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A late Oligocene basalt from Keach Hill, near Campbell Town, and its stratigraphic significance

by J. L. Everard, F. L. Sutherland & S. M. Forsyth

Department of Infrastructure, Energy and Resources
Mineral Resources Tasmania

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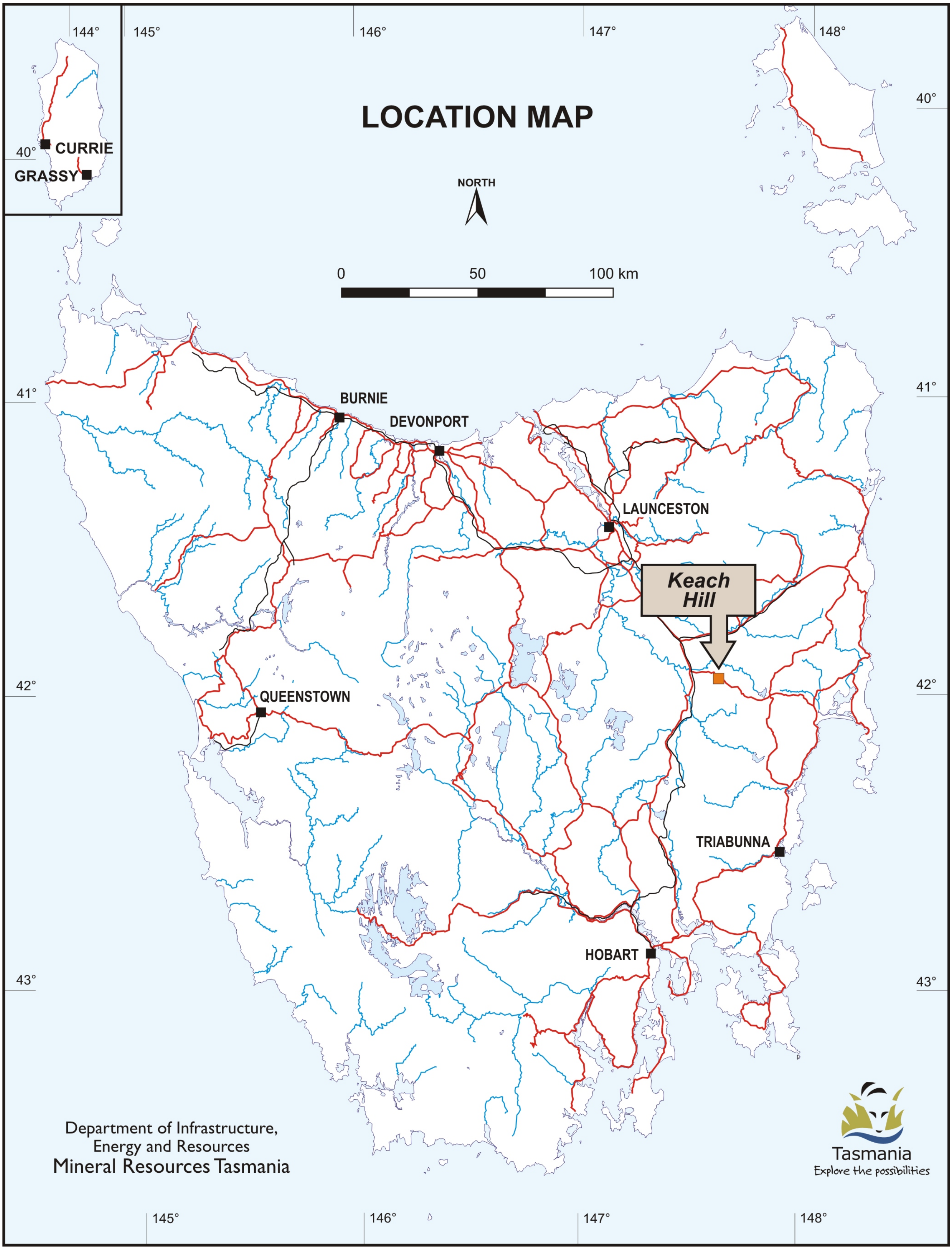

Mineral Resources Tasmania PO Box 56 Rosny Park Tasmania 7018

Phone: (03) 6233 8377 ● Fax: (03) 6233 8338

Email: info@mrt.tas.gov.au ● Internet: www.mrt.tas.gov.au

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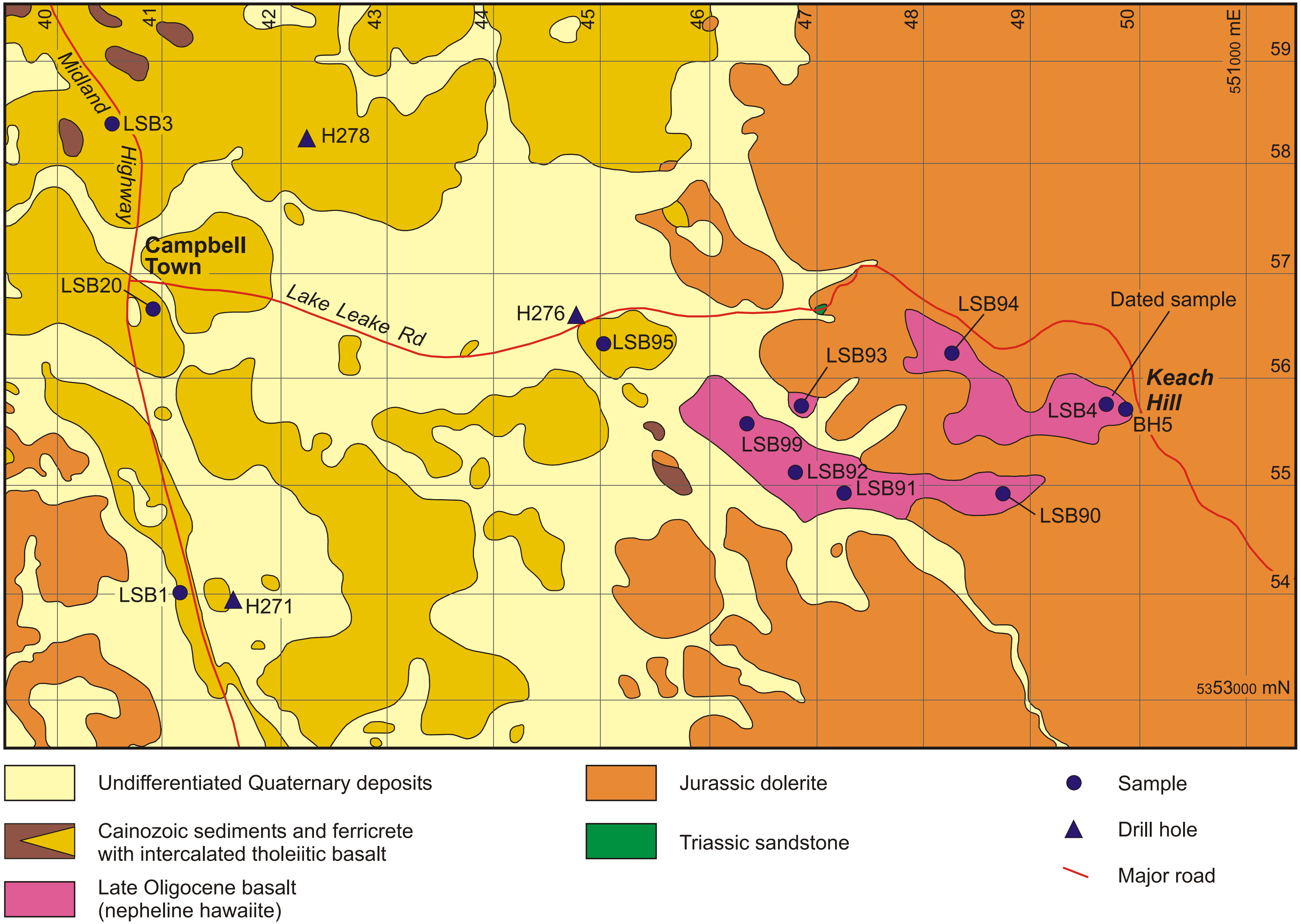

Figure 1

Simplified geological map of the Campbell Town–Keach Hill area, modified from Gulline et al. *(1991), showing basalt types, location of surface samples and drill holes.*

Abstract

Nepheline hawaiite cropping out at Keach Hill, nine kilometres east of Campbell Town, has been dated by the K/Ar method at 27.2 ± 0.2 Ma (late Oligocene). Nearby surface samples range chemically from similar nepheline hawaiite to olivine nephelinite, and petrographically comprise three textural varieties, including one characterised by abundant lherzolite debris. These rocks form a series of flows descending westward to the plains near Campbell Town, where drilling shows that they are overlain by two younger flows. The latter are petrographically typical of the tholeiitic basalts widespread in the northern Midlands, which are therefore probably younger than 27 Ma.

Introduction

This work follows from regional geological mapping of the area east of Campbell Town, which falls on the Snow Hill 1:50 000 scale map sheet (Gulline *et al*., 1991). Several petrographically distinct varieties of Cainozoic basalt were initially noted amongst specimens collected from this area by A. B. Gulline. In 1989–1993, more systematic sampling was followed by petrography and chemical analysis of representative specimens. A distinctive nepheline hawaiite flow cropping out at Keach Hill (550 000 mE, 5 355 800 mE) was selected for dating.

Basalt chips collected from percussion drill holes in the Campbell Town area, drilled in 2000 as part of a regional groundwater investigation (Taylor, 2000), were also examined. The relationships in one hole show that nepheline hawaiite is overlain by tholeiitic basalt, part of an extensive series of similar flows widespread in the northern Midlands, which have been difficult to date directly.

