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HOLOCRYSTALLINE PANTELLERITE FROM MT. NGUN-NGUN, GLASS HOUSE MOUNTAINS, QUEENSLAND, AUSTRALIA†

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ABSTRACT. Some recent studies have produced evidence that peralkaline soda rhyolites may develop by volatile transfer of alkali metals from the holocrystalline core to the glassy margin of small intrusive or extrusive bodies. Other studies suggest that peralkaline residual liquids may be a normal product of fractional crystallization of basaltic magmas. A road metal quarry in Mt. Ngun-Ngun in southeast Queensland has exposed fresh, holocrystalline pantellerite. A new bulk chemical analysis and microprobe analyses of the major mineral phases confirm the peralkaline nature of the rock. Petrographic study and modal analyses of the principal textural varieties show that there is no significant compositional variation between them, although concentration of riebeckite in small fractures and shear planes indicates the potential mobility of alkali and iron. It is suggested that the chemical, field, and petrographic data support the view that the rock was intruded as a truly peralkaline magma, and that riebeckite and aenigmatite crystallized at shallow depth from a late-stage, water-saturated interstitial liquid.

INTRODUCTION

Several recent studies (Noble, 1965; Ewart, Taylor, and Capp, 1968; Romano, 1970) have shown that peralkalinity of soda rhyolites may vary markedly between the crystalline or devitrified portions of the rock and closely associated glassy bands or chilled margins. In general, the greatest excess of alkalies over alumina is found in the glassy phase, while the divitrified or holocrystalline phases of the rock may show little or no normative *ns* and perhaps notably lower *ac*. Such observations suggest that peralkalinity may be a secondary characteristic imposed by late-stage volatile transfer of alkalies from the core to the margin of small intrusive or extrusive rhyolite magmas. However, other evidence suggests that peralkaline magma may be a typical end product of the fractional crystallization of oceanic basalt. Peralkaline extrusive rocks are common in the East African rift system, which may represent the initial stage of opening of a new oceanic rift system. Peralkaline extrusive rocks are also found on Socorro Island, near the crest of the East Pacific Rise (Bryan, 1970) and in eastern Queensland, Australia where they are associated with basic lavas showing the normative characteristic of oceanic basalt (Bryan, 1968; Morgan, 1968; Green, 1968). Smith and Lindsley (1971) also report peralkaline pegmatoids in Oregon flood basalt. Bryan (1970) showed that a peralkaline residual liquid could be produced as a consequence of the separation of aluminous titanaugite from a moderately alkalic basalt. Augites of typical sea-floor basalt are also aluminous (Muir and Tilley, 1964; Bryan, 1972). Removal of this augite might be expected to yield alumina-deficient residual liquids. Thus, it appears that peralkaline rhyolite could be a typical end product of the crystallization of either ocean ridge basalt or alkali basalt. Such a relationship would be strengthened, though by no means proved, if it can be shown that peralkalinity is a

