
THE PETROLOGY AND ORIGIN OF SUPERFICIAL QUARTZITES.

[with 2 supporting reprints

by

H.F. WHITWORTH B.Sc.

Superficial quartzites are of widespread occurrence in Eastern Australia but their mode of origin does not seem to have received much detailed investigation. The term superficial quartzite is used to distinguish that group of comparatively young rocks of no great thickness found as a capping to rocks belonging to many different geological ages, but mainly associated with the Tertiary and Cretaceous Series. They have been termed "Grey Billy" by miners and in certain localities have been highly esteemed by aboriginals, who have utilised them for making their stone implements.

Two main types of occurrence are known each of entirely different origin although containing lithologically similar rocks:-

(a) Those associated with basalt flows and evidently resulting from the contact metamorphism of either loose or slightly consolidated sandy sediments.

(b) Those found as thin cappings over Tertiary or Cretaceous sediments in the arid interior of the continent, and usually described as surface sands cemented by silica leached out of the underlying material and brought to the surface by capilarity.

(a) CONTACT <u>METAMORPHIC TYPE</u>

Vulcanicity was a marked feature in Eastern Australia during Tertiary times and during the period marked by the elevation of the Great Dividing Range great outpourings of lavas, mainly of basaltic type, took place from many centres of eruption.

These lavas flowed down the existing valleys and in many cases so altered the underlying river sands and gravels as to convert them into quite dense quartzites. Many of these ancient valleys contained gold, tinstone or gems, and have therefor received attention from alluvial miners who have bestowed such terms as "Grey Billy", "Cement" and "Shin Cracker" on the hardened river drifts, and many references to these deposits may be found in mining literature. Such deposits are usually very limited in extent and thickness. Silicification is most complete just beneath the lava and beds of quartzite up to about 15 feet in thickness are known. Alteration usually dies out at a few feet from the basalt the quartzite in some cases passing into unaltered river drift. It is only in cases in which the original drift was very thin that silicification extended downwards for its full thickness.

Owing to superior hardness of the basaltic lavas over the softer bedrocks, many of the old basalt filled valleys are now left as hills, the older hills having been removed by stream erosion, and an examination of many basalt capped hills will show the presence of river drift below the basalt. In some cases the basalt has been removed by denudation leaving only the capping of quartzite over the older bedrock.

Professor David (1) described the occurrence of "Grey Billy" in the New England Tinfields in 1887 but did not dwell at length on their mode of origin.

Dr. W.G. Woolnough (2) drew attention to an occurrence of hard glassy quartzite at Tallong in 1909 which was later investigated in some detail by Waterhouse and Browne (3), who recorded the presence of opal in the cementing material, and discussed at some length its possible mode of origin. Dr. Ida Brown (4) described deposits of quartzite containing fossil wood of Tertiary age from Moruya and Ulladulla.

Other deposits, which have been examined by the writer are on the Dividing Range east of Dunedoo, at Gunning & Dalton. These three occurrences are all similar to those already described, but the Dalton ore has had most, if not all, of the basalt removed, and the quartzite bears numerous impressions of Tertiary leaves.

Petrological characters.

The rock types present in these deposits are somewhat diversified and vary accordingly to the type of the original river drifts and nature of the cementing material. Some types are dense in texture, buff in color, opaque, and possess a sub-conchoidal fracture, and resemble stoneware in general appearance. These appear to have been derived from clayey sediments. Other types have been derived from sands and gravels and show corresponding variations of color. Some of these appear to have had a certain amount of original clay mixed with them and these possess a dull, opaque appearance, whilst the clay free sands and gravels have been converted to semi translucent quartzites of more normal aspect.

Microscopic examination shows that three types of cementing material are present, quartz, chalcedony, and opal having been recognised. Quartz and chalcedony seem to have acted as cements for the cleaner clay free sands, whilst opal is confined to those carrying a considerable proportion of clay. Many of the clean sands which are cemented by secondary quartz show beautiful examples of regrowth, the quartz cement having grown in optical continuity with the original quartz sand grains. One specimen from Tingha, when examined, showed the sand grains outlined by tiny inclusions of some opaque substance with secondary quartz in optical continuity entirely filling the pore spaces giving the rock almost a granitic texture rendering it indistinguishable from the regionally metamorphosed quartzites of Devonian Age.

The cementing material in the more clayey types is of great interest. In some of these definite chalcedony and opal may be seen as described by Brown & Waterhouse (5) but in some cases the groundmass is almost opaque and many of the grains of quartz show no sharp edges but appear gradually to merge into the matrix. The groundmass is quite isotropic and its refractive index is much below that of quartz and from all appearances consists of opal heavily charged with some indefinite earthy matter. In some cases the quartz grains are seen to be bordered with chalcedony which merges quite imperceptably into the opaline groundmass, which appears to have been the result of attempted regrowth of quartz grains. Any evidence of corrosion of quartz grains by invading waters, if present, are not conspicuous.

ORIGIN.

It has been stated generally that these quartzites have been formed by the cementing action of siliceous waters derived from the overlying basalt. This statement is open to the objection that basalts are not silica rich rocks, and it is unlikely that their residual waters contain much silica. The available evidence is that they contain gaseous mineralisers and alkalis, the alkalis, according to recent workers having been derived from early formed felspars by the solvent action of the mineralisers. These mineralisers and alkalis in the waters gave rise to the zeolites and calcite which so commonly fill the steam cavities in basalt flows. Chalcedony filled amygdules are rare compared with the zeolite and calcite filled ores.

Another suggestion which has been advanced is that the groundwaters present in the sediments were heated and exerted a solvent influence on the sand grains and later deposited their content of silica as the temperature fell during the cooling of the basalt. A suggestion worthy of consideration is that this ground water became further activated by some of the alkalis and mineralisers derived from the basalt and dissolved the colloidal silica which Clarke (6) states is usually deposited with sediments at the time of their precipitation from water. The same writer states that quartz may be deposited from solutions of alkali silicates owing to the falling temperatures. This explanation of the formation of the quartzites with quartz and chalcedony as a cement seems fully satisfactory, but the development of large amounts of opal in the clayey sediments and in them only seems to need further explanation, and the writer desires to advance the hypothesis that the clay itself has yielded the opal by dissociation into hydrous silica and anhydrous silicate of alumina (mullite) or possibly even bauxite.

In an endeavour to test this hypothesis specimens of clay were fired at temperatures just sufficient to cause incipient vitrification (generally about 1200°C) and the resultant test pieces were sectioned and examined microscopically In several instances the development of an isotropic substance having the optical properties of opal was noted, and needles of mullite were observed in some cases to be embedded in this. The conversion of clay to mullite and silica may be represented by the following equations:-

$$3\ (Al_2O_3 .\ 2\ SiO_2\ .\ 2\ H_2O) + \text{heat} = 3\ (Al_2O_3 . 2\ SiO_2)\quad 6H_2O$$

$$3\ (Al_2O_3 .\ 2\ SiO_2) + \text{heat} = 3\ Al_2O_3 .\ 2\ SiO_2\quad 4\ SiO_2$$

A perusal of the technical literature on the ceramic industry, shows that a reaction of this type has been recognised for some time and the separation of the "silica glass," as it is termed, is one of the causes of hardening of clays at temperatures below their fusion points.

In a recent paper by Heindl, Prendergast and Mong (7) descriptions are given of a number of experiments designed to find the temperature required for the development of mullite from clays. These experiments show that with rising temperature, silica glass begins to form at less than 1000°C, mullite first develops at about 1300°C. and the reaction appears to be complete at about 1600°C. Xray diffraction patterns were carried out by these experimenters who thus showed the presence of both mullite and cristobalite in specimens of fixed kaolin, in which neither of these substances could be observed microscopically owing to their fine grain size. Other test pieces yielded diffraction patterns for mullite but failed to show the presence of either quartz or cristobalite and from this it was deduced that the silica, liberated from the clay during the development of the mullite, was present in a non-crystalline form, possibly as opal.

In the case of quartzites formed by the heating of somewhat clayey sands by basalt flows it is not to be expected that mullite is present as it is estimated that basaltic lavas on eruption are only at a temperature of approximately 1100°C, and the temperature to which underlying sediments might be heated is therefor much below this figure, whilst the formation of mullite does not take place below 1300°C. A temperature of 1000°C, however, is quite sufficient to cause the liberation of siliceous glass or opal to form from clays, and a microscopic examination has shown its presence in many of the more opaque or clayey quartzites which have been derived from clayey sediments.

It is further contended that in those specimens of quartzite which show corrosion of the sand grains that this has been brought about by interaction between the quartz and clay, for it is well known that these two substances tend to flux each other at high temperatures.

In the presence of alkali silicates at high temperatures the dissociation of clay proceeds beyond the mullite stage this mineral losing its silica and leaving a residue of corundum. It has already been shown that alkalies, probably in the form of alkali silicates, are abundant in the residual waters of a cooling basalt mass, and these possibly have assisted in the dissociation of clays at temperatures well below those recorded in experimental work. The time factor must also be considered in reactions of this type, and it may well be that the dissociation observed experimentally to take place in a few hours at a temperature of 1000°C, might take place at a considerably lower temperature in a much longer time, such as that required for the cooling of a lava flow.

(b) QUARTZITES FORMED AS CAPPINGS OVER TERTIARY AND CRETACEOUS SEDIMENTS.

Turning now to the superficial quartzite occurring in the more arid interior of Australia, largely as thin cappings to the Tertiary and Cretaceous sediments, but by no means confined to them, we find that they were mentioned quite early by geologists who visited this region, but it was not until the discovery of opal that they attracted much attention, and their association with several deposits of precious opal has been sufficiently well marked to provoke comment from several writers on the subject. In 1881 H.Y.L.Brown (8) noted the presence of siliceous cappings at Mount Poole, near Milparinka and referred to them as "quartzite boulder conglomerates porcellanised in some way to an intense hardness .... and bearing the appearance of having been fused". Later in 1884 Wilkinson (9) described an occurrence of "argillaceous quartzite with pebbles .... with a semi concretionary structure" from Corona Station.

In 1892 Jaquet (10) visited the newly discovered opal fields at Whitecliffs and described the superficial quartzites which form such a conspicuous feature there and referred to them as being composed of "quartz grains cemented together by a matrix of opaline quartz", which statement has since proved to be very nearly correct. Andrews (11) has given an excellent description of the occurrence of quartzite at the Lightning Ridge opal fields.

MODE OF OCCURRENCE.

The quartzites occur mainly as horizontal beds, having maximum thickness usually of less than 20 feet, often underlain by or interstratified with soft sandy clays though sometimes as a thin skin or case hardening on solidified rocks. They seldom occur as large continuous sheets but are more often cappings to mesas or buttes and are remnants of a once extensive deposit. According to Kenny (12) they are pre-eminently developed as cappings to outliers of the Eryian Series (Tertiary) but are also developed on outcrops of Cretaceous sediments. In some places they have a slight inclination to the horizontal and dip below the plains of Pleistocene and Recent alluvium, and they have been encountered by bores at a considerable depth beneath the present day surface of the plains.

PETROLOGICAL CHARACTERS.

Certain beds appear to be composed of massive or compact material, whilst others consist of loose boulders lying in soft unconsolidated sediments, and others have the appearance of loosely condolidated conglomerates but closer investigation shows these to be aggregates of concretionary siliceous nodules. The sizes of the nodules vary from several inches to a small fraction of an inch in diameter and some beds bear a striking resemblance to pisolitic laterites. A bed of such material occurs in the opal ground at Whitecliffs and has received the local name of "Geyser" which is possibly an abbreviation of "Geyserite" some varieties of which it closely resembles. Some of the more massive beds occuring in the opal dirt have received the expressive names of "Steel bands" and "Shin cracker".

Microscopical examination shows that they all represent sediments varying in grain size from coarse gravel to fine clay, but it is only in the finer grades that bedding may be observed. They are of a dull buff color in hand specimen and lack the translucent appearance of most of the old Palaeozoic quartzites. The massive non concretionary types are all excessively hard and break with a semi-conchoidal fracture, the freshly broken face possessing a subvitreous lustre. Under the microscope the groundmass appears opaque, and the rocks are indistinguishable from the more clayey quartzites associated with the basalts. A careful examination reveals the presence of opal as mentioned by Jaquet who refers to the cement as consisting of "kaolin impregnated by opaline quartz". Chemical analysis shows the presence of free alumina in a bauxite form but it is difficult to obtain a quantitative estimation of its amount in the groundmass. Some of the specimens examined by the writer contained a calcareous cement and strictly speaking should not be dealt with here, but as they are indistinguishable from the quartzites to the naked eye may perhaps be included with the group of "Grey Billies".

The gradual merging of quartz grains into the groundmass is quite a marked feature, as in the case of the quartzites formed beneath basalt flows, and in some of these types some chalcedony is present in the cementing material. Many of the quartz grains which merge into the groundmass are rimmed with chalcedony which gradually passes into the opal of the groundmass.

The association of precious opal and "Grey Billy" is so marked that it is thought that a brief mention of the micro-structure of precious opal should be included. The precious opal occurs largely in sharply bounded veinlets in quartzite or common "potch opal" and its play of colours is quite noticeable by transmitted light, and between crossed nicols closely resembles the interference colours of crystals of olivine or augite in rock sections of normal thickness. The colors are arranged in definite patterns and bear such a strong resemblance to the twinning laminations of calcite that it is difficult to avoid the conclusion that the precious opal represents a replacement of calcite by silica.

Several of the specimens of "Grey Billy" examined show an imperfect pisolitic structure in the groundmass, consisting of small concretions of light colored opaque material in an opaline isotropic groundmass. This structure is quite unlike the concretionary forms of the calcite in the calcareous types of "Grey Billy", and it was this pisolitic structure which first led the writer to suspect the presence of bauxite in the groundmass. The amount of bauxite present in the groundmass must be fairly high for some rocks which contained only about 10% of groundmass showed over 1% of free alumina soluble in 10% of caustic alkali and this is present to over 10% of free alumina in the groundmass. It is thus seen that the groundmass is very similar to that present in the more argillaceous quartzites underlying basalt, and consists of a mass of opal rendered opaque with bauxite.

ORIGIN.

Woolnough (13) includes these "Grey Billies" under his general term "Duricrust" and explains their formation as due to the rise of siliceous waters by capilarity and deposition of the silica at the surface by evaporation; during a period of alternating high rainfall and semi aridity, on a highly perfect peneplain surface. Both he and Andrews (11) agree that this process is not now going on and the recent discovery of Tertiary leaves in the beds at Whitecliffs suggests that the silicification took place in Tertiary times.

