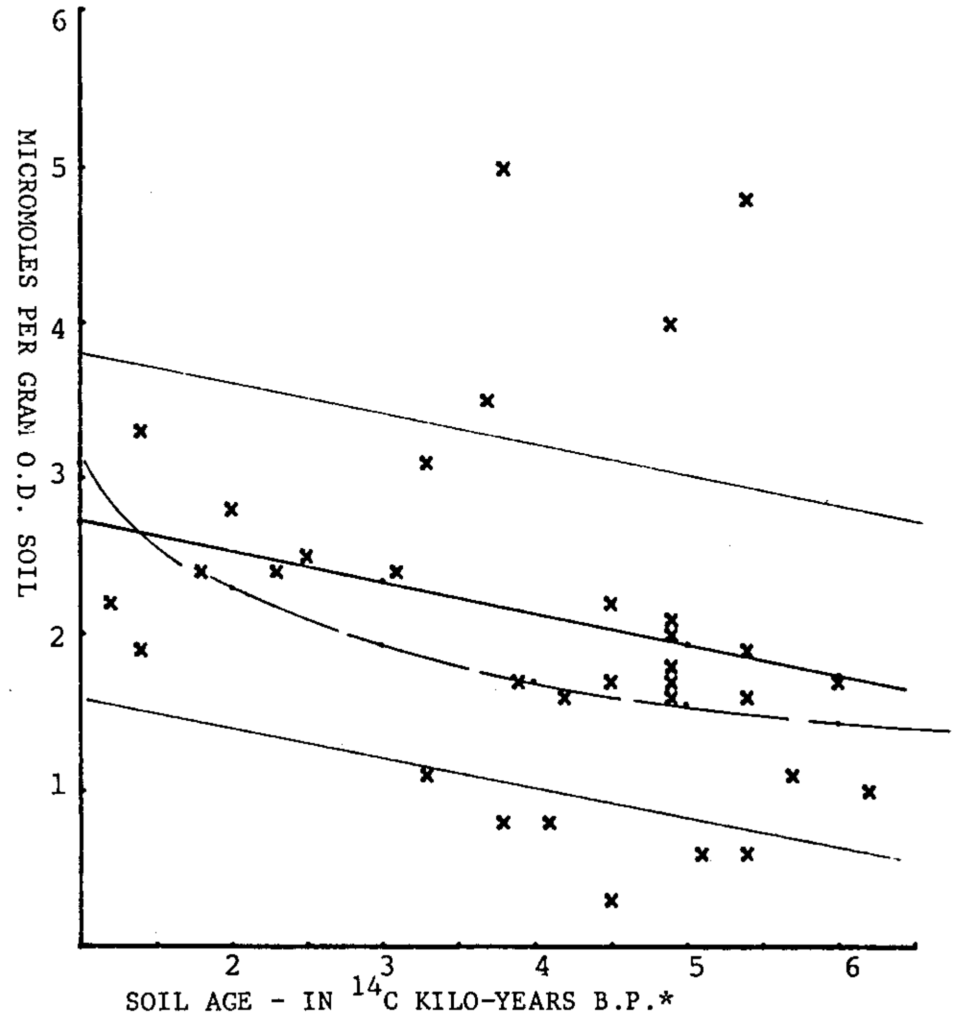


TABLE 6.10

SOIL AGE-SODIUM CONCENTRATION CORRELATION COEFFICIENTS, COEFFICIENTS OF DETERMINATION, AND STATISTICAL SIGNIFICANCE

SODIUM CONCENTRATION PARAMETER	CORRELATION COEFFICIENT	COEFFICIENT OF DETERMINATION (LINEAR)	STATISTICALLY SIGNFICANT AT 95% CONFIDENCE LEVEL?	MAXIMUM CORRELATION COEFFICIENT (NON-LINEAR)	MAXIMUM COEFFICIENTS OF DETERMINATION (NON-LINEAR)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?
AVERAGE A_1 HORIZON CONCENTRATION	0.268	0.072	NO	0.316 (Power)	0.100	NO*
AVERAGE A_2 HORIZON CONCENTRATION	0.122	0.015	NO	0.114 (Power)	0.013	NO
AVERAGE B HORIZON CONCENTRATION	0.110	0.012	NO	0.071 (Power)	0.005	NO
A_1/A_2 RATIO	0.118	0.014	NO	0.167 (Power)	0.028	NO
B/A_2 RATIO	0.110	0.012	NO	0.141 (Exponential)	0.020	NO
$A_1/A_2+B/A_2$ RATIO	0.063	0.004	NO	0.110 (Power)	0.012	NO

* Significant at 90 percent confidence level.

6.4.6 Sodium

As indicated in Table 6.10, all regression coefficients for the sodium parameter-age correlation are low. Only one coefficient of determination explains even 10 percent of the variation in the relevant parameter (A_1 horizon sodium concentrations). The age-A_1 horizon concentration scattergram is presented in Figure 6.23 . The trend indicated by both the linear and power curves is for a slight decrease in sodium concentrations with increasing soil age. Again, this trend is common to all the calculated sodium-age regression equations, with the exception of those applying to the B/A_2 parameter, which show a slight increase with age (see Table 6.10).

6.5 GRAIN SURFACE TEXTURES

Product moment correlation is not an appropriate technique for use with the grain surface textural data because the latter are on a nominal scale. Consequently, Kendall's Correlation Coefficient (τ) has been used to indicate the degree of association between soil age and the various textural counts. The resulting values of τ, and their significance, are given in Table 6.11. Those correlations which yielded a value of τ significant at the 95 per cent confidence level, are presented as regression plots in Figures 6.24, 6.25 and 6.26. From Table 6.11, and the regression plots, three general points emerge:

1. That textural counts for the A_1, A_2 and B horizons yield significant values of τ when correlated with soil age. The A_2/B ratio does not correlate significantly with soil age.

TABLE 6.11

KENDALL'S CORRELATION COEFFICIENT (τ), STATISTICAL SIGNIFICANCE, AND COEFFICIENTS OF DETERMINATION FOR SOIL-AGE TOTAL TEXTURAL COUNT DATA ASSOCIATION

HORIZON	KENDALL'S CORRELATION COEFFICIENT (τ)	SIGNIFICANT[1] AT 95% CONFIDENCE LEVEL?	LINEAR COEFFICIENT OF DETERMINATION	MAXIMUM NON-LINEAR COEFFICIENT OF DETERMINATION
A_1	0.610	YES	0.485	0.394 (Power)
A_2	0.534	YES	0.561	0.601 (Power)
B	0.454	YES	0.638	0.785 (Power)
A_2/Bratio	-0.151	NO	0.067	0.076 (Logarithmic)

1. The following hypotheses were tested:

   H_0: that no relationship exists between soil age and the relevant horizon textural count.

   H_1: that a correlation does exist between soil age and the relevant textural count.

   Note that z was calculated from τ, and used to test the hypotheses.
   The rejection level was set at 95% ($\alpha = 0.05$).