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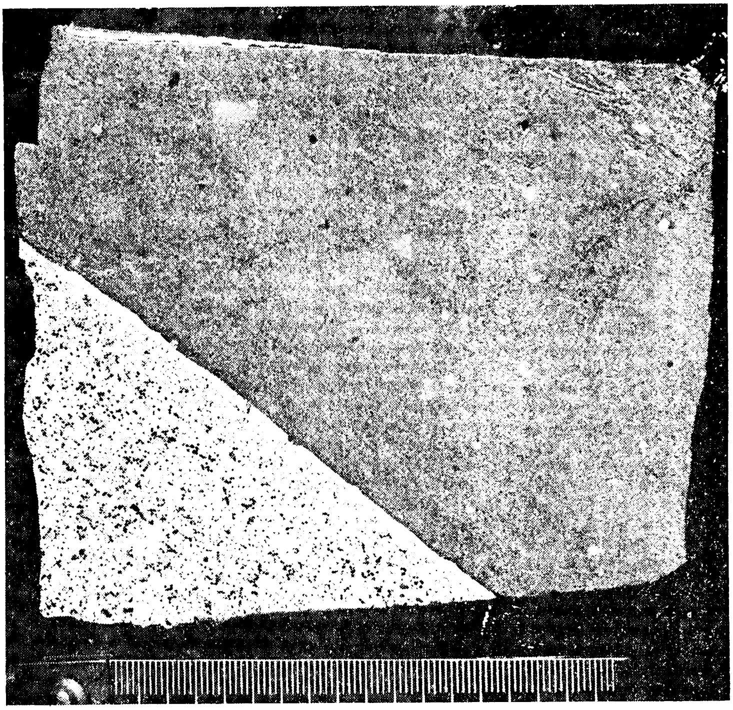
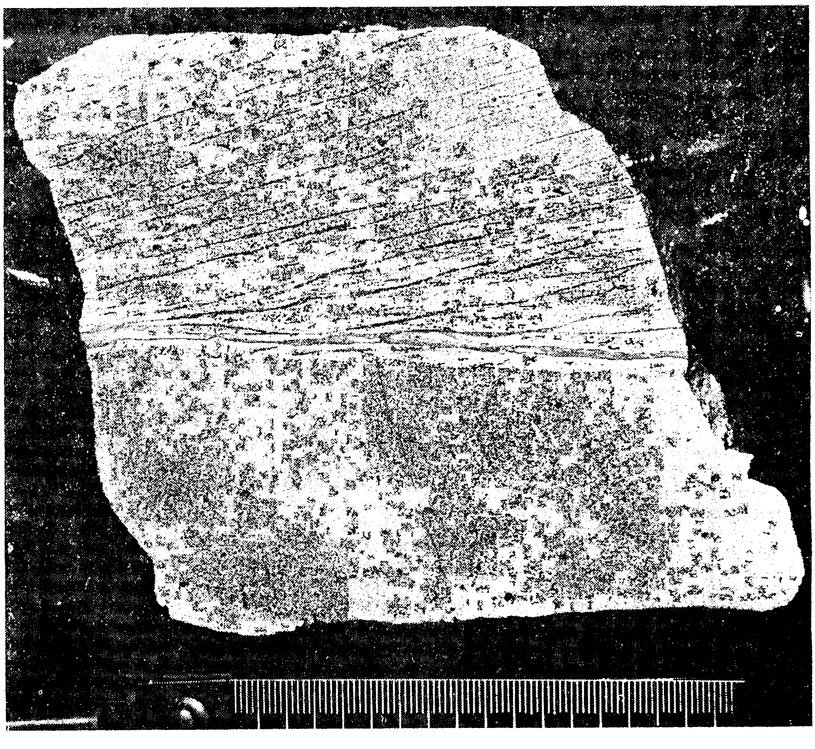


A.



B.

primary magmatic feature of at least some of the known occurrences of comendites and pantellerites.

Mount Ngun-Ngun is one of a group of dome-shaped hills and conical peaks known as the Glass Houses, which rise abruptly from the coastal plain of southeastern Queensland 56 to 72 km north of Brisbane. The first, and to date, the only detailed account of the Glass House rocks was given by Jensen (1903, 1906) who recognized the form and structure of the volcanic plugs or mamelons (as he called them) and their arrangement along north-south and east-west lines. He described comendites, pantellerites, and trachytes and reported the occurrence of arfvedsonite, riebeckite, cossyrite (aenigmatite), barkevicite, aegirine, and possibly guaranite, eucolite, and several other rare minerals. Jensen (1906) called the Mount Ngun-Ngun rock a pantellerite, basing the name on a chemical analysis; earlier (1903) he had referred to this and other alkali rhyolites as trachytes.

A road metal quarry on the east side of Mount Ngun-Ngun has provided new exposures of the interior structure of part of the intrusion and gives access to fresh samples revealing a variety of textural development. Of these, the two most important varieties are an aphanitic gray phase and a predominantly white spotted phase (pl. 1). The purpose of this paper is to report new observations on the form and structure of Mount Ngun-Ngun, a new petrographic description and bulk chemical analysis of the rock, and to discuss the mineralogical relations between the two textural varieties.

THE GEOLOGY OF MOUNT NGUN-NGUN

The location and spatial relations of the Glass Houses are shown in figure 1. The sedimentary rocks, which underlie the coastal plain and through which the igneous rocks were intruded, are largely horizontally-bedded Jurassic sandstones and shales. The alkali rhyolites have been dated as Lower Miocene, 25 m.y. (Webb, Stevens, and McDougall, 1967). Basalt flows of the same age (Webb, personal commun.) overlie Jurassic sandstone to the north and preserve a Lower Miocene surface with a gentle easterly slope at elevations between 190 to 240 m (600-800 ft) above sea level. Most of the Glass Houses rise above this level, indicating subaerial effusive activity. Mount Ngun-Ngun rises about 180 m (600 ft) above the coastal plain. It has steep sides, and, except for a narrow summit ridge, more gentle slopes near the top. Columnar joints are ubiquitous and near vertical in all observed exposures.