It has been suggested that during periods of rainfall the water soaked downwards, owing to poor run-off, due to the perfection of peneplaination, and dissolved silica from the surface material, and that during periods of aridity this water was drawn to the surface by capilarity and deposited its silica in the pore spaces of the surface, sands as opal or chalcedony.

Certain difficulties are in the way of accepting this hypothesis in its entirety, not the least being that of assuming the upward rising solutions passing through a 20 foot band of quartzite in the later stages of the formation of such a bed. It has also been shown that capillarity will not bring water to the surface from greater depths than about 12 inches. It is true that in arid regions water does rise towards the surface from considerably greater depths than this, but it never reaches the surface but evaporates in the soil at some considerable depth. By this means salts may be deposited actually in the soil some distance below the surface. The above objections may be overcome by assuming that the siliceous cementing material has been derived largely from clays which have dissociated in situ into opaline silica and bauxite.

As we have already seen the quartzites do contain free alumina, and if this has been derived from interstitial clay some silica must have been set free during the process and this silica might quite conceivably have remained within the rock and acted as a cementing agent. The dissociation of clay into bauxite and silica under certain conditions of climate involving heat and moisture, is well known, and Leith and Mead (14) who have made an exhaustive study of bauxite deposits in United States of America regard this as the normal mode of weathering of clays in humid sub-tropical climates. They also state that the partial dissociation of clay to bauxite and silica is more common than is generally known. Normally the silica produced by this reaction is removed in solution in the run off but it is probable that under certain conditions of peneplanation some of it might be retained where it is produced and thus be available as a cementing medium.

Jacquet (10) and Andrews (11) referring to the Whitecliffs and Lightning Ridge opal fields pointed out that the "Grey Billy" usually rests on beds of soft white kaolin. It has been found recently that these beds are markedly bauxitic, and this implies the liberation of much silica at some period. It is probable that this silica was removed by ground waters and deposited in other beds nearby as a siliceous cement. Leith and Mead state that both clays and carbonates act as precipitants for silica in solution and it is probable that some of the beds of Grey Billy represent clayey sediments and others calcareous marks which have acted as precipitating agents for silica derived from clays which have undergone dissociation either complete or partial. It is interesting to note in passing that shells and bones replaced by opal are of common occurrence in the opal fields and the similarity of the colour banding of precious opals and calcite twinning lamellae has already been mentioned. The fine laminations present in many of the bands of "potch opal" suggest that they represent twin beds of finely laminated clays which have been replaced by opal.

F. W. Clarke (15) states that the deposition of colloidal silica causes the settling of finely devided clay from water, whilst Leith and Mead (16) state that "of particular interest is the possible early precipitation of quartz cement from colloidal silica solutions which are so often produced simultaneously with the fragmental products of rock decay" and later that "the intimate association of chert and limestone cannot always be satisfactorily explained as due to introduction of silica from without after the rock has been indurated, but seems, in some cases to be due to primary precipitation with the carbonate". They thus suggest that the silica may be deposited with the clay or carbonates at the time of deposition of the sediments and that this silica begins to harden quite early. Dissociation of the clay contents later would complete the hardening of such sediments.

From a microscopic examination of many specimens of Grey Billy it is thought that most of them have been formed mainly by the hardening of arenaceous sediments which originally contained a clayey bond, the hardening having been brought about by dehydration of any colloidal silica present at the time of deposition followed in some cases at least by partial dissociation of the clay content into bauxite and silica.

The ultimate fate of the silica produced during the dissociation of the loose incoherent beds of clay underlying the Grey Billy may now be briefly considered. It is known that the reaction took place during a period of peneplanation and consequently low run off, so it is unlikely that it escaped in solution in river waters. It therefore either went to the surface to be precipitated on the evaporation of the water or else soaked downwards and was precipitated at a depth. We have seen that it is unnecessary to assume that siliceous cement has come from a depth to account for the presence of the quartzite at the surface and we know that thin beds of siliceous material exist at some depth below or in the clay. These beds may easily have been caused by downward leaching and precipitation of silica from the clay. Several analagous cases of downward leaching are known. Browne (17) describes the occurrence of secondary nodular ironstone some distance below the surface in the soils around Sydney. In this district the surface soil often consists of pure white quartz sand passing downwards into a yellow sandy loam whose iron and clay content gradually increases with depth and frequently large nodular masses of secondary ironstone occur at a depth of from 2 to 4 feet below the surface. It is stated that these have been formed in the soil and are an indication that poor underground drainage has prevented the removal of the iron leached from the upper soil by rain water.

Along the coase of New South Wales the writer has had the opportunity of examining many dunes of wind-blown sea sands Owing to a mantle of vegetation many of these dunes are now stationary and in all of these the upper layers of sand are now quite white in colour, unless discoloured by organic matter, all traces of iron staining and shelly material having been removed by the leaching action of rain water, possibly aided by organic acids formed by decaying vegetation. In cases where the bases of such dunes are visible it is usual to see a considerable thickness of sand cemented to a fairly hard rock by calcareous or ferruginous cements.

These two examples of downward leaching show how this process may give rise to fairly hard rocks of a calcareous or ferruginous nature below the surface of unconsolidated sediments, and as there is no reason why such a process should not take place with siliceous cements, it is possible that the beds of Grey Billy may once have been covered by thick beds of clay from which the silica was dissolved on dissociation to be redeposited at a depth below the surface to form the "Grey Billies".

CONCLUSION.

It has been the aim of the writer to show the important part played by clays in the production of hard quartzites from loose incoherent sediments, and it is believed that the explanations offered more nearly express the true mode of formation of these rocks than some of the older ideas advanced from time to time.

REFERENCES.

(1) David T.W.E.D. Vegetable Creek Tinfield--Mem.Geol.Survey N.S.W. p 45 and p 81.

(2) Wollnough W.G. The General Geology of Marulan and Tallong. Proc.Linn Soc. N.S.W. 34 1909 p. 782

(3) Waterhouse W.L.& Browne W.R. Note on the Occurrence of quartzite containing common opal and chalcedony at Tallong, N.S.W. Journ. Roy.Soc. N.S.W. Vol.83, p 140.

(4) Brown Ida,A. Some Tertiary Formations on the South Coast of N.S.W. Journ. Roy. Soc. N.S.W. Vol. 59 p.387

(5) Waterhouse & Brown W.R. Loc. cit.

(6) Clarke F.W. The data of Geochemistry U.S. Geol.Surv. Bull No.770 p.482.

(7) Heindl, Prendergast & Mong-"The Physicial Properties of Fired Kaolins" U.S. Bureau of Standards. Journal of Research Vol. 8 Feb. 1932, pp 201-4, 211-2.

(8) Brown H.Y.L. The N.S.W. Parliamentary Papers 1881 p. 427.

(9) Wilkinson C.L.

(10) Jaquet J.B. Ann.Report Dept. Mines N.S.W. 1892 pp 140-2

(11) Andrews E.C. Ann. Report Dept. Mines, N.S.W. 1924.

(12) Kenny E.J. Mineral Resources of the West Darling District (unpublished)

(13) Woolnough W.G. Pres. Address. Roy Soc. N.S.W. 1927

(14) Leith & Mead Metamorphic Geology pp 25-37.

(15) Clarke F.W. Data of Geochemistry p 482.

(16) Leith & Mead-- Metamorphic Geology p 121 and 135.

(17) Brown W, R. "The Probable Tertiary Age of some N.S.W. Sedimentary Soils" Journal Roy Soc. N.S.W. Vol. LX11 p. 260

2

(Reprinted from the Journal and Proceedings of the Royal Society of New South Wales, Vol. LXV.)

THE MINERALOGY AND ORIGIN OF THE NATURAL BEACH SAND CONCENTRATES OF NEW SOUTH WALES.

By H. F. Whitworth, B.Sc.

(With twenty Text Figures.)

(Communicated by C. A. Sussmilch.)

(Read before the Royal Society of New South Wales, June 3, 1931.)
Issued October 20th. 1931.

THE MINERALOGY AND ORIGIN OF THE NATURAL BEACH SAND CONCENTRATES OF NEW SOUTH WALES.*

By H. F. Whitworth, B.Sc.

(With twenty Text Figures.)

(Communicated by C. A. Sussmilch.)

(Read before the Royal Society of New South Wales, June 3, 1931.)

Occurrence.

At many places along the coast of New South Wales, between the mouth of the Shoalhaven River on the south, and the Queensland Border on the north, deposits of naturally concentrated heavy minerals occur on the beaches. The minerals have been concentrated by wave action during heavy south-east gales, and the deposits are usually best developed from the centres to the northern ends of the beaches. The most extensive deposits occur on the beaches to the north of Port Macquarie, those on the Southern beaches being much smaller. Raised beaches, only a few feet above sea-level, occur on the North Coast, and many of these contain layers of heavy mineral concentrates. In localities such as these, in which the waves are eroding the raised beaches, the deposits of concentrates on the present day beaches are particularly heavy, sometimes reaching a thickness of three feet, a width of twenty yards, and a length of over a mile after a heavy storm.

During periods of fine weather, the concentrates dry and become remixed with the beach sand, largely by the action of the wind, but at each high tide, a line of black sand is usually left at high water mark, thus indicating the presence of heavy minerals in the sand.

* Published by permission of the Under-Secretary for Mines.

Economic Importance.

The beaches and raised beaches of the North Coast have been worked intermittently during the past thirty-five years or so, for their gold, platinum, tin and monazite contents, but have failed to yield a satisfactory return. A large part of the work has been done by fossickers, who confined their attention to the heavy concentrates or "sniggers" formed during storms. More recently some attention has been paid to some of the South Coast beaches, and in 1925 a little cassiterite and gold were obtained from the beach at Thirroul. As the amount of concentrate on this beach is small, operations were conducted on a small scale, and have since been abandoned. Although both gold and cassiterite are known to occur on other beaches on the South Coast, little or no work has been done on them.

Attention is now being paid to some of the North Coast beaches as a possible source of zircon and rutile, the former for use in the manufacture of zirconia, which is now used as an opacifier in the enamelling of iron and steel, and the latter for the manufacture of titanium white, a pigment of great covering power, now finding an extensive use in the paint industry.

Composition.

The colour of the natural concentrates varies from a pale grey to a very dark grey, according to the amount of ilmenite present, and in some localities, it is so dark in colour that it is commonly known as "black sand." Owing to the fineness of the mineral grains, and their high degree of rounding, the concentrate is extremely mobile when dry.

A microscopic examination reveals the fact that the grading is very even and that the main constituents are zircon, ilmenite and rutile. As these three minerals have similar specific gravities, and as the grains are of approximately the same size, the percentage weight of each in a given sample may be determined with a fair degree of accuracy by a simple count of the number of grains of each mineral present in a small sample. This count is conveniently made with the aid of a microscope with a magnification of about 200 diameters, immersing the sample in a highly refracting liquid. Nitro-benzene was found to be suitable for this purpose, for, its refractive index being about 1.55, any quartz grains present are rendered almost invisible in ordinary light, whilst zircon and rutile grains stand out in high relief owing to their much higher refractive power. Providing that more than 1000 grains are counted in at least ten different fields of the microscope, the error in estimating the percentage weights of the minerals present does not appear to be high.

The approximate mineralogical composition of a number of samples of natural concentrates from different localities is given below.

Locality.	Zircon.	Ilmenite.	Rutile.	Other Minerals.
Corrumbin ..	53%	27%	13%	7%
Byron Bay ..	43%	36%	13%	8%
Ballina	62%	26%	7%	5%
Berrie Point ..	75%	14%	9%	2%
Fingal Beach..	54%	30%	11%	5%
Iluka	52%	28%	18%	2%
Collaroy	40%	43%	15%	2%
Thirroul	60%	25%	13%	2%
Terrigal	45%	39%	13%	3%

The term "Other Minerals" in the above table does not include quartz, the presence of which implies imperfect concentration. Some of the samples examined contained about 25% of quartz whilst others were practically free from this mineral. Quartz is easily removed from the heavy minerals by panning or by shaking and dry blowing. Either of these methods will yield a concentrate practically free from quartz, with the loss of very little of the heavy minerals present.

The following analyses, published in "The Mineral Industy of New South Wales" (N.S.W. Geological Survey 1928) serve to illustrate the chemical composition of the sands:

	No. 1	No. 2
SiO_2	27.46	20.36
ZrO_2	50.78	43.77
TiO_2	14.00	23.50
Al_2O_3	1.72	0.34
Cr_2O_3	0.42	0.34
FeO	4.83	4.48
MnO	0.25	trace
CaO	trace	absent
MgO	0.42	0.44
P_2O_5	0.24	1.25
Rare Earths	trace	1.61
Organic Matter	trace	0.32
SnO_2	trace	3.81
Gold	1 dwt. 7 gr. per ton	1 dwt. 10 gr. per ton
Platinoid Metals	less than 10 gr. ,,	less than 10 gr. ,,

No. 1.—Natural beach sand concentrate from between the Richmond River and Evans Heads. Analyst, J. C. H. Mingaye.

No. 2.—Natural beach sand concentrate from two miles south of Evans Heads. Analyst, H. P. White.

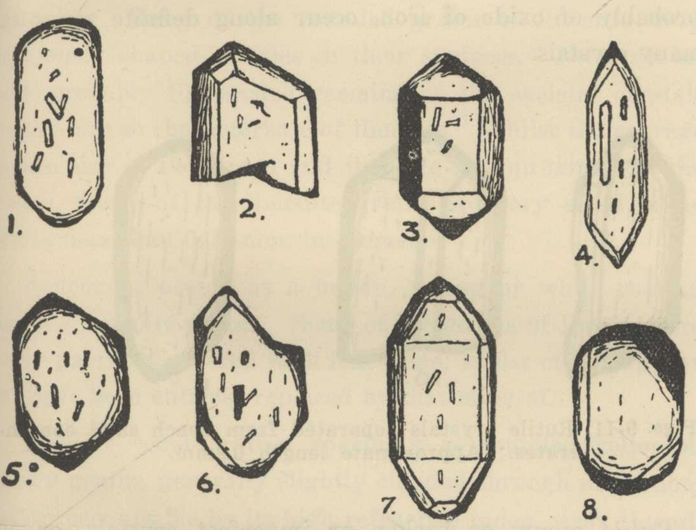
The writer has examined many samples of these naturally concentrated sands under the microscope, and in addition to zircon, ilmenite and rutile, the following minerals have been recognised:—

Leucoxene	Green spinel
Epidote	Brown spinel
Chromite	Cassiterite
Magnetite	Chalcedony
Limonite	Sapphire
Tourmaline	Pyroxenes
Monazite	Hornblende
Xenotime	Andalusite
Garnet	Staurolite
Pleonaste	

Raggatt (Bulletin No. 13 Geological Survey of New South Wales) states that Columbite is present in some cases. Owing to the opaque nature of this mineral, and the presence of a large amount of ilmenite, which is also opaque, it is impossible without the aid of magnetic separation and chemical tests on the separated fractions, to verify the presence of Columbite.

