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Three long lava flows in north Queensland

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Abstract. The Kinrara, Toomba, and Undara basaltic lava flows are from 55 to 160 km long and range in age from 13 to 190 ka. The lavas were emplaced down low gradients (0.2° to 0.4°) with volumes ranging up to 30 km^3. They were not unusually hot at eruption (1130°-1160°) nor unusually fluid. Gentle topography controlled the flows, and shallow drainage lines captured them. Lava tubes operated in places, and some drained to form caves. Injection under surface crust was widespread, producing inflation features ranging from tumuli and low plateaus to extensive ridges. Sustained eruption was essential for the development of the long flows, but each is composite, with pauses between successive pulses that partially covered the earlier, longer flows. The lava structures are mainly pahoehoe but some 'a'a lavas are present. Of the three volcanoes involved, Undara is a simple low-angle lava cone with a 200-m-wide crater, Toomba is a low-angled cone with several eruption centers, and Kinrara has a deep crater with evidence of strong fountaining. Effusion rates are not known but may have been relatively low, similar to those observed in Hawaiian volcanoes. Lava tubes, most of which remained undrained, are believed to have been of major importance in flow emplacement. Given the evidence of successive flows and the time needed to develop widespread inflation, it is suggested that the two long flows over 100 km involved many decades of eruption.

1. Introduction

Cenozoic volcanic regions in north Queensland are part of a long belt in eastern Australia (Figure 1) (reviewed by *Johnson* [1989]). The north Queensland lava field provinces range in age from 8 Ma to Holocene, but earlier Cenozoic activity (from 45 Ma) also occurred in the region.

Four north Queensland provinces (McBride, Chudleigh, Sturgeon, and Nulla) contain a number of long basaltic lava flows (here, nominally over 50 km) that are up to 160 km long and were emplaced on very low gradients of < 0.5 °. Long lava flows such as these are of particular interest in considering many questions of flow behavior, and how flows can advance such great distances. Significant cooling down a flow is expected to increase lava viscosity with advancing crystallisation, leading to significant flow thickening, limiting continued advance down such low gradients. Insulation by flow through enclosed lava tubes is considered essential to produce such long flows.

The north Queensland flows are larger in volume and length than the well-documented historic flows from Hawaiian volcanoes and are more comparable to some Icelandic flows such as Laki. They are orders of magnitude smaller than flood basalt flows, such as those in the Columbia River province. Three of the long north Queensland flows, Undara, Toomba, and Kinrara, are discussed in this paper. Their areas and volumes, chemical compositions and inferred rheology, and morphological features (including vent structures and common flow features) are considered. Flow details are described which are interpreted to have formed by the common process of inflation, involving mobile melt beneath solidified crust. Unresolved questions of eruption rate are considered, relative to comparitively fast emplacement or much slower emplacement for these long flows, with their impressively gentle slopes.

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2. Geological Setting

2.1 Cenozoic Eastern Australian Volcanic Zone (EAVZ)

The Cenozoic Eastern Australian Volcanic Zone (EAVZ) extends 4000 km south from Torres Strait to Tasmania (Figure 1). It is up to 500 km wide and runs broadly parallel to the trend of the eastern Australian coastline. The zone is composed of a large number of well-defined areas of volcanic rocks, termed volcanic provinces. The EAVZ is distant from plate boundaries and is generally well inside the Indo-Australian plate (Figure 1). However, the zone almost reaches the New Guinea region where volcanism is close to the complex plate margin against the Pacific plate. Here volumes of volcanic materials increase and their petrological character changes [*Johnson et al.*, 1978; *Hamilton and Johnson*, 1984].

The total volume of the EAVZ is around 20,000 km^3. In area, the volcanism is more impressive. In north Queensland, for example, the total volcanic area of 23,000 km^2 comprises more than 10% of the region. Age determinations of volcanic activity in the EAVZ range from 70 Ma (late Cretaceous) to 4.3 ka (Holocene). Although the Cenozoic contains concentrated periods of sporadic volcanic activity, the EAVZ is marked by very long inactive intervals. Many individual provinces show activity over well-delineated time ranges. In others, volcanism has been sporadic, with intervals as long as 5 to 10 Ma between eruptive episodes.

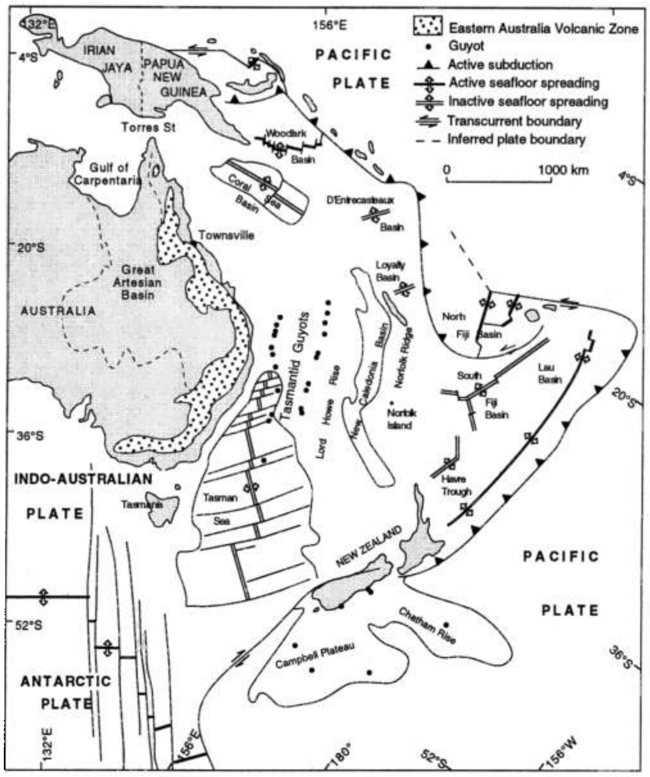

Figure 1. Generalised plate features, SW Pacific [redrawn from *Johnson*, 1989]. © Australian Academy of Science 1989, reprinted with the permission of Cambridge University Press.

Most of the provinces in the EAVZ occur either as predominantly mafic or as felsic-mafic associations. This compositional distinction parallels a volcano classification of *Wellman and McDougall* [1974], who characterized central-type as those containing significant amounts of felsic rocks, with lava field and high potassium types usually being exclusively mafic.

A number of origins have been proposed for the intraplate EAVZ volcanism. Hotspot models have been successful in accounting for a progression of ages in the central-type provinces of eastern Australia [*Wellman and McDougall,* 1974] and for the progression of volcanism in the off-shore Tasmantid and Lord Howe Seamount chains [*McDougall and Duncan,* 1988]. The context for the EAVZ mafic volcanism is more complicated. One paradox, for example, involves the youngest volcanism (less than 10 ka) having occurred at opposite ends of the EAVZ, in north Queensland and Victoria. *Sutherland* [this Issue] discusses the origin of the north Queensland volcanism. A general association between the EAVZ and uplifts of the highlands along the eastern regions of the Australian continent has been argued by many authors since *Taylor* [1911]. The uplift that formed the eastern highlands has been considered "to be a consequence of the lithospheric distension and detachment that preceded seafloor spreading in the Tasman and Coral Seas" [*Johnson*, 1989, p. 289]. The relationship between the uplift mechanism and the Cainozoic volcanism is discussed in detail by *Lister and Etheridge* [1989].

2.2. North Queensland Cenozoic Volcanic Provinces

There are 11 basaltic provinces north and inland from Townsville, as well as small outliers (Figure 2). The provinces range in age from 44 Ma to Holocene . The younger provinces are all lava field-type, delineated by continuous extrusives in which hundreds of monogenetic mafic volcanic centers occur. In each province, these centers occur within oval-shaped areas up to 80 km across. Two much older provinces (not shown on Figure 2) consist of isolated intrusive centers with no associated lavas preserved due to erosion. General characteristics of these volcanic areas are outlined by *Stephenson* [1989] and *Knutson* [1997].