FIGURE 6.24

PLOT OF TOTAL GRAIN SURFACE TEXTURES ON A_1 HORIZON SAMPLES FROM NEW SOUTH WALES AGAINST SOIL AGE

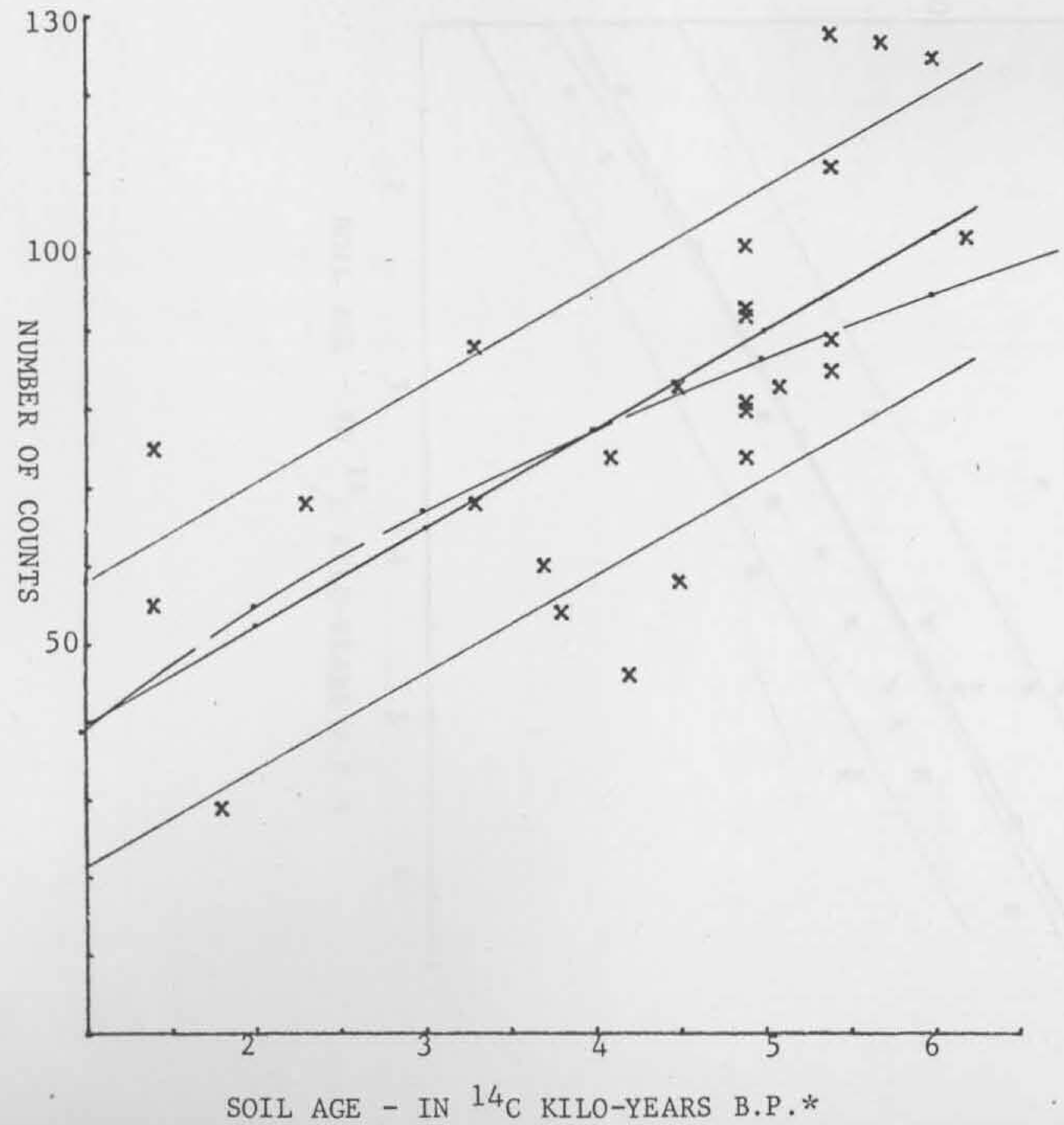


FIGURE 6.25

PLOT OF TOTAL GRAIN SURFACE TEXTURES ON A_2 HORIZON SAMPLES FROM NEW SOUTH WALES AGAINST SOIL AGE

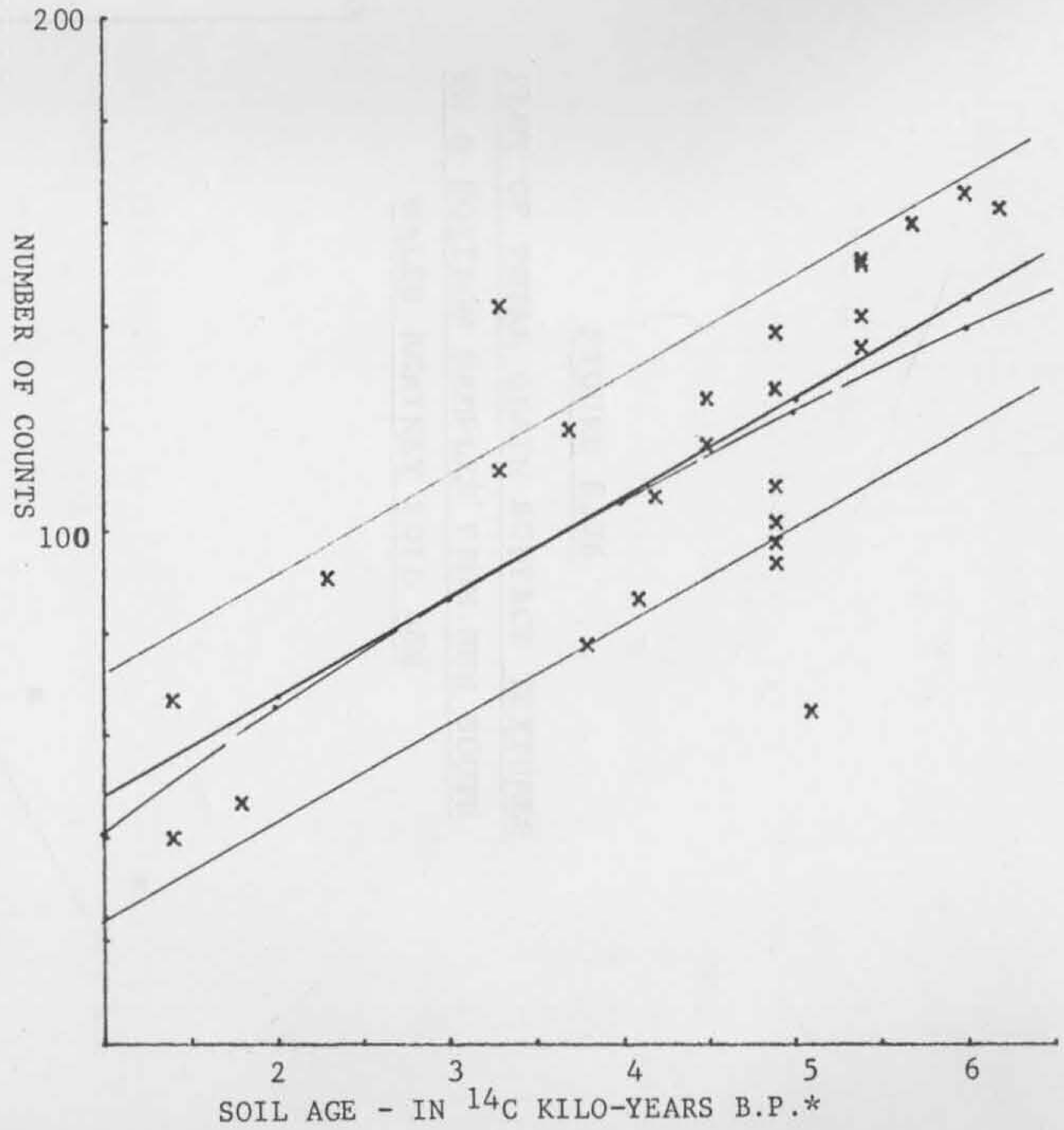
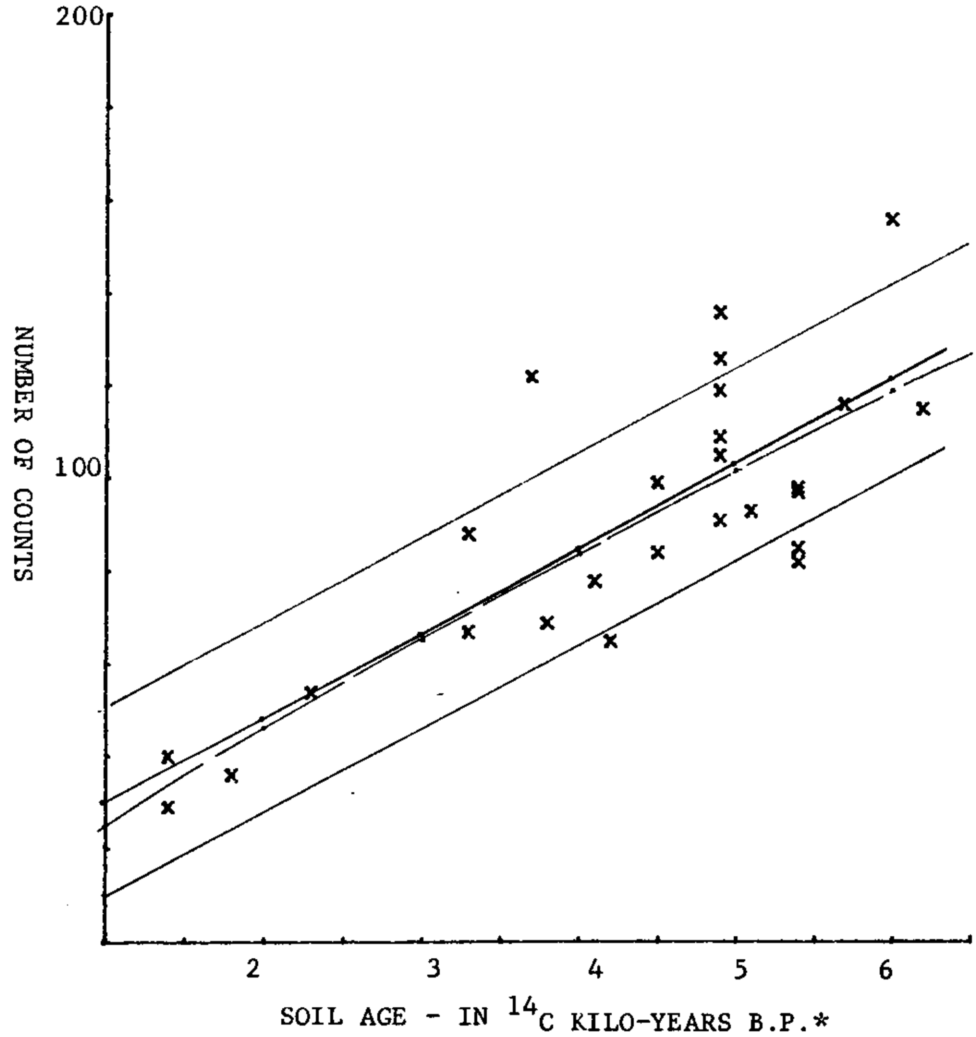


FIGURE 6.26

PLOT OF TOTAL GRAIN SURFACE TEXTURES ON B HORIZON SAMPLES FROM NEW SOUTH WALES AGAINST SOIL AGE



2. All regression lines shown in Figures 6.24, 6.25 and 6.26, indicate a marked increase in total texture counts, with increasing soil age.

3. Both the linear and non-linear (power) regression functions explain a moderate proportion of the variation in the data, especially in the A_2 and B horizons (see Table 6.11).

4. In relation to the confidence limits on the regression plots (± 1 standard deviation), the trend indicated by the linear regression lines should indicate useful relationships.

6.6 GRAIN SURFACE COATINGS

Results of the age correlations of the grain coating data are presented in Table 6.12[1]. Two aspects of the coating data are used: the number of extensively coated grains (in a 50 grain sample); and the total number of coated grains (i.e., extensive plus partial coatings). Both parameters relate to the degree of coating development on the sampled grains.

