TASMANIA
DEVELOPMENT
AND RESOURCES

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An assessment of the resource potential for nepheline syenite at Cygnet and elsewhere in Tasmania

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Summary

Nepheline syenite competes with feldspar as a source of alkalis and alumina for the glass and ceramics industries. The only comparable rocks known in Tasmania are dykes of feldspathoidal sanidine porphyry, which occur as a volumetrically minor component of the Cretaceous alkaline rocks near Cygnet, south of Hobart. However, available published and unpublished data suggest that the field relationships, chemical characteristics and texture of these rocks are unfavourable, especially when compared internationally to commercially exploited deposits.

The dykes are narrow, reportedly usually less than two metres wide, and workable quantities would be difficult to identify. The variability of the rocks would make grade and quality control very difficult. Their high iron content (rarely less than 2% and commonly much higher) would make them unsuitable for clear glass manufacture and most other uses, and the fine grainsize of the groundmass would probably make beneficiation, involving magnetic separation of ferromagnesian minerals such as pyroxene, amphibole and garnet, difficult. The area has not been specifically explored for nepheline syenite and it is possible, although not probable, that such a search could locate larger, economically worthwhile, quantities of more suitable material.

The alkaline rocks occur almost exclusively on private land in a moderately hilly, fairly densely populated rural area. Although access and transport would be relatively easy, there could be environmental and land tenure problems with extraction, if a viable resource were found.

Although not examined in detail, the potential for feldspar in Tasmania is not favoured by the relative lack of major pegmatite development in Tasmanian granitoids. Perhaps the best potential is in northeast Tasmania, where leucocratic alkali-feldspar granites and related aplites have low contents of iron and mafic minerals. Separation of quartz and mica, possibly as by-products, would probably be necessary.

INTRODUCTION

Nepheline syenite is a felsic, leucocratic, silica-undersaturated and generally coarse-grained intrusive igneous rock, typically consisting of feldspar (usually alkali feldspar), nepheline and smaller amounts of mafic constituents such as biotite, pyroxene and amphibole. It is chemically equivalent to the volcanic rock phonolite.

The petrogenesis of these undersaturated felsic alkaline rocks is not well understood. Some small volume plugs and domes of phonolite found in intraplate tectonic settings, both continental and in oceanic islands, are fairly readily accounted for as the ultimate products of the extreme fractionation of mafic alkaline magmas such as alkali basalt, basanite or olivine nephelinite. This mechanism seems inadequate to account for larger volcanic provinces and large intrusions, often exposed over hundreds of square kilometres, in which evidence for large volumes of the inferred parental mafic rocks is usually absent. In these cases, partial melting of an alkali basalt composition in the lower crust may be a more viable explanation. In some ring complexes associated with carbonatites, metasomatism (fenitisation) is important. Another class of nepheline syenite seems to have been produced by metasomatism (nephelinitisation) of pre-existing granite gneiss.

Desilicification of granitic magmas by assimilation of limestone, an idea expounded particularly by Daly earlier this century, has largely been discounted by more recent field and experimental data.

APPLICATIONS

This and the following two sections are largely summarised from Bolger (1995), Robbins (1986) and Harben (1979). A more comprehensive discussion of most aspects of the industry is given by Minnes *et al.* (1983) and Allen and Charsley (1968). A relatively up-to-date worldwide reference to companies and operations is the *Industrial Minerals Directory* (Griffiths, 1991).

Nepheline syenite can be a valuable commodity because of its high alkali and alumina content. It is used as a raw material, competing with feldspar, in the glass and ceramics industries. Nepheline syenite has also been used as a source of alumina for the aluminium industry in Russia, but elsewhere it has not been competitive against bauxite in this regard.

About 70% of nepheline syenite production in the Western World is used in the glass industry, 28% in ceramics, and 2% in fillers and other minor applications.

In glass manufacture the alkali content acts as a flux, whilst alumina reduces the tendency of the glass to devitrify, as well as strengthening and hardening the glass. The alumina content required in glass ranges from 1.5–2.0% in flat glass to 15% in some fibreglass. It is noteworthy that the production of clear glass requires a total iron content of less than 0.10% (as Fe_2O_3) in the feldspar/nepheline syenite ingredient. Higher iron contents (e.g. up to 0.35% as Fe_2O_3) may be tolerable in the manufacture of coloured glass.

In ceramic manufacture, nepheline syenite or feldspar is added to clay as a flux, and melts during firing. A low iron content (<0.07% as Fe_2O_3) is also necessary. The Na/K ratio may be important: sodium feldspar is a better flux and requires a lower firing temperature, whilst potassium feldspar produces a stronger product. Potassium feldspar generally commands higher prices than sodium feldspar, whilst the Na/K ratio in nepheline syenite varies considerably between deposits.

Minor applications include use as fillers and extenders in paint (particularly water-based paints), plastics, rubber and adhesives, where a high whiteness is a necessary attribute. The absence of free silica in nepheline syenite has resulted in its use in abrasives, notably in sandblasting, to avoid the health hazards of silica dust. In this area it competes against garnet, olivine and liquid cleaners.

Nepheline syenite and feldspar can largely be substituted for each other in most applications, with the choice determined by factors such as purity, consistency and transport costs. Feldspar is generally preferred in the manufacture of flat glass as it is quicker to dissolve and easier to disperse evenly. Nepheline syenite may be preferred in high volume ceramic manufacture because a lower firing temperature and shorter firing time is needed, and because it is a better flux due to its higher alumina/alkali ratio. However it is generally more expensive than feldspar.

Prices in 1986 for Canadian nepheline syenite were around $US46/short tonne for ceramic grade material, with lower prices for glass grade and higher for filler grade. Bulk prices for the Norwegian product were £Sterling 55/tonne (glass-grade) to £65/tonne (ceramic grade) (*Industrial Minerals*, February 1986, p. 14).

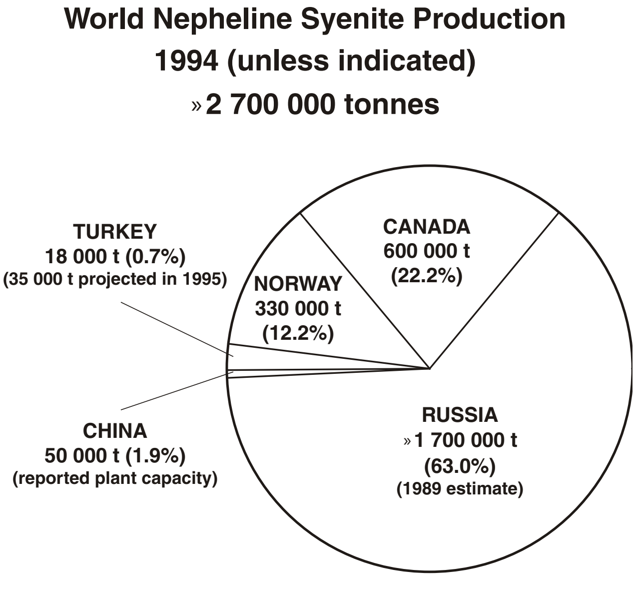
PRODUCTION OF NEPHELINE SYENITE

Until recently almost all the production of nepheline syenite (fig. 1) outside Russia has been from three mines, all owned by the US-based Unimin Corporation, in Canada and Norway.

Canada

At Nephton, Ontario, a sill-like body of nepheline syenite, dated at 1300 Ma, intruded the Blue Mountain Sedimentary Band and subsequently fractionated. The body was folded into a broad syncline during the Grenville Orogeny (1000 Ma) when nearby granitic gneiss was intruded. The nepheline syenite consists of albite (54%), microcline (18%), nepheline (18%), biotite (4%) and minor muscovite and magnetite. The deposit outcrops over an area of about 11 km^2.

Production began in 1936 by Canada Nepheline Limited. A second operation was begun in another part of the same intrusion in 1956 by IMC (Canada)


World Nepheline Syenite Production
1994 (unless indicated)
»2 700 000 tonnes

Source: *Industrial Minerals*, May 1995

Figure 1

Table 1

Representative analyses of exploited nepheline syenites (from Minnes, 1983)

	Canada		Norway	
	raw	processed low-iron grade	raw	processed low-iron grade
	1	2	3	4
SiO_2	59.4	59.9	52.37	55.9
TiO_2	0.004	-	0.61	-
Al_2O_3	23.0	23.5	23.33	24.2
Fe_2O_3	0.7	0.08*	1.1	0.1*
FeO	1.5	nd	1.14	nd
MnO	0.045	-	0.09	-
MgO	0.03	0.1	0.25	-
CaO	0.64	0.6	3.11	1.3
Na_2O	9.5	10.2	6.87	7.9
K_2O	4.9	5.0	8.3	9.0
P_2O_5	0.01	-	0.09	0.1
BaO	-	-	0.47	0.3
H_2O	0.4	nd	0.26	nd
CO_2	0.15	nd	1.88	nd
LOI	nd	0.6	nd	1.0
TOTAL	100.3	100.0	99.9	99.8

Limited. By 1985 both operations were owned by the Indusmin division of Falconbridge Limited, which in turn was purchased by Unimin in 1990.

Production in 1994 was about 600 000 tonnes, but plant capacity is about 850 000 tpa. Except for a small underground operation between 1947 and 1949, all production has been open cut. Reserves are estimated to be adequate for about 100 years. The nepheline syenite is marketed in 15 to 20 grades to mainly North American consumers, with about 20% to Europe. The product has about 23.5% Al_2O_3, 10.5% Na_2O and 5.0% K_2O (see also Table 1).

Norway

A large underground nepheline syenite mine is located on Stjernoy Island, Alta, near North Cape at the northern tip of Norway and 400 km inside the Arctic Circle. The original owners, Elkem A/S (Norsk Nefelin), began production began in 1961, and sold the operation to the Unimin Corporation in 1992 (*Industrial Minerals*, October 1992, p.11–12), which runs the mine as North Cape Minerals A/S.

The nepheline syenite dykes and stocks are of Caledonian age (mid Palaeozoic) and appear to be metasomatised syenite rather than of direct magmatic origin. They are regionally associated with mafic, ultramafic and alkaline rocks, including gabbroic gneiss, hornblendite and carbonatite. The exploited deposit is lensoid (1700 m 300 m) and steeply dipping. The raw resource typically consists of perthitic alkali feldspar (56%), nepheline (34%) and smaller amounts of hornblende, pyroxene, biotite, magnetite, sphene and calcite. Further details of the geology are given by Geis (1979).

Processing, including magnetic separation, is necessary to reduce the iron content. Three grades, with Fe_2O_3 from 0.1% to 0.4%, in a variety of sizings are produced. The product is much more potassic than the Canadian material (see Table 1). About 70% is used in the glass industry and most of the rest in ceramics. European countries are the main markets, but Australia, New Zealand and Malaysia have also been customers.

About 330 000 t was produced in 1994, but plant capacity is 370 000 tonnes. Total production since 1961 has been about 9 million tonnes.