Four provinces, McBride, Chudleigh, Sturgeon, and Nulla (Figure 2), contain 20 lava flows that are longer than 50 km. Three of these (Undara and Kinrara in the McBride province and Toomba in the Nulla province) are described in this paper. The four long flow provinces are mainly Pliocene in age, with the best preserved long flows being late Quaternary.

2.2.1. Physiography. Regions where the basaltic provinces occur have mild topographic relief. A coastal escarpment in north Queensland rises up to 500 m above a low coastal plain (10 to 100 km wide) and is part of the eastern Australian Great Escarpment [*Ollier*, 1982]. Behind this coastal escarpment, the country generally slopes towards the Burdekin River valley, a broad river basin which flows south, roughly parallel to the coast. West of the Burdekin, around 200 km from the coast, is the Great Divide (Figure 2). This is a broad, regional uplift watershed dividing drainage north west to the Gulf of Carpentaria and east to the coast.

The Great Divide uplifts formed prior to basalt eruption [*Wyatt and Webb*, 1970; *Stephenson and Coventry*, 1986] and

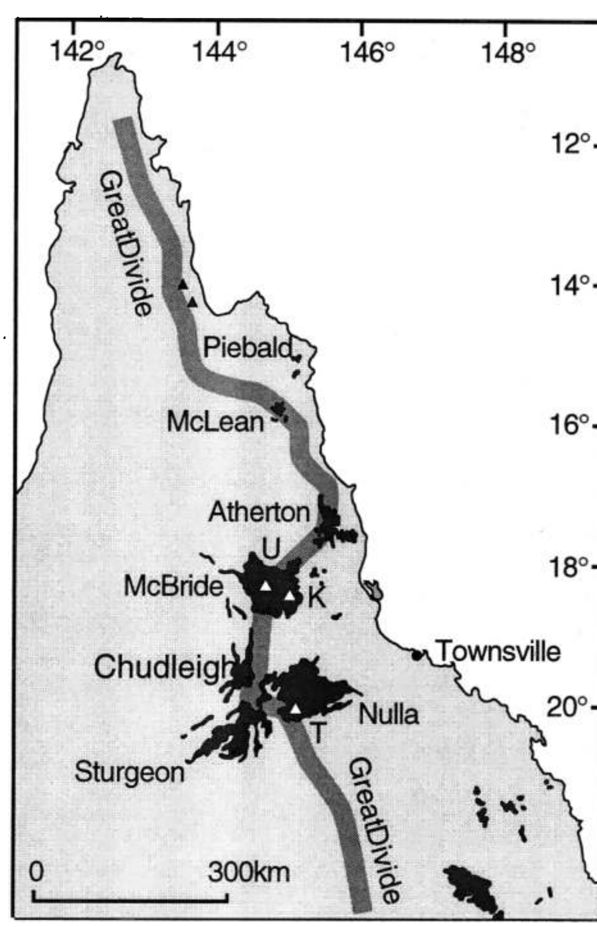

Figure 2. Cenozoic basaltic provinces in north Queensland (two older provinces not shown). U, K, and T indicate the location of the three long flows discussed.

Table 1. Summary Characteristics of Basalt Provinces in North Queensland With Long Flows

	Area, km^2	Volume,* km^3	Centers	Ages
McBride	5500	137	164	3 Ma-20 ka
Chudleigh	2000	50	46	8-0.2 Ma
Sturgeon	5000	125	50	5.8 - 0.9 Ma
Nulla	7500	187	46	5.2 Ma-13 ka

*Average thickness of 25 m assumed.

may have been related to underplating associated with plumes which were active in the later Tertiary. The uplifts are around 100 km across and rise up to 600 m. The "heads" of the plumes might be indicated by the volcanoes, which typically form oval-shaped areas 60 to 80 km long and 35 to 45 km across, in the center of each province. The Cenozoic volcanic provinces do not seem to have been focused by exposed structural boundaries and are not controlled by bedrock geology.

2.2.2. The Cenozoic volcanic provinces. Summary characteristics of four provinces in the Townsville-Ingham hinterland with long flows are given in Table 1. Long flows do not appear to have been developed in three other lavafield provinces in north Queensland (Piebald, McLean, Atherton).

These four provinces contain predominantly alkaline basalts (mostly hawaiites, defined normatively after *Johnson* [1989]), with less abundant alkali basalts and basanites, minor olivine tholeiites, and rare mafic phonolite. Xenoliths of mantle or lower crustal origin are common in some of the alkaline basalts but are virtually absent in the Nulla province. Aspects of the geochemistry and likely origin of the lavas are discussed by *Johnson* [1989], *O'Reilly and Zhang* [1995], and *Zhang et al.* [1996].

The volcanism formed broad constructional plateaus built of relatively thin lavas that flowed in radial directions down shallow drainages with low gradients. In a few cases, the long lavas reached and flowed down larger river courses, such as the Einasleigh and Burdekin rivers (Figures 3a and 3c). The volcanic centers produced unobtrusive low-angle lava cones, small pyroclastic volcanoes, and a few composite cones. In the Nulla province, there was very limited pyroclastic activity.

Age determinations (K/Ar) support field evidence indicating that eruptive activity was intermittent [*Stephenson* , 1989]. Individual monogenetic volcanoes were erupted within each province after long periods of dormancy (up to a million years). The resumed volcanism commonly produced lavas of similar compositions (e.g., Nulla province [*Holland and Stephenson*, 1996]. This recurring, intermittent cratonic volcanism raises interesting questions about the origin of the magmas and the short-lived eruption of lavas with significant volumes. Additionally, given their recurring eruptive history over several million years into the Holocene, the McBride and Nulla provinces are unlikely to be extinct.

3. Three Long Flows

Characteristics of three of the long lava flows are summarized in Table 2. Some details of these flows will be described and compared, generally in sequence, from Undara (the largest; McBride province), Toomba (Nulla province), to Kinrara (McBride province). The discussion will consider flow fields, petrography, lava surfaces, the nature of the source volcanoes, and evidence for successive flows. Estimates are given for the lava temperatures and viscosities. Evidence of widespread lava rises and ridges which have been formed by crustal inflation in each flow is described. Lava tubes have been recognized in each example, and their distributions are outlined. The emplacement of these long lavas are discussed in section 4, relative to these characteristics.

The three long flow lava fields are shown in Figure 3 and longitudinal profiles are shown in Figure 4. Each had a