Description of the Minerals Present.

The *zircon* is nearly all of the colourless variety, although a few pale pink and pale blue grains are present. It occurs both as well rounded grains and as perfect doubly-

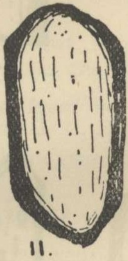


Figs. 1-8. Zircon crystals separated from beach sand concentrates. Approximate length 0.2mm.

terminated, pyramid capped tetragonal prisms. The crystals average about .2 mm. in length and about .1 mm. in breadth, whilst the rounded grains average about .15 mm. in diameter. The occurrence together of well rounded grains and perfectly preserved crystals, seems to imply that the crystals have been transported from their original source as inclusions in some other mineral which has protected them from erosion, and which has liberated them comparitively recently. The zircon is easily recognisable from its high refractive index, brilliant lustre on crystal faces, and its high double refraction. The double refraction is so high that most grains show only a high order white interference colour, though some show pale pinks and greens on the edges. Inclusions are common, some are definite crystals of rutile, whilst others appear to be hollow cavities, irregular in some cases, and elongated parallel to the "C" axis of the zircon, in others. Tiny dust-like inclusions, probably of oxide of iron, occur along definite zones in many crystals.


9.


10.


11.

Figs. 9-11. Rutile crystals separated from beach sand concentrates. Approximate length 0.2mm.

Rutile occurs as broken or imperfect crystals, or as rounded grains. The colour varies from a deep reddish brown through various shades of brown to a deep yellow. Many of the deeper coloured grains are almost opaque, and unless examined carefully in a very strong light, may be mistaken for ilmenite. The lustre on crystal faces and on freshly broken surfaces is very high, and the refractive index is so high that the lustre is quite noticable even when immersed in nitro-benzene, the refractive index of which is about 1.55. The double refraction of rutile is high, and interference colours are masked by the strong natural colour. Pleochroism is weak, and is only noticeable in the lighter coloured varieties. In size, the rutile grains are approximately equal to the zircons, the crystals averaging about .2 mm. in length, and the rounded grains about .15 mm. in diameter.

Ilmenite occurs both as imperfect crystals and as rounded grains. It is quite opaque, and of a bluish black colour by reflected light, whilst the lustre is somewhat metallic. Many of the rounded grains of ilmenite show curiously shaped cavities in their surfaces. These grains are probably the eroded remains of the skeletal crystals which are so characteristic of ilmenite. Whilst the average grain size of the zircon and ilmenite is approximately the same, many of the ilmenite grains are very small, some being less than 0.05 mm. in diameter.

Leucoxene occurs as a brown, yellow or white coating on the ilmenite grains. Some of the grains of ilmenite are only partially covered with leucoxene, whilst others appear to have been entirely replaced by that mineral.

Epidote occurs rather sparingly as rounded yellowish green grains, generally slightly clouded through alteration. It is recognisable by its high refractive index, weak though distinct pleochroism, bright interference colours, and the clouding previously mentioned. The amount of epidote varies greatly in different samples of sands. As the specific gravity of epidote (3.4) is considerably below that of zircon, ilmenite and rutile (4.53, 4.65, and 4.25 respectively) its presence is an indication of imperfect concentration.

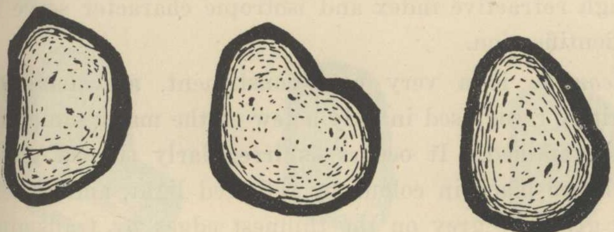
Chromite. The presence of small amounts of chromic oxide is shown by the analyses previously quoted, and a careful search reveals the presence of chromite in dark brown flakes which are almost opaque, being translucent on the thin edges only. The flakes are isotropic, and possess a very high refractive index. A few brown opaque octohedral crystals of chromite have been noted in some cases.

Magnetite occurs rather sparingly and is most easily detected by means of a magnet. The grains separated in this manner are jet black to brownish black in colour, and are often partially altered to limonite. Some perfectly formed octohedral crystals are present.

Limonite is present as small reddish brown earthy opaque grains, some of which appear to have a concentric structure. Much of the limonite present appears to be an alteration product of magnetite.

Tourmaline is very variable in amount, being very rare in some sands and forming up to 2% of the volume of others. As in the case of the epidote, this variation may be accounted for by the comparatively low specific gravity of the tourmaline (about 3.1). The tourmaline occurs both in the form of rounded grains and as short prismatic crystals with rounded ends. The colours are very varied, blue, pink, brown, black, and yellow grains being present. The pleochroism is very strong, changes being from colourless, yellow or brown to black, blue to pink, blue to colourless, blue to brown, pink to colourless and pink to brown. The characteristic absorption, which is greatest when the prism edge of the crystal is parallel to the vertical cross hair of the microscope, serves to identify any crystals of tourmaline present. The rounded grains are quite easily recognisable by their comparatively low refractive index and low double refraction, and their strong pleochroism.

Monazite, owing to its softness, occurs mainly as rounded grains which are slightly below the average grain size of the sands. Many of the grains have a peculiar bean-like or pear-like shape which seems to be characteristic (see figs. 12-14). The colour is pale yellow or yellowish green and pleochroism is absent. The refractive index is high and the grains show a characteristically pitted surface.



12. 13. 14.

Figs. 12-14. Monazite grains separated from beach sand concentrates. Approximate length 0.15mm.

The double refraction is about the same as that of zircon, and the grains show a high order white interference colour sometimes showing pale pinks or greens on the thin edges. The amount of monazite varies in different sands, in some cases being present to the extent of over 1%. The specific gravity of the monazite is sufficiently above that of the zircon, ilmenite and rutile to allow it to be concentrated by panning.

Xenotime. In the absence of micro-chemical tests, the determination of this mineral is in doubt, but in certain analyses both the phosphorous pentoxide and rare earths are shown in excess of that required for the monazite present. This implies the presence of another phosphate mineral of the rare earth group. Many of the sands examined contain a yellow mineral, often opaque through alteration, crystallising in a manner to the zircon, and having a very high refractive index and double refraction. This mineral has been provisionally classed as xenotime.

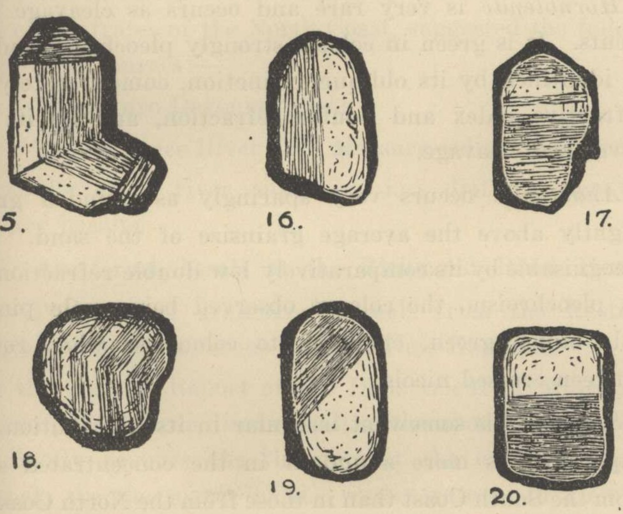
Garnet is present in practically all the sands examined, and occurs as irregularly shaped fragments which are not well rounded. Perfectly formed crystals are not present, although occasionally a crystal face may be seen. Both pink and colourless varieties are present. The combination of high refractive index and isotropic character serve for its identification.

Pleonaste is a very rare constituent, and has been definitely recognised in only a few of the many samples of sand examined. It occurs as irregularly shaped grains, which are black in colour by reflected light, and either a dark green or grey on the thinnest edges by transmitted light, the colouring being so strong that the centres of the grains are opaque.

Green Spinel is slightly more abundant than the pleonaste, and occurs as bright green grains which may be recognised by their high refractive index and isotropic character.

Brown Spinel occurs rather sparingly as dark brown translucent, isotropic flakes, having a high refractive index.

Cassiterite usually is a rare constituent, but in some cases owing to its relatively high specific gravity (6.65), it has been concentrated locally and samples containing as much as 25% of this mineral have occasionally been obtained. Most samples of the sands will yield a concentrate rich in cassiterite and monazite by panning. The identification of cassiterite is somewhat difficult owing to its variable colour. The colours are grey, yellowish brown, dark brown, brownish red and colourless. Pleochroism is very faint, and is best seen in the grey coloured grains. Well preserved crystals are rare, but a few prismatic crystals and geniculate twins have been seen. Many grains are either parti-coloured or zoned, which is a very useful character in the determination of cassiterite. The colour banding in some grains shows sharp changes of direction, as in Fig. 18. Such grains are evidently all that remains of an originally twinned crystal. The refractive index is high and the double refraction is so high that interference colours can seldom be seen even on thin edges.



Figs. 15-20. Cassiterite crystals separated from beach sand concentrates. Approximate length 0.15mm.-0.2mm.

Chalcedony is present both as angular fragments and as rounded grains which are either colourless or pale green. It is most easily recognisable by the fact that it fails to extinguish when rotated between crossed nicols, owing to its cryptocrystalline character. Its presence, like that of quartz, implies imperfect concentration.

Sapphire is a rare constituent, and occurs as flat basal cleavage plates. It is recognisable by its high refractive index, weak double refraction, pale blue colour and faint pleochroism.

Pyroxenes. Two varieties of pyroxene are present, one being colourless, and the other being pale green and pleochroic, changing to a pale pink when rotated between crossed nicols. The colourless variety is often much clouded by alteration, and is possibly diopside. The coloured pleochroic variety is apparently hypersthene.

Hornblende is very rare and occurs as cleavage fragments. It is green in colour, strongly pleochroic, and can be identified by its oblique extinction, comparatively low refractive index and double refraction, and by its well developed cleavage.

Andalusite occurs very sparingly as rounded grains, slightly above the average grainsize of the sand. It is recognisable by its comparatively low double refraction and its pleochroism, the colours observed being pale pink or pale bluish green, changing to colourless when rotated between crossed nicols.

Staurolite is somewhat irregular in its distribution, and apparently is more abundant in the concentrated sands from the South Coast than in those from the North Coast. It occurs as rounded grains of a brownish red colour, and is identifiable by its strong pleochroism and bright interference colours. Many of the grains of staurolite contain small inclusions which all elongated parallel to the long axis of the staurolite. Some of these inclusions are surrounded by dark haloes in the staurolite.

In addition to the above minerals, there are at least three others which have not yet been definitely identified. One of these is dark brown in colour and has a very high refractive index and double refraction, and is generally clouded through decomposition. This mineral is possibly sphene. Another mineral is brownish yellow in colour, quite opaque, and occurs as rounded grains with a brilliant lustre. The other unidentified mineral occurs as small prismatic crystals which are dark brown in colour, have straight extinction, and are almost opaque.

Origin.

The late J. E. Carne, in discussing the auriferous beach sand concentrates of the North Coast, suggested the following possible sources:—

(a) The Siluro-Devonian rocks.

(b) The Clarence River Coal Measure sedimentary rocks.

(c) The early river channels, i.e., drifts under the Tertiary basalts.

(d) Auriferous basalt at the Richmond River Heads.

(e) The present drainage channels from the Eastern margin of the stanniferous rocks of New England.

In the Annual Report of the Department of Mines for the year 1895, Carne discusses all of the above possibilities, and finally favours the theory that the early drainage channels are the source of the concentrates. In view of the fact that concentrates, similar to those of the North Coast, occur on the beaches between the mouths of the Hunter and Shoalhaven Rivers, in districts in which no Tertiary drifts are known, the writer began a series of experiments to determine whether the Triassic sedimentary rocks might not be their source.

Samples of Triassic sandstone from around Sydney were crushed and concentrated by panning, and some interesting results thus obtained. Six samples, each of 1000 grams, were treated by this method and yielded the following amounts of heavy mineral concentrates:—

Yellow sandstone	Dawes Point	.74 gms.
Yellow sandstone	Mosman	.86 gms.
Ferruginous sandstone	Willoughby	.45 gms.
White sandstone	Sailor's Bay	.22 gms.
White sandstone	Wynyard Square	.65 gms.
Yellow sandstone	Miller's Point	.35 gms.

A sample of Triassic sandstone from Broke, near Singleton, yielded only .11 gms. of heavy minerals per 1000 gms.

Several samples were treated in duplicate in order to determine whether the variations in the amounts of concentrate obtained were due to experimental error or not.

In each case the experimental error was found to be small, and it thus appears that there is a considerable variation in the amounts of heavy minerals present in different horizons of the Triassic Series.

A sample of Upper Coal Measure sandstone from near Muswellbrook yielded 0.5. gms. of heavy minerals per 1000 gms.

After warming the concentrates obtained from the sandstone with dilute hydrochloric acid, to remove iron stainings and to dissolve any particles of metallic iron introduced during crushing operations, it is seen that they bear a strong resemblance to the natural beach concentrates. In all cases they consist mainly of zircon, ilmenite and rutile, together with most of the other minerals found on the beaches. In addition to zircon, ilmenite and rutile, the following minerals have been observed:—

Haematite	Monazite	Cassiterite
Limonite	Staurolite	Tourmaline
Garnet	Epidote	Pyroxenes
Magnetite	Hornblende	

The relative proportions of zircon, ilmenite and rutile in the concentrate obtained from the yellow sandstone from Dawes Point are as follows:—

Zircon	36.6%
Ilmenite	31.3%
Rutile	23.0%
Other minerals	9.1%

The main differences between the concentrates obtained from the sandstones and the natural beach concentrates are the smaller degree of rounding in the former, and the higher percentage of monazite, epidote, staurolite, hornblende and pyroxenes.