Regional Geology

Physiographically the northern Midlands of Tasmania consists of a gently north-sloping plain which, interrupted by a few low hills (e.g. Hummocky Hills, Isis Hills, Macquarie Tier), extends as far south as Woodbury. The area is flanked both to the west and to the east by higher country, and has been termed the Midlands Graben (Andrews, 1910; Banks, 1962). There is clear evidence for bounding faults only in the west, where the Late Carboniferous to Triassic Parmeener Supergroup rocks are downthrown by 700–1000 m along the Great Western Tiers by the NW to NNW-trending Tiers Fault and its splays (Matthews, 1974; Forsyth, 1986, 1989; Matthews *et al*., 1996). To the east, in contrast, the less elevated hills of the Eastern Tiers rise from the plains over an irregular line, and neither topographic lineaments nor geological mapping (Gulline *et al*., 1991) provide evidence for control by a major fault. More probably the region is essentially a half graben, complicated by discordant Jurassic dolerite intrusions. This structural style extends further north to the Launceston and Tamar areas, which were shown by Longman *et al*. (1964) and Longman (1966) to comprise a series of half grabens, formed by the displacement of gently west-dipping Parmeener Supergroup rocks and sheet-like Jurassic dolerite intrusions by east-side-down normal faults.

On the plains in the Campbell Town district, Triassic sandstone and Jurassic dolerite are discontinuously overlain by Cainozoic cover of commonly vesicular tholeiitic basalt, intercalated clay and sand, and associated ferricrete, laterite and bauxite (Matthews, 1974; Gulline *et al*., 1991; fig. 1). The basalt extends from near Epping Forest in the north (Blake, 1959; Matthews *et al*., 1996) to south of Ross (Forsyth, 1989).

A volcanic centre is inferred at *Truelands*, about ten kilometres ENE of Campbell Town (c. 550 500 mE, 5 361 500 mN; datum AGD66) and at an altitude of about 460 m, near which overlapping terrace-like features visible on aerial photography represent several tholeiitic flows that descended westward, and probably fanned out on to the plains (Gulline *et al*., 1991). Other unrecognised feeders for the basalt are undoubtedly present.

Because of the subdued relief, neither the form of the dolerite intrusions nor the thickness of the basalt flows is easily determined from geological mapping, but a present basalt thickness of up to 30–45 m west of Campbell Town was estimated (Matthews *et al*., 1996). More recent drilling results, reviewed below, show that the Cainozoic cover (mainly basalt) is thicker (>84 m) immediately east of the town (Taylor, 2000).

At Keach Hill, on the edge of the Eastern Tiers further east of Campbell Town, basalt rests on Jurassic dolerite at an altitude of about 500 metres. From there another series of flow remnants descend westward for about four kilometres, reaching the floor of the Midlands plain at an altitude of about 230 m (fig. 1; plate 1; Gulline *et al*., 1991). Petrography shows that these flows are alkalic in character, and quite different from the more widespread tholeiitic basalts.

Drilling

Mineral Resources Tasmania drilled thirty percussion holes in the northern Midlands and Fingal Valley as part of a regional groundwater program in 2000 (Taylor, 2000). Ten of these holes, in the Ross–Campbell Town–Conara area, encountered Cainozoic basalt. Of particular interest is hole H276 at *Quorn Hall*, about four kilometres east of Campbell Town, which reached a depth of 84 m without encountering pre-Cainozoic basement (fig. 1, 2). Logging by Taylor (2000), based on chips recovered at mostly three metre intervals, showed that the hole passed through at least two flows of massive to variably vesicular basalt and penetrated at least 36 m into a third, lower flow (fig. 2). The flows are separated by a few metres of gravel and clay.

The pea-sized chips retained from the hole were re-examined. Those from the two upper flows are pale

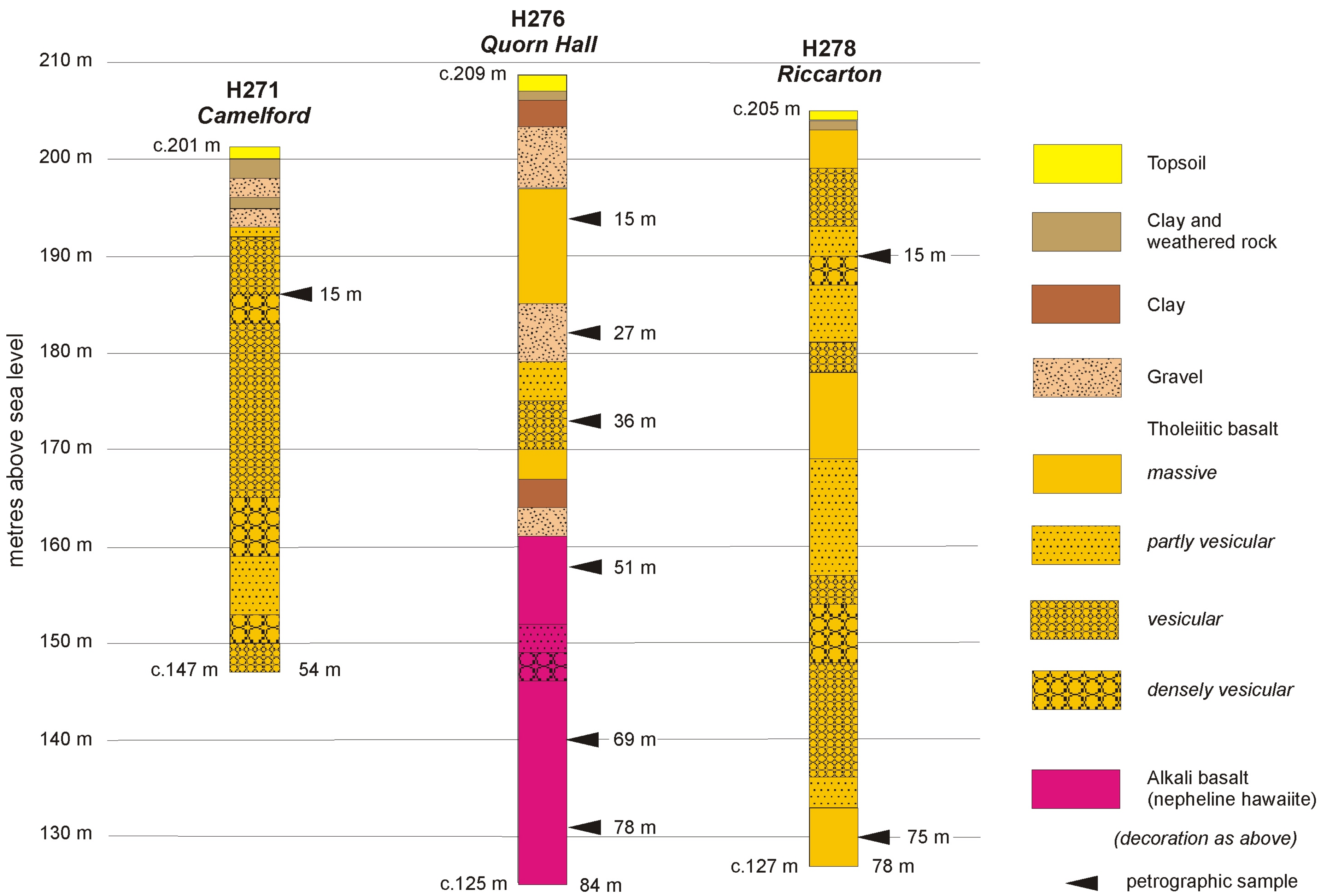

Figure 2. *Graphic logs of sampled percussion drill holes, Campbell Town area (modified after Taylor, 2000) showing basalt types and depth of samples taken for petrography.*

Plate 1

View looking WNW from Keach Hill, with outcrops of nepheline hawaiite near dated sample locality in foreground. The Quorn Hall drill hole (H276), which passed through tholeiitic basalt into nepheline hawaiite, was located immediately in front of the farm buildings in the middle distance near the centre of view. Macquarie Tier in left distance and Great Western Tiers on skyline behind, with Millers Bluff on left and Drys Bluff on right.

to medium-grey, medium to coarse-grained, mostly finely to minutely vesicular basalt with a rough fracture, although a few larger vesicles up to 2.5 mm across are present. The interval logged as gravel (at about 27 m) also contains a few chips of Jurassic dolerite and soft, fine-grained brick-red ochre. The lower interval of clay and gravel at 42 m and 45 m contains dark grey mudstone, poorly-sorted lithic sandstone and fragments of basalt.

In contrast, chips from the lower basalt flow, below about 48 m, are mostly dark grey, fine grained, massive or with small round vesicles (at 60 m and 63 m), exhibit a subconchoidal fracture, and sometimes contain visible olivine phenocrysts. Reddish chips at the top of the interval (at 48 m) suggest an oxidised flow top, implying an hiatus before deposition of the overlying sediments and flow. Veinlets (≤2 mm wide) and encrustations of white calcite, a concretion of pyrite and carbonate about 5 mm across, and subordinate chips of khaki-green to grey shaly mudstone (at 60 m) were also noted.

Microscopic petrography (see below) confirms that the lower flow in the *Quorn Hall* drill hole is distinct from the two upper flows, and resembles some of the basalt flows that extend westward from Keach Hill. The nearest surface outcrops of similar basalt are one to two kilometres southeast of the drill hole (fig. 1).

Other notable thicknesses of basalt near Campbell Town were drilled at *Riccarton* (H278, >78 m) and *Camelford* (H271, >54 m), also without reaching basement (fig. 1, 2). Examination of chips of basalt collected from these holes showed that they are entirely of the pale vesicular type, and similar to the two upper flows in the *Quorn Hall* drill hole.

Petrography

Detailed descriptions of each sample are given in Appendix 1. Localities of both surface and drill-hole samples are given in Table 1 and x-ray diffraction results are given in Table 2.

In hand specimen, samples of the Keach Hill flows are massive to less commonly slightly vesicular, dark grey to black basalts with an uneven to hackly fracture. They are aphanitic apart from scattered olivine phenocrysts and variable amounts of yellow-orange weathering lherzolite nodules and debris.