Those age-coating parameter correlations which yielded a statistically significant association are shown as regression plots in Figures 6.27 to 6.31. The coefficients of determination of the various regression functions are indicated in Table 6.12.

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1. The characteristics of the data again required the use of Kendall's Correlation Coefficient, and a z score to determine significance.

TABLE 6.12

KENDALL'S CORRELATION COEFFICIENT, STATISTICAL SIGNIFICANCE, AND COEFFICIENTS OF DETERMINATION FOR SOIL AGE - GRAIN COATING DATA

PARAMETER	KENDALL'S CORRELATION COEFFICIENT (τ)	STATISTICALLY SIGNIFICANT AT 95% CONFIDENCE LEVEL?	COEFFICIENT OF DETERMINATION (LINEAR)	MAXIMUM NON-LINEAR COEFFICIENT OF DETERMINATION
A_1 HORIZON EXTENSIVE COATING COUNT	0.631	YES	0.434	0.562
A_2 HORIZON EXTENSIVE COATING COUNT	0.504	YES	0.339	0.603
B HORIZON EXTENSIVE COATING COUNT	0.799	YES	0.697	0.593
A_1 HORIZON EXTENSIVE + PARTIAL COATING COUNT	0.755	YES	0.707	0.696
A_2 HORIZON EXTENSIVE + PARTIAL COATING COUNT	0.482	YES	0.215	0.144
B HORIZON EXTENSIVE + PARTIAL COATING COUNT	0.709	YES	0.724	0.637

