The deuteric mineral sequence in the Enoggera granite, Queensland.

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THE Enoggera 'granite', in which occur the minerals to be described, is situated a few miles to the west of the city of Brisbane, and within the Greater Brisbane area. Deuteric and allied minerals have previously been recorded from quarries in the granite by H. C. Richards [1] and W. H. Bryan,[2] and a specimen is recorded in the Queensland Mineral Index[3] as 'Heulandite occurring as geodes in granite. Loc. Enoggera.' [4]

The granite itself is very varied in character, and Bryan has recognized two main types, a pink phase and a grey phase. The pink phase approaches an adamellite, while the grey is more granodioritic in character. There is, however, every gradation from one type to the other due to admixture, and this reaches its maximum in a hybrid rock formed presumably by the mingling of the two magmas. Therefore, it is obvious that a complete picture of the granite cannot be shown by chemical analyses, but those quoted below will give some indication of its general character and of its variety.

There are three quarries in the granite and the minerals have up to the present been found only in these. Two are in the pink phase and one in the hybrid rock, and all are close to the contact with the Bunya Phyllite division (Ordovician ?) of the Brisbane Schists. The minerals occur as veins and infilling cavities, the latter varying from

[1] H. C. Richards, The building stones of Queensland. Proc. Roy. Soc. Queensland, 1918, vol. 30, p. 102.

[2] W. H. Bryan, Geology and petrology of the Enoggera granite and allied intrusives. Proc. Roy. Soc. Queensland, 1923, vol. 34 (for 1922), p. 142.

[3] B. Dunstan, Queensland mineral index. Queensland Geol. Surv., 1913, publ. no. 241, p. 560.

[4] An examination of this specimen, kindly lent by the Geological Survey, shows that the 'heulandite' is in fact laumontite.

a few inches to about two feet across. All occurrences are in the heart of apparently solid blocks of granite, a feature causing much annoyance in the quarrying operations.

Some reaction appears to have taken place between the contents of the vughs and the surrounding rock, resulting in a rough zonal arrangement. In the vughs themselves there is a medley of minerals consisting mainly of zeolites and calcite. These are usually surrounded by a band of pegmatite consisting of quartz and felspar in rough

Analyses of granites from Enoggera, Queensland (W. H. Bryan, 1923).

	Pink Phase.	Hybrid.	Grey Phase.
SiO_2 ...	73·52	71·50	61·10
TiO_2 ...	0·20	0·41	—
Al_2O_3 ...	11·05	14·13	19·24
Fe_2O_3 ...	nil	0·60	4·66
FeO ...	3·15	3·23	—
MgO ...	1·03	1·17	2·56
CaO ...	1·70	2·70	5·25
Na_2O ...	4·08	2·97	3·82
K_2O ...	3·99	2·86	1·68
H_2O+ ...	0·44	0·32	1·31
H_2O- ...	0·16	0·10	0·64
CO_2 ...	—	—	—
P_2O_5 ...	0·15	0·35	—
	99·47	100·34	100·26
Sp. gr. ...	2·58	2·59	2·71

graphic intergrowth. Occasionally, instead of the pegmatite, a zone of greisenized material is found. This grades into the fresh granite. Pegmatite also occurs as sporadic patches in the granite. These contain the normal minerals of the granite and are perfectly fresh and free from miarolitic structure.

It is of interest to note that only in two places have the gases associated with the magma been recorded as having reached beyond the margin. One of these is in the northern part of the mass, where patches of schorl and the tourmaline-albite-rock occur.[1] The other locality is to the south, where, at Finney's Hill, Indooroopilly, argentiferous galena occurs in considerable quantities. Although about a mile from the nearest granite outcrop, L. C. Ball[2] has reported the

[1] W. H. Bryan, An unusual tourmaline-albite rock from Enoggera, Queensland. Proc. Roy. Soc. Queensland, 1924, vol. 35 (for 1923), pp. 48–60.

[2] L. C. Ball, Queensland Government Mining Journ., 1920, vol. 21, pp. 266, 484, 527.

association of this deposit with a line of dikes. Occurring with it are small quantities of copper, bismuth, and zinc ores.

Laumontite.[1]—This is the most abundant zeolite and occurs in vughs and veins as aggregates of comparatively large crystals, occasionally as isolated crystals up to an inch in length, sometimes in radiating groups, or as parallel crystals filling small veins. It occurs either alone or associated with the other minerals; and it is sometimes intergrown with calcite.