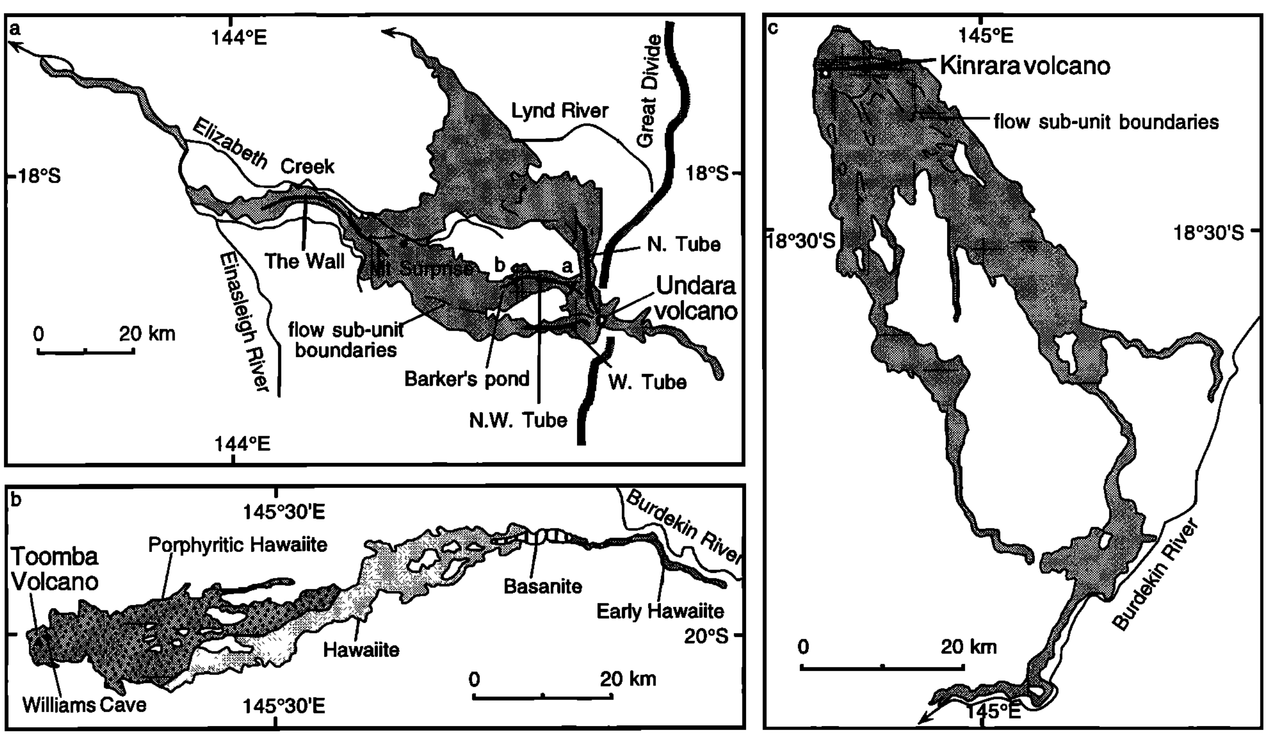

Figure 3. Flow outlines, three long flows, showing composite flow boundaries, based largely on work by *Griffin* [1977], *Burch* [1991], and *Stanton* [1993]: (a) Undara; (b) Kinrara; (c) Toomba.

Table 2. Summary Details of Three Long Flows

	Age,* ka	L, km	A, km^2	V, km^3	Slope	H/D	Cone, %
Undara	190	160	1510	30†	0.3°	0.02	2
Toomba	13	120	650	12	0.2°	0.02	6
Kinrara	20	55	200	1	0.4°	0.125	0.2

Slope is average from the volcano to the terminus of the flow; H/D is height of the volcano relative to the flow length; Cone percent is estimated volume relative to the whole flow [cf. *Rossi and Gundmundsson,* 1996].

*Undara age is by K/Ar. Toomba age is from ^{14}C analysis. Kinrara proved unsatisfactory for K/Ar age analysis, and 20 ka is an estimate.

†Undara volumes assume a nominal 20 m thickness; Toomba and Kinrara volumes were measured from better exposure evidence and topography.

complex history involving episodic emplacement of lavas of varied composition. The respective flow outlines have been delineated from field evidence, aerial photographic patterns and petrological differences. Episodic emplacement can be most easily demonstrated in Toomba, with petrographic contrasts between several different hawaiites, and a single basanite. Although Undara (hawaiite) and Kinrara (basanite) are more chemically uniform, some individual flows have been mapped, as shown in Figure 3.

3.1. Petrography

All flows were erupted at subliquidus temperatures, as indicated by the ubiquitous presence of olivine and plagioclase phenocrysts. Some of the lavas also contain pyroxene phenocrysts, and the phenocryst details provide a basis for estimating lava emplacement temperatures and viscosities (as discussed in section 3.4) and have potential for studying lava cooling. At Undara, although the great majority of lavas do not contain pyroxene phenocrysts, augite-phyric basalt occurs in a low central rise in the floor of the crater and on the crater rim. Surface crusts at Undara have been removed by erosion; however, quenched melt is preserved as glass inside the crater (in the final erupted material) and at Barker's pond (Figure 3), 28 km from the volcano. Most of the basalts exposed at the surface have intergranular to subophitic textures and had crystallized beneath lava crusts. The later flows at Toomba contain large plagioclase phenocrysts, accompanied by augite. In both the Toomba and Kinrara flows, glass is common within a few centimeters of the original lava surface, and a fine-grained mesostasis is present in the interior.

Some differences in petrographic textures down these long flows are evident, but details of crystal size variation await more detailed analysis. Interpretation of textures is limited by the fact that proximal specimens and distal specimens are not from the same flow unit. In the Toomba flow field, for example, only the final 20% of the length of the earliest lava flows has not been smothered by later flows. Undara is also likely to have proximal-distal nonequivalence, with studies also hindered by the effects of erosion (see above).

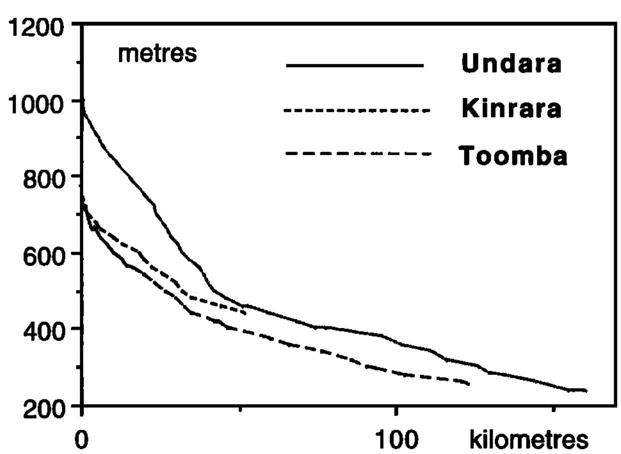

Figure 4. Topographic profiles down three long lava flows.

Segregation structures such as veins [*Kuno et al.*, 1957], vesicles [*Smith*, 1967], sills, and "pipes" are common in all the lavas. Here pipes are equivalent to vesicle cylinders [Goff, 1996] and pegmatoid autoliths [*Rogan et al.*, 1996]. Summary descriptions of different types of segregation structures from distal parts of the Toomba flow are given by *Spry and Stephenson* [1996]. In The Toomba flow, they are present only at depths below ~1 m. In contrast, pipes are found in surface outcrops in the Undara flow, implying erosion of at least 1 m of the flow surface.

3.2. Lava Surfaces

Lava surfaces are used in modern flows to distinguish between two fundamentally different lava emplacement modes (pahoehoe and 'a'a). No original surface structures are preserved on the Undara flow except on multiple flow units in some lava cave entrances and on some cave floors. Most show pahoehoe surface structures, with only rare 'a'a. Due to erosion, however, the usual Undara surface outcrops are composed of boulders in a thin stony regolith. On the Toomba and Kinrara flows, original flow surfaces are well preserved, although original thin glass skins were probably quickly lost. These young lavas show very little effect of weathering, except for discolouration of olivines and minor precipitation of secondary carbonate. The Toomba and Kinrara flows contain well-preserved ropy pahoehoe surface structures. Rubbly 'a'a surfaces can be found locally in the Toomba flow, to within 10 km of the flow terminus. These local 'a'a surfaces are usually transitional with the more common pahoehoe. 'A'a lavas occupy earlier flow areas within 10 km of the Toomba volcano, in low areas partly smothered by later pahoehoe flows. 'A'a is more extensive in the proximal areas of the Kinrara flow, most common within 20 km of the volcano, where they form discrete units emplaced as latestage channelled flows.