The occurrence of heavy minerals in the Triassic sandstone near Sydney and the Upper Coal Measure sandstones near Muswellbrook leaves little room for doubt as to the origin of the concentrates on the beaches between Newcastle and the mouth of the Shoalhaven River. It is suggested by analogy, that the beach sand concentrates on the North Coast have been derived from the Triassic Series of the Clarence River District. The writer has not yet had an opportunity of preparing a concentrate from the Clarence River sandstones, but the preparation and examination of such a concentrate should prove whether the beach concentrates on the North Coast have been derived from this source.

The origin of the gold and platinum in the beach sand concentrates is, however, still in doubt. As the amounts of concentrates obtained from the sandstones were too small to allow of assays for gold and platinum being carried out, it is not known whether these metals are present in the Triassic sandstones. It is suggested that the gold and platinum must be regarded as local additions to the zircon-ilmenite-rutile concentrate, as they only occur at a few localities along the coast, whilst the zircon-ilmenite-rutile concentrate has a very wide distribution.

Acknowledgments.

The writer's best thanks are due to Mr. D. H. Newland, State Geologist, of New York, for assistance in the identification of certain minerals present in the sands examined, and to Mr. M. Morrison, Curator of the Mining Museum, Sydney, for information regarding the occurrence of the deposits of heavy mineral concentrates on the beaches of the North Coast of New South Wales.

References.

References to the occurrence of the North Coast beach sand concentrates will be found in the following:—

Annual Report, Department of Mines, N.S.W., 1895. Report by J. E. Carne.

Bulletin No. 13, Department of Mines, N.S.W., by H. G. Raggatt, B.Sc.

Journal of the Royal Society of N.S.W., 1892. Report by J. C. H. Mingaye.

(*Reprinted from the Journal and Proceedings of the Royal Society of New South Wales*, Vol. LXVI.)

THE INTRUSIVE IGNEOUS ROCKS OF THE MUSWELLBROOK-SINGLETON DISTRICT.

PART II.

THE SAVOY SILL.

By H. G. RAGGATT, M.Sc.,
and H. F. WHITWORTH, B.Sc.,
Geological Survey of New South Wales,

With Rock Analyses by
W. A. GREIG,
Chief Analyst and Assayer, Department of Mines, New South Wales.

(With Plates II, III and IV, and four text figures.)

(*Read before the Royal Society of New South Wales, July 6, 1932.*)

SYDNEY
PUBLISHED BY THE SOCIETY, SCIENCE HOUSE
GLOUCESTER AND ESSEX STREETS

1932

(*Reprinted from the Journal and Proceedings of the Royal Society of New South Wales, Vol.* LXVI.)

THE INTRUSIVE IGNEOUS ROCKS OF THE MUSWELLBROOK-SINGLETON DISTRICT.

PART II.

THE SAVOY SILL.

By H. G. RAGGATT, M.Sc.,
and H. F. WHITWORTH, B.Sc.,
Geological Survey of New South Wales,

With Rock Analyses by
W. A. GREIG,
Chief Analyst and Assayer, Department of Mines, New South Wales.

(With Plates II, III and IV, and four text figures.)

(*Read before the Royal Society of New South Wales, July 6, 1932.*)

THE INTRUSIVE IGNEOUS ROCKS OF THE MUSWELLBROOK-SINGLETON DISTRICT.

PART II.

THE SAVOY SILL.*

By H. G. RAGGATT, M.Sc.,
and H. F. WHITWORTH, B.Sc.,
Geological Survey of New South Wales.

With Rock Analyses by
W. A. GREIG,
Chief Analyst and Assayer, Department of Mines, New South Wales.

(With Plates II, III and IV, and four text-figures.)

(Read before the Royal Society of New South Wales, July 6, 1932.)

Part I of this paper was read before the Society on June 4, 1930, and consisted of an introduction to a detailed study of the intrusive igneous rocks of the Muswellbrook-Singleton coalfield. In the introductory statement concerning these rocks, it was pointed out that[1] "the field examination . . . . and a preliminary investigation of their petrology indicate that they fall into three groups as follow:

1. Alkaline basic sills.
2. Plugs.
3. Dykes and small sills." (Basalt.)

The alkaline basic sills are those which occur at Savoy, Plashett, Carrington and Fordwich. Their distribution is

* Published with the permission of the Under-Secretary for Mines.

shown in Plate IV of the earlier communication, and all except the last-named are shown in Fig. 1 of this paper. The Savoy mass differs from the other sills by its much higher proportion of acid rocks, which in places contain quartz, a mineral not known to be present in the rocks from the other sills. It also presents some interesting departures from the sill form in its mode of occurrence. It is considered, therefore, that a separate communication giving a detailed account of the geology and petrology of the Savoy Sill is well warranted.

In the following pages the field and general geology is the work of H. G. Raggatt, and the petrology of H. F. Whitworth. There has, however, been free interchange of ideas, and each has criticised the work of the other. The rock analyses are the work of W. A. Greig.

TOPOGRAPHY.

Locality and Means of Access.

The intrusion which forms the subject of this paper occurs eight miles southerly from Muswellbrook and is mainly within the Parish of Savoy, County of Durham. The outcrop extends also into the Parish of Wynn, the Savoy trigonometrical station being on the boundary between the two parishes. The area is part of the "Edinglassie" holding.

The only convenient means of access is by an unsurveyed track which leaves the Muswellbrook-Denman road at the same point as the Wollombi stock route, about the middle of the south boundary of portion 3, Parish of Brougham. The track is unfenced, but well defined as far as Saddler's Creek. The stock route itself cannot be

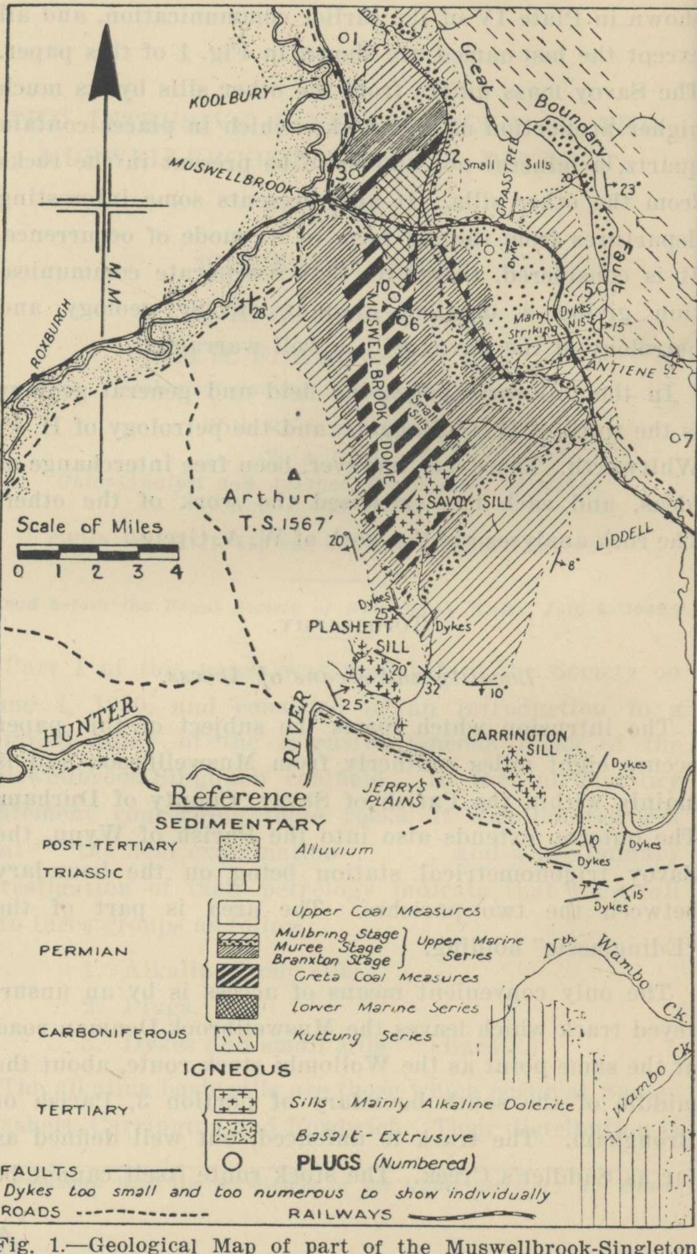


Fig. 1.—Geological Map of part of the Muswellbrook-Singleton district, showing distribution of igneous rocks.

travelled by motor car, but is a useful traversed line for survey purposes.

Physiography.

The topography is related to the geological structure (see Plate II and Fig 1). The Savoy trigonometrical station, which is 1,047 feet above sea level, is situated on a well-defined divide developed approximately along the longer axis of the Muswellbrook dome. Beginning at the north boundary of the map (Plate II), the top of this divide is a gently cruved line convex to the east. It is defined at the north end of the map by the stock route which follows it to the north-western corner of the area occupied by igneous rocks. Thence the divide curves gradually to the south-west through Savoy hill, an acid type of igneous rock forming the top of the ridge. The divide separates the waters of Saddler's and Pringle's Creeks, which are strike streams. The creeks in the north-east quarter of the map are, on the whole, dip streams.

Easterly from the Savoy ridge the hills extend for a considerable distance at the same general level of about 800 feet, the amount of relief being from 150 to 200 feet. On the western side of the Savoy ridge the country rises steeply from Saddler's Creek to a high divide which extends nearly to the Hunter River at Denman. This divide is being cut into from the north by the Upper Hunter River and from the south by the Lower Hunter. Its highest points are Mt. Arthur (1,567 feet) and Mt. Ogilvie (1,518 feet), the only hills within the broad valley of the Hunter which are at all comparable in height with the level (2,000 feet) of the uplifted peneplain out of which the valley is carved.

Southwards there is a gradual fall to the Hunter River six miles away. Beyond this the country rises gradually for approximately four miles to the foot of the Broke-Denman escarpment which borders a plateau (the uplifted peneplain referred to above) with a general level of about 2,000 feet.

Field Relations and General Geology.

As the map (Fig. 1) shows, the Savoy intrusion is situated at the southern end of the Muswellbrook dome. This structure is developed in beds of Kamilaroi (Permian) age. It is asymmetric, the dip on the east and south being from five to eight degrees, and on the west twenty degrees. The intrusion is wholly confined (at its outcrop) to the Greta Coal Measures and is developed mainly on the eastern side of the meridional axis of the dome.

Apart from a well-marked modification of the plan of the outcrop westerly from the Savoy hill, the area occupied by igneous rocks is roughly rectangular in shape, the longer sides being arranged in a direction N. 20° E. (*i.e.*, parallel to strike of the sediments on the eastern limb of the Muswellbrook structure). It is three miles long, and has an average width of slightly more than half a mile. Actual exposures occupy somewhat less than two and a quarter square miles.

Rock Types, Outcrops and Weathering.

In the field three distinct types of igneous rock may be recognised: *dolerite, syenite* and *basalt*, the first-named being by far the most abundant. This is not apparent upon casual inspection, as weathering of the dolerite produces a black soil, whilst the syenite is relatively little decomposed, and appears as fragments scattered through the black soil.

The principal outcrops of *dolerite* are: in the bed of Pringle's Creek and its eastern headwater tributary; along the upper contact parallel to Pringle's Creek; along the lower contact north from the shaft near the Savoy T.S., and in a small creek about three-quarters of a mile south-westerly from the trigonometrical station. There is in fact a general tendency for the dolerite to form fairly good outcrops along the margins of the sill as now exposed, and in the creek beds, and to be represented elsewhere by a deep mantle of black soil. The marginal arrangement of the occurrences suggests the development of a chilled marginal phase, more resistant to erosion than the remainder of the mass. Most of these outcrops are on relatively steep slopes and the products of decomposition are removed as they are formed. This is certainly the explanation of the stream bed outcrops. Pringle's Creek and its eastern headwater tributary are perennially flowing streams which also are able periodically to scour their beds and thus expose relatively fresh areas of dolerite. The tributaries which join Pringle's Creek on the western side, however, rarely flow, and weathering has proceeded to depths of ten feet or more, giving a rich black soil. (For this reason Pringle's paddock is regarded as one of the best in the Muswellbrook district for stock flattening purposes.) It is suggested later (p. 217) that the softening of the rock is due to magmatic processes rather than to the ordinary processes of weathering, but the above-mentioned factors have no doubt been important.

The weathering of the dolerite has also led to the formation of small local deposits of sands with a heavy mineral concentrate consisting largely of ilmenite.

The principal outcrops of the *syenite* are those which form the Savoy hill and the prominent hill westerly therefrom. There is also a fairly large outcrop half a mile north-east from the trigonometrical station, two small outcrops three-quarters of a mile northerly from the foregoing and another, half a mile south-east of the station. It will be seen by reference to the map that the principal outcrops of syenite occur on the top of a ridge. Their presence has in fact largely determined the position of the divide between Pringle's and Saddler's Creeks.

The syenite westerly from the trigonometrical station has quite a steep scarp on its western side with a well-marked bench towards the top. The upper surface slopes down gently to the south-east. Towards the top of the hill the rock becomes markedly drusy, many of the cavities being filled with chalcedony.

The *basalt* outcrops mainly as a selvage to the dolerite at the upper contact and as dykes and sills in the adjacent sediments. It is not known to occur at the lower contact. There are some well-defined outcrops on the stock route, and here and there on the Savoy ridge, suggesting that it originally formed a continuous sheet over the top of most of the dolerite.

Reference might be made here to a sill of basalt which occurs three-quarters of a mile north from the most northerly outcrop of dolerite. It is an almost perfect example of the relationship of outcrop to contour. The following section was measured in the bank of a large dam in portion 83, Parish of Savoy.

Generally this sill keeps to the lower of the two horizons shown and is thus in the same stratigraphical position as the Savoy intrusion (see p. 198).

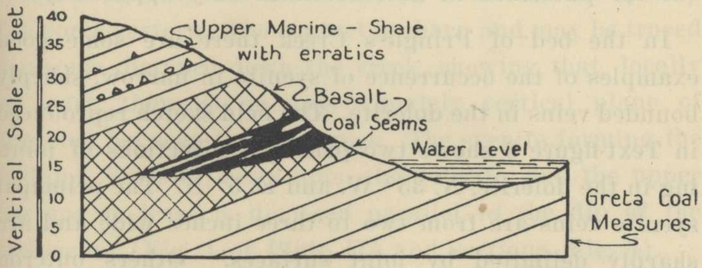


Fig. 2.—Section of a basalt sill exposed in the bank of a dam, portion 83, Parish of Savoy.