China

Although 22 occurrences of nepheline syenite are reported, exploitation only commenced in 1994 at a 50 000 tpa capacity operation owned by the Sichuan Nanjiang Nonmetal Industry Company. The final product is reported to contain 28–34% Al_2O_3, 0.15–0.50% Fe_2O_3, 12–15% Na_2O and 4–6% K2O. Some has been exported. China also has a large feldspar industry.

Turkey

One of the main producers in the rapidly growing Turkish feldspar industry, Matel Hammadde SvT AS, has since 1989 also produced nepheline syenite from the Uludag massif in western Turkey. The syenite contains about 90% feldspar, 7% nepheline and mafic minerals, and up to 3% quartz, and is thus low in nepheline (weakly undersaturated) compared to the large Canadian and Norwegian deposits. It is also relatively high in Fe_2O_3 at 2–3%. Other elements include 16.5% Al_2O_3, 6.6–7.5% Na_2O and 6.6–7.5% K_2O. Production of 35 000 tonnes was planned in 1995, but reserves are in excess of 20 million tonnes.

United States

The American glass and ceramics industries have mainly used locally produced feldspar or Canadian nepheline syenite. However Addington Resources Inc. planned to commence mining of nepheline syenite at Wind Mountain, New Mexico in 1995. Production of 635 000 tpa within 5 to 7 years is planned, comparable to the Canadian operations (*Industrial Minerals*, May 1995, p.17).

Pakistan

The Sarhad Development Authority plans to open a nepheline syenite mine at Koga, northern Pakistan, for the domestic glass and ceramics industries.

Other countries

The state-owned Brazilian company CBPM is reported to be investigating a large deposit capable of providing a product with 21% Al_2O_3, 8.5% Na_2O, 4.85% K_2O and 0.1% Fe_2O_3 after magnetic separation. Deposits in Mexico, Portugal and South Africa have been investigated, but a common problem is a relatively high Fe_2O_3 content.

PRODUCTION OF PHONOLITE

Germany

A subsidiary of the Belgian company, Solvay Alkali GmbH, produces phonolite (the volcanic equivalent of nepheline syenite) at Brenk, for coloured glass and ceramic glazes.

France

About 150 000 tpa of phonolite are quarried at Roche en Regnier, HauteLoire, by the glass manufacturer SAMIN. Processing produces about 60 000 tpa of 2feldspar with about 2.08% Fe_2O_3.

Phonolite was formerly also mined in Czechoslovakia.

PRODUCTION AND TRADE OF FELDSPAR

The world feldspar industry is briefly mentioned, as feldspar competes with nepheline syenite. Most production is from granite pegmatites and aplites, and also from feldspathic sand. Flotation and other techniques may be necessary to separate quartz, mica and other impurities.

More than 50 countries produce feldspar (Lofty *et al*. 1993), but China, Italy, Turkey, the United States and Thailand are the main producers (fig. 2). Some of these countries (notably Italy) are also large consumers with substantial glass and ceramics industries, and China, Thailand and Turkey are the largest exporters. Taiwan is by far the largest importer, with Malaysia, Italy and several other European countries also being significant (fig. 3).

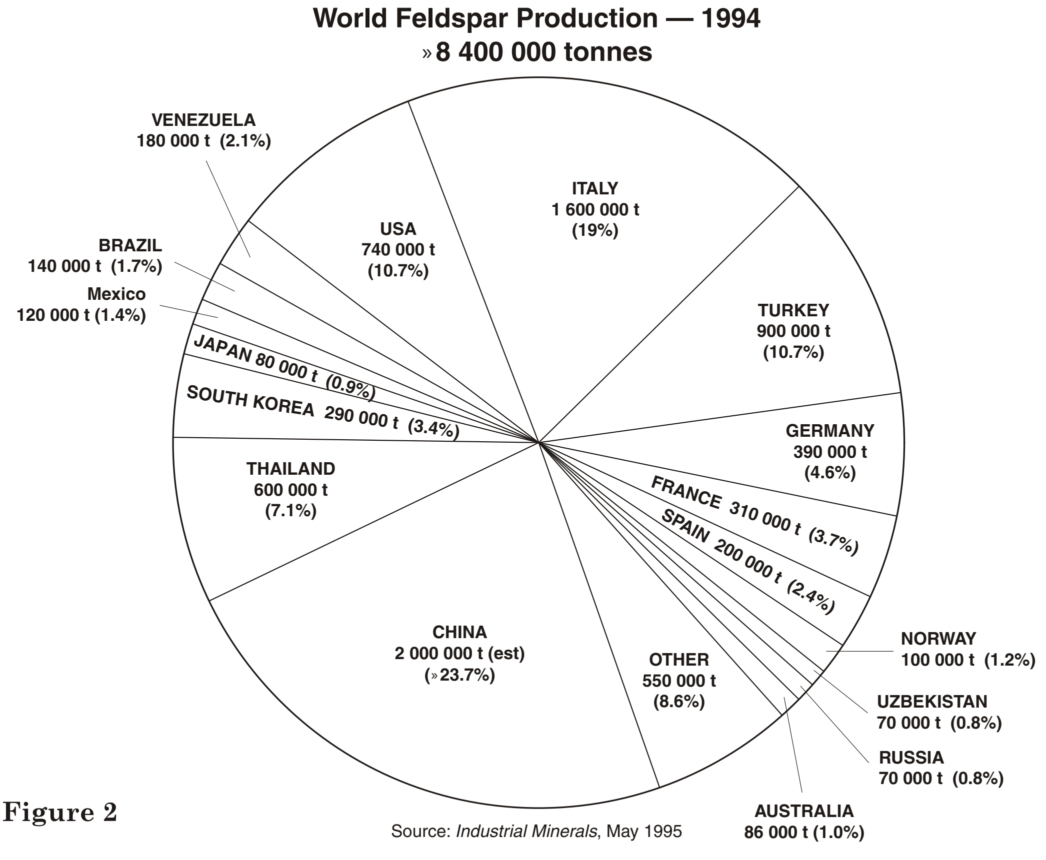


Figure 2

Source: *Industrial Minerals*, May 1995

WORLD TRADE IN FELDSPAR
1991
(Excludes exports through Hong Kong)

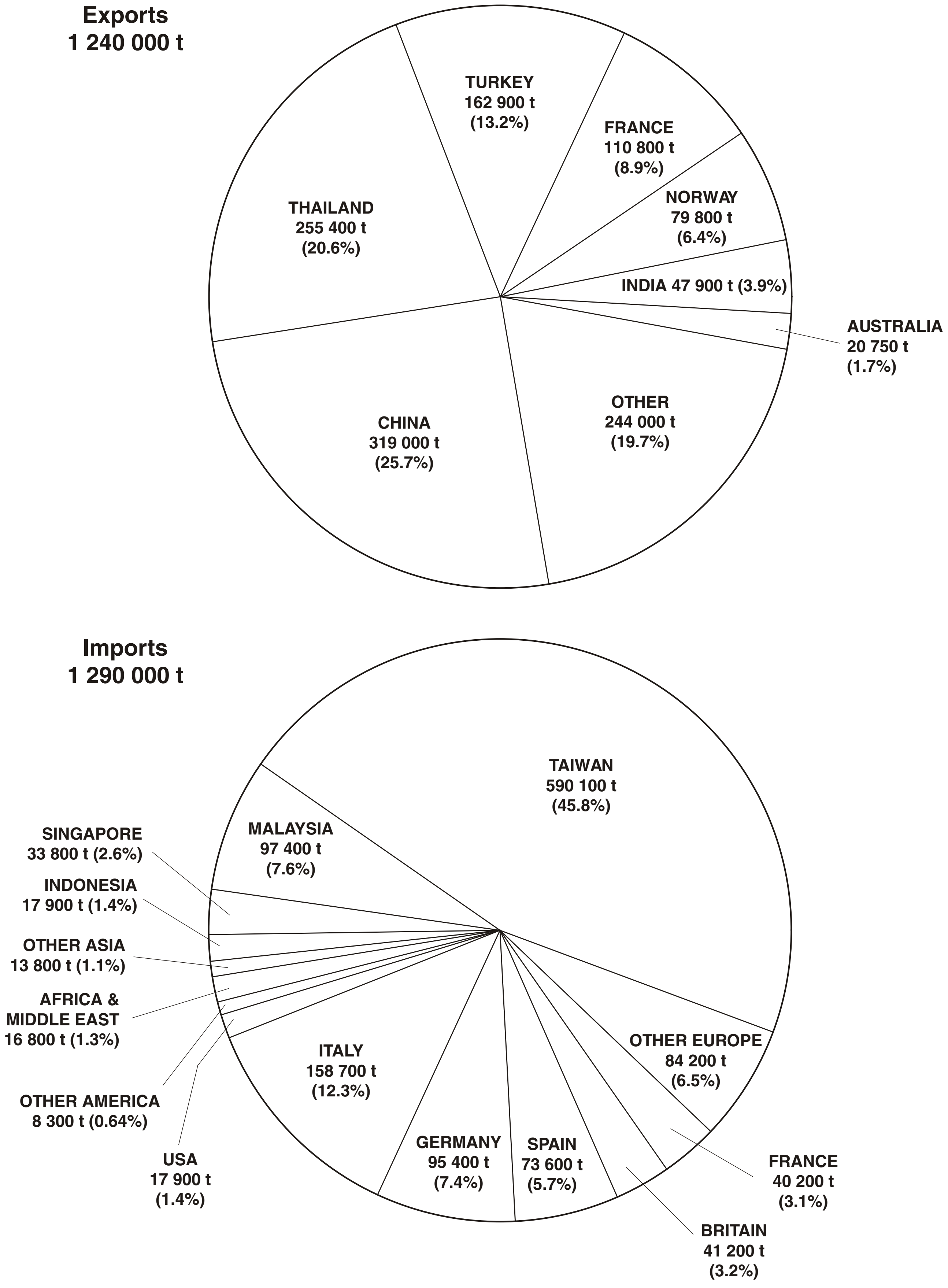


Figure 3

THE FELDSPAR INDUSTRY IN AUSTRALIA

Domestic demand for feldspar in Australia in 1994 was about 60 000 t, of which about 45 000 t (75%) was used in the glass industry and the remainder (25%) for ceramics and other applications. As production was about 90 000 t, Australia is a net exporter. The industry is located mainly in Western Australia with some production from New South Wales. There has been no recorded production from Tasmania or the Northern Territory, from Victoria since 1965, from South Australia since 1989, or from Queensland since 1984.

Local production is dominated (80 000 t) by Commercial Minerals Limited, a wholly-owned subsidiary of the Normandy Poseidon Limited. This company operates open-cut potash feldspar mines in pegmatites at Pippingarra (in the Pilbara) and Muckinbudin (east of Perth) in Western Australia, as well as plants in Perth and Sydney. It also owns another potash feldspar deposit at Londonderry, near Coolgardie (WA) and a sodium feldspar deposit at Broken Hill, NSW. The company has recently opened a 12 000 tpa glass-grade potash feldspar plant in Malaysia, using Pippingarra material, and is reportedly seeking new deposits in Australia and South East Asia. It has also imported nepheline syenite from Unimin to Australia.