FIGURE 6.27

PLOT OF EXTENSIVE COATINGS ON A_1 HORIZON GRAINS FROM NEW SOUTH WALES AGAINST SOIL AGE

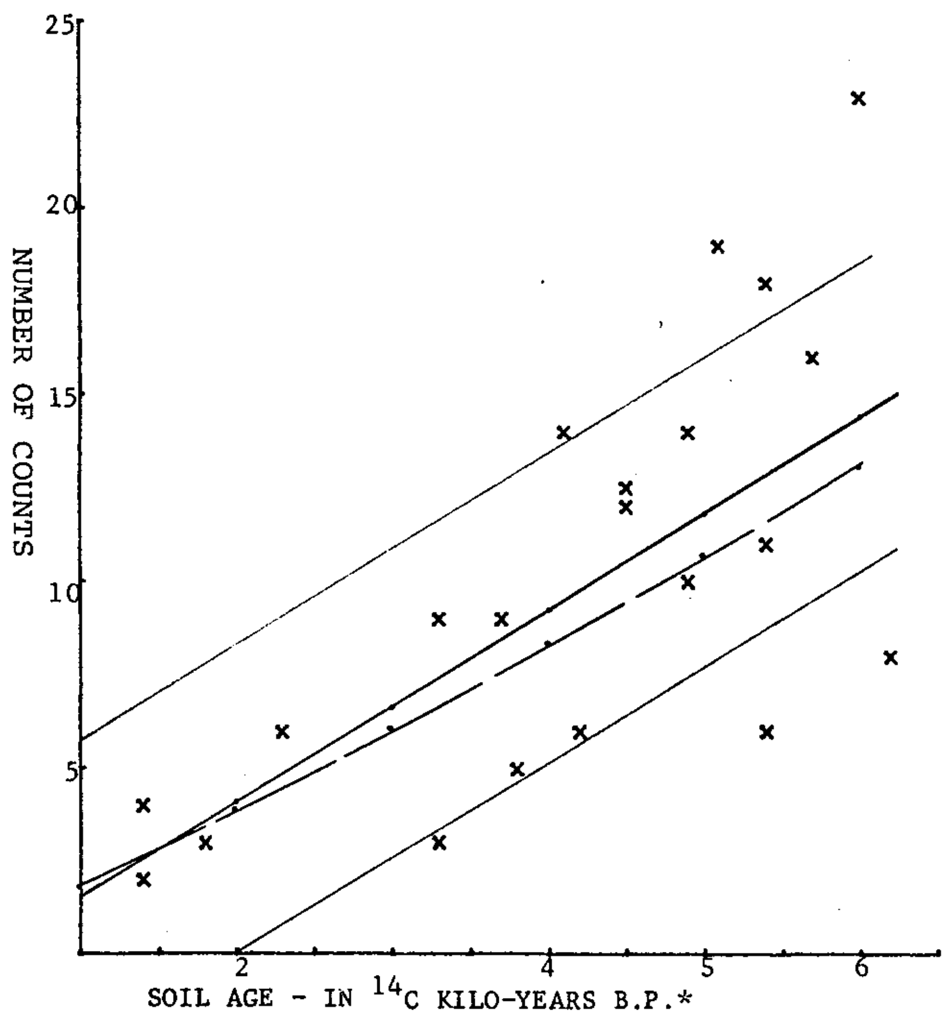


FIGURE 6.28

PLOT OF EXTENSIVE COATINGS ON A_2 HORIZON GRAINS FROM NEW SOUTH WALES AGAINST SOIL AGE

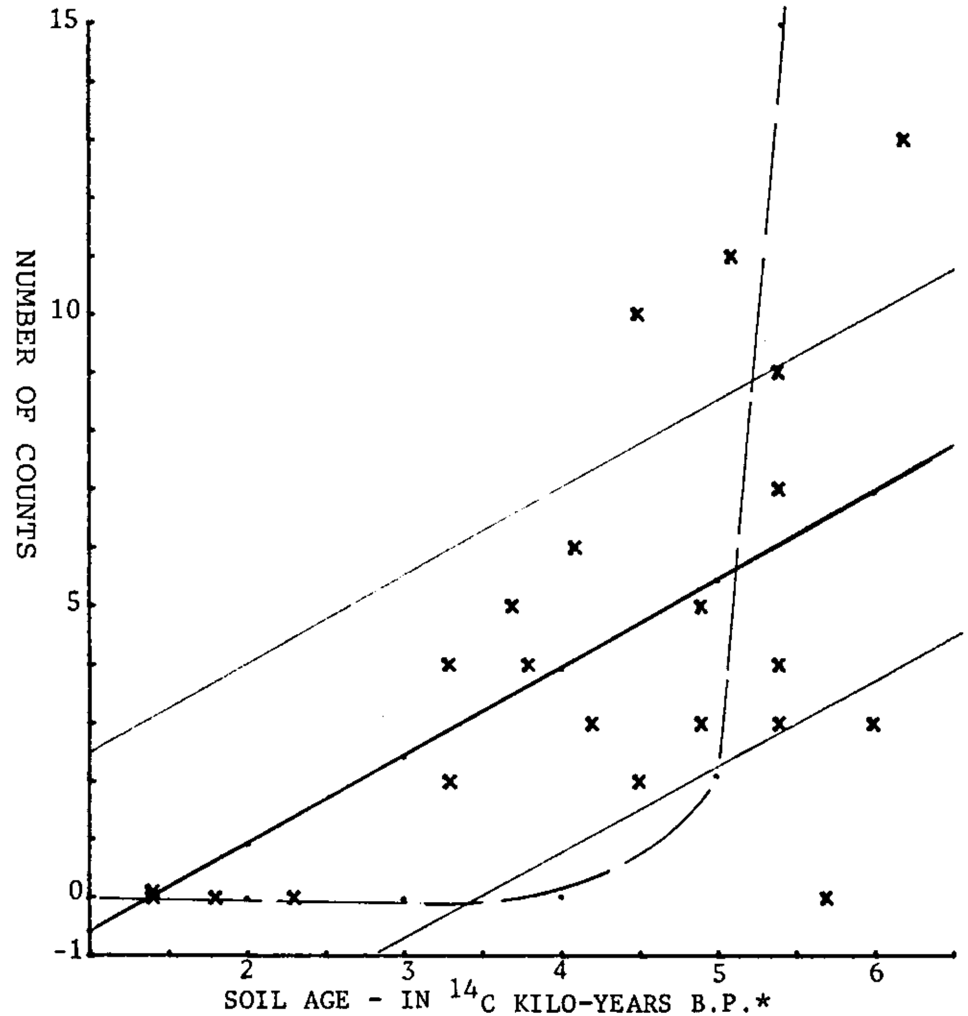


FIGURE 6.29