Field Relationships between the Rock Types.

The relationship between the dolerite and the syenite is clearly shown in the exposures along Pringle's Creek. In the low cliffs forming the bank of the creek, the syenite is shown to occur as veins and sheets in the dolerite, generally not more than three or four inches thick, but in places up to about ten inches thick. The most common form of occurrence in these sections is irregular sheets approximately parallel to the plane of bedding of the sediments, but there are also numerous small veins with no definite orientation. These types of occurrence are illustrated in Fig. 2 of Plate III.*

The tendency for aplitic veins to take on a stratiform arrangement parallel to the roof and floor of intrusive masses has been noted by many writers. It is a striking feature at Prospect, New South Wales,(2) and has been described by Tyrrell for the Howford Bridge sill, Scot-

* The syenite shown on the Section DE may be a residual of one of these veins or of the roof syenite.

land,[3] and by Ichimura for alkaline intrusives in Korea.[4] The latter also refers to similar occurrences in California which have been described by Taliaferro (so far published in abstract form only apparently).[5]

In the bed of Pringle's Creek there are some good examples of the occurrence of syenite in narrow, sharply bounded veins in the dolerite. The field sketch reproduced in Text-figure 3 shows two principal directions of jointing in the dolerite, N. 35° W. and E. 5° N. The principal syenite veins are from two to three inches wide and are sharply delimited by joint surfaces. Others outcrop merely as threads or "stringers".

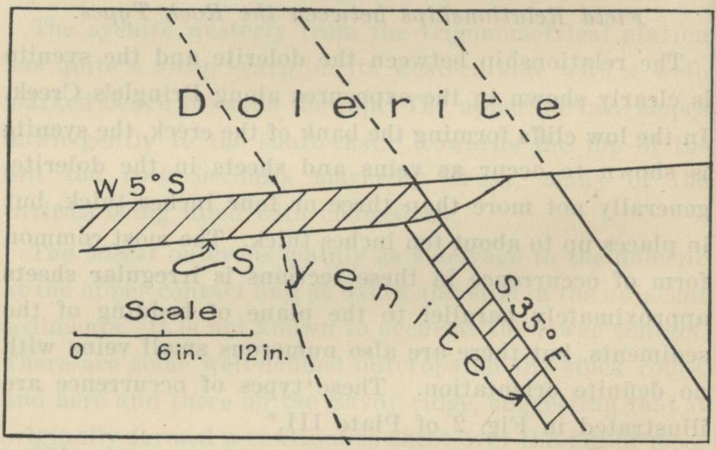


Fig. 3.—Plan showing soda syenite dykes filling joints in analcite dolerite, exposed in the bed of Pringle's Creek. Joints shown by full lines and thin aplitic veins by broken lines. The bearings are strike directions.

The joint directions are approximately parallel to the strike lines of the basalt dykes and to the dominant structure lines of the region.

At the head of a small creek three-quarters of a mile south-west from Savoy T.S., the relationship between the main mass of syenite and the dolerite is well shown, the dolerite forming the south-eastern bank and the syenite the north-eastern. The contact is sharp and may be traced for some distance down the creek, showing that, locally at least, there is an approximately vertical plane of junction between the two types. The syenite forming the hilltops, however, rests upon the dolerite, and the upper surface at least is disposed parallel to the dip of the sediments (Fig. 1 of Plate III and sections, Fig. 4).

There is no conclusive field evidence at the Savoy sill itself as to the age relations between the basalt and the other types of igneous rock. The contact between the two is not well exposed, but there does not appear to be any evidence of gradation between them, and it is doubtful if the basalt can be regarded as a chilled marginal phase of the dolerite. It may be a separate intrusion of related age, since, as already described, it forms a sill on the same horizon as the dolerite a short distance to the north. Evidence of contact effects at the upper surface of the basal precludes the possibility of their being flows.

Form, Limits and Thickness.

That the igneous rocks are intrusive is shown by the contact effects upon the overlying and underlying sediments. The carbonaceous shales are indurated and the overlying coal seam cindered, but these effects are limited to within a few feet of the intrusion. Nevertheless, a very large area of coal has probably been destroyed by this agency.

The top of the sill is about fifteen feet below the top of the Greta Coal Measures, which is well defined in this

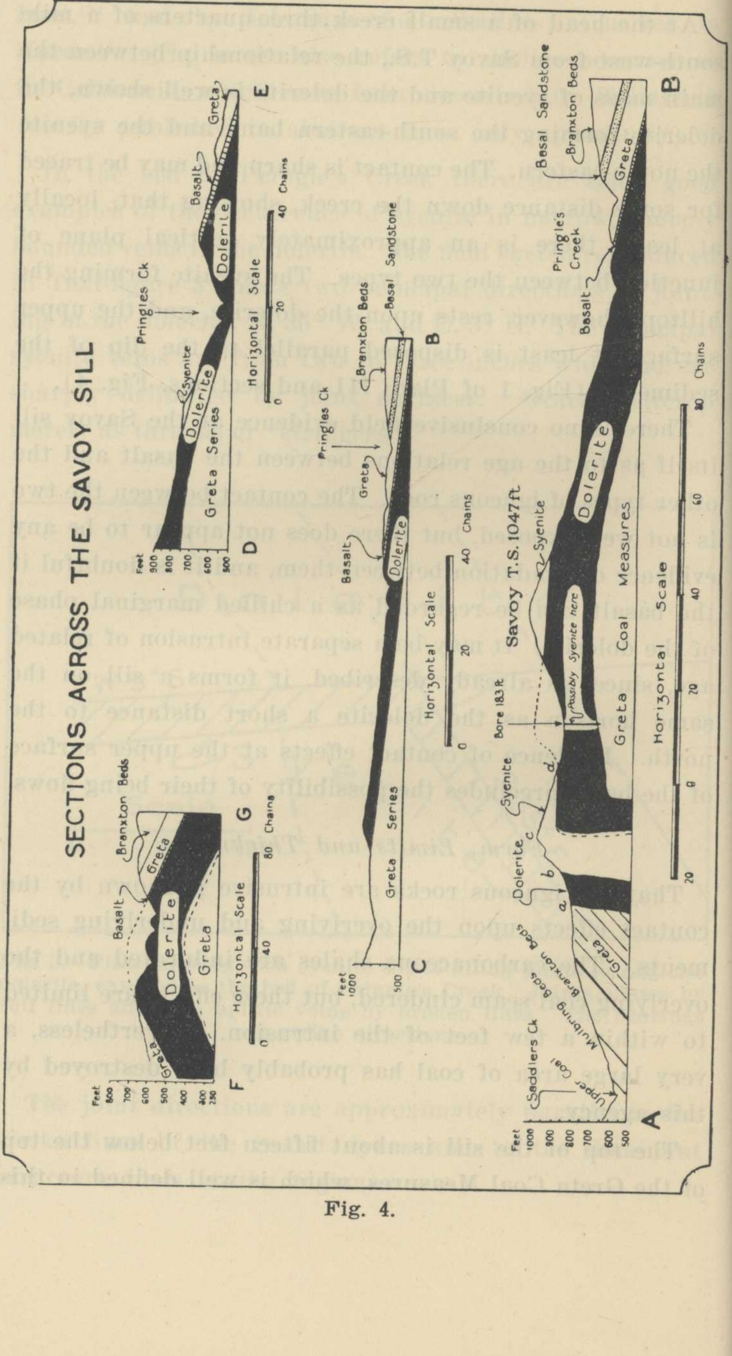

SECTIONS ACROSS THE SAVOY SILL
Feet
Basalt
Branxton Beds
Greta
Dolerite
Horizontal Scale
Chains
F
G
C
D
E
Greta Series
Syenite
Pringles Ck
Basal Sandstone
B
Sadlers Ck
Upper Coal
Mulbring Beds
Branxton Beds
Dolerite
Syenite
Bore 183 ft
Savoy T.S. 1047 ft.
Possibly Syenite here
Greta Coal Measures
Pringle's Creek
A

Fig. 4.

part of the Muswellbrook Coalfield by a white coarse-grained basal sandstone of the overlying Branxton Stage of the Upper Marine Series.

The concordant nature of the upper contact is particularly well shown along Pringle's Creek, where the boundary between the dolerite and the overlying shale outcrops just as if it were the boundary between two conformable sedimentary formations. The dip is E.S.E. at eight degrees (see sections AB, BC, and DE). This condition continues across Pringle's Creek to the south of the Savoy hill, the dip changing from a southerly one in the creek to S.W. at eight degrees near the hill. The upper surface of the sill must, therefore, be curved gently convex upwards at this point (section FG).

A traverse of the lower contact at the northern end of the sill outcrop and of the western edge north of the trigonometrical station shows that the base of the dolerite also remains at the one stratigraphical level, conformable to the sediments (Plate II and section CB).

A shaft which has been sunk (either to prove a coal seam or to obtain a water supply) 20 chains north-east from the Savoy hill, gives confirmatory evidence of this. The shaft is situated adjacent to the western margin of the sill outcrop, is about 145 feet deep and appears to have passed entirely through coal measure strata.

The contact appears to be transgressive, however, for a limited distance north-west and west of Savoy trig. station. Passing westward from the shaft referred to above, the boundary of the igneous rocks transgresses the strike direction of the sediments, and dolerite is found below the level at which it would be expected if it occurred as a simple sill. It might be inferred that the habit of the dolerite was phacoidal at this point, but in the same creek which was referred to as showing the sharp dolerite-syenite contact (whilst the exposures are not very good) one gets the impression that the dolerite transgresses the bedding planes of the westerly-dipping Greta Coal Measures.

The shape of the syenite outcrop, its sharp contact with the dolerite and the topography seem also to indicate that the concordant nature of the intrusion is departed from at this point. This can be explained best by reference to the section AB. Near "a" on this section the Greta Coal Measures dip at 20 degrees a little to the south of west. The distance from "a" to "b" is only six chains, whilst "bc" is a steep scarp, the vertical difference between "b" and "c" being 150 feet. No syenite occurs *in situ* near "a", and there is no sign of a bending over of the syenite parallel to the westerly dip of the Coal Measures. On the contrary, immediately on reaching "c" one looks down a gentle dip slope "cd" (*vide* Plate III, Fig. 1). There is, therefore, little likelihood that the space above "abc" was ever occupied by syenite and that its form when intruded was much as we see it now. It follows that the syenite transgressed the bedding planes of the sediments if they had not already been transgressed by the dolerite.

The limited length of outcrop in a north-south direction over which transgressive contacts can exist, and the elongation of the syenite outcrops in an east-west direction suggest that this rock may have a partly dyke-like form. On the other hand, the general inclination of both the larger syenite outcrops in the direction of dip of the sediments, shows that after passing through the dolerite the syenite spread out and took on the sill form. It evidently did not spread very far because there is no sign of it at the upper contact of the dolerite in the sediments, even quite close to the principal syenite outcrops.

We thus have a fairly clear picture of the form of the syenite portion of the intrusion. So far as the dolerite is concerned, its form must have been very similar to that of the syenite, and we have valuable confirmatory evidence afforded by a bore (windmill on map) put down in the saddle southerly from the trig. station. The bore appears to have passed through about 180 feet of dolerite (with possibly a little syenite near the top) and to have passed into indurated shale at that depth.* This thickness of dolerite (considered in relation to the observed facts further south, where as already described its upper surface is covered convex upwards) is best explained by assuming that the dolerite spread out from the plug locally forming a phacoidal sheet (see section AB).

The outcrops in relation to contour are such that it is possible to say that the boundary of the sill from Savoy trigonometrical station to the north-east corner of the outcrop is close to the original limits of the intrusion, but elsewhere we have no knowledge of its actual limits which are hidden under a cover of sediments.

There are no exposures giving a direct section across the full thickness of the sill, but measurement shows that the thickness is between 275 and 300 feet (*vide* section CB). Unless the boundary of the plug of dolerite westerly from Savoy trigonometrical station is drawn too far west

---

* From information kindly supplied by Messrs. White Bros. of "Edinglassie".

on the section AB, the bore put down in the dolerite westerly from Savoy places a minimum of 200 feet upon the thickness of the sill at this point, where, also, the syenite has a thickness of about 100 feet.

Geological Age.

(In the following brief statement, unless specifically referred to, the term "basalt" does not include the basalts of the dykes and small sills.)

The petrological description shows that a close resemblance exists between the Savoy rocks and those from certain other alkaline intrusive masses which are held to be of Tertiary age.[6] The age of the dolerites and syenites is arrived at through their association with normal olivine basalts of which the age is directly ascertainable.

The basalts which cap the highlands around the Hunter Valley (and which cannot be distinguished from the olivine basalts of some of the plugs) are correlative with the basalts of the region referred to by Sussmilch as the Merriwa tableland.[7] Evidence of the geological age of these basalts is furnished by the fossil leaves, fruits and fishes which occur in beds beneath them. Summarized accounts of the Tertiary leads and the volcanic rocks associated with them are given by David[8] and by Andrews.[9] These authors show that a threefold development of Volcanic rocks may be recognised: (*a*) Newer basalts, (*b*) alkaline series, (*c*) older basalts ranging from Eocene to Pliocene in age. David (*loc. cit.*) also suggests that the alkaline series may be in part younger than the newer basalts. Woolcott considers the newer gold bearing leads, such as those at Gulgong, to be from Upper Miocene to Lower Pliocene in age.[10]

It is certain that alkaline dolerite rocks intrude the olivine basalts of the tablelands in which the Hunter is incised, as the following observations show.

In 1911 W. N. Benson stated that theralitic types overlie "normal Tertiary olivine basalt" near Mount Barrington.[11] This area has since been visited by W. R. Browne, who states (verbally) that nepheline-bearing analcite dolerite occurs as sills intrusive into the olivine basalts. W. G. Woolnough also observed "dykes of coarse-grained olivine dolerite" including essexite intruding the "Tertiary basalt cap" at Mount Warrawalong ([11], pp. 184-185).

In 1929 a volcanic neck was noted by one of us (H.G.R.) near Wingen containing breccias and basalt like those in the Sydney district. These appear to have been intruded by a pipe-like mass of a syenitic rock similar to the aplitic types of the Hunter Valley sills. In 1931 also a composite sill of coarse-grained dolerite and "normal olivine basalt" was noted at Murulla. At this locality small dykes of the basalt appear to intrude the dolerite and the dolerite passes into a fine-grained contact facies very like the basalt. Further, it is impossible to distinguish the sill basalts from the basalt in the talus which is derived from the tableland flows.