3.3. The Nature of the Volcanoes and Evidence for Successive Flows

Undara crater, on the crest of the Great Divide, is the only source volcano identified for the extensive Undara lava flow field. The summit region shows no evidence of pyroclastic material and forms a cone 425 m in diameter which rises only 10 to 40 m above the surrounding lava field. The summit crater is ~330 m across and 60 m deep. The crater wall exposes highly vesicular to massive basalt. Outcrops on parts of the rim show flow banding, highlighted by slight weathering differences. A bench halfway down the crater slope may indicate an interim lava lake level. The crater floor, ~190 m across, is covered by fine red soil, but there is a low topographic rise of porphyritic basalt in the center. Aerial photographs suggest lava overflow from several points around the rim, although these are not easily confirmed in outcrop. The Undara lavas flowed north, following the Lynd River drainage, west along the Einasleigh River drainage (reaching the river down Junction Creek) and a shorter distance east. The western flows went around high granitic bedrock inliers east of Mount Surprise (Figure 3a). Details of the flow succession in the Undara flow are uncertain, but the lavas containing the north tube appear to have been emplaced after the north west tube and associated lavas (Figure 8a).

The Toomba volcanic cone is a low-aspect composite structure built up by a number of effusion centers including low domes and short, possibly fissure-controlled vents trending approximately northwest. The volcano is 4 to 5 km across and 100 m high, with several small low-angle pyroclastic cones. Most of the volcanic edifice is built of plagioclase-phyric pahoehoe lavas (with localized 'a'a on some steeper slopes). Twenty large tumuli (up to 100 m across and 20 m high) occur at places around the cone; they formed by inflation and do not appear to have been lava conduits. Areas of contrasting, aphyric 'a'a lava lie in areas of slightly lower topography. As their edges are smothered by the main pahoehoe of the cone, they are interpreted to represent early lavas. No lava channels have been recognized anywhere on Toomba.

Field details of the Toomba composite flow are outlined on Figure 3. An early hawaiite flow reached the Burdekin River and flowed 10 km down it. Only 22 km of this early hawaiite is visible, because it was smothered by a chemically distinct basanite flow which, in turn, was largely covered by a later hawaiite flow. Farther up the composite flow, this hawaiite was succeeded by a strongly porphyritic hawaiite. Similar porphyritic lavas occur in much of the flow back to the volcano, but full geochemical details (not pursued here) suggest there are at least 10 distinguishable units making up Toomba [*Burch*, 1991]. At the Toomba volcano, some of the pyroclastic cones contain more fractionated basalt (e.g., Table 3, GCO5). Of the four successive flow types just referred to, each covered an earlier unit, but the flows are progressively shorter. It is suggested the later flows encountered more obstruction, having to flow over the previous ones, and because the later flows are more strongly porphyritic (in plagioclase and augite) and are likely to have been cooler and more viscous.

Kinrara volcano is well preserved. *Stanton* [1993] records the volcanic cone to be ~400 m in diameter, with a steep crater 300 m wide and 86 m deep. Parts of the cone are pyroclastic and lava fountains formed a spatter and reconstituted lava rim, with agglutinate lava flowing down the steep outer slopes. Kinrara contains an inner crater that cuts underlying older basalt, penetrating 16m below the level of the paleosoil horizon. A low spatter cone a kilometer north of the main crater is surrounded by lavas from the main crater. Within 20 km of the crater, the 'a'a lavas making up the cone pass downflow into more abundant pahoehoe. Kinrara lavas flowed mainly south east, reaching and following drainage lines around an older basalt inlier. Individual flow lobes join near Valley of Lagoons, where the lavas reached the Burdekin River and followed it for 15 km. Close to the crater are two well-developed lava channels, which are ~20 m wide and 5 to 10 m deep, with near-vertical sides and levee banks. The north east channel has sheet lava overflows 500 m from the volcano. Beyond this distance it formed lava rubble levees, eventually passing into 'a'a lava 4 km from the volcano.

The Undara and Toomba low-aspect cones (Table 2) show remarkable similarities to postglacial shield volcanoes in Iceland [*Rossi*, 1996]. Volumetrically, the two north Queensland cones comprise about 2% and 6% of the total flow volumes, compared with the 1-3% in Iceland [*Rossi and*

Table 3. Examples of Chemical Analyses

	Undara Crater Lip	Distal Undara (143 km)	Toomba Volcano Bomb	Toomba Hawaiite post Basanite	Toomba Basanite (81 km)	Toomba Terminus (120 km)	Toomba Distal Glass (118 km)	Kinrara Crater	Distal Kinrara (40 km)
	U31	TAL3	GCO5	FVL9	FVL8	FVend	34289	C1	S12
SiO_2	47.8	47.01	47.6	46.40	43.00	47.90	50.58	46.1	46.84
TiO_2	1.86	1.8	2.08	2.03	2.06	2.09	2.61	1.81	1.72
Al_2O_3	15.6	15.99	16.5	15.20	14.60	15.23	16.89	15.09	15.35
FE_2O_3	10.89	11.7	10.74	11.50	12.89	11.22	9.35	11.07	11.07
MnO	0.15	0.16	0.15	0.16	0.20	0.16	0.15	0.15	0.15
MgO	7.88	7.59	6.74	9.29	8.74	9.12	4.48	8.12	8.55
CaO	8.94	8.16	8.21	8.02	9.07	7.91	8.9	8.33	7.98
Na_2O_3	4.37	3.94	4.49	4.11	5.28	3.48	4.77	4.27	3.59
K_2O	1.89	1.91	2.23	2.07	2.30	1.90	2.59	2.05	1.82
P_2O_5	0.68	0.62	0.61	0.63	1.46	0.52	0.66	0.71	0.61
X, %	14	(11)	25	(12)	(10)	19	20	9	8
T	1140C	1150C	1140C	1150C	1150C	1150C	1140C	1150C	1150C
Visc	72	80	154	53	12	172	210	53	105

Whole rock analyses by XRF, fused discs. The Toomba distal glass composition (34289) was from nine spots analyzed by wavelength-dispersive probe. This glass is the residual melt composition in a lava with a bulk composition closely similar to the listed specimen FVend. X % is measured phenocryst percent (values in parenthesis are surmised). T is the temperature used to calculate viscosity (Pa s), corrected for X% phenocrysts using data of *Pinkerton and Stevenson* [1992].

Gudmundsson, 1996]. The Kinrara cone is much steeper, and its cone volume is much smaller, comprising around 0.2% of the total flow volume.

3.4. Lava Temperatures and Likely Viscosities

The physical nature of lavas is important for understanding their flow behavior. Two critical properties are paramount. temperature and fluidity.

3.4.1. Temperatures. Mineral parageneses have been interpreted from thin sections, and temperatures were modeled from analyzed wholerock major element compositions using the thermodynamic model, "Melts" [*Ghiorso and Sack*, 1995]. The model conditions used involved QFM fugacity and evolving crystallization with fractionation. The results correctly predict the textural sequence found in thin sections (olivine, plagioclase, clinopyroxene, magnetite). Chemical analyses are listed in Table 3, and paragenesis examples for distal samples from each flow are given in Figure 5, which also shows the measured mineral abundances. The presence of olivine phenocrysts and minor plagioclase suggests the general temperatures in most of the lavas from each of the three flows were ~1150°C. The volcano rim lavas at Undara and the flows at and near the Toomba volcano contain pyroxene phenocrysts in addition to olivine and plagioclase and paragenesis models suggest cooler temperatures (20° to 30° cooler). However, the model crystal contents at such temperatures are twice the phenocryst modes measured in these rocks.