The Minerals Corporation Limited produces potash and sodium feldspar and aplite from three mines (Triple Chance, Lady Beryl and Black Hill) near Broken Hill, NSW. Production in 1994 was about 4500 t for the domestic glass industry, but the company is increasing production and also plans to produce a ceramic-grade product.

Industrial Minerals Australia Pty Ltd reportedly produced 1800 t of feldspathic rhyolite at Lue, NSW, in 1994 and owns feldspar deposits in Western Australia.

Plans by Ariadne Australia in the early 1980s to commence mining alaskite (leucocratic granite consisting mainly of alkali feldspar and quartz) for feldspar, mica and quartz at Oberon, NSW (*Industrial Minerals*, December 1979, p.9) did not eventuate.

NEPHELINE SYENITE AND RELATED ROCKS IN TASMANIA — CYGNET–KETTERING AREA

Virtually the only known occurrence of undersaturated felsic rocks in Tasmania is in the Cygnet–Kettering district, where they are a component of a series of dykes, sills and small stock-like bodies of syenite and related alkaline rocks.

The alkaline rocks of the Cygnet area were first recorded by Johnston (1888). Their unusual petrology attracted the interest of geologists around the turn of the century, particularly after gold was discovered in the area (Twelvetrees and Petterd, 1900; Macleod and White, 1900; Twelvetrees, 1903, 1907). Since then the only petrological studies available are by Edwards (1947) and Ford (1983). The distribution of the rocks was mapped in detail by Farmer (1981), although he did not map out the various types. The following account and conclusions with regard to the rock's potential as nepheline syenite resource is based mainly on the data of Ford and the mapping of Farmer.

The alkaline rocks at Cygnet intrude both Permo-Carboniferous glaciomarine sedimentary rocks and Jurassic dolerite (Skeats, 1917; Farmer, 1981, 1985) and have been dated as Cretaceous (Evernden and Richards, 1962; McDougall and Leggo, 1965). The main area is centred near or just west of the township of Cygnet. Small intrusions are found over an area of about 100 km^2, but the actual mapped area of surface outcrop or inferred bedrock is very much less. A smaller adjacent area occurs to the east between Oyster Cove, Kettering and Woodbridge.

The alkaline rocks can be subdivided into two main categories.

Syenite porphyry (oligoclase porphyry)

This is the most abundant type near Cygnet and apparently the only type near Kettering. All the relatively large intrusions, such as at Helliwells Point, Farewell Hill, Black Jack Ridge and Mt Windsor, appear to consist of this type, but it also occurs as dykes and sills. The larger intrusions were thought to be sheet-like by Clarke (*in* Farmer, 1985, p.69). Mapping provides some evidence for this at Black Jack Ridge, Mt Windsor and possibly Wheatleys Bay and Regatta Point. However the bodies at Helliwells Point and Farewell Hill could equally be small stocks, up to 400 m across.

The syenite porphyries are silica oversaturated rocks usually containing phenocrysts (5–25 mm) of plagioclase (typically oligoclase) and occasionally also potash feldspar and/or hornblende, and a few embayed quartz crystals (to 4 mm). Small inclusions of green clinopyroxene are common in the plagioclase phenocrysts, particularly in their cores. The groundmass ranges from very fine-grained (10–25 m) to relatively coarse-grained (2 mm) and consists of mainly potash feldspar, quartz, hornblende and salitic clinopyroxene. Apatite, sphene, pyrite, barite, calcite and aragonite have also been identified as groundmass phases.

Ford (1983, chapter 2, p. 6–8) distinguished two sub-types on petrographic criteria. Rocks with slightly larger phenocrysts have a coarser and more leucocratic groundmass richer in potash feldspar, in which the sparse ferromagnesian minerals (probably both pyroxene and amphibole) are replaced by pseudomorphs of chlorite and magnetite. Those with smaller feldspar phenocrysts and a finer-grained groundmass may also contain euhedral phenocrysts of fresh hornblende.

This latter sub-type appears to be transitional into more mafic rocks lacking feldspar phenocrysts but containing aligned hornblende phenocrysts up to 25 mm long in a fine-grained groundmass. These hornblende porphyries are known from two dykes, at Oyster Cove and Petcheys Bay.

Xenoliths of amphibolite up to 100 mm across are reported by Ford in syenite porphyry near Petcheys Bay and at Farewell Hill. The author has also observed them at Perch Bay near Woodbridge.

Xenoliths of marble and quartzite are reported by Ford in these rocks from the Kettering–Woodbridge area, and locally derived xenoliths of Permian country rocks may occur near contacts.

Sanidine porphyry

This type is found only in the Cygnet area, as "numerous small dykes and sills" (Clarke *in* Farmer, 1985, p.69), "a system of relatively isolated dykes from about 1 to 10 metres in width" (Ford, 1983, chapter 1, p.22), but "usually no wider than about 2 m" (Ford, 1983, chapter 2, p.17). They intrude, and are therefore younger than, the syenite porphyries as well as the Permo-Carboniferous rocks and Jurassic dolerite. A K-Ar date from sanidine (99 Ma; Evernden and Richards, 1962), presumably from a sanidine porphyry, is indistinguishable from two K-Ar dates from hornblende (95 Ma, 98 Ma; McDougall and Leggo, 1965), presumably from syenite porphyries.

These rocks are highly variable both mineralogically and chemically but most contain flow-aligned phenocrysts of sanidine (up to 50   5 mm), often with aegirine inclusions particularly near the rims. Garnet (melanite; i.e. essentially titaniferous andradite), pyroxene (aegirine), hauyne and sphene may also occur as phenocrysts. The fine-grained grey, green or brown groundmass (50–80% by volume) consists of variable proportions of sanidine, nepheline, clinopyroxene (aegirine) and garnet (melanite). The distinction between the grey groundmass rocks and the green groundmass rocks (tinguaites) is caused by the respective dominance of feldspar or aegirine. Other, mostly accessory minerals recorded in the groundmass include plagioclase, amphibole, biotite, muscovite pseudomorphs after andalusite, cancrinite, hauyne, sodalite, analcite, scapolite, pectolite, eudialyte (one locality), sphere, allanite, zircon, apatite, magnetite, calcite and pyrite.

Near Lymington a "grey groundmass" dyke is reported by Ford (1983, ch.2, p.20) to intersect two "green groundmass" dykes, indicating an at least locally valid age relationship.

The only xenoliths reported are small (10 mm) inclusions of phengitic mica and pyrite in a dyke near Mt Mary (Ford, 1983, ch.1, p.26; ch.2, p.29–33).

Two dykes, near Kings Hill and at Petcheys Bay, contain both oligoclase and later, subordinate sanidine phenocrysts in a light brown groundmass (70%) of feldspar, pyroxene, garnet and magnetite. They are chemically transitional between the syenite and sanidine porphyries.

One of the dykes (400 mm wide) near Langdons Point consists of a unique garnet trachyte rock, containing phenocrysts of garnet (spessartine) and epidote, both with sanidine overgrowths, in a groundmass (80%) of sanidine, epidote and chlorite.

Syenite aplites, syenite pegmatites and orthoclasites

The main occurrence of these rocks is near Robleys Point on the western shore of Port Cygnet, where they intrude the 'hybrid' rocks (see below). They have also been reported on the opposite (eastern) shore of Port Cygnet (Edwards, 1947) and at Petcheys Bay (Edwards, 1947; Clarke *in* Farmer, 1985).

The aplites occur as numerous intersecting late dykes and veins mostly less than one metre wide, but rarely up to three metres in width. They consist mainly of variable proportions of potash feldspar, usually subordinate oligoclase/andesine, and minor (5–10%) quartz. Biotite, green pyroxene, magnetite, garnet, amphibole, chlorite, apatite, zircon, sphene, muscovite and corundum have also been reported as minor or accessory phases. Grainsize ranges from 0.1 to 1 mm, with the narrower dykes generally being finer grained. They have an equigranular granoblastic texture and some resemble the groundmass of the syenite porphyry.

The garnet orthoclasites of the Robleys Point area, according to Edwards, are dykes up to 0.3 m wide. They are similar to the syenite aplite dykes (which they cut and displace), but also contain melanite garnet in the groundmass.

The syenite pegmatites are described by Edwards as consisting of abundant sanidine phenocrysts, partly replaced by microperthitic exsolution, in a potassic groundmass of orthoclase, magnetite and minor pyroxene, muscovite and sphene with very little quartz.

'Hybrid' rocks

An enigmatic suite of rocks is exposed on the western foreshore of Port Cygnet for several hundred metres both north and south of Robleys Point (formerly Regatta Point). Twelvetrees (1902) interpreted these rocks as the diverse differentiation products of a small syenite stock, but Edwards (1947) and later Ford (1983) showed that they resulted from the thermal metamorphism and potassic metasomatism of Jurassic dolerite by the Cretaceous alkaline intrusions. The term 'hybrid' is somewhat misleading, as no author has suggested that the rocks originate by direct liquid mixing of magmas.

Petrographically the alteration of dolerite becomes evident several hundred metres from the syenite contact, with the retrogressive replacement of pyroxene by hornblende, magnetite and biotite. This thermal metamorphic stage is essentially isochemical and the doleritic texture is preserved.

Hornblende and igneous plagioclase are replaced by albite, melanite garnet, aegirine-augite and sphene in rocks closer to the contact. The onset of alkali (mainly potassium) metasomatism leads to the appearance of sanidine, and sometimes nepheline or zeolites. The 'hybrid' rocks have been classified as melanocratic or leucocratic, depending on whether they are dominated by components of doleritic or syenitic origin. However geochemically they cannot be modelled by simple linear mixing of two components.

Farmer (1981) mapped the contact between altered dolerite and syenite near Robleys Point as a fault, and showed that neither extends more than one hundred metres or so inland, where both have intrusive contacts against Permo-Carboniferous sedimentary rocks. Clarke (after field notes of Farmer, 1985) noted that much of the large inland extent of hybrid rocks mapped by Leaman and Naqvi (1967) consists of highly baked tillite and Bundella Mudstone. He considered that much of the remainder of the 'hybrid zone' consists of highly variable, steeply-dipping syenitic dykes and that the "true hybrid rocks (i.e. those rocks which cannot be assigned to either syenite or baked sedimentary rocks or dolerite with any confidence) are also very irregular in their distribution" and do not form an "even, widespread zone".

The hybrid rocks are associated with a strong magnetic anomaly, centred just off-shore and aligned NNW-SSE parallel to the shore (Leaman and Naqvi, 1967).