The colour varies from white to light red, depending on the percentage of iron present, and is intensified on prominent cleavage lines. The streak is colourless. In the hand-specimens the mineral is opaque. The lustre varies from vitreous to pearly, basal sections being less lustrous than the prismatic. There are three cleavages, two very good ones parallel to (100) and (110), and a third not so well developed parallel to (001). The cleavage is more pronounced in those parts of the crystals which project into the cavities. At their distal ends they are often compact: this changes into a lamellar stage and finally into a splintery stage where both prismatic cleavages are well developed. The hardness varies from 3 in the well-cleaved splintery crystals to 5 in the more compact ones. Specific gravity 2·2 to 2·3.

The optical extinction on cleavage fragments is in part 30° with positive elongation, and in part nearly straight, again with positive elongation. Fragments with straight extinction show a negative biaxial figure with small optic axial angle and the optic axial plane parallel to the elongation near the border of the field. Fragments with 30° extinction do not show definite interference-figures. Refractive indices of cleavage fragments α' 1·508, γ' 1·524 approx.

When heated in a closed tube the mineral gives off water. In the bunsen-burner flame it splinters and glows at the edges, soon losing its pink colour. When heated more strongly with the blowpipe it curls up and fuses with intumescence to form a bead which cools to a white enamel. Treated with strong hydrochloric acid in the cold, it dissolves slowly, but in hot hydrochloric acid it decomposes readily, forming a gelatinous mass. It shows a marked efflorescence even at ordinary temperatures.

The following analysis of the laumontite is supplied by courtesy

[1] This description is based largely on a communication from Mr. M. H. Hey of the British Museum of Natural History, to whom some small fragments were submitted.

of the Queensland Government Analyst, to whom samples were submitted.

			Recalculated.
SiO_2	...	50·96	52·13
TiO_2	...	nil	nil
Al_2O_3	...	22·52	23·04
Fe_2O_3	...	0·20	0·20
MnO	...	nil	nil
MgO	...	trace	trace
CaO	...	12·05	11·85
Na_2O, K_2O	...	0·14	0·14
H_2O+	...	12·34	12·64
H_2O-	...	1·30	—
CO_2	...	0·36	—
		99·87	100·00

The material was separated as far as possible from calcite with which it is intergrown, but the 0·36 % CO_2 in the analysis seems to indicate that a little still remained. The modified analysis is calculated free from $CaCO_3$ and moisture.

Gismondite.—This zeolite was found only on one specimen where a few plate-like crystals almost microscopic in size were grown on chlorite. It is colourless, biaxial and negative, and forms double twins united as fourlings.

Prehnite occurs as characteristic globular and hemispherical masses of small radiating crystals. The colour varies from colourless to light green, but the surfaces of the rounded masses are often stained green, brownish, or yellowish. Generally it occurs in the central part of the vughs, associated with the other minerals; but occasionally it is the sole occupant of cavities, where it occurs as masses of elongated crystals lining the walls.

Calcite.—Calcite is one of the most abundant minerals present. The crystals vary from microscopic size to rhombohedra about three inches in length. It occurs in four distinct forms:

(*a*) Well-formed crystals with sharp boundaries coated with a thin layer of calcite and chlorite.

(*b*) As crystals filling interstices between other early crystals, viz. quartz, laumontite, felspars.

(*c*) As minute crystals encrusting other minerals, particularly in the vughs.

(*d*) Lining joint-planes in the granite.

These occurrences seem to denote three generations: (*a*) being the earliest formed; (*b*) and (*c*) are of the same age, and are sometimes found coating (*a*) along cleavage traces; while (*d*), the third generation, occurs as secondary calcite, which may have arisen from the solution and redeposition of the earlier generations.

The calcite often has a considerable percentage of iron present, which stains it yellowish-brown to pinkish-brown. In some cases this ferrocalcite appears in spherical form, and of a deep brown colour. In other cases it occurs as minute rhombohedra encrusting laumontite, kaolinized felspar, quartz, and prehnite. Chalybite showing good crystalline form with curved faces also occurs in the centres of vughs. On it there are minute crystals of calcite.

Chlorite occurs in the rock surrounding the vughs as well as in the vughs themselves. Some of it appears to have resulted from the decomposition of the ferromagnesian minerals in the granite, for where these are intact the chlorite is practically absent. Sometimes it appears as pseudomorphs after hornblende, more often as streaks running through other minerals, but never in both forms in the one specimen. It often coats crystalline forms of other minerals; and is also found intergrown with calcite and quartz, giving them a pale green colour.