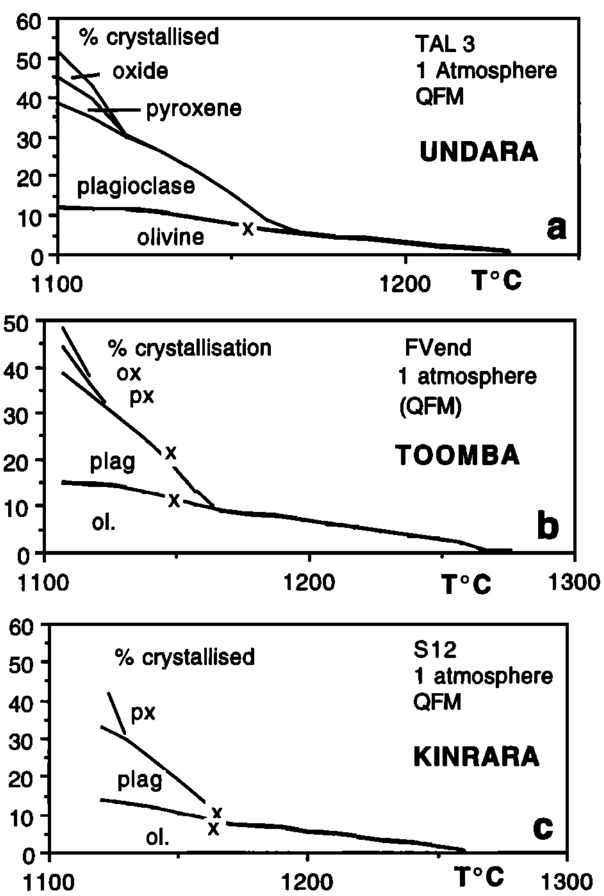

Figure 5. Models for crystallization using "Melts" [*Ghiorso and Sack*, 1995] of three long flow distal compositions: TAL3 (Undara, 143 km); BB1 (Toomba, 119 km); and S12 (Kinrara, 40 km). The points marked by crosses show measured modes (for TAL3, early plagioclase could not be distinguished in the intergranular texture).

In those specimens which contain abundant glass, the composition of this quenched melt is capable of providing a model (liquidus) emplacement temperature. Ten Toomba glasses, from different hawaiites and from the basanite, were analyzed by energy dispersion microprobe analysis (three spots), from various places from the volcano to near the flow terminus. The liquidus temperatures calculated for these glasses (using Melts) range from 1130° to 1155°C and their scatter does not appear to confirm higher temperatures closer to the volcano. Because earlier units have been smothered by later ones, it was not possible to trace relative temperatures down any one flow unit. In general, parallel to the work of *Ho and Cashman* [1997] on the 500-km-long Ginkgo flow in the Columbia River Basalt Group, the shorter Toomba flow appears to show little cooling (if any) down its length. Five other Toomba specimens gave temperature results from 1200° to 1300°C, affected by presumed alteration of the glass. The composition of a distal Toomba glass crust (34289), 116 km from the volcano, was analyzed by wavelength-dispersive electron microprobe analysis (School of Oceanography and Earth Sciences, University of Hawaii; nine spots). The liquidus for this composition indicated by Melts is 1153°C and its calculated viscosity, after adjustment for the measured 20% crystal content, is 151 Pa s (Table 3).

3.4.2. Viscosities. Viscosities were calculated from the whole rock compositions. The residual melt compositions were modeled at the temperatures stated in Table 3, with the Melts thermodynamic crystallization program [*Ghiorso and Sack*, 1995]. Viscosities for these residual compositions were calculated using data of *Shaw*[1972], and corrected for the measured crystal content [after Pinkerton and Stevenson, 1992]. Lower temperatures were used for two compositions (Undara volcano and Toomba volcano) because of the presence of pyroxene phenocrysts in the rocks. All the viscosity results are comparable with experimental measurements reported for basalts [*Ryan and Blevins*, 1987] and examples quoted by *Keszthelyi and Pieri* [1993]. Within the limitations of the data, the log flows described do not seem to show the temperature decreases and large viscosity increases that accompany emplacement of channelled flows [e.g., *Crisp et al.*, 1994].

3.5. Lava Rises and Ridges

The recognition of inflation features [*Walker*, 1991,*Hon et al.* 1994] in lavas is important in the context of flow emplacement because it involves the development of an insulating crust with moving melt flowing beneath it. The mobile melt beneath the solidified crust can jack up the crust, leading to considerable thickening (>10) of the flow. In each of the flow fields, such lava features are abundant and are distinctive on aerial photographs (Figure 6). A variety of inflation features are usually developed, including tumuli (local mounds rising up to 10 m or higher above the flow field), more extensive plateau rises, and ridge structures. These positive topographic features are typically gashed by gaping fractures ("clefts," up to 4 m across and 8 m deep) which are well-preserved in the younger Toomba and Kinrara flows.

Lava rises can be recognized in numerous places in the Undara flow. Although the original lava surfaces have been

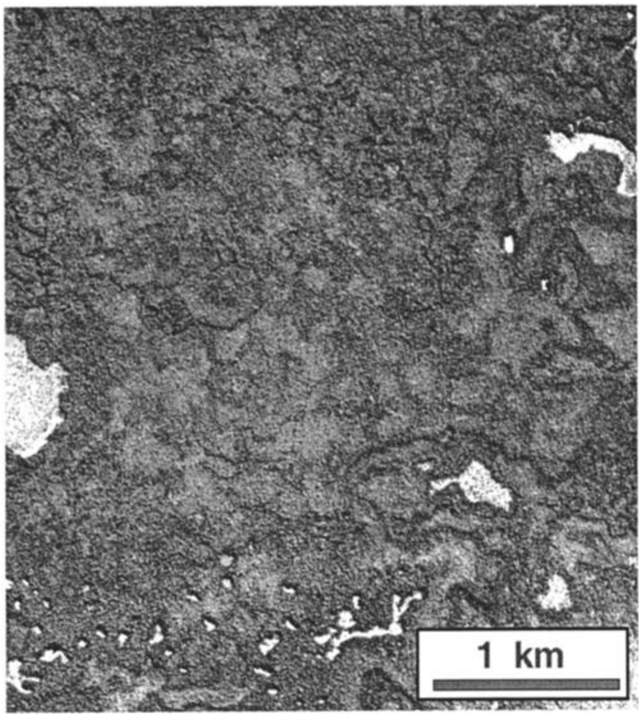

Figure 6. Aerial photograph showing lava rise patterns with edges emphasized by vegetation contrasts, Toomba flow, 35 km from the volcano. Left and right corner, older basalt kapukas. Lower left corner, flow edge. The lower chain of smaller white areas is lava pits dusted with diatom sediment. Upper right depression with diatom sediment (Lolworth, run 2, 119, 1991).

considerably eroded, their residual shapes preserve structures similar to inflation features in the Toomba and Kinrara flows. Undara rises are usually less pronounced than those in the Toomba flow, with typical heights being up to 5 m. This is assumed to be a primary feature of the Undara flows, even though erosion has softened and lowered the relief. However, Undara does have an unusual ridge 40 km long, north and west of Mount Surprise known as "The Wall" (Figures 3 and 7). It rises up to 20 m above the adjacent sheet flows and is typically 200 m wide, forming a nearly flat-topped ridge with a pattern mimicking the nearby course of Junction Creek. Typical crosssections are shown on Figure 7. In places, the top of The Wall has shallow longitudinal furrows up to 10 m wide and numerous oval-shaped depressions up to 100 m across. Lava fields, up to several kilometers wide, occur adjacent to the Wall in places [*Stephenson and Whitehead*, 1996; also noted by *Harris*, 1996].