Geochemistry

Three alkaline rocks from the Cygnet area were amongst the first Tasmanian rocks to be chemically

Table 2

Selected analyses, syenite porphyries (from Ford, 1983 unless otherwise stated)

	A	CY25-1	CY5-1	CY7av	CY64-1	CY16-1
SiO_2	64.03	60.58	59.75	66.33	59.55	66.22
TiO_2	0.44	0.49	0.59	0.35	0.53	0.37
Al_2O_3	17.60	16.45	16.8	17.84	18.27	19.20
Fe_2O_3	1.93	2.44	3.13	1.89	2.78	0.59*
FeO	1.30	2.04	2.48	0.19	2.70	nd
MnO	0.10	0.17	0.22	0.01	0.09	-
MgO	0.70	1.68	1.85	0.08	1.24	-
CaO	3.17	4.31	4.87	2.56	4.67	2.26
Na_2O	4.64	4.54	5.01	4.47	4.96	4.49
K_2O	4.58	4.08	3.68	4.85	5.06	4.34
P_2O_5	0.14	0.23	0.31	0.09	0.30	0.01
LOI	1.60	2.51	0.98	1.58	1.27	1.30
Total	100.20	99.52	99.67	100.24	101.40	98.78
CIPW norms						
Q	12.37	8.77	5.73	16.67	1.28	19.14
C	-	-	-	0.82	-	3.11
Or	27.43	24.84	22.03	29.05	29.85	26.31
Ab	39.80	39.59	42.95	38.31	41.90	38.98
An	13.87	12.85	12.66	12.26	12.63	11.43
Di	0.90	6.09	7.80	-	6.96	-
Hy	1.59	2.67	2.35	0.18	1.63	0.02
Mt	2.83	3.64	4.59	-	4.02	-
Il	0.84	0.95	1.13	0.42	1.00	0.49
Hm	-	-	-	1.91	-	0.34
Rt	-	-	-	0.12	-	0.11
Ap	0.32	0.54	0.71	0.20	0.68	0.02
Total	99.95	99.94	99.95	99.94	99.95	99.95

A:	Average of 45 analyses from Ford (1983) (42) and Edwards (1947) (3).
CY25-1:	Stock-like intrusion at Helliwells Point, south of Kettering (approximately EN200222).
CY5-1:	Western side of stock-like intrusion at Farewell Hill, west of Kettering (EN152241).
CY7av:	From apparently relatively large intrusion, Black Jack Ridge, Lymington (EN042165) (average of three similar analyses).
CY64-1:	Wattle Grove Road, 1 km west of Cygnet (EN047204). Analysis with the lowest normative Q.
CY16-1:	Wattle Grove Roar near Kings Hill, 2 km westof Cygnet (EN036204). Analysis with lowest total iron. Norm calculated at mean Fe2O3/FeO = 1.45 for syenite porphyries.

analysed (MacLeod and White, 1900; Paul, 1906). A further two analyses of syenite porphyry, four of the sanidine-bearing dyke rocks and six of the 'hybrid' and related rocks were tabulated by Edwards (1947). More recently Ford (1983) analysed more than 80 samples of the alkaline rocks and more than 40 samples of the 'hybrid' and related rocks for both major and many trace elements. This later data is the basis for the following discussion, which is restricted to major element geochemistry and its bearing on the nepheline syenite resource potential of the area.

Average and representative chemical analyses for the syenite porphyries (n = 45) and the sanidine porphyries (n = 36) are presented in Tables 2 and 3. As the fine grainsize of the groundmass precludes modal analysis for most rocks, the CIPW norms are used to give a rough idea of their mineral proportions. It should be borne in mind, however, that in reality many of the minerals deviate from their ideal composition, and that some minerals are not directly represented. In particular, hornblende in the syenite porphyries and melanite garnet in the sanidine porphyries will be largely expressed as *Di*, *Hy* and *An* in the CIPW norms. One consequence of this is that the normative *Q* will give only an approximate estimate of the amount of free quartz in the over-saturated rocks.

All the analysed syenite porphyries are over-saturated, with normative *Q* varying from 1.3% to 28.6%, whilst only 13 of the 36 sanidine porphyries are over-saturated. The remainder

Table 3

Selected analyses, Sanidine porphyries (from Ford, 1983 unless otherwise stated)

	B	CY81-2	CY61-1	CY94	X44-2	CY73-1
SiO2	57.84	66.12	63.99	55.40	60.04	57.04
TiO2	0.47	0.72	0.13	0.27	0.30	0.33
Al2O3	19.17	19.27	19.87	20.05	17.73	19.76
Fe2O3	3.16	0.37	1.82	2.05	3.20*	3.15
FeO	1.23	0.10	0.09	0.56	nd	0.50
MnO	0.15	-	0.05	0.13	0.15	0.13
MgO	0.49	0.16	0.27	0.32	0.46	0.24
CaO	2.52	0.17	0.53	3.45	1.50	2.75
Na2O	4.76	3.87	6.19	6.23	6.83	7.08
K2O	8.05	9.66	6.17	7.39	7.90	7.93
P2O5	0.11	0.01	0.02	0.09	0.06	0.05
LOI	2.09	0.97	1.79	1.61	1.06	2.60
Total	100.04	101.42	100.92	97.55	99.23	101.56
CIPW norms						
Q	-	6.03	2.91	-	-	-
C	-	2.15	2.11	-	-	-
Or	48.56	56.82	36.78	45.51	47.59	47.35
Ab	28.90	32.59	52.83	22.57	27.59	20.24
An	7.33	0.77	2.51	5.14	-	-
Ne	6.61	-	-	17.53	11.13	20.51
Ac	-	-	-	-	6.63	2.13
Ns	-	-	-	-	0.74	-
Di	2.68	-	-	1.78	5.12	1.29
Wo	0.52	-	-	4.08	0.42	4.92
Hy	-	0.39	0.67	-	-	-
Mt	3.15	-	0.07	1.50	-	1.09
Il	0.90	0.20	0.24	0.53	0.57	0.63
Hm	1.04	0.36	1.78	1.09	-	1.69
Rt	-	0.60	-	-	-	-
Ap	0.25	0.02	0.04	0.21	0.13	0.11
Total	99.94	99.96	99.94	99.94	99.92	99.96

B:	Average of 36 analyses from Ford(1983) (32) and Edwards (1947) (4).
CY81-2:	Dyke on foreshore south of Langdons Point (EN065172). Contains lowest iron of analysed sanidine porphyries.
CY61-1:	Dyke, Wattle Grove Road near Kings Hill (EN035202). 'Brown groundmass rock' with both plagioclase and sanidine phenocrysts. Contains third lowest iron content of analysed syenite porphyries.
CY94:	Gardners Creek, south of Clarks Hill (EN083198).
X44-2:	Tinguaite dyke, foreshore at Langdons Point (EN069178).
CY73-1:	Dyke of 'green groundmass rock' from Forster Rivulet Road near Mt Mary saddle (EN043189). Contains sanidine and garnet phenocrysts, also aegirine, hauyne and analcime.

contain usually small to moderate amounts of normative *ne*, which however reaches over 20% in a 'grey groundmass' rock from near Mt Mary (CY73-1) and in a 'green groundmass' dyke from Lymington (CY85A,B). In the former rock, *ne* is modally expressed as hauyne and analcime, as well as nepheline. Although control between field, petrographic and analytical data is poor, there is probably no systematic chemical distinction between the grey and green groundmass rocks.

All the syenite porphyries and most of the sanidine porphyries are miaskitic: i.e. their Agpaitic Index, molar ($Na_2O + K_2O$)/Al_2O_3, is less than unity and their CIPW norms contain *An* (anorthite) and lack *Ac* (acmite) and *Ns* (sodium silicate). Only seven analysed samples are agpaitic: most are 'green groundmass' (tinguaite) dykes from the Lymington area (e.g. X44-2, table 3) but they include 'grey groundmass' rocks from near Mt Mary (CY73-1, table 3) and from near Wheatleys Bay (CY74-2). These rocks have high total alkali contents, and X44-2 contains small amounts of the rare alkali zirconosilicate eudialyte. Elsewhere in the world (e.g. Lovozero and Khibina massifs, Kola Peninsula; Illimaussaq, Greenland), a large number of rare alkali silicate minerals are associated with agpaitic nepheline syenites.

A plot of total alkalis ($Na_2O + K_2O$) against silica (SiO_2) for the alkaline rocks (fig. 4) shows that the sanidine porphyries (squares) have higher alkalis (10–17%) and lower silica (mostly 54–61 %) than the syenite porphyries (circles, alkalis 7–13%, silica 59–69%), although there is a slight overlap.

The distinction between the syenite and sanidine porphyries is also clearly seen in a plot of K_2O against Na_2O (fig. 5). The syenite porphyries define a fairly tight cluster centred near 4% K_2O, 5% Na_2O with a couple of obvious outliers possibly

Table 4

Miscellaneous analyses (from Ford, 1983 unless otherwise stated)

	CY91-1	JROCK2-2	CY97-2	CY31-1	CY106-3	DP(11)
SiO2	55.27	55.47	62.91	63.57	57.94	58.3
TiO2	0.80	0.38	0.20	0.31	0.17	1.3
Al2O3	16.66	20.30	19.43	17.47	20.37	12.3
Fe2O3	2.28	1.59	2.77	1.41	2.97	5.6
FeO	5.32	2.70	0.46	0.16	0.69	4.4
MnO	0.19	1.89	0.05	0.06	0.05	0.15
MgO	2.04	0.34	0.32	0.33	0.22	2.3
CaO	5.15	2.63	0.84	1.36	2.67	4.9
Na2O	4.47	1.75	4.44	2.15	2.68	4.2
K2O	6.75	9.76	8.51	11.26	9.64	4.6
P2O5	0.49	0.09	0.05	0.04	0.04	0.17
LOI	1.50	1.80	0.54	0.38	3.12	2.9
Total	100.92	98.70	100.52	98.50	100.56	100.22
CIPW Norms						
Q	-	-	2.38	5.14	-	6.98
C	-	-	1.51	-	0.79	-
Or	40.11	59.52	50.29	67.81	58.46	27.67
Ab	21.59	15.27	37.56	18.53	22.56	36.18
An	5.50	12.86	3.84	4.86	13.32	1.15
Ne	8.90	-	-	-	0.38	-
Di	14.19	-	-	1.18	-	15.60
Wo	-	-	-	-	-	1.21
Hy	-	3.57	0.79	0.28	-	-
Ol	3.67	3.08	-	-	0.39	-
Mt	3.32	2.37	1.06	-	1.94	8.26
Il	1.52	0.74	0.37	0.47	0.33	2.51
Hm	-	-	2.03	1.43	1.70	-
Sph	-	-	-	0.15	-	-
Ap	1.12	0.20	0.11	0.09	0.09	0.39
Total	99.92	99.97	99.94	99.94	99.96	99.95

CY91-1:	Dyke of hornblende porphyry, Petcheys Bay (EN003177)
JROCK2-2:	Dyke (0.4m) of garnet trachyte, Langdons Point (EN070177). Contains garnet and epidote phenocrysts.
CY97-2:	Syenite aplite near Robleys (Regatta) Point (EN067191). Contains the lowest normative Q of six analyses.
CY31-1:	Orthoclasite near Robleys Pont (EN065188).
CY106-3:	'Hybrid rock', near Robleys Point (EN06661909). Contains the lowest total iron of analysed ne-normative hybrid rocks.
DP(11):	Minor (0.4 m) felsic segregation in Tertiary mafic potassic nepheline benmoreite, Droughty Point, Hobart (from Sutherland, 1976).

transitional to the sanidine porphyries, which have higher K_2O (6–11%) and a large range in Na_2O (1.2–7.5%).