In thin section they typically contain small microphenocrysts of olivine and subordinate augite in a variably fine-grained groundmass consisting of pink titaniferous clinopyroxene laths, magnetite grains, small flakes of biotite, potash feldspar, nepheline and, in some samples, sodalite (Plate 2; Table 2). Most samples also contain anhedral xenocrysts of olivine, subordinate clinopyroxene and orthopyroxene, and rare spinel, which may be surrounded by reaction coronas and almost certainly are derived by the disaggregation of lherzolite nodules (Plates 2e, f; 3c, d). There are also occasional unusual xenoliths of partly

Table 1
Sample localities

Field No.	Tasrok No.	Locality	Classification	AMG (metres E)	AMG (metres N)	TS	CA	X	Comments
BH5		Keach Hill near Lake Leake Road	nepheline hawaiite (type 1)	549900	5355700	Y			
LSB1#	R004509	Old pit, 2 km south of Campbell Town	tholeiitic basalt	541200	5354000	Y		>1.09	
LSB3#	R004511	Old quarry, Gatty Park, Campbell Town	tholeiitic basalt	540500	5358400	Y		1.24	
LSB4	R005501	Keach Hill, near summit	nepheline hawaiite (type 1)	549700	5355780	Y	Y	>22.4	dated sample (K-Ar)
LSB20#	R004510	Forster Street, Campbell Town	tholeiitic basalt	540900	5356700	Y	Y	1.44	
LSB90	R005541	1.3 km SW of Keach Hill	nepheline hawaiite (type 3)	548750	5354880	Y		14.9	
LSB91	R005542	2.5 km WSW of Keach Hill	nepheline hawaiite (type 2)	547270	5354880	Y		8.74	
LSB92	R005543	3 km WSW of Keach Hill	Jurassic dolerite	546730	5355120	Y		3.97	
LSB93	R005544	3 km west of Keach Hill	nepheline hawaiite (type 3)	546920	5355750	Y	Y	7.58	
LSB94	R005545	1.7 km WNW of Keach Hill	nepheline hawaiite (type 3)	548300	5356210	Y		26.8	
LSB95	R005546	South of Lake Leake Road near *Quorn Hall*	tholeiitic basalt	545010	5356330	Y	Y	>3.41	
LSB99	R005550	3.5 km west of Keach Hill	nepheline hawaiite (type 2)	546330	5355580	Y	Y	1.45	
H276 /15 m		North of Lake Leake Road near *Quorn Hall*	tholeiitic basalt	544740	5356570	Y			hole ID No. 17748
/27 m		As above	Jurassic dolerite	"	"	Y			
/36 m		As above	tholeiitic basalt	"	"	Y			
/51 m		As above	nepheline hawaiite (type 3)	"	"	Y			
/69 m		As above	nepheline hawaiite (type 3)	"	"	Y			
/78 m		As above	nepheline hawaiite (type 3)	"	"	Y			
H278 /15 m		Truelands Road near *Riccarton*	tholeiitic basalt	542210	5358230	Y			hole ID No. 17756
/75 m		As above	tholeiitic basalt	"	"	Y			
H271 /15 m		*Camelford*, 4 km south of Campbell Town	tholeiitic basalt	541610	5353890	Y			hole ID No. 17755

TS = thin section; CA = chemical analysis; X = magnetic susceptibility (× 10^{-3} SI units)
# described by Matthews *et al*. (1996)
Co-ordinate datum AGD66

Table 2

X-ray diffraction results

Sample	Minerals identified
LSB4	Clinopyroxene, nepheline, olivine, k-feldspar, apatite, mica, magnetite
LSB99	Clinopyroxene, nepheline, olivine, apatite, magnetite, sodalite

Note: LSB99 may contain K-feldspar, but peak overlap makes it difficult to confirm
Analyst: R.N. Woolley
Date: 29 June 2005

reacted country rocks (Plate 4). Except as a component of country rock xenoliths, only one sample (H276/78 m) contains any plagioclase.

Three textural variants are recognised:

- 'Type 1', which includes the dated sample LSB4, is a microporphyritic variant with a very fine-grained groundmass and scattered coarse-grained late-stage segregations of mainly nepheline, aegirine-augite, pink amphibole and potash feldspar.
- 'Type 2' is also a microporphyritic type but with a better-crystallised poikilitic groundmass characterised by large nepheline platelets and minor secondary palagonite.
- 'Type 3', to which are assigned samples from the lower flow in the *Quorn Hall* drill hole (H276) as well as some surface samples, is characterised by very abundant lherzolite debris, including large olivine anhedra (c. 30 vol%) in a fine-grained groundmass.

Tholeiitic basalt from the plains east of Campbell Town is easily distinguished in the field by its paler grey colour, more vesicular character, and the absence of abundant mesoscopically visible olivine. In thin section it may contain scattered, usually deeply embayed microphenocrysts of olivine (LSB95) and less common orthopyroxene (sample H276/15 m) in a usually intergranular groundmass of plagioclase, colourless clinopyroxene (augite and/or pigeonite), minor olivine, opaque minerals, and variable amounts of poorly crystalline mesostasis or glass. Further descriptions of the tholeiitic basalts of the northern Midlands can be found in Matthews *et al*. (1996).

Geochemistry

Three samples of the Keach Hill flows, and one of the overlying tholeiitic basalt, were chemically analysed by standard x-ray fluorescence techniques at the Tasmania Department of Mines laboratories, Hobart (Table 3). Further analyses of tholeiitic basalts from the Campbell Town area can be found in Matthews *et al*. (1996).

Although all the analyses of the Keach Hill flows are strongly alkalic, there are distinct differences between them. The dated 'type 1' sample (LSB4) is strongly fractionated (Mg# 52.35) and quite potassic (2.32% K_2O). 'Type 2' sample LSB99 is less fractionated (Mg# 61.65), less potassic and has markedly lower SiO_2 and higher CaO. Large differences in incompatible element ratios such as K_2O/P_2O_5 and Zr/Nb suggest that these rocks are not consanguineous and were probably derived from different parent magmas.

'Type 3' sample LSB93, which is strongly contaminated with lherzolite debris, has very high MgO, Mg#, Ni and Cr, and clearly does not represent a liquid composition. Consistent with petrographic observations, its major element composition can be modelled to within 1% by the addition of 13% olivine (Fo_{90}) to 'type 2' sample LSB99 (all residuals <0.50%, except 0.84% for SiO_2). Contamination by mantle-derived olivine is also consistent with the much higher Ni and slightly lower levels of most incompatible trace elements in sample LSB93 compared to LSB99, although clearly a Cr-bearing phase such as spinel and/or chrome diopside is also involved.

Samples LSB4 ('type 1') and LSB93 ('type 3') classify as nepheline hawaiite (*ne* > 5; *ab* > 5, An_{30-50}) in the normative scheme of Johnson and Duggan (1989), whereas sample LSB99 classifies as an olivine nephelinite (*ne* > 5; *ab* < 5). Sample LSB95, collected from the surface about 350 m southeast of the *Quorn Hall* drill hole, is a quartz tholeiite.

Geochronology

Part of sample LSB4 was forwarded by the Australian Museum to AMDEL with a request to carry out K/Ar dating if the sample was considered suitable. Results obtained by standard analytical procedures, calculated according to currently accepted decay constants (Steiger and Jäger, 1977) yield an age of 27.2 ± 0.2 Ma (Table 4). This corresponds to late Oligocene (Chattian) on recent numerical time scales (e.g. Young and Laurie, 1996).

Discussion

Plugs and small flows of alkali basalt and related rocks abound in the hilly country of the southern Midlands, but in the northern Midlands, north of about Woodbury, they are largely restricted to isolated outcrops on the hills flanking the half graben, on the floor of which tholeiitic basalt predominates.

The alkali basalts range from olivine melilitite to alkali olivine basalt, but also include many evolved alkaline types, including nepheline hawaiite comparable to the Keach Hill flows.

Ten K/Ar dates, broadly from alkali basalts of the Midlands, have been previously published (Sutherland and Wellman, 1986; Sutherland, 1989; Zwingmann *et al*., 2004). In addition, five new $^{40}Ar/^{39}Ar$ dates (Everard *et al*., 2004; Lo *et al*., in prep.) are from this area.

Table 3

Chemical analyses

Field No.	SB4	LSB99	LSB93	LSB95	LSB20*
Analysis No.	910714	930578	930573	930574	910349
Tasrok No.	R005501	R005550	R005544	R005546	R004510
AMG (mE)	549700	546330	546920	545010	540900
AMG (mN)	5355780	5355580	5355750	5356330	5356700
Locality	Keach Hill	West of Keach Hill	West of Keach Hill	Quorn Hall	Forster Street
SiO_2 (%)	43.13	40.83	41.67	51.27	49.61
TiO_2	3.10	2.94	2.70	1.76	1.79
Al_2O_3	12.37	11.15	9.29	13.93	14.14
Fe_2O_3	4.16	6.08	4.05	5.64	3.51
FeO	10.98	8.06	8.98	5.22	8.44
MnO	0.21	0.21	0.19	0.16	0.16
MgO	7.69	10.34	15.60	7.36	7.50
CaO	8.97	11.06	9.48	9.32	9.29
Na_2O	4.24	3.61	2.96	2.80	3.04
K_2O	2.32	1.43	1.07	0.75	0.61
P_2O_5	1.77	1.76	1.56	0.48	0.29
H_2O^+	0.99	2.26	2.11	1.45	1.28
CO_2	0.18	0.09	0.10	0.01	0.05
SO_3	0.02	0.06	nd	nd	0.02
FeS_2	0.10	nd	nd	nd	nd
TOTAL	**100.23**	**99.88**	**99.76**	**100.15**	**99.73**
FeO_{tot}	14.72	13.53	12.62	10.29	11.60
Mg#(0.20)	52.35	61.65	72.22	60.06	57.63
Sc (ppm)	13	14	14	21	25
V	131	195	170	170	125
Cr	136	195	700	270	190
Co	51	50	60	51	46
Ni	156	200	580	150	135
Cu	62	44	54	28	41
Zn	213	155	140	105	110
Ga	27	27	22	22	20
As	<20	<20	<20	<20	<20
Rb	51	21	17	31	20
Sr	1472	1250	1050	370	330
Y	47	34	33	26	24
Zr	560	330	310	125	115
Nb	96	105	91	21	11
Mo	13	5	<5	<5	<5
Sn	<9	<9	<9	<9	<9
Ba	716	470	450	190	155
La	84	68	64	20	<20
Ce	215	170	140	58	29
Nd	115	78	67	27	<20
W	<10	<10	<10	<10	<10
Pb	<10	15	14	16	<10
Bi	<5	6	5	5	<5
Th	<10	25	22	12	10
U	<10	<10	<10	<10	<10