Epidote has been found only in one quarry where it ranges from microscopic crystals to those about half an inch in length. It has the typical green colour and appears to be associated largely with chlorite. It occurs enclosed in the outer zone of quartz crystals which protrude from the pegmatite. Most of it crystallized out early, but in one specimen, consisting of a network of veins, it occurs growing on the laumontite.

Pyrite is very abundant, and occurs as a constituent of the granite as well as in the vughs and veins. Crystals range in size from microscopic to well-shaped crystals over an inch across. It is very silvery in colour when fresh, but soon tarnishes to a brassy yellow. It is noted that in the cavities the pyrite is in the untarnished condition. Pyrite also occurs in a fresh condition lining joint-planes in the granite. Limonite pseudomorphs occur on the surface and in more weathered parts.

Tourmaline occurs as radiating crystals, sometimes in small groups, sometimes in masses. It is associated with kaolin, quartz, calcite, pyrite, and radiating groups of laumontite. In one locality it is not far from the schorl-rock and tourmaline-albite-rock described by Bryan.

Fluorite.—Only one specimen containing fluorite has been collected. It is purple in colour, and occurs as well-shaped crystals associated with quartz and kaolinized felspar, which it appears to have followed, as it encrusts the pegmatite. On the other hand, it definitely precedes the laumontite.

Molybdenite has previously been recorded as occurring as small flakes at several localities within the granite. It occurs in cavities sometimes associated with quartz and pyrite, sometimes with quartz, chlorite, and calcite. Often small portions are scattered through the granite within a radius of a few inches from a cavity.

Blende has been found only in one quarry, where two specimens were collected by the author. In both cases it is associated with pyrite, while in one quartz, prehnite, calcite, and chlorite are also present. Blowpipe tests indicate that it contains a fairly large percentage of iron. This mineral has not previously been recorded as occurring in the granite, though Ball (loc. cit.) has recorded zinc associated with the silver-lead ore in the phyllites at Indooroopilly.

Kaolin.—One of the most noticeable features in the quarries is the occurrence of patches, often quite large in extent, in which the felspars have been completely kaolinized and the whole rock reduced to a decomposed, crumbly state. It often encloses pyrite, quite fresh and free from limonitic material, and in some places tourmaline and laumontite also occur with it.

Felspar.—The felspars present are so completely kaolinized that it is difficult to determine what they are. In several specimens, however, the vughs are quite empty, and here the felspars are much fresher. They prove to be very like those of the granite itself, that is, acid andesine; but some are richer in soda and should be classed as oligoclase. No albite has been found.

Origin and Relationship of the Minerals.

The mutual relationship of the minerals described above is fairly clear. In the granite itself the order of crystallization is normal. In the pegmatite zone graphic and allied structures are developed, pointing to simultaneous crystallization. Quartz appears to have been in excess of the felspar in the pegmatite zone, and after the felspar had ceased, it continued to produce crystals that are found protruding into the cavities.

Chlorite and epidote occur next, both being found as inclusions in the outer margins of the quartz crystals. Chlorite appeared slightly previous to the epidote, as it is sometimes seen enclosing it, and the junctions between the two are never very sharp. Streaks of chlorite are seen through the felspar crystals. It seems to have been deposited during practically all stages of the sequence. Epidote, on the other hand, seems to have had a more restricted range. Most of it crystallized at this time; but in one specimen, consisting of a network of veins of these minerals, it occurs fairly late in the sequence, and is found coating laumontite. Pyrite appears at this stage, generally as well-shaped crystals.

It is probable that the next group of minerals to be developed is the pneumatolytic group. This includes tourmaline, molybdenite, blende, and fluorite. These are not found associated with one another, but have all formed after pyrite and before calcite.

The next mineral in the sequence is calcite. This is certainly not a weathering product, and it is very abundant. Similar calcite occurs in other portions of Australia, and W. R. Browne[1] has recorded it from several localities in basic rocks in New South Wales. In the present instance it is not known definitely where the lime for the calcite came from. It may have been an original constituent of the magma, or it may have arisen from the decomposition of the plagioclase felspars. Calcite appears again in the sequence immediately following and in part contemporaneous with laumontite.