A diagrammatic cross section of Mount Ngun-Ngun (fig. 2) shows the present configuration of the peak and its inferred relation to the

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PLATE 1

Textural variations in pantellerite

A. Contact between fine gray phase (upper) and coarsely spotted phase (lower). Scale divisions in millimeters. These phases correspond to modal data in table 1.

B. Contact between sheared gray phase transitional to spotted phase (upper) and unsheared gray phase (lower). Note concentration of riebeckite along sheared contact and lighter color of coarser version of gray phase compared to A. Scale division in millimeters.

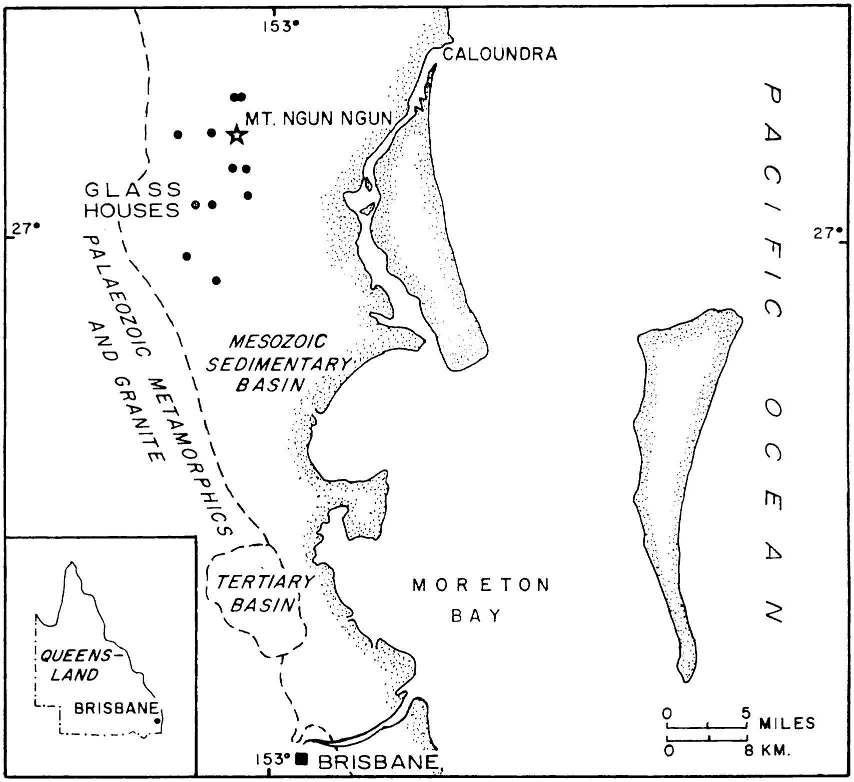

Fig. 1. Location map of Glass House Mountains, Queensland, Australia.

early Miocene surface. The original surface form, as suggested by the vertical columns, may have been a cumulo-dome. Remnants of the enclosing volcanic cone, if it ever existed, have not been found. Junctions between the marginal rock phases, veining, and flow-layering all trend between north-south and northwest-southeast in the quarry and have dips varying from 60 degrees westerly to vertical. Veining and flow layering usually meet at acute angles, but in some places they are parallel (pl. 1-B).