* from Matthews *et al*. (1996); other analyses previously unpublished
Mg# (0.20) is molar 100Mg/(Mg + Fe^{II}) calculated at Fe_2O_3/FeO = 0.20

CIPW norms (calculated at Fe_2O_3/FeO = 0.20)

Field No.	SB4	LSB99	LSB93	LSB95	LSB20
Q	-	-	-	1.39	-
or	13.88	8.68	6.50	4.49	3.66
ab	11.28	4.88	9.33	24.11	26.14
an	7.97	10.29	9.14	23.63	23.59
ne	13.54	14.40	8.87	-	-
di	20.87	27.95	23.05	16.47	17.50
hy	-	-	-	22.78	15.46
ol	18.64	20.40	30.93	-	6.57
mt	3.66	3.42	3.18	2.58	2.89
il	5.96	5.75	5.26	3.39	3.45
ap	4.07	4.12	3.64	1.11	0.68
TOTAL	**99.87**	**99.89**	**99.90**	**99.95**	**99.94**
An/plag*	39.97	66.53	48.01	48.02	45.96
Classification	nepheline hawaiite	olivine nephelinite	nepheline hawaiite	quartz tholeiite	olivine tholeiite

* molar 100an/(an+ab) of normative plagioclase

Table 4

Potassium-argon analysis, sample LSB4

Analytical data			
	%K	1.987	
		1.992	
		1.9895	mean used in calculation
		= 5.0885×10^{-4} moles/g	
	^{40}K	= 5.938×10^{-8} moles/g	
	^{40}Ar*	= 9.4726×10^{-11} moles/g	radiogenic argon
	^{40}Ar*/^{40}Ar$_{total}$	= 0.957	
Constants			
	K	= 39.098 amu	
	^{40}K	= 0.01167 atom%	
	λ_β	= $4.962 \times 10^{-10} y^{-1}$	(Steiger and Jäger, 1977)
	λ_α	= $0.581 \times 10^{-10} y^{-1}$	
Equations			
	t	= $1/\lambda \ln\{1 + [(\lambda_\alpha + \lambda_\beta)/\lambda_\alpha]^{40}Ar^*/^{40}K]\}$	
	λ	= $\lambda_\alpha + \lambda_\beta$	
Age		**= 27.2 ± 0.2 Ma**	Analytical uncertainty at 1σ

The age range of these data is from 21.2 ± 0.2 Ma (olivine nephelinite, Spring Hill; Zwingmann *et al.*, 2004) to 36.8 ± 0.2 Ma (basanite at Blessington; Everard *et al.*, 2004), with a median age of c.26–27 Ma. Thus the 27.2 ± 0.2 Ma K/Ar date from Keach Hill fits in very well with the pattern of the previous data. In particular, the nearest previously dated basalt is a nepheline hawaiite from Burburys Sugarloaf, west of Ross and about 18 km ESE of Keach Hill (Matthews, 1974; Matthews *et al.*, 1996), which yielded an indistinguishable age of c.27 Ma, albeit by the ^{40}Ar/^{39}Ar method (Lo *et al.*, in prep).

It has not yet been possible to date the tholeiitic basalts of the northern Midlands directly. Commonly the basalts are finely to coarsely vesicular, weathered pale to medium-grey except where glassy, and generally lack well-crystallised potassium-bearing minerals. Nevertheless, the suggestion by early workers (Nye and Blake, 1938; Blake, 1959) of a Pliocene (i.e. 1.8–5.3 Ma) age for the basalts of the northern Midlands can almost certainly be discounted, as no Tasmanian basalt has yet yielded a radiometric age younger than 8.5 Ma (Baillie, 1986).

Much of the surface outcrop of tholeiitic basalt near Campbell Town shows signs of Tertiary lateritic weathering, and the more intensely lateritised flows now form bauxite deposits (Owen, 1954). The lateritisation is associated with remnants of the erosional Woodstock Surface (Nicolls, 1960), which north of Conara is developed on post-basalt deposits of weakly cemented siliceous gravel.

Although it would provide a minimum age for the tholeiitic basalt, the age of the Woodstock Surface can only be inferred. Colhoun (1989) suggested a Pliocene age, but palaeoecological analysis of early and middle Miocene marine deposits in northern Tasmania indicate tropical water temperatures during the Batesfordian (late early Miocene) with marine excursions in coastal areas (Quilty, 1972). Inland, the optimum conditions for lateritisation of basalt probably occurred at this time.

Palynology provides maximum age constraints for some of the tholeiitic basalt of the area, as discussed by Matthews *et al*. (1996). In particular, Lower *Nothofagidites asperus* zone (early to middle Eocene) spores obtained by S. M. Forsyth from clay and sand underlie basalt in a percussion hole (IH59) three kilometres east of Conara (Matthews, 1983). Everard (*in* Matthews *et al.*, 1996) suggested a middle to late Eocene age (i.e. c.49–34 Ma) for the basalt, close to the maximum permitted by the palynological data.

In contrast, Sutherland and Wellman (1986) suggested that the tholeiitic lavas of the ancestral Macquarie, South Esk and Little Swanport river valleys "may be younger than the Oligocene alkaline lavas of the western Midlands immediately to the southwest" and suggested an early to middle Miocene age (i.e. c.24–11 Ma). They noted a similar age relationship near Lemont, in the southern Midlands, where quartz tholeiite overlies undated nepheline mugearite, although an olivine tholeiite at Pencil Point, about eight kilometres southwest of Lemont, yielded a late Oligocene (25.6 ± 0.2 Ma) K/Ar date (Sutherland and Wellman, 1986). Further south, the tholeiitic basalts of the Coal River valley may be somewhat younger, as an altered glassy sample near Campania yielded a >10 Ma minimum age, and is underlain by a 24.2 ± 1.0 Ma (minimum age) alkali basalt (Sutherland and Wellman, 1986).

The drill hole at *Quorn Hall* demonstrates that, at least locally, the tholeiitic basalts of the Campbell Town area overlie the flows emanating from Keach Hill, probably with an hiatus expressed by the oxidised flow top, and are therefore younger than 27.2 Ma. In view of their degree of weathering and lateritisation, it seems probable that they are older than middle Miocene (i.e. > c.16 Ma). They may be broadly coeval with the 25.6 Ma quartz tholeiite at Pencil Point, 45 km south of Campbell Town, or with tholeiitic basalts of the Great Lake area, about 60 km to the west, which are dated at 22.3–24.3 Ma (Sutherland *et al*., 1973; adjusted for decay constants of Steiger and Jäger, 1977). The latter include the youngest date yet obtained from Tasmanian tholeiitic basalts. An age of <27.2 Ma for the tholeiitic basalts of the Campbell Town area implies that they are diachronous with the petrographically similar tholeiitic basalts of the Avoca area, dated at *Eastbourne* (about 17 km NNE of *Quorn Hall*) as c.30 Ma by the $^{40}Ar/^{39}Ar$ method (Lo *et al*., in prep.).

It may be worth noting that the *Quorn Hall* (H276) and *Riccarton* (H278) drill holes show that the pre-Cainozoic basement east of Campbell Town locally lies at an elevation of less than 125 m above sea level (fig. 2). This is below the modern elevation of the drainage outlet in the north of the Longford Basin; for example the South Esk River has cut into Jurassic dolerite at an elevation of about 150 m near Perth (e.g. Matthews, 1983). This may indicate that sometime after 27 Ma, a closed depression existed within the basin in the Campbell Town area, although no evidence has been found of aquagene volcanic rocks that might indicate the existence of a lake. Alternatively, the closure may have developed after eruption of the basalts by gentle southward tilting or down faulting.

Conclusion

At least three petrographically distinct varieties of basalt (nepheline hawaiite to olivine nephelinite) crop out near Keach Hill, and form a series of flows descending to the plains near Campbell Town. One variety yielded a Late Oligocene K/Ar age of 27.2 ± 0.2 Ma, broadly comparable to that of similar basalts in the Midlands region, whereas another clearly underlies more widespread tholeiitic basalt in a drill hole near Campbell Town. The date is comparable to that of similar alkali basalts in the Midlands region, and appears to place a maximum age of c.27 Ma for the tholeiitic basalts of the Campbell Town region. However, the following caveats, although on balance considered unlikely, are made:

(a) If any loss of radiogenic argon from the dated rock has occurred, the 27 Ma date of the Keach Hill rock would be merely a minimum age. Although the sample is fresh, its mesostasis is very fine grained and retention of argon may not have been complete.

(b) The lower basalt in the drill hole is clearly a different flow to the dated rock. Although probably part of the same volcanic episode, it is also possible that it is of a quite different age and was from an unrelated, unidentified centre.

(c) The tholeiitic basalts probably erupted from multiple, as yet unidentified centres or fissures, and may have a considerable range of ages. The base of the upper tholeiitic flows in the *Quorn Hall* drill hole lies at a slightly higher elevation than in other holes (fig. 2), and it is possible that they are atypically young.

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[4 July 2007]

APPENDIX 1
Detailed petrographic descriptions

Keach Hill — Type 1

Sample LSB4 (R005501) (Plate 2a, b)

This, the dated sample, is a medium to dark grey, massive aphanitic basalt. Under the microscope (three thin sections) it is seen to consist mainly of small olivine microphenocrysts in a very fine-grained opaque-rich feldspathoidal groundmass, together with several types of xenocrysts and inclusions (Plate 2*a*, *b*).