Plots of total alkalis ($Na_2O + K_2O$) against alumina (Al_2O_3) (fig. 6) and Al_2O_3 against SiO_2 (fig. 7) show that both groups have Al_2O_3 typically in the range of 16.5–21%, although the syenite porphyries show a negatively skewed distribution to the lower end of this range. The three outliers with lower Al_2O_3 are all syenite porphyries from near Cygnet township with relatively high K_2O, and include the gross outlier in Figure 5.

A critical requirement for commercial nepheline syenite is a low total iron content, preferably less than 2%, and that beneficiation to lower values is practicable. Few of these rocks, and none of the undersaturated ones, fulfil this requirement. A plot of total iron as Fe_2O_3 against SiO_2 (fig. 8) shows a broad negative correlation for both the syenite porphyries and the sanidine porphyries. Those with the lowest SiO_2 and least likely to contain free quartz are generally those with unacceptably high iron, and vice versa. Most of the rocks with less than 2% Fe_2O_3* are felsic, strongly over-saturated syenite porphyries which will contain abundant free quartz, probably both as the small embayed crystals reported by Ford (1983), and as a groundmass phase. In general, the sanidine porphyries are more iron-rich than the syenite porphyries. This is also clearly seen in plots of total alkalis against total iron (fig. 9) and total iron against alumina (fig. 10).

The two hornblende porphyry analyses available are much more mafic than the syenite porphyries, with lower SiO_2 and very high total iron (e.g. fig. 8 — filled triangles). However their Na_2O, K_2O and Al_2O_3 contents overlap with the ranges shown by each group (e.g. fig. 5, 6).

Similar plots (fig. 11–17) are presented for the 'hybrid' rocks and associated aplites, pegmatites and orthoclasites from the Robleys Point foreshore. Again, few of the analysed samples have acceptably low levels of iron, and none of the undersaturated rocks do. The same discouraging strong negative correlation between total iron and SiO_2 is also evident for these rocks (fig. 15). The 'hybrid' rocks show a very large scatter of K_2O and Na_2O (fig. 12) consistent with alkali metasomatism. Total alkalis are broadly positively correlated with SiO_2 and Al_2O_3 (fig. 11, 13) and negatively with total iron (fig. 16).

CYGNET ALKALINE ROCKS
Key to Figures 4 to 10

CIPW normative character

	Q>5%	Q<5%	*ne*
Syenite porphyry	○	◐	
Sanidine porphyry	□	◨	■
Hornblende porphyry			▼
Garnet trachyte			✳ (*ol-hy* normative)

◨	Samples CY23-1, CY44-1, CY61-1, CY78-1, CY80-2, CY86-2, CY92-1, CY95-1, CY98-2
✳	Sample JROCK2-2
◐	Samples CY47B-1, CY45A-1, CY64-1, CY71-1, CY75-1
▼	Samples CY91, CY91-1
○	Samples CY5-1, CY11-1, CY25-1, CY47A-1, CY47C-1, CY48-1, CY49, CY49-1, CY52-1, CY53-1, CY7A-1, CY7D-1, CY7E-1, CY8-1, CY10-1, CY14-1, CY16-1, CY18-1, CY21-1, CY45-1, CY45B-1, CY45C-1, CY55-1, CY60-1, CY63-1, CY67-1, CY69-1, CY70-1, CY76-1, CY83-1, CY87-1, CY88-1, CY89-1, CY90-1, CY120, S10, S4-2, CY130, JE9, JD4
■	Samples CY13-2, CY19-2, CY44, CY46-2, CY56-2, CY62-3, CY73-1, CY74, CY74-2, CY79-2, CY84-2, CY85A-2, CY85B-2, CY85C-2, CY94-2, CY94, X44-2, CYX44, CY123-1, JF3, JF4, KC1, KC2
□	Samples CY40-1, CY44CM-1, CY81-2, X50-2