PETROGRAPHY

The Ngun-Ngun pantellerite can be described in terms of two principal textural varieties. The fine-grained gray phase consists of subhedral alkali feldspar and riebeckite crystals 0.10 to 0.15 mm in length enclosed by pools of anhedral quartz and a crypto-crystalline quartzo-feldspathic matrix. The feldspar laths are typically twinned on the Carlsbad law, and sections perpendicular to the a-c plane show parallel extinction. Some crystals show minor irregularities in extinction which are suggestive of slight patchy compositional zoning. There is some tendency toward parallel orientation of feldspar laths which is consistent with megascopic color banding in the rock. Riebeckite crystals are of somewhat more ir-

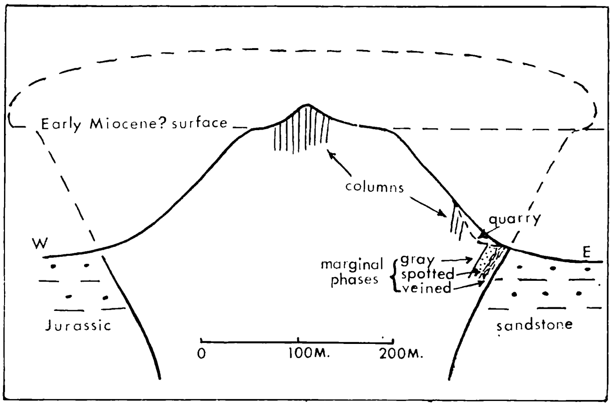

Fig. 2. Diagrammatic east-west cross section of Mt. Ngun-Ngun.

regular form than the feldspar and may poikilitically enclose small laths of the latter mineral. The riebeckite also shows a more irregular crystallographic orientation than the feldspar, and this along with its poikilitic habit suggests that it has crystallized somewhat later than the feldspar, probably after most flowage had ceased. The riebeckite is strongly pleochroic, appearing almost opaque except in sections of less than normal thickness, and shows abnormal purplish interference colors and incomplete extinction in appropriate orientations. The pleochroic scheme is α, dark blue to black; β, blue to dark blue; γ, medium yellow to yellow-green. The optic plane is perpendicular to [010], and the optic sign is negative. Aenigmatite occurs as small overgrowths on the outermost fringes of the riebeckite and rarely as distinct subhedral crystals in the matrix. It is nearly opaque in transmitted light and is most easily identified by its relatively high reflectivity in polished thin sections.

The spotted phase differs from the gray phase mainly in the mode of development of the riebeckite, which is concentrated into distinct poikilitic patches and rarely into distinct stubby subhedral prisms 0.20 to 0.30 mm in longest dimension. Aenigmatite again appears on the outer extremities of the riebeckite patches and also as very rare interstitial groundmass grains.

Both textural varieties contain scattered phenocrysts of anorthoclase and bipyramidal quartz. The anorthoclase may show distinct zoning from a relatively potassic core to a more sodic rim. These phenocrysts were considered to be too widely dispersed to be estimated by point counting in standard-sized thin sections.

Modal analyses of both the aphanitic gray phase and the spotted phase were carried out in reflected light on polished thin sections. Quartz and alkali feldspar could not be distinguished in reflected light, but riebeckite and aenigmatite are readily identified, and it is the difference in distribution of these minerals that largely accounts for the textural variations. The results show that the dark mineral proportions are very similar in the two rocks (table 1), the only questionable difference being in the amount of riebeckite.

The significance of the difference in riebeckite content may be tested by the criterion:

$$\frac{\left(\frac{k_1}{n_1} - \frac{k_2}{n_2}\right)}{\sqrt{pq\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}}$$

where k_1 = number of riebeckite counts in gray phase,
n_1 = total counts in gray phase,
k_2 = number of riebeckite counts in spotted phase,
n_2 = total counts in spotted phase,

$$p = \left(\frac{k_1}{n_1} + \frac{k_2}{n_2}\right)$$

$q = 1 - P$,
and $n_1 \cong n_2$.

The data of table 1 give a value of −0.960, and since either set of riebeckite counts might have been the larger, a two-tailed test is appropriate. The standard tables (Hodges and Lehmann, 1964, p. 358) show that the probability of equalling or exceeding this value in random samples drawn from a common parent population is about 0.34, so there is no reason to doubt that the two samples were drawn from populations having the same proportion of riebeckite.

CHEMICAL COMPOSITION

Electron microprobe analyses of the principal minerals are given in table 2. The homogeneity index is small for all major elements except K in alkali feldspar, which shows a distinct concentration toward the core

Table 1

Modal composition of Ngun-Ngun pantellerite. Court area, gray phase, 24 x 11 mm; count area, spotted phase, 16 x 17 mm; reflected light, 400x magnification.