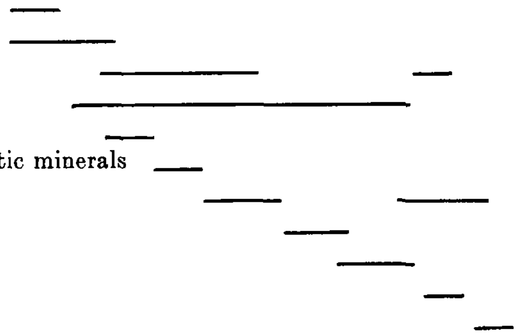
Prehnite follows the calcite. The relationship of this mineral to laumontite is an interesting one. In most cases large laumontite crystals definitely enclose spherules of prehnite, but some small crystals of laumontite appear to be surrounded by prehnite. However, in most cases the prehnite is definitely older than the laumontite.

Laumontite sometimes appears to be intergrown with calcite, alternating plates of each occurring in some specimens. This occurs generally near the junction of laumontite and calcite masses, and may be due to the partial replacement of the laumontite by the calcite. The laumontite definitely crystallized before the calcite in this case.

[1] W. R. Browne, Note on the occurrence of calcite in a basalt from the Maitland district, N.S.W. Journ. Roy. Soc. N.S.W., 1923, vol. 56 (for 1922), pp. 278–284. Notes on the petrology of the Prospect intrusion, with special reference to the genesis of the so-called secondary minerals. Ibid., 1925, vol. 58 (for 1924), pp. 240–254.

The normal order of crystallization is as follows:

(*a*) Oligoclase (?)
(*b*) Quartz
(*c*) Epidote
(*d*) Chlorite
(*e*) Pyrite
(*f*) Pneumatolytic minerals
(*g*) Calcite
(*h*) Prehnite
(*i*) Laumontite
(*j*) Gismondite
(*k*) Ferrocalcite



Note: The minerals under (*f*) include tourmaline, molybdenite, blende, and fluorite, not found associated with one another, but all after pyrite and before calcite.

The order shown in the table is characteristic of all specimens, and no departure in any way is made from it. Therefore, it is seen that so far as the silicates are concerned, the order is one of increasing hydration; an order that has also been noted in vesicles by W. F. P. McLintock[1] and by C. N. Fenner.[2]

Oligoclase (?)	...	$m\text{NaAlSi}_3\text{O}_8 + n\text{CaAl}_2\text{Si}_2\text{O}_8$.
Epidote ...	...	$4\text{CaO}.3(\text{Al,Fe})_2\text{O}_3.6\text{SiO}_2.\text{H}_2\text{O}$.
Prehnite ...	...	$2\text{CaO}.\text{Al}_2\text{O}_3.3\text{SiO}_2.\text{H}_2\text{O}$.
Laumontite	...	$\text{CaO}.\text{Al}_2\text{O}_3.4\text{SiO}_2.4\text{H}_2\text{O}$.
Gismondite	...	$\text{CaO}.\text{Al}_2\text{O}_3.3\text{SiO}_2.4\text{H}_2\text{O}$.

The main features of the vughs may be summed up as follows:

(1) The granite itself is abnormal, and is on the whole lime-rich.

(2) The felspars round the vughs are completely kaolinized and veined with chlorite.

(3) The magma was rich in volatiles, as is shown by the pegmatites and the occurrence of cavities.

(4) Igneous minerals crystallized in these cavities after their formation, as is shown by the marginal pegmatites.

(5) Patches of kaolin associated with fresh pyrite also seem to point to the action of volatiles.

(6) Pneumatolytic minerals are well represented in the sequence.

[1] W. F. P. McLintock, On the zeolites and associated minerals from the Tertiary lavas around Ben More, Mull. Trans. Roy. Soc. Edinburgh, 1915, vol. 51, pp. 1–33.

[2] C. N. Fenner, The Watchung basalt and the paragenesis of its zeolites and other secondary minerals. Ann. N.Y. Acad. Sci., 1910, vol. 20, pp. 93–187.

(7) The minerals have lime for their chief base.

(8) Calcite, generally regarded as a secondary mineral, is present in large quantities and occurs in a similar manner to the other minerals.

(9) Typical oxidation products are rare or absent, while the minerals do not occur near the surface, nor are they intimately associated with joints.

(10) The minerals generally were deposited in an order of increasing hydration.

Thus the cooling history of the magma is seen to consist of three principal periods. During the first, the main magmatic consolidation took place. This was followed by a period of pegmatite formation and the initiation of cavities in the rock. While the rock was still hot the deuteric period occurred, beginning with the kaolinization of the felspars and chloritization of the ferromagnesian minerals; then followed the deposition of chlorite and epidote, the pneumatolitic minerals, some calcite, the zeolites, and finally many vughs and veins were completely filled with calcite.