The olivine microphenocrysts are typically small (100–300 µm), equant to less commonly prismatic euhedra and subhedra. There are also much rarer euhedral elongate (e.g. 300 × 25 µm) microphenocrysts of pale yellow augite.

Other olivine grains are larger (≤1.5 mm), anhedral and clearly xenocrystal. They may display weakly zoned rims and irregular, weakly resorbed margins. There are also a few similar but smaller (≤400 µm) anhedral xenocrysts of augite.

The groundmass is very fine grained and pervaded by a dense dissemination of equant opaque grains (mostly ≤30 µm across and typically in the range 1–5 µm, but rarely ≤150 µm). There are also scattered small (typically 20–80 µm) ragged grains of deep orange-brown, weakly pleochroic biotite. The mesostasis consists of tiny colourless laths (30–50 × 3–5 µm) of clinopyroxene in a base of potash feldspar and feldspathoid (identified by XRD as mostly nepheline, Table 2), but plagioclase is absent. Numerous small (100 µm–1 mm) diffuse patches are free of opaque grains, and composed of clear coarser-grained nepheline.

Several late stage segregations, some up to 1.5 × 0.7 mm, are composed of relatively coarse-grained (≤500 × 200 µm) nepheline and subordinate elongate to almost acicular grains of strongly pleochroic (deep blue-green to greenish-grey) length fast aegirine-augite (Plate 4*a*, *b*). Some may also contain potash feldspar. Another similar, crudely square (500 × 500 µm) segregation consists of pale yellow-green aegirine-augite, finely granular nepheline(?) and an opaque phase.

There are several types of inclusions displaying textures suggestive of disequilibrium with the host rock. One common type, typically ≤1 mm across, consists of a sieve-textured, pale yellow-green aegirine-augite containing numerous small bleb-like inclusions of orange-brown iddingsitised olivine (Plate 4*c*, *d*). In places, a pleochroic (pale pinkish-brown to orange-brown to colourless) mineral, possibly a sodic amphibole, is intergrown with the aegirine-augite.

An unusual small (2 × 1.5 mm) inclusion (Plate 4*e*, *f*) is composed of an almost colourless cleavage fragment of pigeonite (2V near 0°, optically positive), which is altered along cleavage surfaces, and in quite large patches, to green sodic clinopyroxene (most likely aegirine-augite), intergrown with a sodic amphibole (strongly pleochroic from yellow to dark pink). Both the aegirine-augite and sodic amphibole poikilitically enclose small relict inclusions of anhedral olivine, which is partly altered to olive-green 'bowlingite' along grain boundaries. Also present are clusters of relict zoned calcic plagioclase, with margins partly replaced by K-feldspar. The xenolith may have once been an aggregate of pigeonite and calcic plagioclase ± olivine. Pigeonite suggests a tholeiitic origin, and the presence of olivine suggests affinities to Cainozoic basalt rather than Jurassic dolerite. It was partly converted to an alkali-rich secondary assemblage by reaction with the host rock.

Sample BH5

This rock closely resembles sample LSB4. Abundant subhedral olivine microphenocrysts (typically ≤250 µm), rare larger (≤500 µm) olivine anhedra (possibly xenocrysts) and rare weakly coloured subhedral augite microphenocrysts (typically 400 × 150 µm) are set in a fine-grained groundmass, consisting mainly of clinopyroxene laths (typically 75–25 µm × 2–10 µm), densely disseminated equant opaque grains (2–15 µm to rarely 70 µm across) and a feldspathoidal mesostasis. Minor orange-brown biotite is present as ragged anhedral grains (≤50 µm). There are numerous irregular to elongate late-stage segregations (250 µm–1 mm) of clear well-crystallised nepheline, sometimes enclosing small inclusions of prismatic to acicular, pale green aegirine-augite.

An inclusion about 200 µm across of finely granular (10–20 µm) recrystallised olivine is probably a reacted xenocryst. There are also larger (≤400 µm) inclusions of pale green aegirine-augite poikilitically enclosing small grains of iddingsitised olivine.

Keach Hill — Type 2

Sample LSB99 (R005550) (Plates 2c, d; 3a, b)

Abundant olivine and rare clinopyroxene microphenocrysts are set in a mostly well-crystallised groundmass of clinopyroxene, nepheline, sodalite, magnetite and palagonite, with minor biotite and accessory apatite.

The olivine microphenocrysts are fresh or occasionally marginally altered, typically euhedral to subhedral, more-or-less equant and 150–400 µm across. There are a few larger (1–1.6 mm), corroded anhedra. Rare clinopyroxene microphenocrysts (≤300 μm) range from euhedra to corroded irregular anhedra. They are pinkish, sometimes weakly zoned, biaxial positive, and probably titaniferous augite. They optically resemble groundmass clinopyroxene, which occurs as abundant small euhedral granules and elongate prisms (≤100 × 25 μm). An opaque mineral, probably magnetite, occurs as a dense dissemination of small (typically 10–50 μm), equant, usually isolated grains and less commonly as aggregates (one 700 μm across). Both clinopyroxene and magnetite are poikilitically included within platelets (≤500 μm across) of clear colourless nepheline and sodalite (identified by XRD, Table 2) There are also irregular patches (rarely ≤500 μm across) and narrow interstitial fillings of pale yellow-brown isotropic palagonite, in places with oxidised amber-orange margins, also bearing clinopyroxene and magnetite inclusions. Sparse small (20–40 μm) ragged angular interstitial grains of biotite are too strongly coloured (pleochroic from dark red-brown to almost opaque) to show birefringence. Acicular microlites (<1 μm wide) of apatite occur as inclusions within nepheline and palagonite.

Sample LSB91 (R005542)

This rock (two thin sections) resembles LSB99, but in the groundmass nepheline is less well crystallised and large platelets with poikilitic inclusions are rare.

Abundant olivine microphenocrysts (typically 250–500 μm, grading to smaller granules) are subhedral to anhedral and often slightly resorbed, and show marginal alteration to a pleochroic khaki-brown material. There are rare small (≤400 μm) microphenocrysts of pinkish titaniferous augite which grade in size to similar groundmass augite.

Rare larger (500 μm–1.5 mm) olivine anhedra are more strongly corroded and may be surrounded by a reaction zone, finer grained and richer in clinopyroxene than the rest of the groundmass. A single (1.2 × 0.6 mm) anhedron of spinel consists of a fresh deep brown isotropic core and an opaque altered rim about 150 μm wide. An anhedron (600 × 300 μm) of pale yellow-green clinopyroxene (biaxial positive), possibly a glomerocryst or fragment of a twinned crystal, contains numerous small (~15–20 μm) globular inclusions of olivine(?), is zoned with a pink titaniferous rim, and has an irregular margin, suggesting corrosion by and reaction with the groundmass. These grains are xenocrysts; very likely olivine and spinel, and probably clinopyroxene, and are derived from disaggregation of lherzolite xenoliths.

The groundmass is composed mainly of clinopyroxene (typically elongate laths, up to 500 × 40 μm but more commonly ≤250 μm long); equant to irregular, angular opaque grains (25–100 μm) and a few larger (~200 μm) aggregates; and interstitial low birefringence anhedra, probably mainly nepheline (uniaxial positive). A few interstitial patches of isotropic palagonitic glass are usually oxidised to amber or orange. Similar material fills a few small (250–500 μm) round amygdales.

Keach Hill — type 3

Sample LSB93 (R005544) (Plate 2e, f)

This porphyritic basalt contains very abundant (c.30 vol.%) phenocrysts, mainly of olivine, in a fine-grained groundmass. The larger (1–3 mm) olivine phenocrysts are anhedral, with irregular jagged outlines showing little sign of resorption with the groundmass, and are probably xenocrysts. Smaller phenocrysts (typically 500 μm–1 mm, but grading down to about 100 μm), are typically subhedral to rarely euhedral, and probably cognate.

A large (3 mm) anhedral xenocryst of pale yellow clinopyroxene displays simple twinning and is riddled with numerous small dark irregular (melt?) inclusions ('sieve texture'). Similar but smaller (~1 mm) sieve textured clinopyroxene xenocrysts also contain small granular inclusions of olivine, and have a narrow clear rim of pale pink titaniferous augite suggesting re-equilibration with the groundmass. Clinopyroxene is also present as euhedral to subhedral microphenocrysts (200–500 μm), which are zoned with colourless cores and pale pink titaniferous rims.

An anhedral opaque grain (350 × 250 μm) with jagged margins contains a small (60 μm) core of dark brown spinel, suggesting that some other smaller opaque grains (100–200 μm) may also be reacted spinel xenocrysts.

An anhedral xenocryst (~1 mm) of possible orthopyroxene is surrounded by a reaction corona, 300–500 μm wide, of pale yellow granular clinopyroxene.

Composite xenocrysts of olivine and sieve-textured clinopyroxene, and olivine and an opaque phase (after spinel?), are also present.

The anhedral, mainly larger phenocrysts are almost certainly xenocrysts derived from the disaggregation of spinel lherzolite or spinel wehrlite xenoliths.

The groundmass consists of small (25–75 μm long) pale yellow clinopyroxene laths, abundant equant angular opaque grains (typically 10–20 μm across) and a clear low birefringence mesostasis, probably mainly nepheline (uniaxial negative). There are minute (≤20 μm) traces of deep red-brown biotite and small irregular patches of clear pale yellow isotropic palagonite.

There is some pale amber to orange alteration of olivine phenocrysts.

Sample LSB90 (R005541) (Plate 3c)

The rock resembles LSB93 but is more altered.

Abundant olivine phenocrysts (≤5 mm but mostly 500 μm–2 mm) are more rounded than in LSB93, anhedral, and probably xenocrysts. They range from largely fresh to completely serpentinised, but all are surrounded by a narrow orange-brown rim of iddingsite. Smaller (100–500 µm), sometimes subhedral phenocrysts are mostly completely replaced by iddingsite.