An origin by inflation can be suggested for The Wall, analogous with the distal inflation ridges in the Toomba flow [*Whitehead and Stephenson*, this issue]. The Wall ridge developed above a 300-m-wide tube localized over the former course of Junction Creek. *Atkinson et al.* [1975] and *Atkinson and Atkinson* [1995] drew special attention to The Wall, emphasizing similarities with sinuous features on the Moon. *Atkinson* [1988] interpreted The Wall to have formed by the growth of lava levees but raised the possibility of tube inflation. *Harris* [1996] discussed an inflation origin for The Wall, comparing it with Martian sinuous ridges. Softening of the topography by erosion makes it difficult to distinguish between alternative collapse or inflation pit origins for the oval depressions mentioned above. The longitudinal furrows referred to may represent inflation clefts, filled by wall collapse and weathering. Possible lava inflation pits have been recognized elsewhere in the Undara lava field, alongside lines of lava tube caves.

In the Toomba flow, a wide variety of lava rise features are developed throughout the flow and rise to 20 m above adjacent lava surfaces. Tumuli are common on the proximal edifice and typically show lava breakouts from axial clefts. Numerous tumuli are present farther down the flow, but here breakouts are uncommon. The distal Toomba inflation ridges (up to 10 km long) are described by *Whitehead and Stephenson* [this issue]. Large depressions are common, and examples 30 to 40 km down the flow from the Toomba volcano are described by *Stephenson and Whitehead* [1996], up to 100 m across and 18 m deep. They have well-developed clefts up to 4 m across and 8 m deep near their edges. Some of the depressions have flat floors with pahoehoe lava patterns that can be traced up their flanks. They are interpreted as lava inflation pits [*Walker*, 1991], formed where inflation surrounded an area which retained the original lava level.

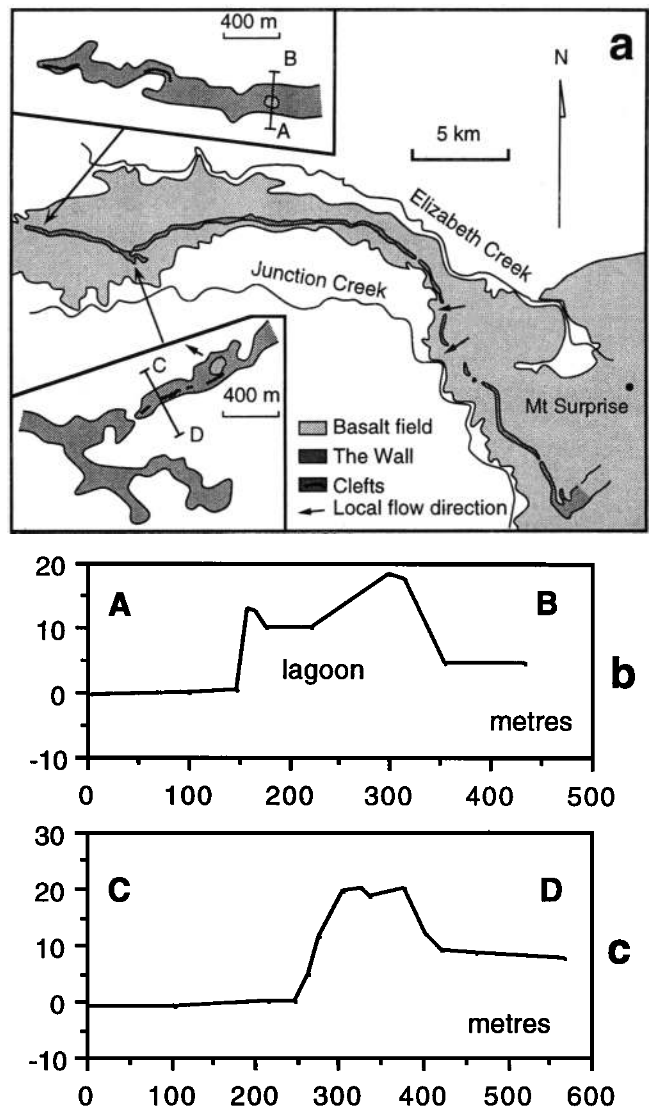

Figure 7. (a) The Wall, Undara (location see Figure 3a). (b) Topographic profile AB. (c) Topographic profile CD.

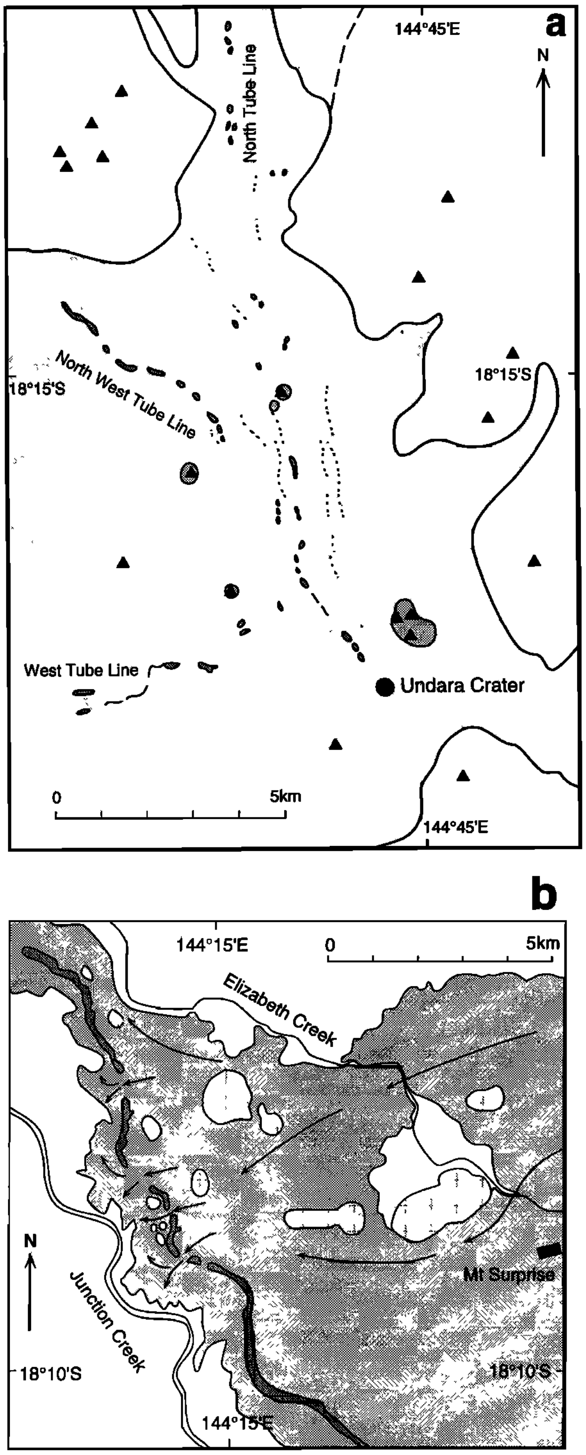

Figure 8. (a) Patterns indicating that the north Undara tube line was established after the north west line (based on aerial photo interpretation). The map shows the tube lines indicated by depressions and vegetation patterns (tube caves are not shown but are located close to the line of depressions). The Undara lava field is shaded and the small triangles show older volcanoes. (b) Sketch map showing the Undara Wall, west of Mount Surprise, and the low saddles in it where later lavas banked against the east side of The Wall have poured across it. These lavas were probably fed by the north Undara tube flow, past Mount Surprise. In this area, the lavas flowed around the granite hills shown. The Undara lavas today occur between Elizabeth Creek and Junction Creek, which have extensively eroded the edges of the lava field.