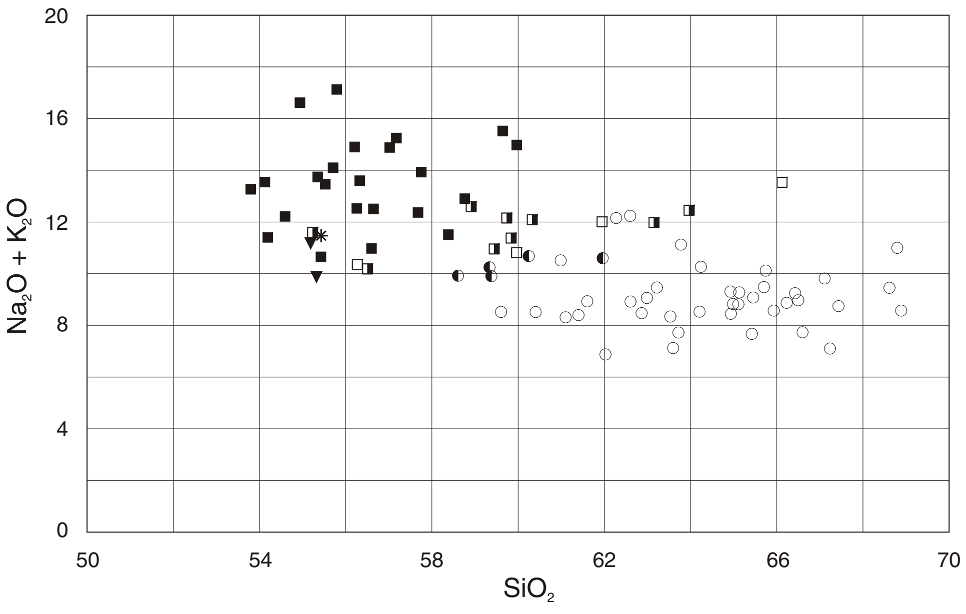


Figure 4

Plot of total alkalis against silica, Cygnet alkaline rocks

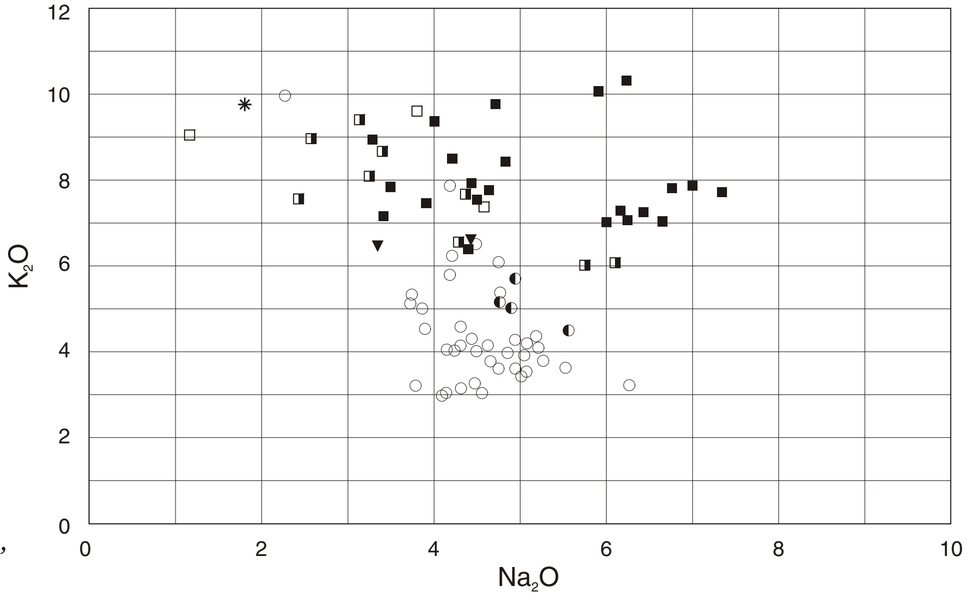


Figure 5

Plot of potash against soda, Cygnet alkaline rocks

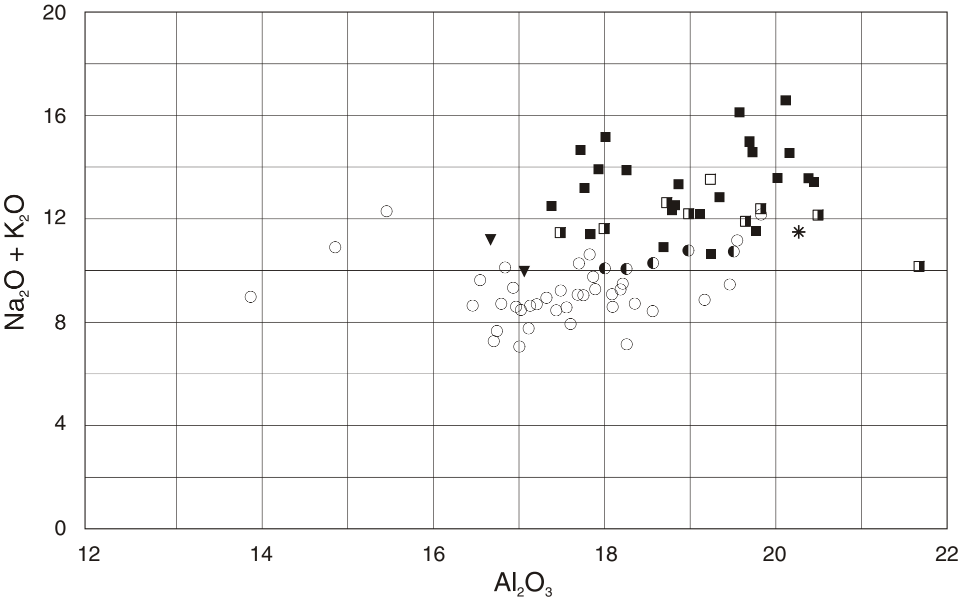


Figure 6

Plot of total alkalis against alumina, Cygnet alkaline rocks

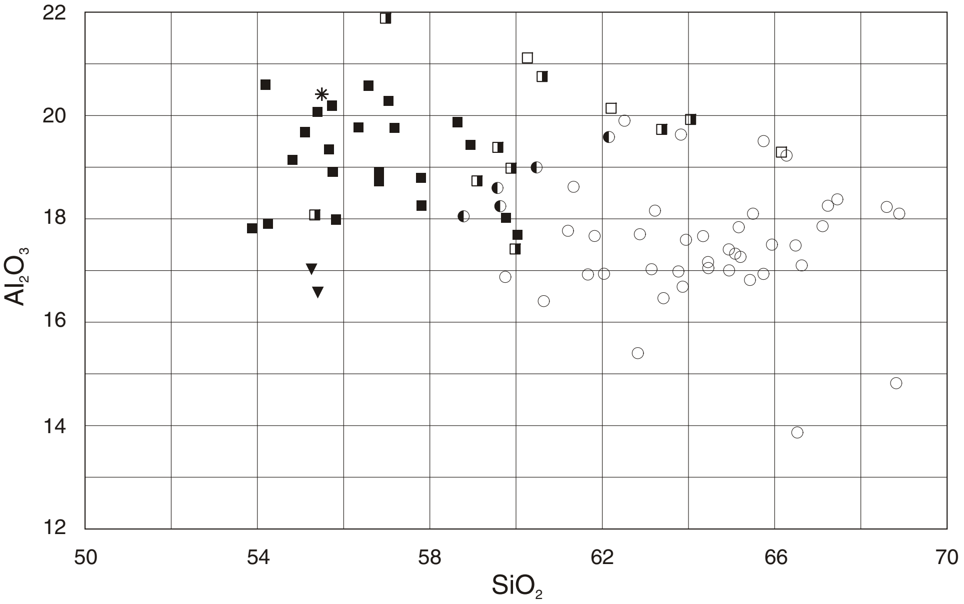


Figure 7

Plot of alumina against silica, Cygnet alkaline rocks

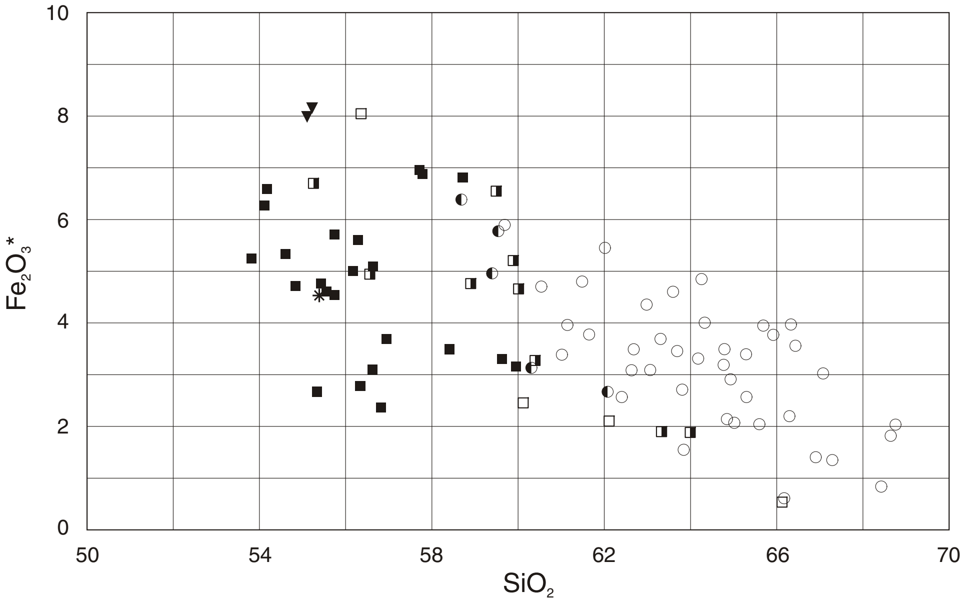


Figure 8

Plot of total iron against silica, Cygnet alkaline rocks

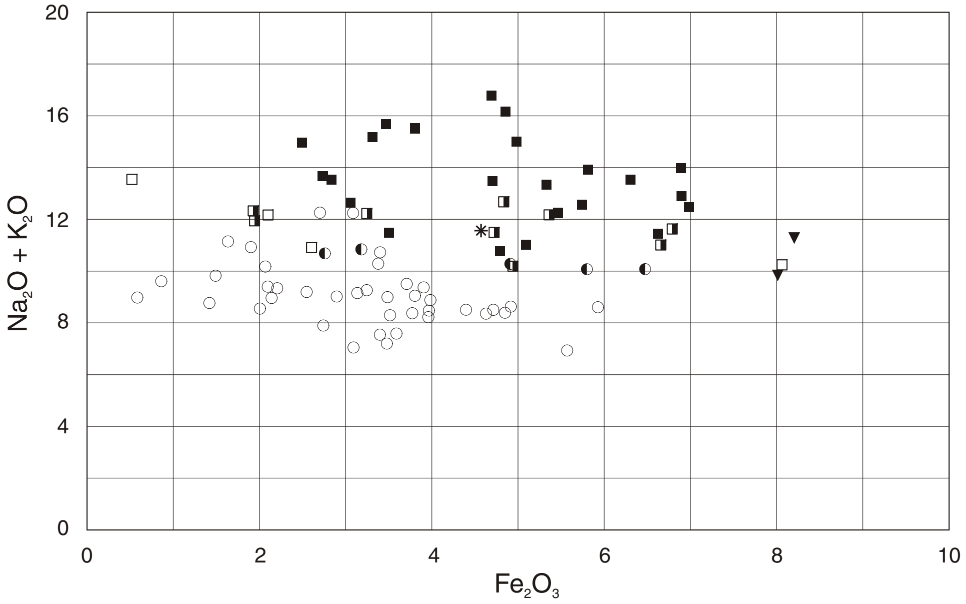


Figure 9

Plot of total alkalis against total iron, Cygnet alkaline rocks

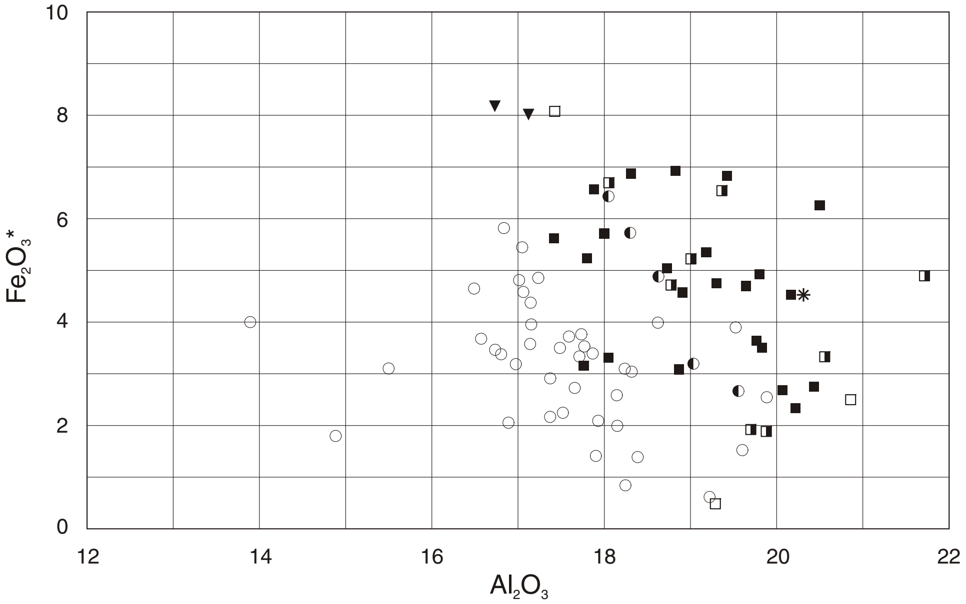


Figure 10

Plot of total iron against alumina, Cygnet alkaline rocks

HYBRID AND RELATED ROCKS, CYGNET AREA
ROBLEYS ('REGATTA') POINT
Key to Figures 11 to 17

	CIPW normative character		
	Q>5%	Q<5%	*ne*
Hybrid rocks	▽	◭	▼
Syenite aplites, pegmatites and orthoclasites	◇	⬗	

◭	Samples CY26-1, CY33-B, CY36-3, RP30-3, CY102WHT-1, 4-3, CY109-3, CY113A-3, CY114F-3, CY114DK-3, CY116-1, RP19-3, RP20-2, RP20DK-3, RP25-2, GA12, GA14
▼	Samples CY29-3, CY34, CY101-3, CY102BLK-3, CY104-2, CY105-3, CY106-3, CY106DK-3, CY108-3, CY110-3, CY111-2, CY113B-3, CY113C-1, CY115-3, GA11, GA16
▽	Samples CY35-1, RP4-2, CY117-3, 18-3, CY103-1, RP10-3, RP17A-3, RP17B-2, RP20PLE-2
◇	Samples CY28-1, CY30-1, CY96-1, CY99-1, JB2, CY27-1, CY31-1, CY32-1, JD1
⬗	Samples CY97-2

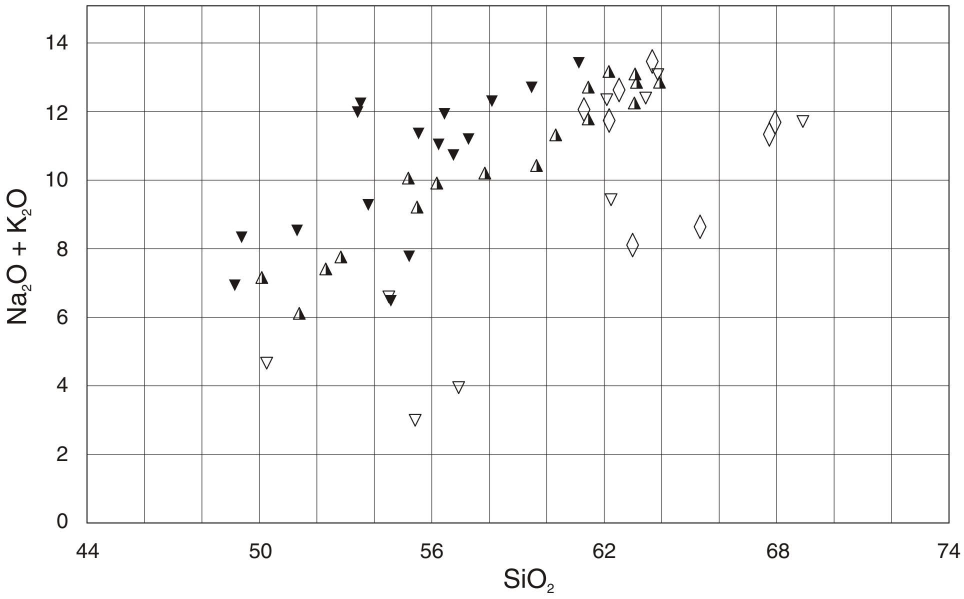


Figure 11

Plot of total alkalis against silica, hybrid and related rocks, Robleys Point area