A few small (500 µm–1 mm) anhedral xenocrysts have cores of brown spinel and opaque reacted rims. Some of the larger (150–400 µm) opaque grains may be completely reacted spinel xenocrysts. Rare small (≤500 µm) aggregates of fine-grained clinopyroxene may be recrystallised clinopyroxene xenocrysts. One composite grain, 2.5 mm across, consists of fresh olivine and finely granular clinopyroxene.

The very fine-grained groundmass consists of minute clinopyroxene laths (20–40 µm), equant angular opaque grains (10–40 µm) and a clear mesostasis, at least partly of nepheline (uniaxial negative).

Sample LSB94 (R005545) (Plate 3d)

Abundant large (≤2 mm) anhedral xenocrysts of olivine are replaced by fine-grained pale yellow serpentine, rimmed by bright red iddingsite, with only occasional traces of relict unaltered olivine. Smaller (≤500 µm) phenocrysts are commonly subhedral to euhedral and completely replaced by iddingsite. There are also large (≤3.5 mm) anhedral xenocrysts of sieve-textured, very pale yellow to colourless clinopyroxene-bearing abundant small inclusions of olivine, now replaced by iddingsite. Some relatively large (≤500 µm) anhedral opaque grains may be reacted spinel xenocrysts.

The less altered groundmass consists of small (≤50 µm) clinopyroxene laths, abundant opaque grains (5–50 µm) and an indeterminate low birefringence mesostasis, probably largely nepheline. There is some segregation within the groundmass into irregular lighter patches and discontinuous, 'stylolitic' veinlets of low birefringence material, and darker, clinopyroxene-rich zones.

Tholeiitic basalt

Sample LSB95 (R005546)

The hand specimen is a medium-grey to greenish-grey basalt with numerous spherical to flattened vesicles up to 3 mm across.

Subhedral, deeply embayed to skeletal phenocrysts of olivine (300 µm–1.5 mm) comprise 5 to 10% of the rock. They are partly altered, with turbid cores and narrow, dark brown to almost opaque completely iddingsitised rims. There are a few scattered small (≤500 µm) microphenocrysts and glomerocrysts of colourless, weakly zoned augite.

The intergranular groundmass consists mainly of stubby plagioclase laths (typically 150–400 × 20–50 µm), colourless clinopyroxene (largely or wholly augite) granules (≤50 µm), iddingsitised olivine granules and usually elongate to almost acicular opaque grains (50–150 µm long). There is also a small interstitial amount of a turbid pale brown, poorly crystalline to almost glassy mesostasis. The section is about 10% void.

Jurassic dolerite

Sample LSB92 (R005543)

Jurassic dolerite crops out at the western end of a small but prominent ridge, although basalt is shown here on the Snow Hill map sheet.

In thin section the rock is a typical medium to coarse-grained dolerite, consisting of plagioclase and clinopyroxene (1–3 mm, both augite and pigeonite) interlocking in a subophitic to ophitic texture. There are also sparse equant opaque grains (500 µm–1 mm) and a small amount of turbid mesostasis.

Samples from drill holes

H276/15 m (Quorn Hall near Pinnacles Creek) (Plate 5a, b)

This is a vesicular tholeiitic basalt containing small orthopyroxene phenocrysts (≤1 mm × 250 µm) in a fine-grained intergranular groundmass of plagioclase laths (≤250 µm long), clinopyroxene granules (mostly ≤70 µm) including both augite and pigeonite, elongate to acicular opaque grains, and a small amount of poorly crystalline mesostasis including opaque dust. The larger vesicles are round and up to 2.5 mm in diameter.

Similar orthopyroxene-phyric basalt crops out elsewhere in the Campbell Town area (e.g. sample LSB1; fig. 1). Analysed samples are chemically quartz tholeiites (Matthews *et al*., 1996).

H276/27 m

This typical coarse-grained Jurassic dolerite with abundant mesostasis is from an interval logged by Taylor (2000) as gravel. Chips from this interval also include pale grey, nearly massive basalt and soft, grey to brick-red ochre.

H276/36 m

This tholeiitic basalt resembles the 15 m sample, but is finer-grained (plagioclase laths ≤150 µm) and more altered. The texture is intergranular with some relict fresh clinopyroxene. Abundant irregularly shaped patches of brown alteration are probably altered glass.

H276/51 m (Plate 5c, d)

This porphyritic basalt contains anhedral olivine xenocrysts (≤1 mm) and subhedral to euhedral phenocrysts of olivine and pale yellow to pinkish, weakly zoned titaniferous augite. Small (≤200 µm) irregular but rounded opaque anhedra represent reacted spinel xenocrysts, as one contains a relict core of fresh brown spinel. The very fine-grained groundmass comprises clinopyroxene laths, densely disseminated opaque blebs (2–20 μm) and an indeterminate mesostasis. There is some patchy pale yellow to amber alteration of olivine. The rock resembles 'type 3' Keach Hill sample LSB93, but has somewhat less abundant olivine xenocrysts and finer grained opaque grains and mesostasis.

H276/69 m

This is a very altered 'type 3' basalt, probably originally similar to H276/51 m. Olivine is completely replaced by secondary minerals including serpentine, yellow-green 'bowlingite' and carbonate. Densely disseminated opaque blebs (2–20 μm) lie in an altered low birefringence mesostasis. Unreacted spinel xenocrysts are present.

H276/78 m

Olivine phenocrysts (500 μm–1.5 mm) include both probably cognate euhedra and xenocrystal anhedra. There are also xenocrysts of spinel, with opaque reaction rims, and orthopyroxene, with finely granular reaction rims of clinopyroxene(?). Sparse subhedral to euhedral microphenocrysts (≤300 μm) of pale pink titaniferous augite grade down to elongate prisms and laths in the groundmass, which also contains relatively sparse small plagioclase laths (50–100 × 10–20 μm), densely disseminated equant opaque grains (5–50 μm) and patches of clear low birefringence material. There are patches of dark green to khaki-brown alteration in the groundmass, and turbid brown alteration of olivine. A small (4 mm) xenolith of interlocking plagioclase and clinopyroxene, probably Jurassic dolerite, is present.

H278/15 m (Riccarton)

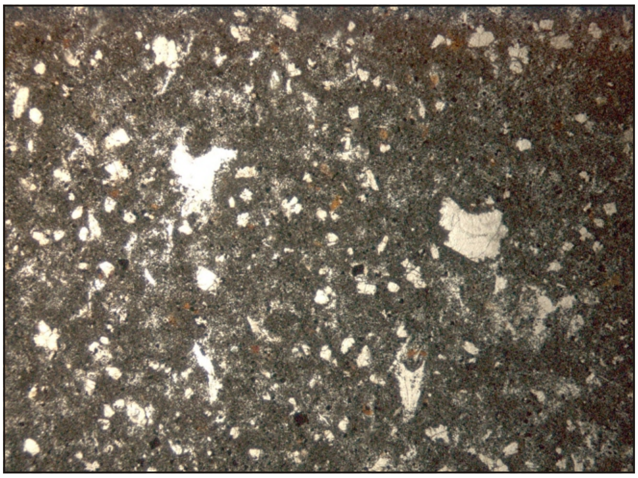
This altered fine-grained vesicular tholeiitic basalt resembles H276/36 m. Possible altered olivine phenocrysts lie in a fine-grained intergranular groundmass of plagioclase laths (≤150 μm), relict clinopyroxene granules and patches of brown alteration, probably after glass. Irregular to flattened vesicles several millimetres long are present.

H278/75 m

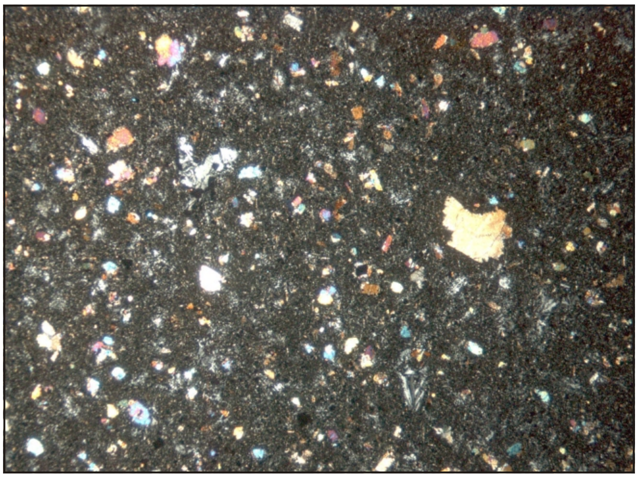
This coarse-grained intergranular to subophitic tholeiitic basalt consists of plagioclase laths (≤600 μm), clinopyroxene granules (≤200 μm) (mostly or wholly augite) and abundant dark brown interstitial alteration, probably after glass. Elongate opaque grains are embedded in the alteration, which includes minor carbonate.

H271/54 m (Camelford)

This vesicular but fairly fresh, predominantly intersertal tholeiite consists of plagioclase laths (typically 150–500 × 30–100 μm) subophitically intergrown with clinopyroxene granules (≤400 μm; mainly augite), and much interstitial black glass. There are small amounts of pale amber isotropic palagonite. About 20% of the thin section is void.

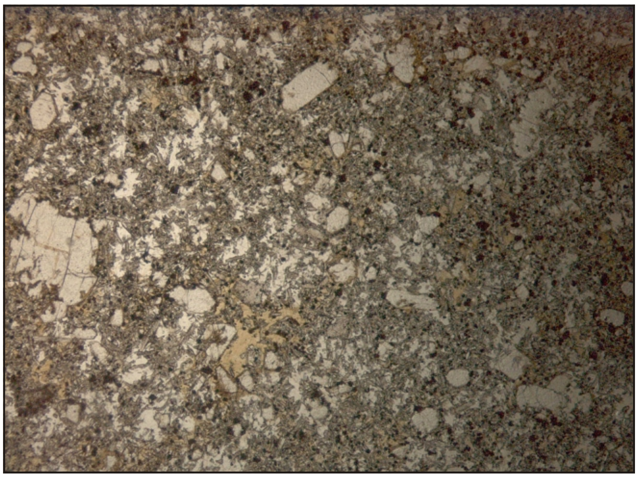


(a) Plane polarised light.