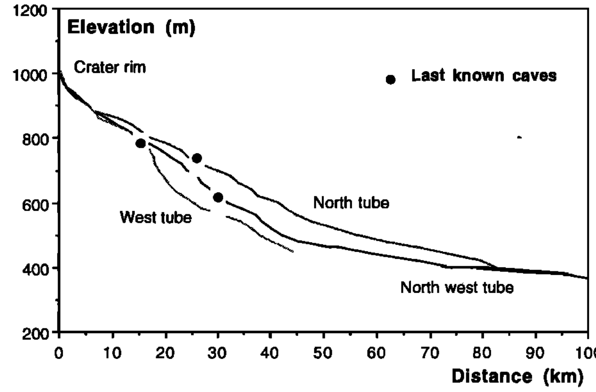

Figure 9. Lava surface topographic profiles down three Undara lava tubes.

Inflation structures are also common in the middle and distal parts of the Kinrara flow, particularly in the central zone where lava flowed into a broad topographic depression and stagnated during a period of inflation. Although inflation ridges are present in the distal flow fields, they are not developed as distinctively as those described above in the other long flows. It is noteworthy that the average thickness of the Kinrara lava field, 5 m, is considerably less than that of the other flows (18 to 20 m).

3.6. Lava Tubes

The importance of lava tubes has long been recognized in relation to flow emplacement, as tubes provide efficient insulation of flowing lava. The most familiar tubes are those which drained, leaving accessible tunnel-like caves up to 20 m across which are common in some steeper near-vent lava fields and in some moderately inclined lava fields. Undrained tube systems more than 10 times wider than such visible caves can be interpreted, especially in association with some well-defined lava rise ridge features. More irregular lava inflation patterns (e.g., those depicted in Figure 6) indicate the former presence of a complex of connecting tubes.

Undara has three well-developed tube systems, indicated by aligned lava caves and depressions (Figures 3 and 8). The main north west line of such features maintains an apparently continuous course with numerous drained caves over a distance of 30 km [*Atkinson et al.*, 1975; *Atkinson and Atkinson*, 1995]. Many of these classic, large caves are close enough to one another to suggest that they were parts of the same conduit system. Although the spacing between other caves is much greater and direct connection has not been established, their close alignment and the associated line of depressions also support the concept of an active, single north west tube system. A line of depressions continues beyond the last known cave (Barkers Cave, adjacent to Barkers pond shown in Figure 3), and it is likely that a tube continued farther west from this point but did not drain. Aerial photograph patterns indicate that the north lava tube from Undara was formed later than the north west tube (Figure 8a). This timing is confirmed where the north flow, at 70 km from the volcano, was dammed by The Wall and can be seen to have poured through saddles (Figure 8b).

The tube lines can be considered in relation to the gradient required for draining, 0.5°, as argued by *Hatheway and Herring* [1970]. Surface profiles down the three Undara lava tube lines are shown in Figure 9. The slope of the north west line averages 0.7° for 30 km from the volcano, consistent with draining to develop the caves. Barker's Cave (adjacent to Barker's pond, Figure 3a) is in this tube line and has a surveyed slope of 1.1° over 600 m after an initial, steeper entrance. The north tube line has a lower gradient (0.7° declining to 0.5°) and fewer caves. The west tube line has an initial gradient of 0.8° but also has only a few, drained caves. The steeper slopes of the drained tubes are consistent with *Hatheway and Herring* [1970], though the last caves occur before the breaks in slope. Unknown, inaccessible caves could be present.

Topographic cross sections surveyed across the Undara flow field show that the north west tube axis line occurs near the crest of a broad ridge that is up to 2 km across and 6 m high (Figure 10). While the origin of this ridge is unconfirmed, it is possible that progressive lava buildup may have resulted from repeated crust breakouts from the main lava stream, accompanied by local inflation. No lava channels are now evident. Recognizable lava rises are common, but in many places, the tube caves are located adjacent to them and do not appear to be directly related. These relationships suggest that the lava tube now indicated by the chain of drained lava caves was developed late in the flow's evolution. The entrances to many caves show up to five successive flow units with pahoehoe surfaces. The caves, with ceilings up to 20 m above the floors, were eroded through the lower units which are commonly concealed by tube wall lining. The caves contain well-developed lava level lines which may have been produced by advancing tube erosion, rather than by fluctuating lava depths. *Kauahikaua et al.* [this issue] have recorded details of progressive erosion in active Hawaiian lava tubes.

Toomba has several caves within 4 km of the volcano (Figure 3a), including the interesting Williams cave which developed three tube levels. Caves, as drained lava tubes, do not appear to have developed in the main part of the flow, presumably because any operating tubes did not drain due to the low gradients (0.4°, decreasing to 0.1°), less than the required 0.5° [*Hatheway and Herring*, 1970].

Kinrara also has a complex system of drained lava tubes located up to 6 km from the volcano [*Stanton*, 1993]. These lava caves have a typical height of 8 m and have very well preserved flow features. Below the steep volcano, slopes decrease from 0.75 to 0.5 and are lower beyond ~8 km.

4. Emplacement of the Long North Queensland Flows

The three examples described are unusually long flows emplaced down very low topographic gradients (Figure 4). Some earlier concepts of important factors accounting for lava length [e.g., *Walker* , 1973; *Stephenson and Griffin*, 1976] need to be reconsidered. *Walker* 1973] had suggested that unusual length was favored by high effusion rates. A rate of 1000 m^3 s^{-1} might be extrapolated for Undara from his data, which would imply emplacement in ~1 year.

Keszthelyi and Pieri 1993] questioned high effusion rates for the long Carrizozo flow in New Mexico and argued that the structures and lava slopes in this flow were closely similar to those developed in low effusion rate Hawaiian sheet flows. The present work would likewise suggest low effusion rate for Undara and Toomba. With its well-developed fountaining, lava channels, and relatively more common 'a'a lava, Kinrara may have involved relatively higher effusion rates than Undara and Toomba [cf. *Rowland and Walker*, 1990]. However, its middle

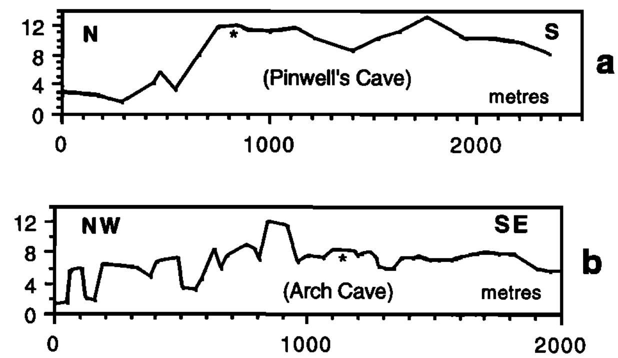

Figure 10. Topographic profiles across the north west Undara lava flow: (a) Pinwell's Cave (11 km from the crater); (b) Arch Cave (22 km from crater). The Undara basalt edges occur at the ends of the Pinwell profile, at the NW end and 3 km beyond the SE end of the Arch profile. Profile locations are shown on Figure 3a.

and distal lava fields have similarities to those of Toomba, and an initial period of high effusion may have been followed by sustained low effusion rates.