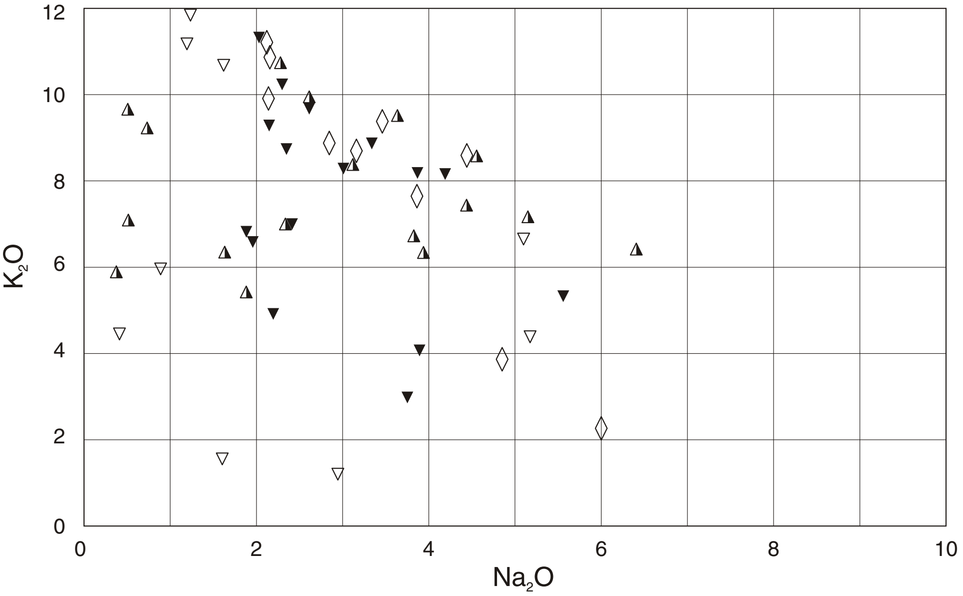


Figure 12

Plot of potash against soda, hybrid and related rocks, Robleys Point area

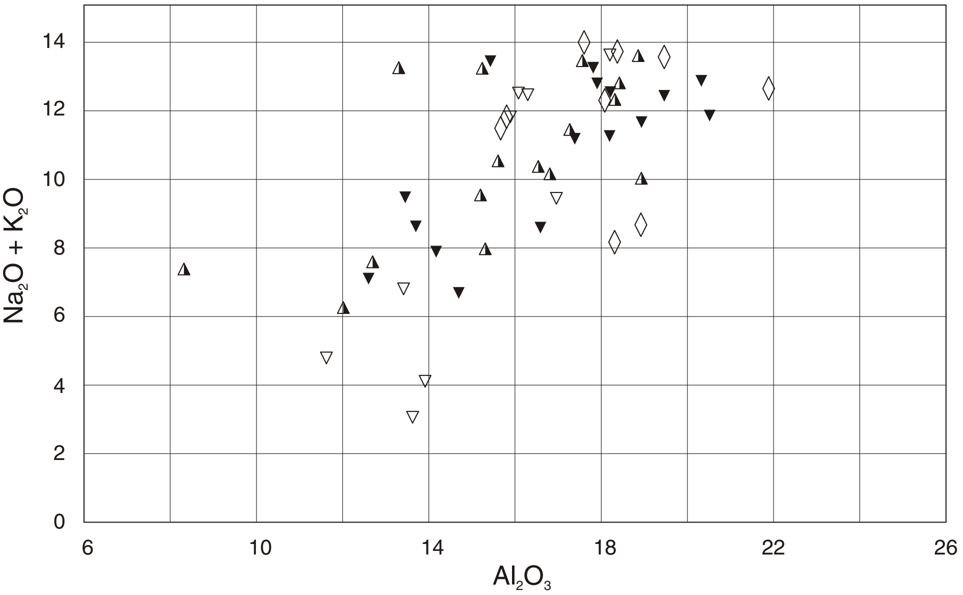


Figure 13

Plot of total alkalis against alumina, hybrid and related rocks, Robleys Point area

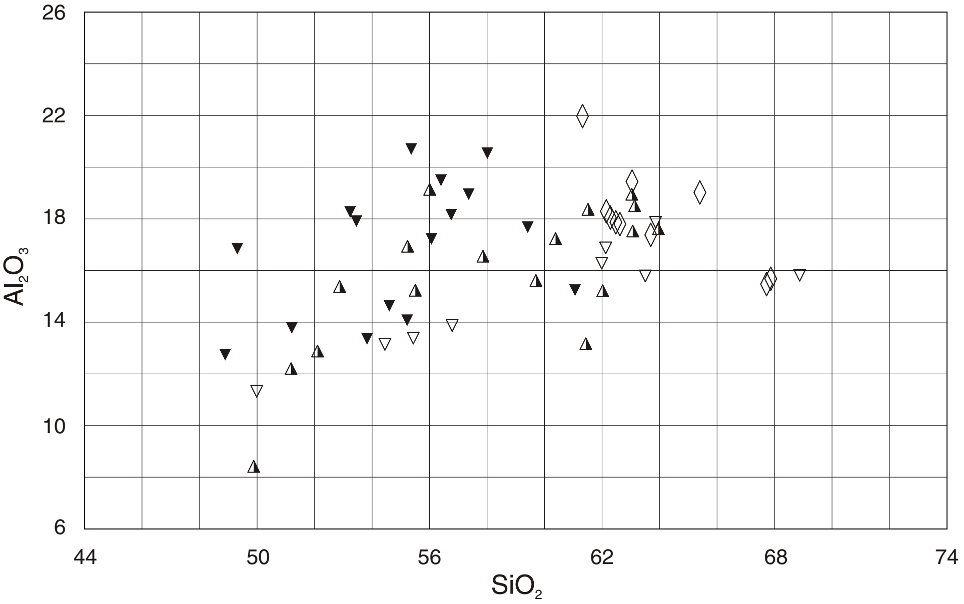


Figure 14

Plot of alumina against silica, hybrid and related rocks, Robleys Point area

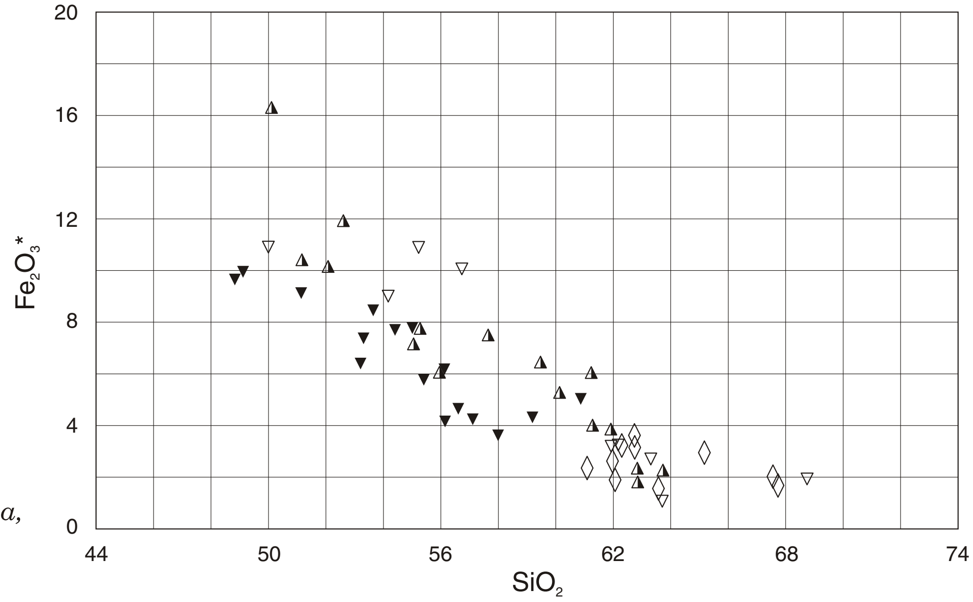


Figure 15

Plot of total iron against silica, hybrid and related rocks Robleys Point area

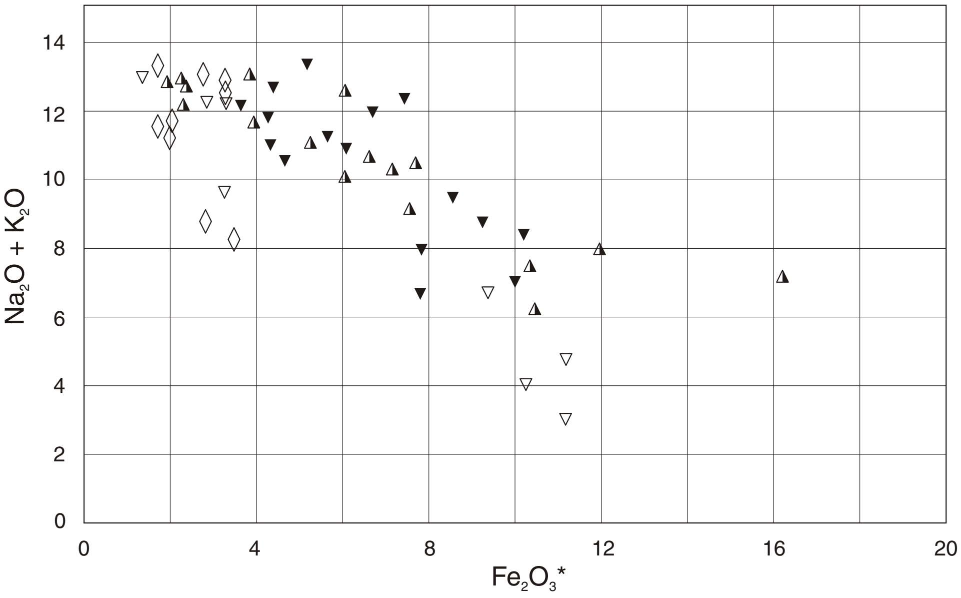


Figure 16

Plot of total alkalis against total iron, hybrid and related rocks, Robleys Point area

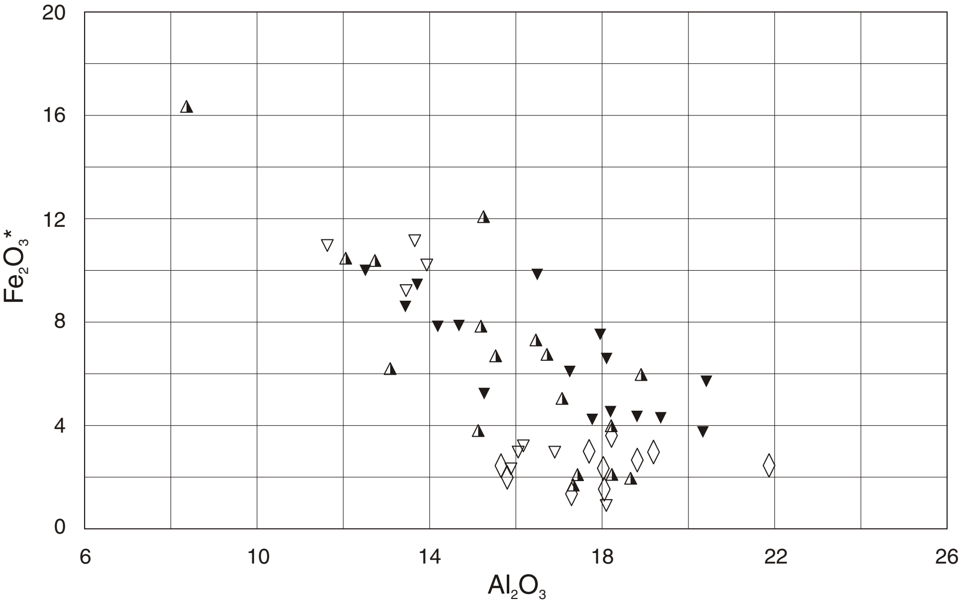


Figure 17

Plot of total iron against alumina, hybrid and related rocks, Robleys Point area

KING ISLAND

Thick (up to 200 m) 'syenite' dykes (or possibly a single north-trending dyke, displaced by cross-faults) intrude the lower part of the Neoproterozoic(?) volcano-sedimentary succession north of Grassy and just inland of the east coast of King Island (Waldron *et al*. 1993). The 'syenite' is not particularly alkaline and contains normative and modal quartz. It contains abundant augite, often pseudomorphed by chlorite, as well as plagioclase. In addition to the presence of quartz, its reported Fe_2O_3 content (c.6–7%) is highly discouraging to any consideration as a source of nepheline syenite or feldspar. The rock is better described as a quartz dolerite and is chemically similar to the more felsic members of the Rocky Cape dolerite dyke swarm on the Tasmanian mainland.