	Count summary			
	Riebeckite	Aenigmatite	Other*	Total
Gray phase	322	59	4916	5196
Spotted phase	361	62	5003	5428
Total	683	121	9819	10624

	Volume percent		
	Riebeckite	Aenigmatite	Other*
Gray phase	6.19	1.13	92.7
Spotted phase	6.67	1.14	92.2

* Includes phenocrysts and quartzo-feldspathic groundmass.

of the feldspar phenocrysts. The considerable amount of iron found in this mineral must be assigned to the tetrahedral site to obtain the best formula balance. It has been reported as Fe_2O_3, although the oxidation state cannot be determined by microprobe analysis. Even higher iron content was found in alkali feldspar of pantellerites by Carmichael (1962), Chayes and Zies (1962), Ewart, Taylor, and Capp (1968), and Bryan (1970); and in these cases too, assignment of iron to the tetrahedral site seemed appropriate.

The riebeckite analysis is similar to other published analyses, in which H_2O and fluorine may total up to 2.5 percent by weight and in which approximately half the iron oxide may be present as Fe_2O_3. The summation of X + Y ions is much greater than the seven of the ideal formula, but such departures are not unusual in riebeckite (Deer, Howie, and Zussman, 1962, p. 355). The aenigmatite is not unlike that reported from Pantelleria by Carmichael (1962) and Zies (1966) and from Socorro Island (Bryan, 1970), although it is somewhat lower in Na_2O and TiO_2 and higher in iron, features which have been confirmed by careful replicate analysis. In this respect it more nearly resembles the aenigmatite from a basalt pegmatoid described by Lindsley and Haggerty (1971).

Our chemical analysis (table 3B) is peralkaline in contrast to Jensen's analysis, which is normatively peraluminous in spite of the fact that he

TABLE 2

Electron microprobe analyses of major mineral phases. Numbers in parenthesis are $\delta / \sqrt{\overline{N}}$, where $\overline{N}$ is the mean count, and δ is its standard deviation. A value greater than 3 indicates distinct inhomogeneity for that constituent. n.d. = not determined. Total iron is calculated as FeO in riebeckite and aenigmatite and as Fe_2O_3 in anorthoclase.

	Riebeckite		Aenigmatite		Anorthoclase	
SiO_2	49.2	(1.2)	39.9	(1.6)	66.9	(1.1)
Al_2O_3	0.25		0.73		18.3	(1.5)
TiO_2	0.65		7.66	(3.6)	0.00	
FeO (Fe_2O_3)	35.5	(1.8)	43.9		(0.47)	
MnO	0.75		0.75		0.00	
MgO	0.00		0.02		n.d.	
CaO	1.26	(4.7)	0.71		0.00	
Na_2O	7.92	(2.0)	6.83	(1.4)	6.92	(4.5)
K_2O	1.47	(4.1)	0.05		6.82	(16.4)
	97.0		100.6		99.4	
O =	23		20		32	
Si	8.075		5.812	5.937	12.052	16.007
Al	0.048	5.106	0.125		3.891	
Ti	0.084		0.838	6.272	— —	
Fe	4.870		5.337		0.064	
Mn	0.104		0.092		— —	
Mg	0.000		0.005		— —	3.989
Ca	0.221	3.050	0.111	2.045	— —	
Na	2.520		1.926		2.419	
K	0.309		0.008		1.510	

called the rock a pantellerite (Jensen, 1906). Jensen's norm appeared to be seriously in error with regard to mafic constituents, but the corundum remains in our recalculated norm given for his analysis in table 3. The lower Al_2O_3 and higher Na_2O in our analysis clearly account for the normative differences and are more consistent with other recent analyses of pantellerites. Our normative amounts of acmite and sodium metasilicate also are consistent with the modal amounts of riebeckite and aenigmatite. The higher Fe_2O_3 and total H_2O in Jensen's analysis suggest that he may have worked with somewhat weathered material. The quarry sample we selected for analysis is an unweathered banded rock containing both the gray and spotted phases; the modal data suggest that variation in the relative proportions of these phases would not appreciably affect the bulk chemistry. Trace elements (table 4) are also similar to those reported by Noble and Haffty (1969) for Mediterranean pantellerites, although Zr and Rb values are higher than average.

TABLE 3

Chemical composition and C.I.P.W. norms of Ngun-Ngun rocks.