PLOT OF EXTENSIVE COATINGS ON B HORIZON GRAIN FROM NEW SOUTH WALES AGAINST SOIL AGE

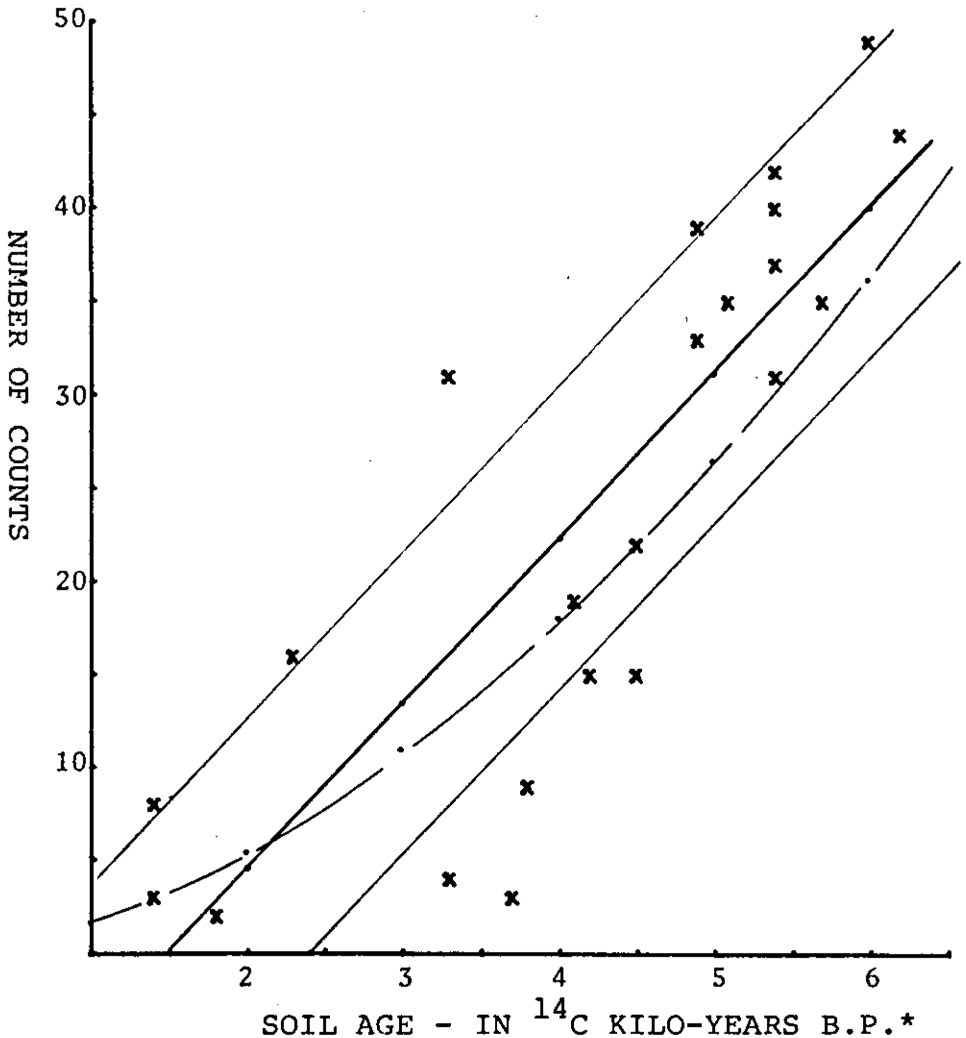


FIGURE 6.30

PLOT OF PARTIAL + EXTENSIVE COATINGS ON A_1 HORIZON GRAINS FROM NEW SOUTH WALES AGAINST SOIL AGE

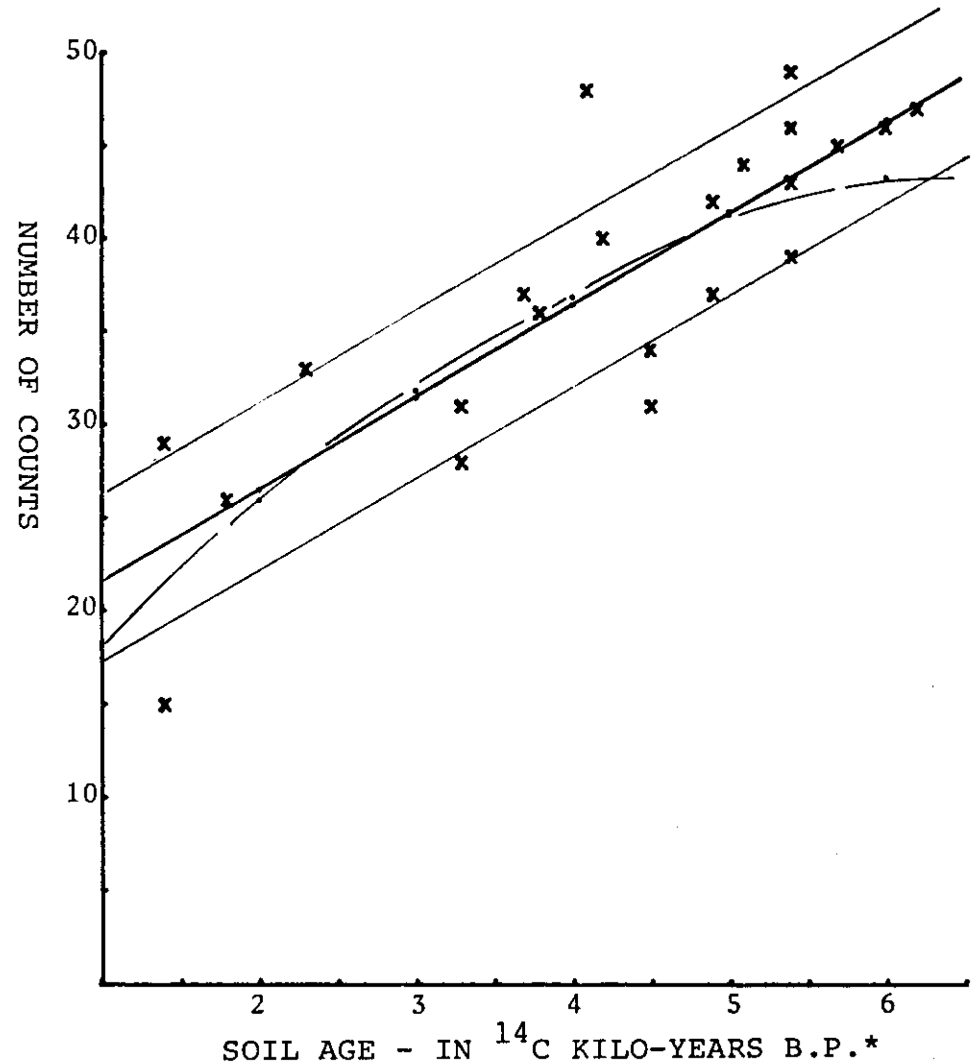
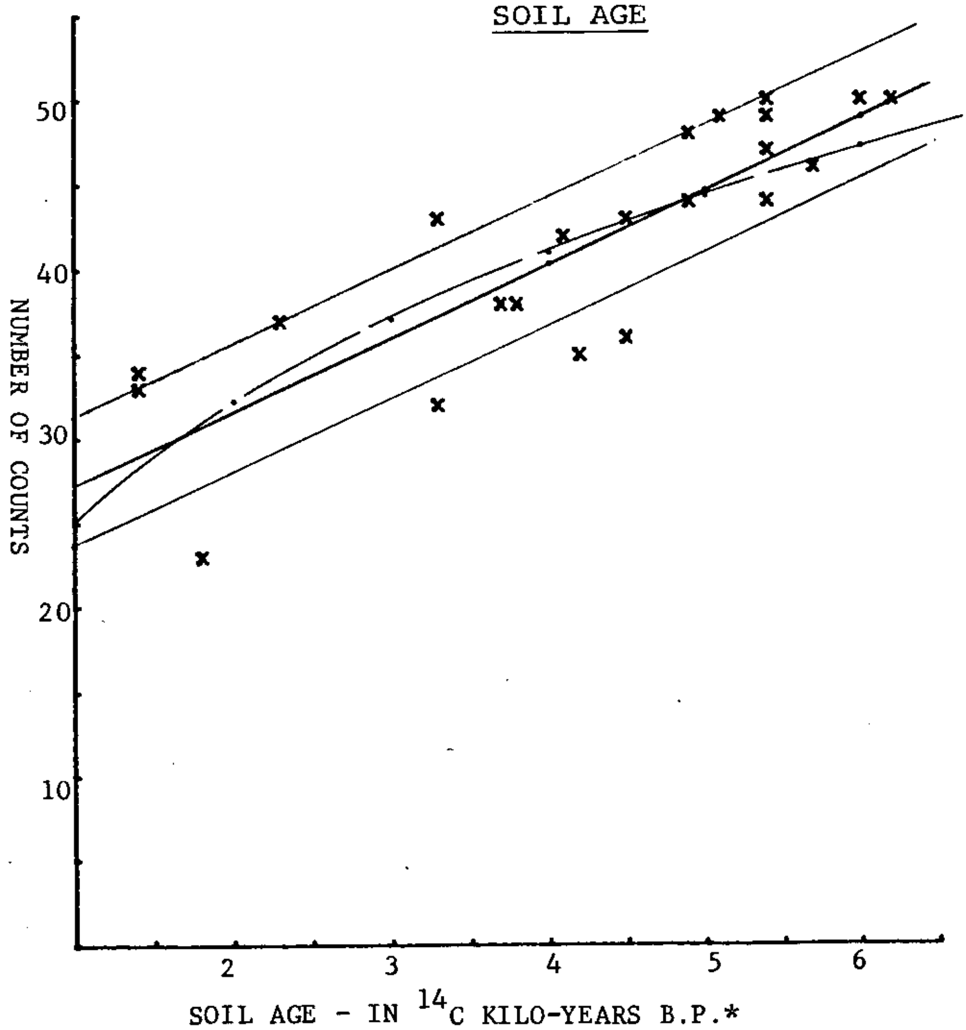