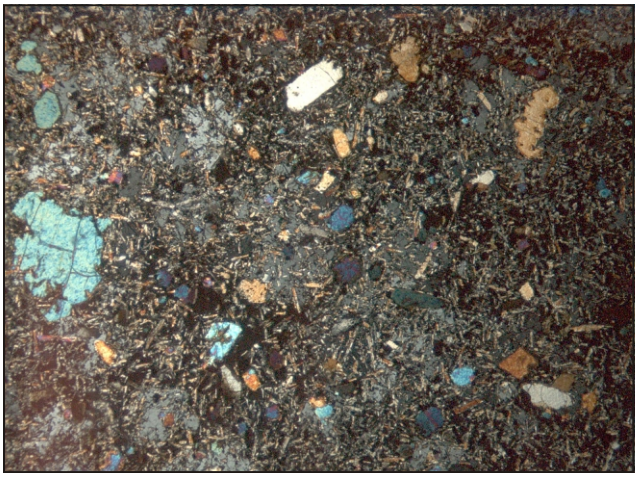


(b) Crossed nicols.

'Type 1' sample LSB4, showing very fine-grained groundmass with biotite flakes (brown), coarser clear nepheline segregations (left and lower right) and olivine phenocrysts and xenocrysts (e.g. right).



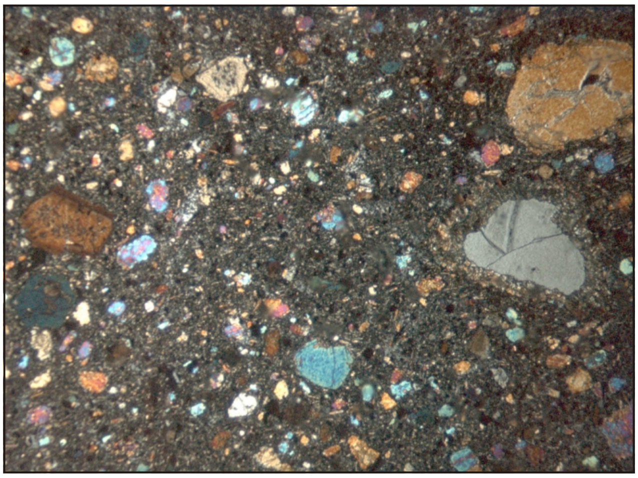
(c) Plane polarised light.



(d) Crossed nicols.

'Type 2' sample LSB99, showing olivine phenocrysts (e.g. left) in a poikilitic groundmass mainly of nepheline, clinopyroxene, magnetite and yellow-brown palagonite.

(e) Plane polarised light.

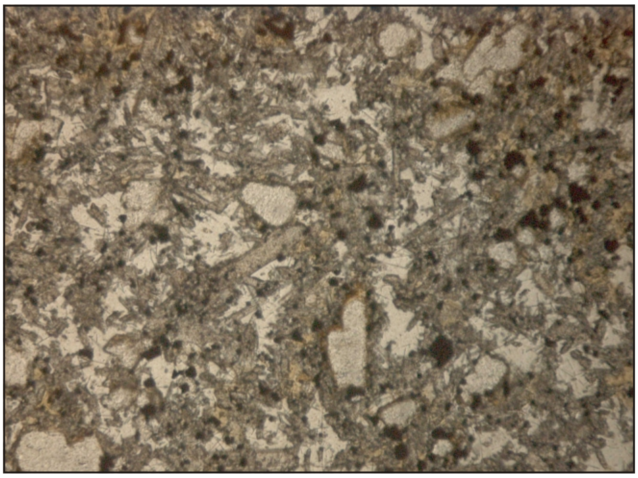


(f) Crossed nicols.

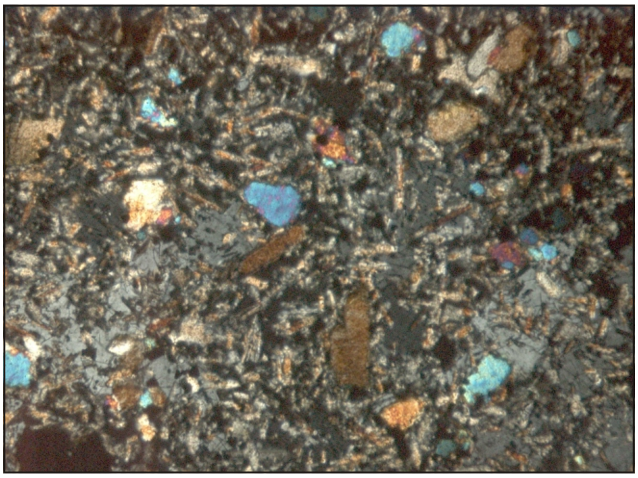
'Type 3' sample LSB93, showing xenocrysts of orthopyroxene with reaction corona (right) and olivine (upper right), phenocrysts of olivine (lower left) and titaniferous augite (lower left) in a very fine-grained groundmass.

Plate 2

Photomicrographs of Keach Hill basalt samples, all with field of view 4.5 × 3.4 mm.

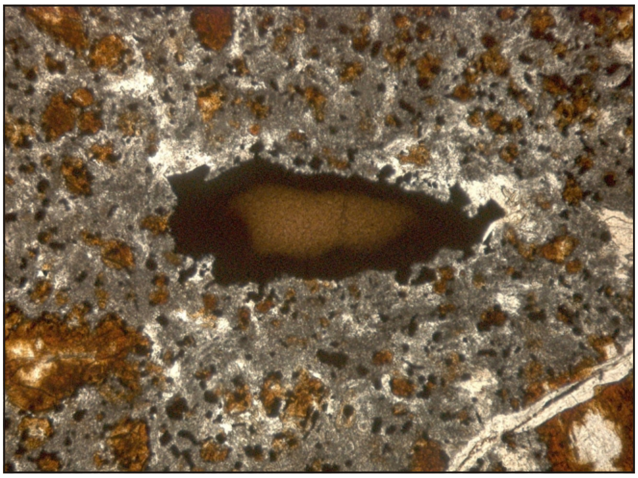


(a) Plane polarised light.

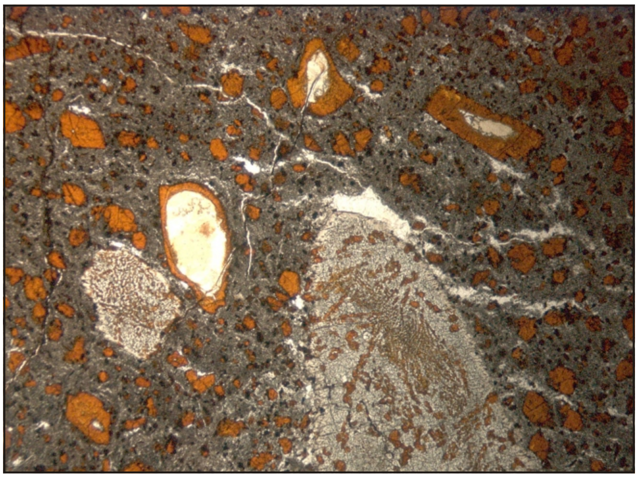


(b) Crossed nicols.

'Type 2' sample LSB99, showing olivine microphenocrysts in a groundmass of nepheline, poikilitically enclosing pinkish titaniferous augite granules and magnetite blebs. Field of view 730 × 550 μm.



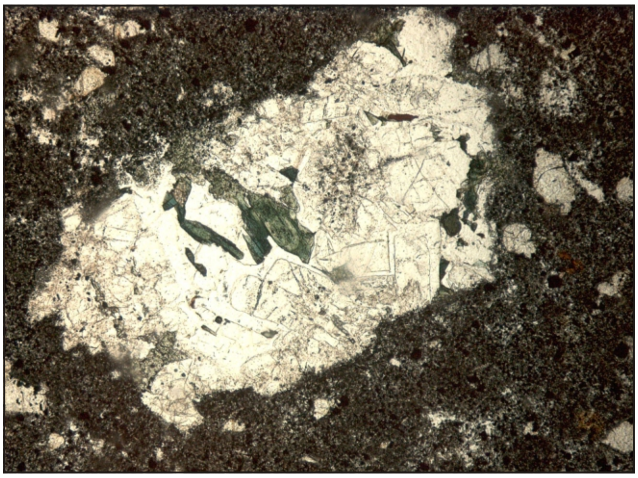
(c) 'Type 3' sample LSB90, showing xenocryst of brown spinel with opaque reaction rim and largely iddingsitised olivine granules, in a groundmass of very fine-grained clinopyroxene (grey), nepheline (clear) and magnetite. Field of view 4.5 × 3.4 mm, plane polarised light.

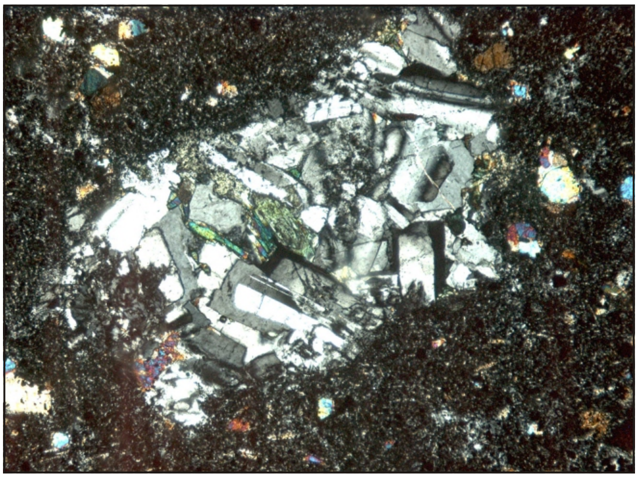


(d) Altered 'type 3' sample LSB94, showing sieve-textured xenocrysts of clinopyroxene with inclusions of iddingsitised olivine; xenocrysts of largely iddingsitised olivine, some with cores of pale yellow serpentine; and a groundmass of very fine-grained clinopyroxene and nepheline, with some clear 'stylolitic' veinlets of coarser nepheline. Field of view 730 × 550 μm, plane polarised light.