TERTIARY VOLCANIC ROCKS

Phonolite is the potential product of the extreme fractionation of basanite or olivine nephelinite, which are widespread in the Tasmanian Tertiary volcanic rocks. However felsic fractionates are extremely rare in Tasmania. One of the few localities known, and the only analysis available, is from the southern eruptive centre at Droughty Point near Hobart, where there are late felsic segregations up to 40 mm across in a mafic potassic nepheline benmoreite (Sutherland, 1976). The segregations contain coarse-grained potash feldspar, nepheline, clinopyroxene and minor iron oxide. Although some are described as mafic phonolites, the high iron content of the only analysed sample is highly discouraging in this context, even if a larger body could be found.

In the Eastern Australian Tertiary volcanic province, of which Tasmania represents the southernmost portion, felsic fractionated rocks are largely restricted to the 'central volcano' subprovinces. These are related to an inferred southward-migrating mantle hot-spot, now located near Bass Strait and yet to reach Tasmania. The Tasmanian Tertiary basalts are an example of a 'lava field' subprovince, and are almost entirely mafic.

Phonolitic dykes of Jurassic age in the northeast Victorian highlands are a potential resource (McHaffie and Buckley, 1995, p.75).

DEVONIAN GRANITIC ROCKS

Although outside the initial scope of this report and therefore not examined in detail, the best chance of establishing a feldspar industry in Tasmania probably lies in the Devonian–Carboniferous granites and related rocks, particularly the alkali-feldspar granites, which have the lowest total iron. Possible targets include feldspar-rich pegmatites, highly leucocratic low-iron aplites and Oberon-type alaskites. There is a relative lack of major development of pegmatites and aplites in Tasmania, and any operation would need to compete with Western Australian pegmatite-derived feldspar and imported products.

CONCLUSIONS AND RECOMMENDATIONS

Although there has been no recorded production of, or exploration for nepheline syenite in the Tasmania, the geology of the State is probably sufficiently well known to conclude that the only rocks worthy of any consideration as a potential resource are the Cretaceous alkaline intrusives of the Cygnet area. However the available field, petrographic and geochemical data indicates that these rocks have a number of unfavourable characteristics that will make the identification of a viable resource difficult.

The syenites of the Cygnet area do not occur as a single body, but as a large number of dispersed small intrusions. The larger of these, possibly sheet-like or stock-like in form, appear to be oligoclase-phyric 'syenite porphyries' which are invariably silica over-saturated and thus do not qualify as nepheline syenite. Potentially they could still be used as a source of feldspar in the glass industry if the manufacturers were prepared to compensate for the presence of quartz in the syenite by reducing the silica sand/syenite ratio in their feedstock; a quartz-bearing syenite is reportedly exploited in Turkey. However if this were the case, more abundant rock types, such as aplite and alkali-feldspar granite, would be equally useable.

Most of the 'sanidine porphyries' of the Cygnet area are undersaturated and do qualify as nepheline syenite, as they lack quartz and commonly contain nepheline or other feldspathoids, usually in the groundmass. The available chemical analyses indicate high alkali and alumina contents, some comparable to those of exploited deposits. However the sanidine porphyries are reported only as narrow dykes a few metres wide and appear to comprise a volumetrically minor component of the alkaline complex. This is likely to make the identification of workable tonnages very difficult. As these rocks are quite diverse mineralogically and chemically, there may also be problems with processing or maintaining product specifications.

The 'hybrid' rocks appear to be far too variable and too restricted in their extent for serious consideration. Their geochemistry and complex mineralogy is also unfavourable.

A critical requirement for commercial exploitation of nepheline syenite is a low iron content. One criterion suggested is a Fe_2O_3* (total iron as Fe_2O_3) content of less than 2% in the raw material. The few rocks from the Cygnet alkaline complex that fulfil this requirement are all silica-oversaturated, and most are syenite porphyries. A few of the sanidine porphyry dyke rocks fall only marginally outside this criterion, with either less than 3% Fe_2O_3* (e.g.

CY94, Gardners Creek, Table 3) or less than 3% normative quartz (e.g. CY61-1, Kings Hill, Table 3).

Perhaps more important than the initial iron content is whether the ferromagnesian and refractory minerals can readily be removed by magnetic separation and/or flotation. Glass manufacturers prefer nepheline syenite crushed to -30#+200# (i.e. 75 m to 200 m), with less than 0.1% Fe_2O_3* (low-iron grade), or less than 0.35% Fe_2O_3* (high iron-grade). Ceramic-grade material is crushed finer (to -200#) but must have less than 0.07% Fe_2O_3*. The porphyritic nature of the Cygnet rocks, with ferromagnesian minerals mostly found in the fine-grained groundmass, suggests that there could be difficulty in beneficiating them to this level. The report of aegirine inclusions in the rims of sanidine phenocrysts, if widespread, is a particularly unfavourable feature. An additional problem could be impurities of disseminated sulphide, observed in abundance by the author in the body near Kings Hill.

The field relationships of the alkaline rocks have mainly been established from good coastal exposures, where quarrying would probably not be permitted on environmental grounds. Any exploration should concentrate on inland areas on the Lymington Peninsula, such as around Kings Hill, Mt Windsor and Black Jack Ridge, and possibly also north and east of Cygnet. The aim should be to locate a thick dyke of undersaturated sanidine porphyry, with a relatively coarse-grained groundmass and/or a low iron content. Detailed outcrop and float mapping and sampling of the relatively sporadic exposures is required, followed up by petrographic studies. Only if a zone of such rock were located would further work be justified. This would require closely-spaced drilling and detailed petrographic, chemical and metallurgical work to assess any potential resource.

Previous work does not provide much ground for optimism. However this work has been carried out for regional mapping and petrological research purposes, not to investigate the economic potential of the area for nepheline syenite.

A further consideration is that the relatively dense population of the area, with numerous small, partially-cleared private landholdings, could lead to environmental and land management difficulties.

REFERENCES

Allen, J. B.; Charsley, T. J. 1968. *Nepheline-syenite and phonolite*. HMSO : London.

Bolger, R. 1995. Feldspar and nepheline syenite: Turkish delight in export sales. *Industrial Minerals* 332:25–45.

Edwards, A. B. 1947. Alkali hybrid rocks of Port Cygnet, Tasmania. *Proceedings Royal Society Victoria* 58:81–115.

Evernden, J. F.; Richards, J. R. 1962. Potassium-argon ages in eastern Australia. *Journal Geological Society of Australia* 9:1–49.

Farmer, N. 1981. Geological Atlas 1:50 000 series. Sheet 88 (8311N). Kingborough. *Department of Mines, Tasmania.*

Farmer, N. 1985. Geological Atlas 1:50 000 series. Sheet 88 (8311N). Kingborough. *Explanatory Report Geological Survey Tasmania.*

FORD, R. J. 1983. *The alkaline rocks of Port Cygnet, Tasmania*. Ph.D. thesis, University of Tasmania.

Geis, H. P. 1979. Nepheline syenite on Stjernøy, Northern Norway. *Economic Geology* 74:1286–1295.

Griffiths, J. (ed.). 1991. *Industrial Minerals Directory (Second Edition)*. Metal Bulletin Books Ltd : Surrey.

Harben, P. 1979. Nepheline syenite. Indusmin and the markets. *Industrial Minerals* 144:71–77.

Johnston, R. M. 1888. *Systematic account of the Geology of Tasmania*. Government Printer : Hobart.

Leaman, D. E.; Naqvi, I. H. 1967. Geology and geophysics of the Cygnet district. *Bulletin Geological Survey Tasmania* 49.

Lofty, G. J.; *et al.* (comp.). 1993. *World Mineral Statistics 1987–1991. Volume 2: Industrial Minerals*. British Geological Survey.

McDougall, I.; Leggo, P. J. 1965. Isotopic age determinations on granitic rocks from Tasmania. *Journal Geological Society of Australia* 12:295–332.

McHaffie, I. W.; Buckley, R. W. 1995. Industrial minerals and rocks of Victoria. *Report Geological Survey Victoria* 102.

Macleod, W. A.; White, O. E. 1900. On the occurrence of a new species of garnet at Port Cygnet. *Papers and Proceedings Royal Society Tasmania* 1898–1899:74–76.

Minnes, D. G.; Lefond, S. J.; Blair, R. 1983. Nepheline syenite, *in* Lefond, S. J. (ed.). *Industrial Minerals and Rocks (5th edition)*. 931–960. American Institute Mining, Metallurgical and Petroleum Engineers.

Paul, F. P. 1906. Beitrage zur petrographische Kenntnis einiger foyalitisch Gesteine aus Tasmanien. Tschermaks mineralogische petrographische Mitteilungen. 25:269–318.

Robbins, J. 1986. Feldspar and nepheline syenite. Filling a need? *Industrial Minerals* 228:69–101.

Skeats, E. W. 1917. On the age of the alkali rocks of Port Cygnet and the D'Entrecasteaux Channel in S.E. Tasmania. *Proceedings Royal Society of Victoria* 29:154–164.

Sutherland, F. L. 1976. Cainozoic volcanic rocks, *in* Leaman D. E. Geological Atlas 1:50 000 Series. Sheet 82 (8312S). Hobart. *Explanatory Report Geological Survey Tasmania.*

Twelvetrees, W. H. 1902. Report on gold and coal at Port Cygnet. *Report Secretary of Mines Tasmania* 1901–1902:260–268.

Twelvetrees, W. H. 1903. A geological excursion to Port Cygnet in connection with the Australasian Association for the Advancement of Science in 1902. *Report Secretary of Mines Tasmania* 1902–1903:25–32.

Twelvetrees, W. H. 1907. Report on gold at Port Cygnet and Wheatley's Bay, Huon River. *Report Secretary of Mines Tasmania* 1907:xxxiii–xliv.

TWELVETREES W. H.; PETTERD, W. G. 1900. On haüyne trachyte and allied rocks in the districts of Port Cygnet and Oyster Cove. *Papers and Proceedings Royal Society Tasmania* 1898–1899:2–26.

WALDRON, H. M.; BROWN, A. V.; KEAYS, R. R. 1993. Geological setting and petrochemistry of Eocambrian–Cambrian volcano-sedimentary sequences from southeast King Island. *Report Mineral Resources Tasmania* 1993/28.

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