FIGURE 6.31

PLOT OF PARTIAL + EXTENSIVE COATINGS ON B HORIZON GRAINS FROM NEW SOUTH WALES AGAINST SOIL AGE



Several features of the correlation and regression results are notable:

1. All the correlation coefficients (τ) are significant at the 95 percent confidence level.
2. With the exception of the A_2 extensive plus partial coating regression, the regression functions explain most of the variation in the data.
3. With the exception of the A_2 horizon data, the regression functions indicate a pronounced increase in the occurrence of the grain coatings with increasing soil age.

6.7 SUMMARY

Correlation analysis has been used in Sections 6.2 to 6.6 to determine the statistical association between each soil parameter and soil age. Those correlations which yield statistically significant results (at the 95 percent confidence level) have been further examined by regression analysis, to determine the nature of the association between the parameter and the soil age data. The linear and non-linear functions which best explain variation in the regressed data have been determined and are illustrated on each regression plot.

Table 6.13 presents a synopsis of the statistically significant soil parameter-soil age relationships by presenting the estimated value of each parameter for soils which increment in age by 1000 years. In each case the estimated values are derived from the optimum regression function (which is shown at the base of each column with the coefficient of determination, r^2).

It is appreciated that the estimated parameter values are subject to a variable and in some cases substantial statistical uncertainty (see confidence limits in Figures 6.1 to 6.31), but to improve the clarity of the following discussion each age trend is briefly examined without reference to this uncertainty.

6.7.1 Horizon thickness

Four of the five statistically significant horizon thickness parameters reported in Table 6.13 increase directly with soil age. However, the B/A_2 horizon thickness ratio, which decreases with age, yields the best regression curve fit (highest coefficient of determination) and should be the most useful thickness parameter for geomorphic investigations involving east Australian podzol soils. The increase in the thickness of the A_1 and A_2 horizons (individually and in total) with soil age, supports the findings of Aaltonen (1939) and Mattson and Lonnemark (1939), who observed a similar trend in northern European podzols of comparable age range (see Janny, 1941, p.41). The decrease in B/A_2 ratio with age reflects the increase in A horizon thickness and the comparative constancy of the B horizon thickness. This trend agrees with the findings of Aaltonen (1939) and Mattson and Lonnemark (1939), for although they found that the zone of maximum illuviation moved upward within the B horizon with time, the *overall* thickness of the horizon was constant, or even slightly decreased. The latter phenomenon resulted from a sharper A_2-B horizon transition, a feature noted in the present study (see comments on horizon boundary configuration below).

TABLE 6.13

SUMMARY OF AGE TRENDS IN SOIL PARAMETERS

SOIL AGE	HORIZON THICKNESS					HORIZON BOUNDARY CONFIGURATION	DOMINANT HORIZON COLOUR		HORIZON STRUCTURE	SOIL REACTION				ORGANIC MATTER	IRON		
	A_1 THICKNESS	A_2 THICKNESS	A_2/A_1 RATIO	B/A_2 RATIO	$A_1 + A_2$ THICKNESS	A_2-B HORIZON	A_2-B CONTRAST	B-C CONTRAST	B HORIZON	A_1	A_2	B	C	B HORIZON	B AVERAGE	B/A_2 AVERAGE RATIO	A_1-A_2 + B-A_2
^{14}C yr BP*	cm	cm			cm		COLOUR DISTANT UNITS	COLOUR DISTANT UNITS		pH	pH	pH	pH	percent	micro-grams per gram		
1000	14	12	1.17	17.4	28	GRADATIONAL EVEN	0.84	-0.45	APEDAL SINGLE GRAIN	7.4	6.5	7.2	9.6	0.12	451	1.25	2.83
2000	16	27	1.54	7.9	38	GRADATIONAL EVEN	1.73	0.56	APEDAL SINGLE GRAIN	7.0	6.2	6.9	8.8	0.20	622	1.93	3.69
3000	20	43	2.02	5.0	51	GRADATIONAL EVEN	2.64	1.58	APEDAL SINGLE GRAIN	6.6	5.8	6.5	8.0	0.26	750	2.48	4.32
4000	23	59	2.65	3.6	68	GRADATIONAL EVEN	3.56	2.60	APEDAL SINGLE GRAIN	6.1	5.4	6.2	7.2	0.32	857	2.97	4.83
5000	26	75	3.48	2.8	91	SHARP/EVEN SHARP/ IRREGULAR GRADATIONAL/ EVEN	4.49	3.61	APEDAL MASSIVE	5.7	5.1	5.8	6.4	0.38	950	3.42	5.27
6000	29	91	4.57	2.3	123	SHARP/EVEN SHARP IRREGULAR GRADATIONAL/ EVEN	5.43	4.63	APEDAL MASSIVE	5.3	4.7	5.5	5.6	0.43	1034	3.83	5.65
	LINEAR $r^2=.117$	EXP'L. $r^2=.518$	EXP'L. $r^2=.392$	POWER $r^2=.533$	EXP'L. $r^2=.430$		POWER $r^2=.554$	LINEAR $r^2=.474$		LINEAR $r^2=.353$	LINEAR $r^2=.387$	LINEAR $r^2=.519$	LINEAR $r^2=.838$	POWER $r^2=.565$	POWER $r^2=.139$	POWER $r^2=.268$	POWER $r^2=.152$
	$y=0.003x + 10.3$	$y=10.8e^{0.0004x}$	$y=0.892e^{0.0003x}$	$y=42707x^{-1.13}$	$y=20.89e^{-0.0003x}$		$y=0.0006x^{1.041}$	$y=0.001x^{1.471}$		$y=0.0004x + 7.874$	$y=0.0004x + 6.917$	$y=0.0004x + 7.5929$	$y=0.0008x + 10.391$	$y=0.001x^{0.696}$	$y=18.494x^{0.463}$	$y=0.0167x^{0.6247}$	$y=0.195x^{0.387}$