A number of influences are believed to have favored the long flow developments:

- Continued eruption occurred of relatively large lava volumes. Although the lavas were not unusually hot, their viscosities were typical of many basalt melts at the temperatures estimated.
- Although the topographic gradients were low, around 0.2°-0.4°, they were sufficient for the flows to progress. Flows followed the existing drainage, and the environment provided favorable circumstances for unhindered flow, with open vegetation and sandy stream and river courses. From the absence of water interaction structures in the lavas, such as pillows, hyaloclastites or contemporary water injection, the larger rivers followed by the flows (Burdekin and Einasleigh) must have contained low water levels at the time, typical of the present long dry seasons.
- The importance of lava tube mechanisms for insulated transportation of hot fluid lava has been emphasised by many authors [e.g., *Greeley*, 1987]. In agreement, it is emphasized that major lava supply in the north Queensland long flows was advanced along insulated conduit systems, some of which were up to an order of magnitude wider than familiar drained lava tubes. This influence is related to the first (above), tube system stability being related to the steadiness of eruption [e.g., *Guest et al.*, 1987; *Kauahikaua et al.*, this issue].
- It is possible that flow advance was sustained by repeated breakouts from static flow fronts. Some local breakouts can be recognized in the Toomba and Kinrara flows but are conjectural for Undara.
- A considerable fraction of the lava volumes involved inflation. Numerous lava rises can be identified on air photographs, and by counting their local abundance over different parts of the Toomba and Kinrara flows (see Figure 6), it is estimated that many hundreds were formed. Similar patterns can be recognized over parts of the older Undara flow, but only vestigial residuals can be recognized in outcrop because of considerable erosion. On the Toomba flow, most of the lava rises were probably developed sequentially, and the time likely to have been involved for each was appreciable. The thickest vesicular crusts observed on Toomba lava rises are

up to 3m, indicating ~60 days formation time, from *Hon et al.* [1994, equation (1)]. They appear to be equivalent to those detailed in inflated flows in Hawaii by *Cashman and Kauahikaua* [1997]. The full depth of inflation clefts at Toomba is obscured by fallen rocks, but they have been observed to range up to 8 m. Using the crustal cooling model given by *Hon et al.* [1994, equation (2)], this estimates local inflation could have involved 15 months. Similar crust thicknesses, around 3 m, can be inferred from outcrops in the Undara flow, near the west end of The Wall, described earlier. Inflation structures are developed in the middle and distal parts of the Kinrara lava fields, but their details have not been measured.

In the case of the Toomba flow, it is important to distinguish between the emplacement of each flow unit and the development of the entire flow field, which is made up of at least four petrographically distinguishable flow units. Mapped outcrop evidence indicates that each unit was erupted in succession and smothered the previous units. The flow lengths of each of the recognizable petrographic units are progressively shorter, and the volume of each successive flow probably declined.

The historic Laki lava field [*Thordarson and Self*, 1993] has a volume similar to the total Toomba flow. Laki was emplaced from a 27-km-long vent complex in the very short period of 8 months. In its short eruptive history, Laki had 10 eruptive episodes, with a tephra volume of 2.6% of the total erupted, and associated lava surges. The lava has a complex association of features ranging from pahoehoe-like to 'a'a -like surfaces, and lava channels and tubes are common in all areas (proximal to distal) [*Thordarson and Self*, 1993]. In the case of Undara and Toomba, successive lava units were involved in each, with characteristic inflated pahoehoe structure. It is considered likely that the emplacement time of each of these lava units involved years or tens of years. It is argued that these sheet lava fields could have developed in a similar way to those recorded in Hawaii by *Mattox et al.* [1993], with inflation rates similar to those measured there by *Hon et al.* [1994].

5. Models for Flow Emplacement

Several mathematical models have been described to account for flow emplacement. The channel-fed model of *Pinkerton and Wilson* [1994] is capable of providing typical flow lengths for the three north Queensland flows, even for low effusion rates (10 to 15 m^3 s^{-1}). However, such model estimations of potential flow length are invalid because of the different flow conditions. The only flow which is partly appropriate for that model is Kinrara, which is channelled near the volcano.

Effusion rates remain conjectural for the north Queensland long flows. By comparison with Hawaiian lavas, nominal effusion rates can be considered [*Rowland and Walker*, 1990]. Assuming such a rate of 10 m^3 s^{-1} the emplacement times for the early stages of the Undara flow (main NW tube system, The Wall, terminal section; 12 km^3) would be 38 years. For Toomba, the emplacement time for the 4 km^3 early unit, which reached and flowed down the Burdekin River, would have been around 12 years. The emplacement period for the complete flows in each case, at this assumed nominal effusion rate, would have been longer again, especially if long pauses in eruption occurred between units (we are not aware of any firm evidence concerning this question). For a nominal, faster effusion rate of 20 m^3 s^{-1} at Kinrara, emplacement might have occurred in up to a few years.

Cooling of slow effusion flows raises major questions, and lava transport in tubes is generally required to insulate the flows. *Keszthelyi* [1995] modeled the thermal budget for lava tubes and concluded that very long lava flows of many hundreds of kilometers can be produced with effusion rates of the order of 20-100 m^3 s^{-1}. He suggested long flows do not require high effusion rates if the flows are tube-fed. *Sakimoto and Zuber* [this issue] also consider flow and cooling in long basaltic lava tube flows. Their model offers an explanation for the apparently very low cooling which characterizes these long basaltic lava flows. They suggest cooling of only 20°C to 30°C over such distances for circular tube and parallel plate flow models under conditions involving entrance temperatures of 1160° and wall temperatures of 1130°. They authors found that cooling is not especially sensitive to low effusion rates, such as those preferred in the present paper.

All three flows considered here show clear evidence of lava tube systems. Undara lavas contain three extensive lava tube systems with drained caves in the north west tube line occurring up to 30 km from the crater. Lava pits occur for a farther 20 km toward Mount. Surprise, and the 40 km-long ridge comprising The Wall continues beyond. These pit and ridge features are believed to have developed above a wide subcrustal tube system. The remaining 60 km of the Undara flow contains inflation structures, but no further pits or ridges are known. Lava tube caves have only been found within 5 km of the Toomba volcano, but tubes are likely to have remained undrained farther down. *Whitehead and Stephenson* [this issue] found evidence from inflation structures near the Burdekin River for wide subcrustal lava conduits which are an order of magnitude wider than any known drained tubes. At Kinrara, channels can be found up to 8 km from the volcano, but strongly channelled flows with lava overflows are confined to within 6 km of the volcano [*Stanton* , 1993]. Beyond this distance channel levees occur, composed of rubble. In nearby areas of the lava field, a number of drained tubes have been found within 6 km of the volcano. No drained tubes have been found in the distal parts of the flow, but the presence of lava rises indicates tube-fed flows.

6. Summary and Conclusions

The three long basaltic lava flows described are up to 160 km long and are compound, built up of successive flows. They are intermediate in length between Hawaiian lavas and the far larger flood basalts such as the Columbia River Basalts. The lavas were emplaced on very low slopes, averaging 0.2° to 0.4°. Two volcanoes, Undara and Toomba, are inconspicuous "Icelandic" lava shields, whereas the third, Kinrara, has a steeper pyroclastic cone with a deep crater and two lava channels. Thicknesses of the lava shield flows are similar, near an average 20 m, whereas the shorter, slightly steeper flow from Kinrara is only 5 m. The lavas are fairly similar chemically. Estimated lava temperatures are around 1150°C, and viscosities are estimated to have ranged from around 50 to 210 Pa s. Evidence suggests temperature down the flows did not fall more than about 20°. Lava surface structures are predominantly pahoehoe, with more extensive 'a'a in the Kinrara flow. Extensive lava tube systems are evident from the presence of drained caves near the volcanoes, especially at Undara. Inflation structures are widespread including examples up to 20 m high at Undara and Toomba, which indicate extensive undrained emplacement tube systems.

These low-slope flows have many close similarities to the coastal sheet flows which occur in Hawaii. The flows all appear to have formed as tube-fed flows, but the tubes involved were generally much larger than any of those tube examples familiar as drained caves. From their similarity to certain well-documented low-slope, low-effusion lavas in Hawaii, it is proposed the extensive lava fields of Undara and Toomba could have developed from periods of sustained eruption involving low effusion rates, perhaps as low as 10 m^3 s^{-1}. Kinrara may have involved higher effusion rates. Recent cooling models appear to account well for these long lava flow characteristics.

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