Whilst there is, therefore, some doubt about the details in the local order of intrusion and extrusion of the igneous rocks, it is clear that all of them are of late Tertiary age, a most important conclusion in its relation to the tectonics of the region.

The argument thus briefly presented is a general one and must be supported by further petrological work, but as the detailed petrology of all the sills has not yet been completed, a full discussion of their geological age must be reserved.

We have not come to a final conclusion with regard to the geological age of the basalts of the small sills and dykes, and as these have yet to be fully described only a few brief comments are offered at this stage. These basalts are undoubtedly of the same age as those noted by one of us (H.G.R.) at Jerry's Plains, which W. R. Browne considers may be correlated with basalts in the Greta Coal Measures near Raymond Terrace.(12) He regards the Jerry's Plains basalts as interbedded in the Upper Coal Measures. We are not prepared to confirm or deny the correctness of this correlation. It is doubtful, however, if sufficient field work has yet been done to determine whether the basalts referred to by Browne are flows or sills. The age of these rocks relative to the sediments in which they occur is made difficult by the fact that the absence of contact phenomena does not necessarily imply that the basalts are interbedded, as the absence of alteration at the contact of Tertiary intrusives with Kamilaroi sediments is quite remarkable in some places. (Tests carried out in the laboratory of the Department of Mines, 1928, on shale from beneath the Carrington sill showed little alteration until temperatures approaching 1,000° C. were reached.)

W. R. Browne came to his conclusion mainly on petrological evidence, but it is considered by one of us (H.F.W.) that on the same basis many of the dyke basalts have a very close resemblance to some of the rocks included in the Garrawilla Series by E. J. Kenny (in lit.).

Kenny regards these as being largely contemporaneous lavas in the Jurassic,[13] though he has also stated that some of the rocks are probably intrusive.[14]

It may be possible to determine the age of these basalts from a consideration of tectonics, but we do not appear to be in a position at present to say definitely to which of the two earth movements which have affected the region they should be assigned. As stated on page 213, however, this evidence suggests a Tertiary or at least a post-Triassic age for the dyke basalts.

All that can be said at this stage is that the basalts are of late Kamilaroi age or younger, and that they may prove to be Jurassic or Tertiary.

Tectonics in Relation to Injection of Igneous Rocks.

The petrological research shows that there is no line of distinction between the syenite of the principal outcrops and that of the dykes. From this and the fact that the syenite occurs in sharply bounded dykes in the dolerite, it is clear that (i) the consolidation of the latter was complete before the injection of the syenite, (ii) differentiation of the magma had been effected in a reservoir removed from the place of intrusion prior to injection, (iii) the syenite was injected during a time of crustal stress, which was therefore of late-Tertiary age. The first and second of these points are discussed later (page 229).

With reference to the third, we are far from being in a position to make a satisfactory analysis of the stress directions of the region. It has been subjected to two well-marked orogenic movements, one of which is late Palæozoic and the other post-Triassic. The evidence for the former has been tranversed in some detail by

Osborne[15] and for the latter in brief by one of us (H.G.R.).[16]

Osborne (*loc. cit.*) gives the following trend lines as those which have been developed by the late-Palæozoic disatrophism in the Hunter region: (1) N. 15° W.-N. 20° W., (2) N. 30° W.-N.W., (3) almost due north and south, and (4) N. 20° E.

It would appear, however, from evidence already given[16] and from that briefly reviewed below, that there must still be considerable doubt as to the relative importance of late-Palæozoic and post-Triassic earth movements in producing structures with these trends. For instance, the Lochinvar dome, undoubtedly in part a late-Palæozoic structure, has a fault (Matthew's Gap) developed on its western side parallel to its principal axis, which involves the Triassic equally with the Permian.[16] The Wingen fault also has a strike a little to the north of west, and is almost certainly post-Triassic.

These are major structures. A study of the secondary structures leads also to significant conclusions, but it is only possible to deal very briefly with these in the present paper. The main secondary structures are:

A. Joints and syenite dykes in the Savoy sill. Strike directions: (i) N. 35° W., (ii) E. 5° N.

B. Basalt dykes (Text-fig. 1). Strike directions: (i) N. 15° E. to N. 35° E. (dominant), (ii) meridional, (iii) N. 20° W., (iv) E. 6° N. to E. 20° N. (common).

C. Thrust faults: (i) At Grasstree striking N. 25° W. to N. 30° W. (described in detail by H.G.R.[17]); (ii) at Antiene. Average of strikes about E. 15° N. (see Text-fig. 1).

The basalt dykes striking N. 15° E. appear to cut across the thrust faults at Antiene.

It has been shown above that the structures of Group A are of late Tertiary age, and the thrust faults may be correlated tentatively at least with the Hunter thrust of post-Triassic age.(17) It will be noted that there is fair agreement between the strike directions of these two groups of structures, notwithstanding that one is due to tension and the other to compression. Some of the basalt dykes fit in with the trends of Groups A and C also, and although the dykes with the dominant direction N. 15° E. do not, there is evidence at Antiene that the dykes with this strike appear to cut across some of the faults. Moreover, it is reasonably certain that all the dykes are of the one age. There is, therefore, no reason yet apparent why all the secondary structures may not be regarded as owing their origin to diastrophic disturbances of post-Triassic (probably largely Tertiary) age.

Now, if the trends of A, B and C be compared with those quoted from Osborne as characterising the late-Palæozoic diastrophism, it will be seen that there is a rather remarkable agreement between nearly all of them. If this means that earth movements have been similarly directed in both late-Palæozoic and post-Triassic time, it is difficult to see how, in the absence of other evidence, we can say which of the two played the more important part, the mere citation of a trend being of no value.

So far as the Muswellbrook dome is concerned, it may have originated in the late Palæozoic and become markedly accentuated in the late Tertiary. The dolerite was apparently injected during the first stages of the later movement. The intrusion was plug-like in the first instance, but spread out, conforming to the bedding planes of the incompetent shales of the Greta Coal Measures. The existence of a competent sandstone bed in the Branxton stage of the Upper Marine was probably an important factor in determining the horizon of the intrusion (*vide* [18]). This it may have done directly or indirectly depending upon the age of the basalt overlying the dolerite. Thus if the basalt is older than the dolerite, the sandstone may have caused the former to take on the sill form in the first place, the basalt in its turn determining the horizon of the dolerite.

After the dolerite had consolidated, jointing developed under the influence of regional stresses in directions N. 35° W. and E. 5° N., *i.e.,* inclined to each other at 120 degrees. At the same time the syenite was injected, for the fact that the joints extend across the dykes in places shows that the intrusion of the syenite must have taken place during the period of joint formation (*vide* [19]).

It is possible that the extension of the plan of the outcrop westerly from Savoy hill is also controlled by joints owing their origin to the same stresses.

Depth of Cover at the Time of Intrusion.

According to Sussmilch ([7], p. 42), "the basaltic eruptions appear to have immediately preceded the uplift of the tablelands (Kosciusko uplift) . . ." Thus the flows were poured out upon a peneplain which was subsequently uplifted to form a plateau or tableland, the dolerites being intruded at about the same time. In the Muswellbrook district this tableland is about 2,000 feet above present sea-level. (Woodlands T.S., 2,213 feet on the south side of the Hunter, is on Tertiary basalt;

Bell's Mountain T.S., 2,240 feet to the north-east of Muswellbrook, is on Kuttung rocks.)

Since all the major faults in the area under discussion are pre-Kosciusko (see Osborne, *op. cit.*, p. 451), and there is still basalt on the plateau, the difference between the height of Savoy T.S. (1,047 feet) and the present plateau level is a measure of the maximum amount of cover which could have been present when the intrusion took place. This depth of cover, about 1,150 feet, could only have been reduced by the depth of a pre-uplift valley which might have existed above the present Savoy hill. Of the existence of such a valley there is no evidence; on the contrary, the Savoy, Arthur and Ogilvie trigonometrical stations appear to lie on a ridge which was a pre-uplift divide.

It may be of interest to express the depth of cover in terms of the weight of the rock column. Of the 1,150 feet, a maximum of 650 feet would have consisted of Triassic sandstone and conglomerate (difference between heights of Arthur and Woodlands T.S.), and the remainder largely of shale (Upper Marine and Upper Coal Series). Taking the weight of a cubic foot of sandstone as 137 lb. and of a cubic foot of shale as 162 lb.,[20] the pressure per square foot at the horizon of the intrusion would have been approximately 75 tons.

PETROLOGY.

Three rock types are recognised: analcite dolerite, soda syenite and basalt.

Analcite Dolerite.

This rock forms the main mass of the sill, and although many specimens were collected and examined carefully, no evidence could be found of gravitative differentiation in the portion exposed by denudation. It is somewhat soft, and unaltered specimens are difficult to obtain, even the freshest material from outcrops in watercourses, where the decomposed mantle has been removed by stream erosion, showing a considerable degree of alteration. There are strong reasons for the belief that the softening of the rock is not due to weathering alone, but to the effects of late magmatic processes. This point will be dealt with later in describing the individual minerals of the rock. In hand specimens the rock is seen to be holocrystalline, medium to coarse grained, and of a dark greenish-grey colour. Under the microscope it is seen to be composed mainly of plagioclase, titaniferous augite, ilmenite with interstitial alkali felspar, chlorite, analcite, kaolin, serpentine, talc, brown hornblende, biotite and quartz, and numerous small inclusions of apatite. The fabric is granular to subophitic.

Description of Minerals.

Plagioclase occurs as idiomorphic lath-shaped crystals 1 to 3 mm. in length, and is usually much altered, many crystals having been entirely replaced by kaolin and sericitic material. Twinning is much obscured by heavy deposition of kaolin, but both albite and Carlsbad types are shown. Symmetrical extinction angles of about 32° indicate that it is labradorite, having approximately the composition $Ab_{45}An_{55}$. Zoning is exhibited by some crystals and is of the normal type, the centres being of calcic and the margins of more acid kinds of felspar. A much altered alkali felspar occurs filling many of the interstices of the rock. Much of this material is untwinned and has a refractive index less than that of Canada balsam. As the norm indicates the presence of 7·23% of orthoclase, it is probable that the interstitial felspar contains both orthoclase and albite. The alteration of the alkali felspar is more pronounced than in the case of the labradorite, many areas being quite opaque through deposition of kaolin. One peculiar feature of the interstitial felspar is the occurrence of a few small patches of quite clear unaltered mineral obviously of late crystallisation, suggesting that the kaolinisation of the first formed felspars took place before the deposition of the last interstitial felspars. Distinct evidences of albitisation of labradorite are seen; in places the kaolinised labradorite crystals have a narrow margin of clear unaltered alkali felspar. This process, however, does not appear to have taken place extensively, for only occasional crystals are thus affected.

Augite.—A slightly purple coloured, faintly pleochroic variety occurring in sub-idiomorphic crystals and irregular grains, many of which are ophitically moulded on the felspar laths. The average grain size is 1 to 2 mm. in diameter. The amount present is considerably in excess of the 12% shown in the norm, most specimens examined containing in the vicinity of 25%. A most remarkable feature of the augite is that notwithstanding the high degree of alteration of the rock, it is as a rule quite fresh, and has suffered little or not at all. It occasionally shows a slight reaction rim where it is in contact with the alkaline interstitial materials. These rims are very narrow and indefinite and are apparently of a chloritic character.

Ilmenite is an important constituent, occupying about 5% of the volume of the rock. It occurs in its typical skeletal crystals mainly in the interstitial material, seldom included in the augite or labradorite. The late crystallisation of ilmenite and magnetite has been referred to by Teall[21] in describing the basalts of Franz Josef Land, and by Washington[22] in dealing with the Deccan Trap Rocks of India. Much of the ilmenite is intergrown with biotite and many crystals are coated with leucoxene. Similar ilmenite-biotite intergrowths in dolerite have been described by Tyrrell ([3], p. 553), who states that they are to be explained by a reaction between the ilmenite and the residual sodic liquor.

Interstitial Material.

The interstitial material which occupies probably 25% of the rock space contains, besides the alkali felspars already alluded to, chlorite, kaolin, biotite, brown hornblende, analcite, quartz, serpentine, talc and carbonates, and numerous tiny prismatic crystals of apatite.

Chlorite is the most abundant interstitial mineral, and can be seen partially replacing brown hornblende and biotitie, and also forms pseudomorphs after biotite in which traces of the cleavage planes of the original biotite are still visible. Most of it, however, occurs as indefinite scaly or fibrous masses, filling some of the interstitial spaces of the rock.

Kaolin is seen to be derived from both the felspars and analcite, and some crystals of these minerals are so heavily charged with it as to be opaque. Kaolinisation of the felspars has been somewhat selective, most of the zoned labradorite crystals having been most affected along their more acid margins. As before mentioned, there is distinct evidence that the process of kaolinisation should be regarded as of late magmatic origin, as the last formed felspars are quite unclouded.

Biotite is not plentiful in the rock. It occurs as small flakes often associated with the ilmenite. It is strongly pleochroic and its cleavage planes often show distortion. Much of it is altered to chlorite, the change being preceded by a change to a green coloured biotite, which then changes to typical chlorite.

Brown hornblende is rare, most of it having been altered to chlorite. It is pleochroic in shades of brown, brownish-yellow, and green, and always partly chloritised. Some of the chlorite shows two sets of cleavage traces intersecting at about 60°, indicating that it represents altered hornblende.

Analcite occurs very sparingly, filling some of the triangular interstices of the rock. It is nearly all clouded by decomposition, and some of it shows weak anomalous double refraction.

Quartz.—A very small amount of quartz is present in the rock. It occurs both as irregular interstitial masses and as thin shells around felspar crystals. The second method of occurrence is interesting, and lends weight to Fenner's[23] hypothesis that quartz and micropegmatite in basic rocks are the results of interaction between late magmatic mineralisers and earlier formed minerals. In the present instance it is thought that the kaolinisation of the felspar may have supplied the silica to form the quartz. It will be noticed that quartz is absent from the norm.

Serpentine is present in small amounts. It is of a pale yellowish-green colour, and some is recognisably pseudomorphous after olivine.

Talc occurs in tiny scales replacing some of the serpentine.

Carbonates are rare, and occur mainly in tiny veinlets associated with sericitic material in the felspars.