SOIL AGE	MANGANESE			ALUMINIUM				CALCIUM		MAGNESIUM		SODIUM	SURFACE TEXTURE			EXTENSIVE SURFACE COATINGS			EXTENSIVE + PARTIAL SURFACE COATINGS	
	A_2 AVERAGE	B AVERAGE	A_1/A_2 AVERAGE RATIO	A_1 AVERAGE	B AVERAGE	A_1/A_2 AVERAGE RATIO	B/A_2 AVERAGE RATIO	A_1 AVERAGE	A_1-A_2 + B-A_2 TOTAL	A_1 AVERAGE	B/A_2 AVERAGE	A_1 AVERAGE	A_1 TOTAL	A_2 TOTAL	B TOTAL	A_1	A_2	B	A_1	B
^{14}C yr BP*	micro-grams per gram	micro-grams per gram		micro-grams per gram	micro-grams per gram			micro-moles per gram		micro-grams per gram		micro-moles per gram	number	number	number	number in 50 grain sample	number in 50 grain sample	number in 50 grain sample	number in 50 grain sample	number in 50 grain sample
1000	1.3	2.1	10.0	1323	518	2.32	0.93	53.6	41.5	13.1	1.09	3.1	40	41	25	2	0	0	22	28
2000	2.3	3.7	8.6	1204	750	2.08	1.37	25.1	33.9	9.0	1.33	2.3	53	66	46	4	0	5	27	32
3000	3.2	5.2	7.2	1084	931	1.87	1.73	16.1	26.3	7.2	1.50	1.9	65	87	66	6	0	14	32	36
4000	4.1	6.6	5.8	965	1085	1.65	2.03	11.8	18.7	6.1	1.64	1.7	78	106	84	8	0	22	36	40
5000	4.9	7.9	4.4	845	1222	1.44	2.30	9.2	11.1	5.4	1.75	1.6	90	124	102	11	2	31	41	45
6000	5.7	9.2	3.0	725	1347	1.22	2.55	7.6	3.5	4.9	1.85	1.4	103	140	119	13	32	40	46	49
	POWER $r^2=.140$	POWER $r^2=.222$	LINEAR $r^2=.148$	LINEAR $r^2=.141$	POWER $r^2=.329$	LINEAR $r^2=.235$	POWER $r^2=.247$	POWER $r^2=.350$	LINEAR $r^2=.243$	POWER $r^2=.230$	POWER $r^2=.160$	POWER $r^2=.10$	LINEAR $r^2=.485$	POWER $r^2=.601$	POWER $r^2=.765$	POWER $r^2=.562$	POWER $r^2=.603$	LINEAR $r^2=.697$	LINEAR $r^2=.707$	LINEAR $r^2=.724$
	$y=0.0048x^{0.8138}$	$y=0.0069x^{0.8273}$	$y=-0.0014x + 11.36$	$y=0.12x + 1443$	$y=13.0374x^{0.5331}$	$y=-0.0002x + 2.52$	$y=0.0192x^{0.5619}$	$y=102140x^{-1.0933}$	$y=-0.0076x + 49.1$	$y=583.2x^{-0.5495}$	$y=0.141x^{-0.2956}$	$y=2.67x^{-0.435}$	$y=0.0127x + 27.24$	$y=0.355x^{0.687}$	$y=0.0064x^{0.865}$	$y=0.0007x^{1.094}$	$y=1.58e^{-55}x^{14.903}$	$y=0.008e^{-11.038}$	$y=0.003x + 16.6$	$y=0.0044x + 23.2$

Burges and Drover (1953) reported an increase in the depth of the A_2-B horizon boundary across the Woy Woy barrier (also sampled in this study). Regressing their depth data with ages determined in this thesis, resulted in an exponential curve ($y=27.75e^{0.0003x}$) with a coefficient of determination of 0.969. Estimates obtained from this relationship are in good agreement with the regression estimates presented in Table 6.13.

In summary, the thickness of the A_1 and A_2 horizons, and the A_2/A_1 and B/A_2 thickness ratios, all relate well to soil age and individually (or collectively), should provide a convenient field indicator of the age of podzol soils in eastern Australia.

6.7.2 Boundary Configuration

As indicated earlier in this chapter, the nature of the A_2-B horizon boundary proved to be a reliable indicator of whether a barrier soil was younger or older than 4500 ^{14}C yes BP*. Profiles younger than this age exhibit gradational-even A_2-B horizon transitions, but those older than 4500 years have either a sharp-even, sharp-irregular or gradational-irregular boundary. The latter boundary types are readily distinguishable in the field from a gradational-even boundary. References to the nature of horizon transitions in the chronosequence literature are rare, although Burges and Drover (1953) indicate that the A_2-B transition becomes sharper with increasing soil age, and stronger A-B differentiation with age is a conclusion common to many chronosequence studies (Stevens and Walker, 1970).

6.7.3 Dominant Horizon Colour

The A_2-B and B-C horizon colour contrasts should be useful field indicators of profile age. Both parameters increase directly with age, and the colour contrast-age association given in Table 6.13 would permit 1000 year age differences (or better) to be distinguished in the field, assuming some replication of the simple colour assessment procedure was employed. Several writers have examined soil colour in a chronosequence context and most found trends with age (e.g., Chandler, 1942; Dickson and Crocker, 1954; Birkeland, 1974, 1978). An increase in A_2-B horizon contrast was usually noted in these studies. Dickson and Crocker (1954) attribute the changes in soil colour *value* to organic matter effects, and changes in *chroma* to the development of free iron oxide coatings.

6.7.4 Horizon Texture

Table 6.13 does not include reference to changes in horizon texture because no significant differences were observed in the sandy barrier soils studied. Horizon texture is therefore not a useful age indicator in the Holocene barriers, although in other soil types changes in the proportion of the fine and coarse fractions and changes in clay mineralogy, have been successfully related to soil age (e.g.; Chandler, 1942; Franzmeier *et al.*, 1963; Brewer and Walker, 1969; Birkeland, 1974).

6.7.5 Horizon Structure

A distinction was noted in the field between *apedal single grain* B horizons and those that are *apedal massive*, at least in part. After assigning ages to each site, it is apparent that all profiles over 4500 years* old have B horizons which are *apedal massive* in part or in whole, while those younger than this age are all classed as *apedal single grain.* To the extent that the distinction can be made in the field, this feature may be used in conjunction with the A_2-B horizon boundary configuration, to decide if profiles are older or younger than 4500 years*.

6.7.6 Soil Reaction

The regression estimated pH values for the A_1, A_2B and C horizons all indicate a decrease in pH with increasing soil age, values being lowest in the A_2 horizon at all soil ages. A similar trend towards increasing acidity in older soils has been noted by many workers: for example, Salisbury (1922), Chandler (1942), Burges and Drover (1953), Crocker and Major (1955), Crocker and Dickson (1957), Wilson (1960), and Franzmeier, Whiteside and Mortland (1963). The trend is associated with the leaching of shell carbonate from coastal sand deposits, which occurs quite rapidly once vegetation has become established and organic matter has begun to accumulate in the profile (Salisbury, 1922; Burges and Drover, 1953; Wilson, 1960). From the coefficients of determination shown in Table 6.13 for the age-pH regression, the pH of the C horizon should provide the most useful indicator of soil age.