Plate 3

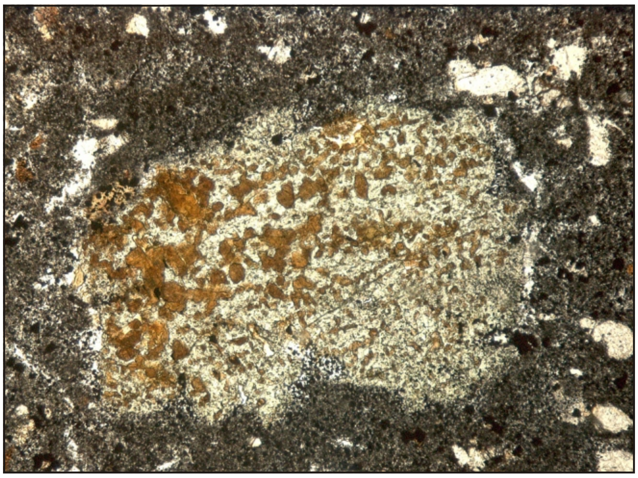
Photomicrographs of Keach Hill basalt samples.

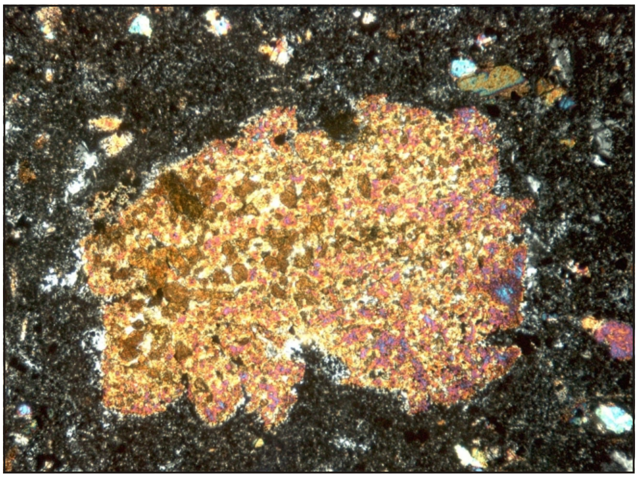




(a) Plane polarised light. *(b) Crossed nicols.*

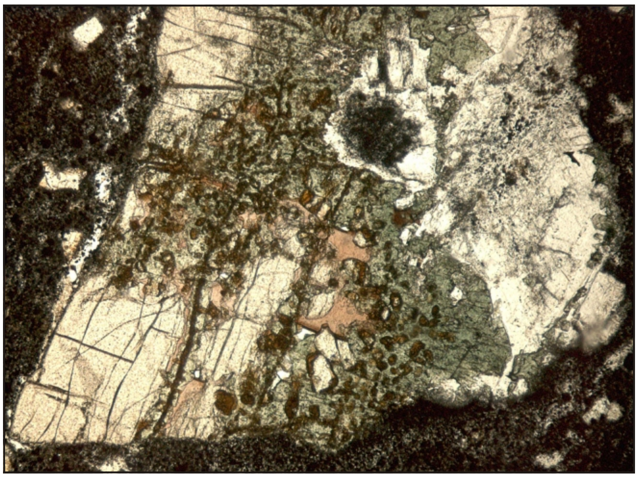
Inclusion of coarse-grained nepheline, potash feldspar and aegirine-augite (green).

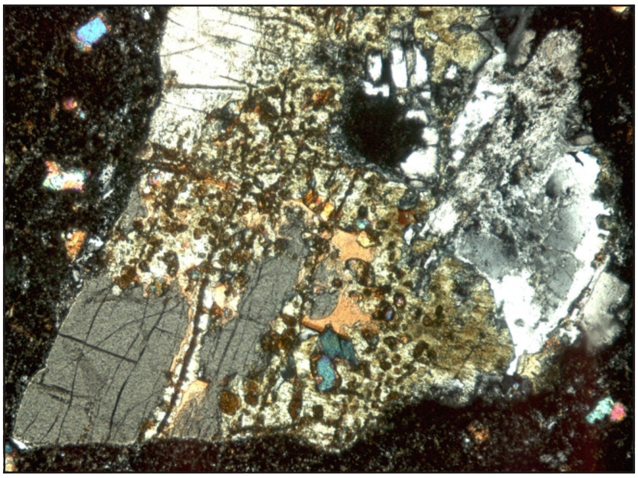




(c) Plane polarised light. *(d) Crossed nicols.*

Inclusion of aegirine-augite (green) poikilitically enclosing granules of iddingsitised olivine (brown).



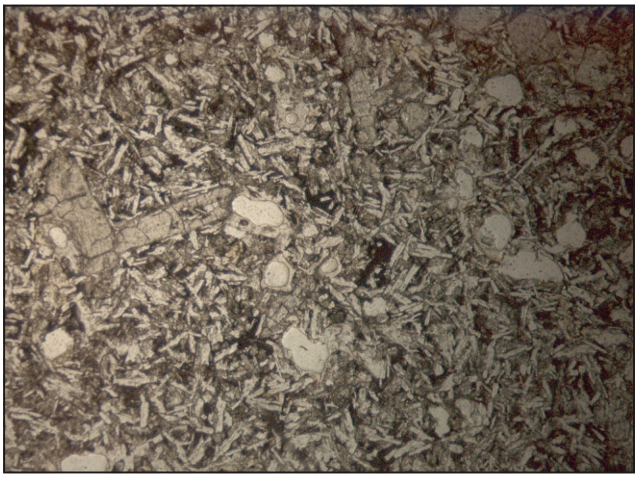


(e) Plane polarised light. *(f) Crossed nicols.*

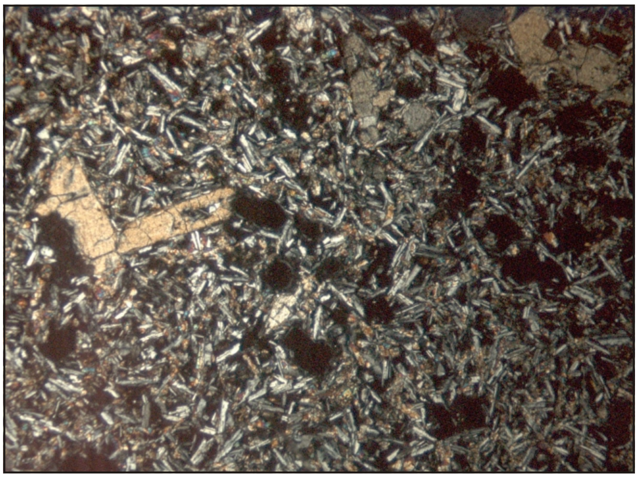
Composite inclusion of pigeonite (left), aegirine-augite (green) enclosing small olivine granules with dark altered rims, sodic amphibole? (pink) and calcic plagioclase partly replaced by potash feldspar (right).

Plate 4

Photomicrographs of inclusions in Keach Hill sample LSB4, all with field of view 730 × 550 μm.

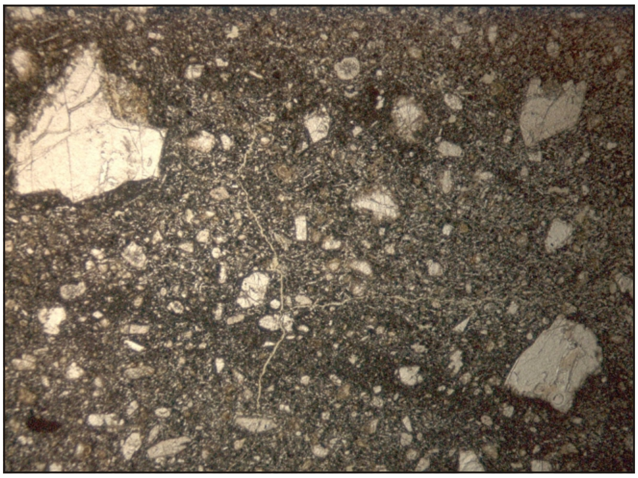


(a) Plane polarised light.

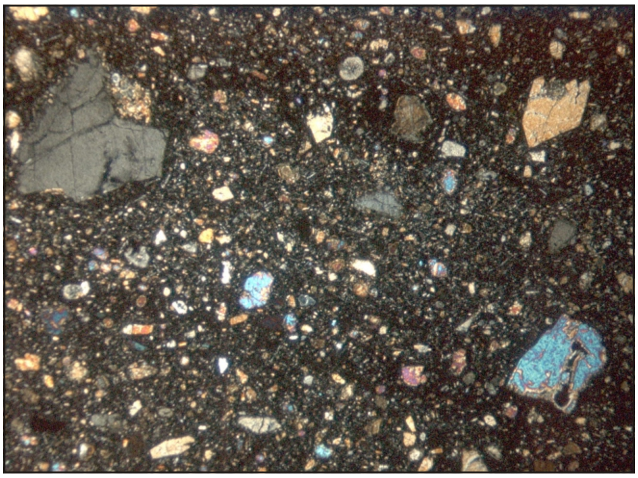


(b) Crossed nicols.

Tholeiitic basalt H276/15 m, showing orthopyroxene microphenocrysts (left, upper right) in intergranular groundmass of mainly plagioclase, clinopyroxene and void.



(c) Plane polarised light.



(d) Crossed nicols.

Nepheline hawaiite H275/51 m, showing olivine xenocrysts (upper left, lower right) and titaniferous augite phenocrysts (upper right) in a very fine-grained groundmass. Compare to plates 2e and 2f.

Plate 5

Photomicrographs of samples from Quorn Hall drill hole (H276), all with field of view 4.5 × 3.4 mm.