Apatite forms small acicular to prismatic crystals up to about 1·5 mm. in length, and is more abundant in the interstitial material than in the labradorite and augite.

Order of Consolidation.

The order of consolidation appears to be somewhat as follows:

Labradorite, augite, olivine, ilmenite, biotite, hornblende, apatite, alkali felspars, analcite, quartz.

The hornblende probably crystallised about the same time as the biotite.

There was much overlap between the crystallisation of the interstitial minerals, and it is difficult to make out the exact order in which they consolidated. The apatite commenced to crystallise early and continued till most of the interstitial material was formed. The reversal of the normal order of consolidation in dolerites is fairly common. In N.S.W. similar orders of consolidation have been noted in the Prospects Mass,(24) the theralitic dolerite from Bombala ((6), pp. 377-378), and the large dolerite sills of the Coonabarabran Area (H.F.W., in lit.).

The development of chlorite, serpentine, talc, and kaolin should be regarded as a late magmatic process, and possibly the analcite, alkali felspar and quartz may, in part, have been derived by interaction between the active mother liquor and the solid crystalline phase of the cooling rock. The late crystallisation of apatite and its consequent frequent inclusion in the interstitial material implies the presence of much fluorine or chlorine in the residual liquors. The action of a hot solution rich in fluorine doubtless caused changes in the earlier formed silicates and would be quite capable of leaching them of part of their silica content which could later have consolidated as quartz. Browne[(24)] implies some such origin for the alkali felspars in the Prospect dolerite. Fenner ([(23)], p. 753), in his paper on the volcanic rocks of the Katmai region of Alaska, summarises much of the literature dealing with the subject of the influence of magmatic gases on the crystallisation of igneous rocks and holds them responsible for the development of quartz and micropegmatites in the interstitial spaces of dolerites.

The late crystallisation of ferromagnesian minerals in basic effusive rocks is explained by Daly[(25)] as being due to the presence of gas fluxes in the vents, thereby lowering the freezing point of the lavas and thus lengthening the temperature interval during which femic minerals may form. Some such process has probably favoured the late solidification of the augite, hornblende and biotite in the dolerite from Savoy.

Soda Syenite.

The relationship of the syenite to the dolerite has been described; the junction between the two is probably quite sharp as the main mass of syenite does not exhibit increasing basicity with increasing depth, and the dolerite is not noticeably more acid near the contact than in the lower portions, and small sharply bounded veins of syenite have been seen occupying joint fissures in the dolerite (see p. 202 and Fig. 3).

The syenite is a medium to fine grained, cream coloured holocrystalline rock, somewhat miarolitic in the upper portions of the main mass, but quite dense lower down. The drusy cavities are filled with quartz crystals, chalcedony or calcite. Under the microscope it is seen to be composed of alkali felspar which make up about 75% of the rock, with interstitial quartz, micropegmatite, indefinite patches of hematite, and a very small amount of each of soda amphibole, biotite, apatite, and ilmenite. The rock is even grained and has a granitic texture.

Description of Minerals.

Felspars are nearly all untwinned, but a few crystals show fine albite twinning and many exhibit either a fine cross-hatching or a "moire" extinction. The index of refraction is below that of Canada balsam and extinction angles are all low (about 5°). From the high Na_2O percentage and the high albite content of the norm, it is certain that much of the untwinned felspar must be soda orthoclase, as very little definite albite is present. Most of the felspar crystals are clouded through deposition of kaolin, and in some specimens examined the deposition of kaolin has been so heavy as to render the rock opaque. Some of the kaolinised crystals are surrounded by rims of clear albite, which exhibit albite twinning and have a refractive index slightly higher than the orthoclase or anorthoclase, but lower than Canada balsam. Rims of quartz are also common, and where felspar is in contact with quartz it is invariably more heavily charged with kaolin than elsewhere, suggesting that the quartz may have been formed by the kaolinisation of felspar.

Quartz.—This mineral occurs mainly in micrographic intergrowth with felspar, but also as irregular interstitial grains. It is most plentiful in the drusy portions of the rock.

Hematite occurs as reddish-brown opaque masses, in places clearly resulting from the alteration of ferro-magnesian minerals, whilst in others a core of magnetite or ilmenite can be seen.

Soda amphibole occurs most plentifully in specimens containing least quartz. It is apparently of early crystallisation, and builds subidiomorphic crystals up to 0·5 mm. in length. It is strongly pleochroic, the colours observed being pale brownish-green, dark brownish-green, and bluish-grey. The extinction angle is about 12°, indicating that it is arfvedsonite.

Biotite is a very rare constituent, and is usually of a very pale yellowish-brown colour.

Apatite occurs as tiny rod-like crystals plentifully scattered throughout the rock. As in the case of the dolerite, it appears to have crystallised rather later than most of the felspar.

Ilmenite occurs mainly as skeletal crystals enclosed in hematite.

Calcite occurs chiefly filling small dusy cavities and veins, but also filling some of the triangular spaces between the felspar crystals.

Chalcedony in its typical cryptocrystalline form occurs sparingly in a similar manner to the calcite.

Order of Consolidation.

Owing to the high degree of alteration and small amounts of ferro-magnesian minerals, their consolidation relationship is not clear. It is evident that the orthoclase and soda orthoclase enjoyed considerable freedom in crystallisation and that quartz and albite crystallised late, the quartz mainly in the interstices, but partly in micropegmatite, and the albite surrounding and possibly replacing orthoclase and soda orthoclase.

Harker[(26)] dealing with the Tertiary igneous rocks of Skye, states that "the association of druses, generally of small size, with xenoliths is a very general phenomenon." No xenoliths, however, are to be seen in the Savoy syenite, and the association of quartz and miarolitic structure are much more likely to be the results of magmatic gas action as is described by Fenner ([(23)], p. 759) in the case of the Virginian dolerites of Triassic Age. At Savoy the miarolitic structure is almost exclusively developed near the top of the sill where concentration of gases might be expected to have taken place.

Basalt.

The exact relationship of the basalt to the dolerite and syenite cannot be determined from field evidence. It is uncertain whether it represents a chilled margin of the dolerite or an earlier intrusion.

In hand specimens the rock is seen to be soft and weathered; it is buff to brown in colour, fine grained and in some places appears to be slightly amygdaloidal. Under the microscope it is seen to be composed mainly of basic plagioclase laths averaging about 25 mm. in length, with much indefinite interstitial material heavily charged with hematite. Ferro-magnesian minerals are represented only by the chloritic material and hematite in the groundmass. Close examination of the interstitial material shows the presence of a little comparatively fresh alkali felspar, some chalcedony and calcite. Many minute crystals of apatite are also present. The amygdaloidal areas are seen to be more in the nature of irregular drusy cavities than smooth steam holes. The filling is usually either chalcedony or calcite, and each cavity is surrounded by a zone of hematite.

The type of alteration of the basalt is similar to that found in the syenite which shows alteration of ferro-magnesian minerals to hematite instead of to chlorite as in the case of the dolerite.

Chemical Composition.

The dolerite and syenite were submitted to analysis, but it was thought that no useful purpose could be served by analysis of the basalt, owing to its high degree of weathering. Analyses of similar dolerites and syenites are quoted for comparison.

It will be noted that the silica percentage of the dolerite is rather higher than is usual in similar rocks, but, apart from this feature, the analysis agrees fairly well with that of the Prospect paleo-essexite, which has been regarded as the undifferentiated type rock. The potash percentage is very close to that of the Prospect rock and, coupled with the presence of alkali felspars, shows the rock to have Essexitic affinities. Owing to the higher silica percentage, felspathoids are almost absent from the Savoy rock. The norm calculated from the analysis agrees fairly closely with the minerals pre-

ANALYSES.

	I.	II.	III.	IV.	V.	VI.
SiO_2	60·76	49·50	46·26	45·57	44·69	56·44
Al_2O_3	14·23	16·46	13·36	14·95	14·17	15·54
Fe_2O_3	5·40	3·70	2·34	2·82	3·35	3·27
FeO	0·99	6·12	10·53	7·35	10·86	3·67
MgO	0·80	5·75	8·87	6·19	6·41	1·73
CaO	4·36	8·14	9·18	8·27	10·28	4·16
Na_2O	5·30	4·40	3·27	4·33	3·64	5·81
K_2O	3·67	1·15	1·23	2·16	2·01	4·27
H_2O+	1·47	2·69	2·08	3·93	2·53	2·06
H_2O-	0·35	0·87	0·15	0·97	1·01	0·44
TiO_2	0·90	0·76	1·78	2·41	0·46	1·16
P_2O_5	0·26	0·48	0·42	0·67	0·45	0·83
CO_2	1·60	0·16	0·06	0·18	Nil.	0·97
MnO	0·18	0·16	0·12	0·31	0·31	—
Cl	Trace.	Trace.	—	—	—	—

NORMS.

	I.	II.	III.	IV.	V.	VI.
Quartz	9·12					
Orthoclase ..	21·68	7·23	7·23	12·79	11·7	25·6
Albite	44·54	26·72	20·44	21·48	8·6	49·2
Anorthite ..	4·17	21·68	18·07	15·01	16·4	3·4
Nepheline ..	—	5·68	3·98	8·24	12·1	—
Diopside ..	8·50	12·14	20·15	17·27	26·5	4·5
Hypersthene ..	—	—	—		—	4·1
Olivine	—	11·09	19·50	10·33	14·6	—
Magnetite ..	0·70	5·34	3·48	4·18	4·9	4·9
Ilmenite ..	1·67	1·52	3·34	4·56	0·9	2·3
Hematite ..	4·96	—	—	—	—	—
Apatite	0·67	1·34	1·01	1·68	1·0	2·2

I. Soda syenite—Savoy Hill, Muswellbrook. W. A. Greig, Analyst.
II. Dolerite—Savoy Hill, Muswellbrook. W. A. Greig, Analyst.
III. Paleo-Essexite—Prospect, N.S.W. Jenson, Jevons, Taylor and Sussmilch, *Proc. Roy. Soc. N.S.W.*, 1911, Vol. XLV.
IV. Scottish Tescherite—average of 5 samples. Tyrrell, G. W., *Geol. Mag.*, 1923, p. 245.
V. Crinanite—Howford Bridge, Mauchline, Scotland. Tyrrell, G. W., *Q.J.G.S.*, Part 3, 1928, Vol. LXXXIV, pp. 557-9.
VI. Analcite Syenite—Howford Bridge, Mauchline, Scotland. Tyrrell, G.W., *Q.J.G.S.*, Part 3, 1928.

sent in the rock, the main differences being that analcite is present in place of nepheline, whilst augite, biotite, serpentine, hornblende and chlorite take the place of diopside and olivine.

The analysis of the Savoy soda syenite agrees fairly closely with that of the Howford Bridge analcite syenite, but shows a slightly higher silica content. But for the presence of quartz in the Savoy rock, the norms also are in fairly close agreement. The norm is very similar to the mode, the only difference being that the diopside of the norm is represented in the rock by soda amphibole and a little mica. It is quite possible that some of the hematite present in the rock represents completely oxidised pyroxene, in which case there would be even less difference between the normative and the actual mineral composition of the rock.

Relationship of the Syenite to the Dolerite.

So many instances of the occurrence of syenitic veins in dolerite are known that it must be regarded as quite a normal phenomenon. The best known example in N.S.W. is the Prospect intrusion described by Jevons[2] and his co-authors; Tyrrell[3] has described veins of analcite syenite in doleritic rocks in Ayrshire. Syenite veins in trachydolerite have been noted by Ichimura[4] in Korea and Northern Manchuria, and they are also known to occur in the large sills and laccolites of California.

Many writers, most notably Bowen[27] and Tyrrell ([3], p. 565), seek to explain this phenomenon on the crystallisation and filter pressing hypothesis whereby the more basic constituents of the magma crystallised, first forming a "sponge" of basic crystals filled with an acid mother liquor. The sponge has been assumed to contract on cooling, and the mother liquor to be driven out by earth movements, pressure of superincumbent rocks or contraction, to solidify in cooling cracks or regions of earth tension. This hypothesis has been strongly opposed by Fenner ([23], p. 759) who points to the fact that in many dolerites and basalts the basic minerals crystallise late. He doubts whether the mere crystallisation of a basaltic magma would at any time yield an acid residuum approximating a syenite in composition, and explains the aplitic veins as due to the magmatic waters containing mineralising agents, removing certain constituents from the earlier formed rocks and depositing them later in cracks and joints. He further supposes the magmatic waters and mineralisers to be the cause of the alteration of the syenitic rocks and the cause of drusy cavities and development of secondary minerals in them.

Daly ([25], p. 396) has drawn attention to the frequent association of trachytic lavas with basaltic types, as well as syenitic veins in dolerites, and seeks to explain all the rocks of the syenite clan as due to contamination of a basaltic magma by assimilation of sediments at great depths, followed by differentiation and the subsequent intrusion or extrusion of first the basic and then the acid phase so formed.

At Savoy there is no evidence of differentiation *in situ,* and the sharp junctions of some of the smaller veins of syenite in the dolerite indicate that the syenite was injected after the dolerite had completely solidified. A microscopic examination of the junction of one of the veins and the dolerite shows no signs of intermixing of the felspars, such as might be expected were the syenites formed from an alkali-rich mother liquor extruded from the spaces of the dolerite. Had the syenite originated by means of "filter pressing" of the dolerite, a trachytoid arrangement of the minerals of the "sponge" ought to be evident due to the contraction following the extrusion of the mother liquor; no such texture can be observed, however, in any specimens of the dolerite so far collected. The weight of evidence seems to point to the fact that the syenite differentiated from the dolerite in a deep seated magma chamber and was injected at some considerable time interval after the dolerite had solidified. The injection of the syenite was accompanied by magmatic waters and gases that were responsible for the kaolinisation of the felspars of the syenite, the development of druses in its upper portion, the leaching of its ferromagnesian minerals, and probably also part of the alteration of the dolerite as well. The arrangement of the small dykes of syenite in the dolerite suggests that they occupy a system of joints of tectonic origin, rather than shrinkage cracks (see p. 211).

In considering the relationship of the syenite and dolerite it is interesting to note that in the case of the Tertiary eruptive rocks of eastern Australia, alkaline trachytic rocks are frequently associated with basalts and usually appear to post date the latter by some considerable time. As there is evidence that the Savoy intrusion is of Tertiary Age, it seems probable that the dolerite should be regarded as the hypabyssal equivalent of the older basalts and the syenite as representing the later trachytes. This matter, however, will be dealt with more fully in a later paper dealing with the whole of the intrusive rocks of the Muswellbrook-Singleton area in which the problem of their ages will be more fully discussed.