		A	B
	SiO_2	72.38	72.46
	TiO_2	0.25	0.15
	Al_2O_3	12.21	11.46
	Fe_2O_3	3.36	2.02
	FeO	0.69	2.03
	MnO	0.70	0.13
	MgO	0.17	trace
	CaO	0.18	0.12
	Na_2O	3.52	5.65
	K_2O	5.20	4.71
	H_2O^+	0.86	0.18
	H_2O^-	0.69	0.37
	P_2O_5	trace	trace
		100.26*	99.28
* Includes NiO, 0.04; Cl, 0.01.			
	Q	31.43	26.19
	Or	30.62	27.84
	Ab	29.90	32.52
	An	0.83	— —
	Ns	— —	1.95
	Ac	— —	6.01
	C	0.51	— —
Di	Wo	— —	0.23
	En	— —	— —
	Fs	— —	0.26
Hy	En	0.40	— —
	Fs	— —	3.43
	Il	0.46	0.30
	Mt	0.64	— —
	He	0.46	— —
	Other	1.60	0.55
		100.33	99.28

A. "Pantellerite", analysis from Jensen, 1906, p. 168.
B. Holocrystalline pantellerite, A. Ewart and G. Langthaler, analysts.

DISCUSSION

Although variations in peralkalinity are usually, and quite properly, discussed in terms of varying proportions of Na_2O and Al_2O_3, it should be recognized that the Fe_2O_3/FeO ratio will have an appreciable effect on the appearance or non-appearance of *ns*, which according to the CIPW convention requires a molar excess of $Na_2O + K_2O$ over molar $Al_2O_3 + Fe_2O_3$. Watkins and Haggerty (1967) have shown that an increase in Fe_2O_3/FeO is common toward the center of basalt lava flows, and a similar relation might be expected in rhyolitic flows or shallow intrusions. Thus, slight variations in partial pressure of oxygen within a single lava flow or intrusion may determine whether a rock will be classified as comendite (containing *ac* but no *ns*) or as pantellerite (containing *ac* and *ns*). Our modal and chemical data indicate that there has been no important transfer of alkalies or mafic constituents between textural variants and that the interior of the Ngun-Ngun intrusion is distinctly peralkaline. There is sufficient normative and modal *ns* to justify retaining the name 'pantellerite' as originally suggested by Jensen (1906). Although we see no evidence for *bulk* chemical changes on the hand specimen scale or larger, textural evidence certainly does suggest the potentially great mobility of riebeckite and aenigmatite, as indicated by the variation in textural distribution of these minerals, including concentration along shear planes and fractures, These textural features imply the presence of an alkaline, iron-rich hydrothermal solution interstitial to a quartzo-feldspathic crystal mush susceptible to shear and flowage prior to final consolidation.

The physical conditions under which the Ngun-Ngun soda rhyolite magma crystallized may be compared to the data of Ernst (1962) and Lindsley (1971), if allowance is made for the greater compositional complexity of the natural rock system. The boundary surface for quartz + aenigmatite + riebeckite-arfvedsonite + liquid + fluid in the system $Na_2O.5\ FeO_x + 8SiO_2$ + water is rather narrowly defined (Ernst, 1962, p. 722-727), and the experimental data suggest that an equivalent natural magma should crystallize at a total fluid pressure of less than 1000 bars, with the temperature in the range 650° to 750°C, log fO_2-20 to -30 bars, and in the presence of excess water. Lindsley (1971) reports synthesis of aenigmatite of the theoretical composition $Na_2Fe_5TiSi_6O_{20}$ from anhy-

TABLE 4

Trace elements in Ngun-Ngun pantellerite.
X-ray fluorescence analyses by A. S. Bagley.

	Spotted phase (ppm)	Gray phase (ppm)
Zr	2917	2410
Rb	407	319
Pb	131	31
Cu	11	4
Ni	3	4
Co	4	6

drous materials at 500° to 700°C at fluid pressures of 500 bars, with oxygen fugacity controlled by the fayalite-magnetite-quartz and nickel-nickel oxide buffers. These experimental results suggest that riebeckite and aenigmatite should crystallize under the conditions implied by the geologic setting and textural details of the Ngun-Ngun pantellerite. Such a paragenesis is also consistent with the appearance of aenigmatite in pegmatoids in basalt, as discussed by Lindsley and Haggerty (1971) and Smith and Lindsley (1971).

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