6.7.7 Organic Matter

As shown in Table 6.13, only the organic matter content of the B horizon was found to be significantly correlated with soil age, although A horizon organic matter parameters have generally been found by other workers to reflect soil age trends (e.g., Salisbury, 1925; Chandler, 1953; Crocker and Major, 1955; Crocker and Dickson, 1959; Franzmeier and Whiteside, 1963). However, tests of statistical significance were not applied to most of the age trends reported in the literature, often too few data points were used to determine the trend, and in most cases the age range of the chronosequence was comparatively small. Further, few investigators seem to have examined B horizon organic matter trends, although Burges and Drover (1953) made some observations at Woy Woy which are in good agreement with the values estimated in Table 6.13. B horizon organic matter content, determined by loss on ignition (see Appendix 3), would seem to be a useful laboratory technique for evaluating profile age.

6.7.8 Cation Concentrations

Those cation parameters which correlated significantly with soil age are listed in Table 6.13, together with regression estimates of the parameter values for 1000 year soil age increments. It is apparent from the regression estimates, and from the reported coefficients of determination, that the most useful cation parameters for soil age studies are: i) calcium concentration in the A_1 horizon (r^2=0.35); ii) aluminium concentration in the B horizon (r^2=0.329); and iii) iron B/A_2 horizon concentration ratio. Other cation parameters in the table, though correlating significantly with soil age (at the 90 percent confidence level), yield lower coefficients of determination, and hence the "best fit" regression functions explain little of the data variation. The combination of A_1 horizon calcium concentrations, B horizon aluminium concentrations, and B/A_2 iron concentration ratios, encompasses both the 'dissipative' and 'accumulative' types of cations mentioned in Chapter Two as being desirable soil development monitors.

The calcium parameter probably reflects the calcium content of the organic matter, which tends to decrease over time as the base is progressively leached from the system (Westman, 1978). The regression function estimates 53.6 micromoles per gram (o.d.) of calcium in a 1000 year old soil, but this falls to only 7.6 micromoles per gram in a 6000 year soil. The trend for the aluminium parameter relates to the accumulation of this cation in the B horizon of virtually all the soils examined during the study. The increase from 518 micrograms per gram (o.d.) to 1222 micrograms per gram is very pronounced and should form the basis for a sensitive laboratory monitor of profile age. The third parameter, the ratio of B to A_2 horizon average iron concentration, also relates to an accumulative cation, but in this case the parameter measures the relative differentiation of the A_2 and B horizons.

Collectively, the three cation parameters should provide useful laboratory monitors of the chemical development of east Australian podzols.

6.7.9 Grain Surface Textures

Of the three regression trends for grain surface texture counts included in Table 6.13, that for the B horizon yields the highest coefficient of determination

(r^2=0.886). However, all three horizon trends (A_1, A_2 and B) indicate a pronounced increase in the frequency of total textural features as soil age increases, and individually or collectively, grain surface textures provide a relatively good monitor of profile age. This conclusion is of some significance, as few attempts at quantifying SEM observations have been previously made, and to the author's knowledge, few statistically significant correlations with environmental parameters have been achieved (see Baker, 1976). In this study the occurrence of the total textural features is associated with the duration of chemical solution and precipitation processes, and the presumed greater activity of these processes in the older more developed soils (Barshad, 1964).

6.7.10 Grain Surface Coatings

All the surface coating parameters reported in Table 6.13 yield quite high coefficients of determination when regressed against soil age. However, the regression estimate of extensive coatings on A_2 horizon grains is of little practical value, because the power regression function yields less than zero count estimates for soils under 5000 years old. (See Figure 6.28 for plot). Further, the estimated A_1 horizon values are of too restricted a range to be useful. Therefore only the occurrence of extensive coatings on B horizon grains, and the occurrence of extensive plus partial coatings on A_1 and B horizon grains remain as suitable soil age monitors. These three parameters do yield an acceptable range of values over the 6000 year period, and hence are useful.

6.8 CONCLUSION

A range of general conclusions may be drawn from the study.

1. In relation to the principal objective of the thesis, set out in Section 1.1, it has been shown that the podzol soils developed in east Australian Holocene sand barrier systems are strongly time-dependent. That is, statistically significant associations exist between a range of physical and chemical soil properties and the radiometrically derived ages of the soil profiles; these associations may be expressed as pedologically meaningful age trends.
2. The non-temporal pedogenic factors also influence the development of the podzol soils in east Australian sand barriers, but within the sampling framework established in the thesis this influence was found to be subordinate to that of the time factor.
3. Some of the soil parameters used in the study were found to be more time-dependent than others. Visual profile morphological features, such as horizon thickness, horizon boundary configuration and horizon colour, generally correlate well with soil age, and yield useful age trends. Laboratory determinations of average horizon pH, B horizon organic matter content, several cation concentration parameters, and the occurrence of sand grain surface textural features and organic-mineral coatings, were

also found to correlate significantly with soil age, and to result in pedologically meaningful and useful age regression trends. In contrast, other parameters derived from the same data, were found not to be age-associated.

4. The statistical uncertainty inherent in the derived age trends will necessitate the use of multiple parameters for reliable age determinations, as recommended by Burke and Birkeland (1978).

5. The determined parameter age trends indicate that a general steady state condition is not attained in east Australian podzol soils within 6000 years of their initiation.

6. Jenny's (1941, 1946, 1961) revised pedogenic factor model provides a suitable conceptual framework within which to design and execute a chronosequence study. This study has shown that most of the pedogenic factors can be quantified, at least sufficiently well to allow comparisons to be made of pedogenic environments.

7. East Australian Holocene sand barrier systems are environmentally suitable for chronosequence studies; they are easily and accurately dated, provide a potential soil age range of zero to 6500 ^{14}C years*, have very uniform parent material and relief, and relatively uniform vegetation and climate.

6.9 IMPLICATIONS

Many implications arise from the findings of the thesis, some being of a general nature, and others more specific. The broader implications are discussed below.

1. The soil parameter age functions derived in the study may be reformulated to make soil age the dependent variable, and used to predict soil age in suitable pedogenic environments in eastern Australia. Such environments would be found in any freely drained, sandy, siliceous deposit, within a temperate climatic region, and having a *Eucalyptus-Banksia* dominated vegetation assemblage. Extension to more tropical or cooler regions would depend on integration of the Cowley Beach or Rheban data, and the resulting age determinations would be less reliably based.
2. The thesis has shown which properties relate best to the time factor. Future time-pedogenic investigations in eastern Australia should concentrate on these parameters and attempt to extend their range, and improve their precision.
3. Extension of this study to dated eastern Australian Inner Barrier deposits could result in longer term age trends and would indicate whether steady state conditions are achieved by the podzol soils within 130,000 years. Complications would arise because of variations in pedogenic factors other than time, but these could probably be allowed for. Parameter age trends determined in this way would be useful in dating east Australian aeolian Pleistocene

deposits, many of which are beyond the range of radiocarbon dating, but do not contain material suitable for use with other dating techniques.

4. The variability of the soil parameter data obtained during this study indicates that the smooth age trends (based on very few data points) which featured prominently in early chronosequence studies (often with poor factorial control), are probably grossly oversimplified.
5. The use of the scanning electron microscope to quantify the occurrence of sand grain textures and grain coatings has indicated that this technique is of more value in the study of chemically-derived microscopic features, than it is in the examination of mechanically derived features, for which it is more often used. In addition, the rationalization and proposed morphogenetic classification of chemical grain surface textures outlined in Chapter Four, should provide a good starting point for future SEM studies of the origins of these features.
6. Some simple profile morphological features have been shown to relate to soil age. These parameters will be most useful in the field assessment of soil age, especially in geomorphic mapping.