Summary.

The Savoy intrusion, one of a number of doleritic igneous masses in the Muswellbrook-Singleton coalfield, is described in detail. It is shown to be mainly a concordant intrusion into the Greta Coal Measures, partly of the simple sill type and partly phacoidal, of which the feeding channel is to some extent exposed. The main mass of the sill consists of dolerite with syenite veins intruding it. These veins are of two types: one stratiform, approximately parallel to the roof of the sill, and the other occupying joints in the dolerite. Syenite also forms the upper portion of the sill adjacent to the feeding channel.

Evidence for the Tertiary age of the intrusion is given. The mode of occurrence of the syenite and the secondary structures of the Muswellbrook district are discussed in relation to the tectonic geology of the region.

In the petrological section of the work, three types of rock are recognised, analcite dolerite, soda syenite and basalt. These are described in detail. Rock analyses of the dolerite and syenite are given and comparisons made with rocks of similar types from Prospect, New South Wales, and from Scotland.

The absence of evidence of differentiation *in situ* at Savoy is emphasised in discussing the relationship between the syenite and the dolerite. It is also pointed out that the injection of the former was accompanied by magmatic waters and gases that were responsible for the

kaolinisation of the felspars of the syenite, the development of druses in the upper portion, the leaching of its ferro-magnesian minerals and probably also part of the alteration of the dolerite as well.

ACKNOWLEDGMENTS.

Our thanks are due to Mr. W. A. Greig, Chief Analyst and Assayer, Department of Mines, N.S.W., for co-operating with us in the preparation of this paper by making analyses of the two main rock types at Savoy.

We also acknowledge our indebtedness to Mr. M. Morrison, both in his former position as Geological Surveyor, and as Curator of the Mining Museum, Sydney.

We are very grateful to Assistant Professor W. R. Browne for his advice and criticism in field and laboratory.

One of us (H.G.R.) wishes to express his thanks to Dr. G. D. Osborne for his criticism of portion of the manuscript and to Mr. F. W. Booker, M.Sc., for his assistance in the field.

REFERENCES.

(1) Raggatt, H. G., and Whitworth, H. F.: "The Intrusive Igneous Rocks of the Muswellbrook-Singleton District. Part I: Introduction", *Journ. Proc. Roy. Soc. N.S.W.*, Vol. LXIV, p. 79, 1930.

(2) Jevons, H. S., Jenson, H. I., and Sussmilch, C. A.: "The Differentiation Phenomena of the Prospect Intrusion", *Jour. Proc. Roy. Soc. N.S.W.*, Vol. XLVI, pp. 130-137, 1912.

(3) Tyrrell, G. W.: "On Some Dolerite Sills Containing Analcite Syenite in Central Ayrshire", *Q.J.G.S.*, Vol. LXXXIV, Part 3, No. 335, p. 543.

(4) Ichimura, T.: "Alkaline Rocks from the Frontier Region near Kainei, Chosen (Korea)", *Faculty Sci. and Agric. Taikohu Imp. Univ., Geol.*, No. 1, pp. 231-235, Fig. 2 and Plate V.

(5) Taliaferro, N. L.: "Geology of the Nipomo Quadrangle, San Luis, Obispo and Santa Barbara Counties, California". Abstract, *Bull. Geol. Soc. Am.*, Vol. 41, No. 1, p. 146, 1930.

(6) Browne, W. R.: "Petrological Notes on Some New South Wales Alkaline Basic Rocks", *Jour. Proc. Roy. Soc. N.S.W.*, Vol. LXI, pp. 371-382, 1927.

(7) Sussmilch, C. A.: "The History of Vulcanism in N.S.W.": Presidential Address, *Jour. Proc. Roy. Soc. N.S.W.*, Vol. LVII,, p. 36 and Fig. 1, 1923.

(8) David, T. W. E.: "Tertiary Stratigraphy of N.S.W.", *B.A.A.S. Handbook*, pp. 608A-614, 1914.

(9) Andrews, E. C.: "The Tertiary and Post Tertiary History of N.S.W.", *B.A.A.S. Handbook*, pp. 518-526, 1914.

(10) Woolcott, H.: "Evidence of the Age of Some Australian Gold Drifts, with Special Reference to the Mammalian Remains", *Rec. Geol. Surv. N.S.W.*, Vol. IX, Part II, pp. 96-97, 1920.

(11) Benson, W. N.: "Preliminary Note on the Nepheline-bearing Rocks of the Liverpool and Mount Royal Ranges", *Jour. Proc. Roy. Soc. N.S.W.*, Vol. XLV, pp. 176-186, 1911.

(12) Browne, W. R.: "An Outline of the History of Igneous Action in N.S.W. till the Close of the Palæozoic Era", *Proc. Linn. Soc. N.S.W.*, Vol. LIV, Part I, p. xxix, 1929.

(13) Kenny, E. J.: "Progress Report, Geological Survey of Coonabarabran-Gunnedah District", *Ann. Rept., Dept. Mines, N.S.W.*, p. 118, 1928.

(14) Kenny, E. J.: *Ibid.*, pp. 130-131, 1927.

(15) Osborne, G. D.: "Some Aspects of the Structural Geology of the Carboniferous Rocks in the Hunter River District, between Raymond Terrace and Scone", *Proc. Linn. Soc. N.S.W.*, Vol. LIV, Part 4, No. 224, p. 456 *et seq.*, 1929.

(16) Raggatt, H. G.: "Note on the Structural and Tectonic Geology of the Hunter Valley between Greta and Muswellbrook, with Special Reference to the Age of the Diastrophism", *Proc. Linn. Soc. N.S.W.*, Vol. LIV, Part 4, No. 224, pp. 273-282, 1929.

(17) Raggatt, H. G.: "Thrust Faults and Compression Joints in the Muree Beds near Grasstree, N.S.W.", *Jour. Proc. Roy. Soc. N.S.W.*, Vol. LXIV, p. 155, 1930.

(18) Bowen, N. L.: "Crystallisation-Differentiation in Igneous Magmas", *Jour. Geol.*, Vol. XXVII, p. 407, 1919.

(19) Rohleder, H. P. T.: "A Tectonic Analysis of the Mourne Granite Mass, County Down", *Proc. Roy. Irish Acad.*, Vol. XL, Section B, No. 12, p. 173.

(20) Kempe, H. R.: "The Engineer's Handbook for 1928", p. 237. Crosby, Lockwood and Sons, London.

(21) Newton, E. T., and Teall, J. J. H.: "Notes on a Collection of Rocks and Fossils from Franz Josephland . .. .", *Q.J.G.S.*, Vol. 53, p. 484, 1897.

(22) Washington, H. S.: "Deccan Traps and Other Plateau Basalts", *Bull. Geol. Soc. America*, Vol. 33, p. 772, 1922.

(23) Fenner, C.: "The Katmai Magmatic Province", *Jour. Geol.*, Vol. XXXIV, No. 7, Part 2, p. 753, 1926.

(24) Browne, W. R.: "Notes on the Petrology of the Prospect Intrusion . . . .", *Jour. Proc. Roy. Soc. N.S.W.*, Vol. LVIII, p. 244, 1924.

(25) Daly, R. A.: "Igneous Rocks and Their Origin." McGraw Hill, New York, p. 229, 1914.

[26] Harker, A.: "Tertiary Igneous Rocks of Skye", *Mem. Geol. Surv. Gt. Brit.*, p. 185, 1904.
[27] Bowen, N. L.: "The Later Stages of Evolution of Igneous Rocks", *Supp. Jour. Geol.*, Vol. XXIII, p. 90, 1915.

Explanation of Plates.

Plate II.

Detailed Geological Map of the Savoy Sill. (Mr. M. Morrison, assisted by Messrs. F. W. Booker and C. St. J. Mulholland, made a preliminary survey of the sill area in 1925, but the detailed work on which the present map is largely based was not carried out until 1929. This was done by one of us (H.G.R.), assisted by Mr. F. W. Booker.)

Plate III.

Fig. 1.—View, looking south, of the syenite hill west of the Savoy Trigonometrical Station, showing the scarp on the western side and the general dip surface to the east. (Compare with Section AB of Text-fig. 4.)

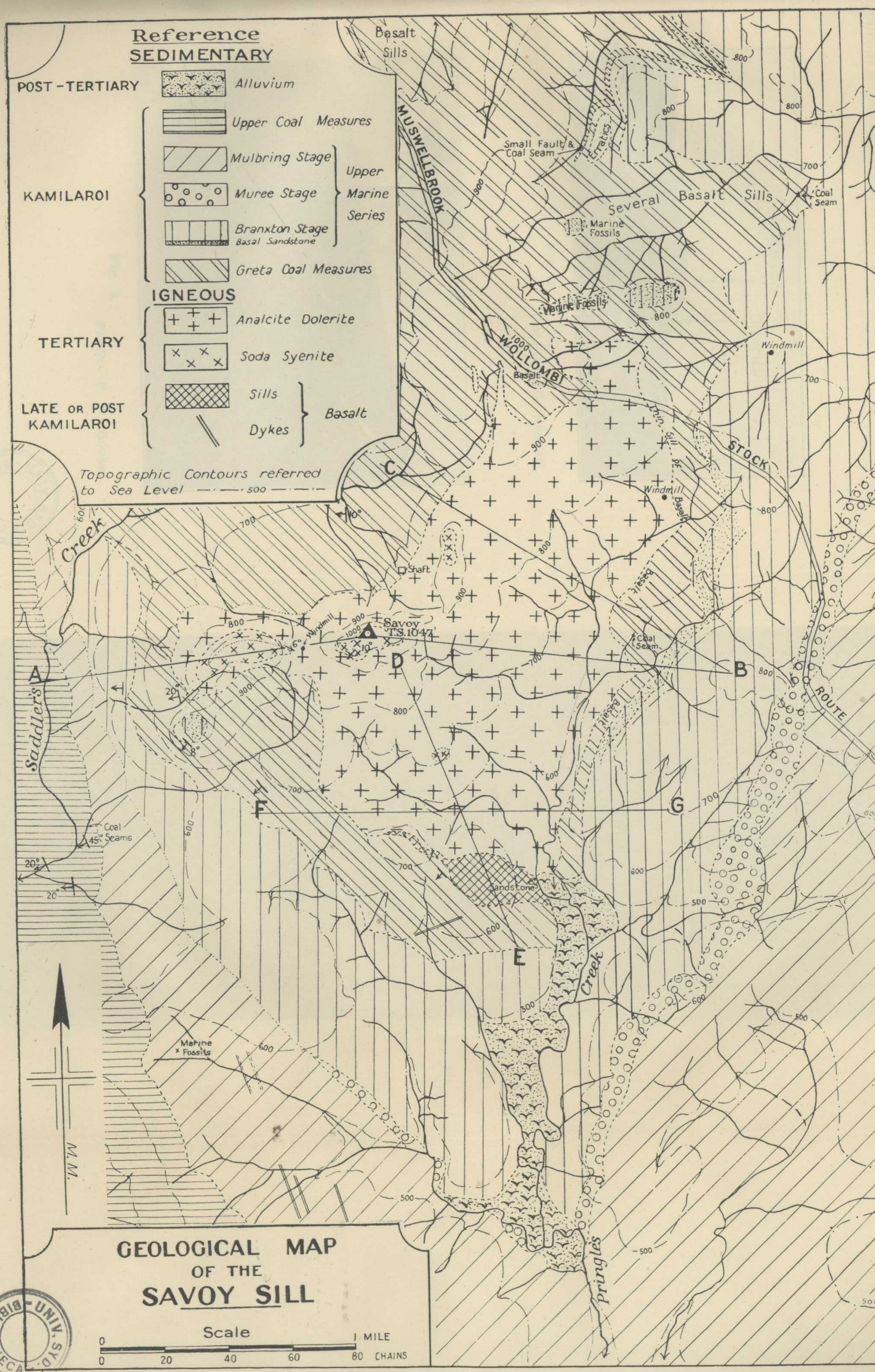
Fig. 2.—Aplitic veins (picked out in white) in dolerite as exposed on the right bank of Pringle's Creek. One vein is dyke-like, but the majority are arranged approximately parallel to the roof of the sill.

Plate IV.

Fig. 1.—Dolerite by ordinary light. Idiomorphic labradorite laths with augite sub-ophitically moulded on them. The grey areas are mainly kaolin and the black portion of the photograph represents chlorite and ilmenite. Several triangular areas of alkali felspar occupying spaces between labradorite crystals are included in the photograph. × 16.

Fig. 2.—Dolerite viewed between crossed nichols. The darkness of the interstitial material is largely due to the heavy deposition of kaolin in the alkali felspars. × 16.

Fig. 3.—Soda syenite between crossed nicols, showing micro-pegmatite areas surrounded by soda orthoclase. The "moiré" extinction of the soda orthoclase is well known. × 32.



Journal Royal Society of N.S.W., Vol. LXVI, 1932. Plate II.

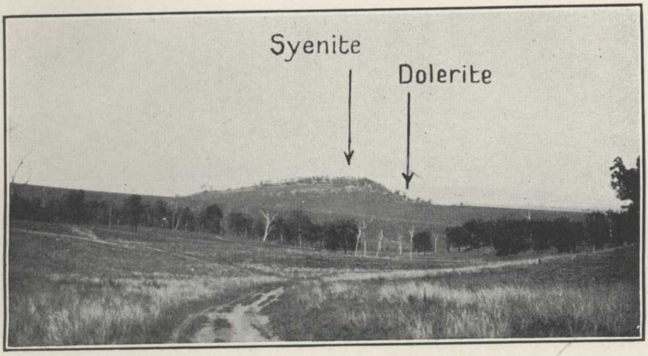


Fig. 1.
Photo.—H. G. Raggatt.

Fig. 2.
Photo.—F. W. Booker.

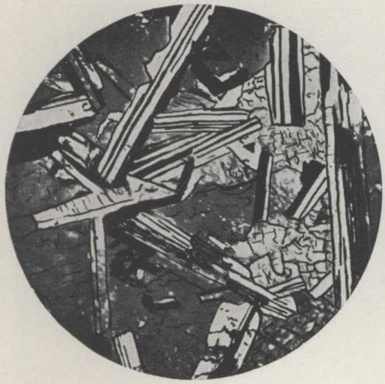


Fig. 1.

Fig. 2.

Fig. 3.