The Regional Context of the McBride Basalt Province and the Formation of the Undara Lava Flows, Tubes, Rises and Depressions

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Abstract

The McBride Basalt Province covers approximately 5500 km^2 and is one of 11 discontinuous regions of Cenozoic volcanic rocks in north Queensland. These provinces are the northernmost part of a chain of volcanics that extend down the entire eastern coast of Australia, from the Torres Strait to southern Tasmania. These volcanics can be subdivided into central volcano provinces, lava field provinces and lesser leucitite provinces. The central volcano and leucitite provinces contain some felsic volcanics and form hotspot trails, whereas the lava field provinces are entirely mafic and do not have a well defined age-latitude relationship. All of the north Queensland provinces are of the lava field type and are centred around the Great Divide, suggesting a genetic relationship between the divide and the volcanic provinces.

164 eruption centres have been identified within the McBride Basalt Province. The majority of flows are less than 3 Ma, with the youngest volcano (Kinrara) being less than 50,000 y. Remnants of older flows of around 8 Ma occur in the southwest. A hiatus in eruptions is evident from 8 Ma to 3 Ma.

Lavas from the 190,000 year old Undara volcano, cover about 1550 km^2. Undara crater is nearly circular with a diameter of around 330 m and is about 60 m deep. It forms the highest point of the McBride Basalt Province, at 1020 m a.s.l., although its low rim rises only 20 m above the surrounding lava field. Unusually for the McBride Province, the Undara vent does not have associated pyroclastic material.

The longest of the Undara flows is some 160 km, with an average gradient of just 0.3°. Thermal insulation provided by the solidification of the crust above the actively flowing lava is required to produce flows of such length. In the distal regions, the confinement of the initial flows within pre-existing drainage channels also assists the development of such long flows. Lava tube caves occur up to 30 km from Undara crater, where the gradient is > 0.6°. Up to five successive flow units, demarcated by pahoehoe surfaces, can be seen in the walls of some caves. The caves developed by erosion through the lower units. Entrance to the caves is by steep collapse structures.

Lava inflation features, such as lava-rise ridges and lava-rise pits, are common in the Undara flows. A particularly long lava-rise ridge, known as “The Wall”, extends for some 40 km. It is up to 20 high, and around 200 m wide. Formation was due to the inflation of a flow in a confined channel. Where a section of a flow solidifies, it is not underlain by actively flowing lava, so can not inflate. Where the surrounding region may undergo inflation, a depression is left at the level of the pre-inflation surface. Such lava inflation pits have more gently sloping sides than lava tube collapses and may contain pahoehoe floors that continue up their flanks. A series of lava-rise pits occur in close alignment to the main lava tube lines at Undara. In places, lava tubes head towards a depression, then are deflected around the solidified obstruction.

Introduction

The Undara lava field is the most extensive of the basalt flows of the McBride Basalt Province in north Queensland, which forms part of the East Australian Volcanic Zone. The Undara basalts are well known for the impressive lava tube caves, but are also notable for the length of the flows and for the lava inflation structures that have developed on the flows.

This paper seeks to place the Undara lava field into its regional context, by providing an overview of the Eastern Australia Volcanic Zone and the McBride Basalt Province. The nature of the Undara basalt flows and their physical features are also reviewed. Although some of the surface details at Undara have been lost through weathering and erosion, similar structures occur in younger and better-preserved basalt flows, such as the Toomba basalt flow, in the Nulla Basalt Province, approximately 190 km to the south, and in Hawaii, where they can be observed during their formation.

The Eastern Australia Volcanic Zone

The east Australian passive margin is characterised by Cainozoic volcanic provinces, which occur from Torres Strait to Tasmania (Fig. 1). These volcanics can be subdivided into central volcano provinces, leucitite provinces and lava field provinces (Wellman & McDougall 1974).

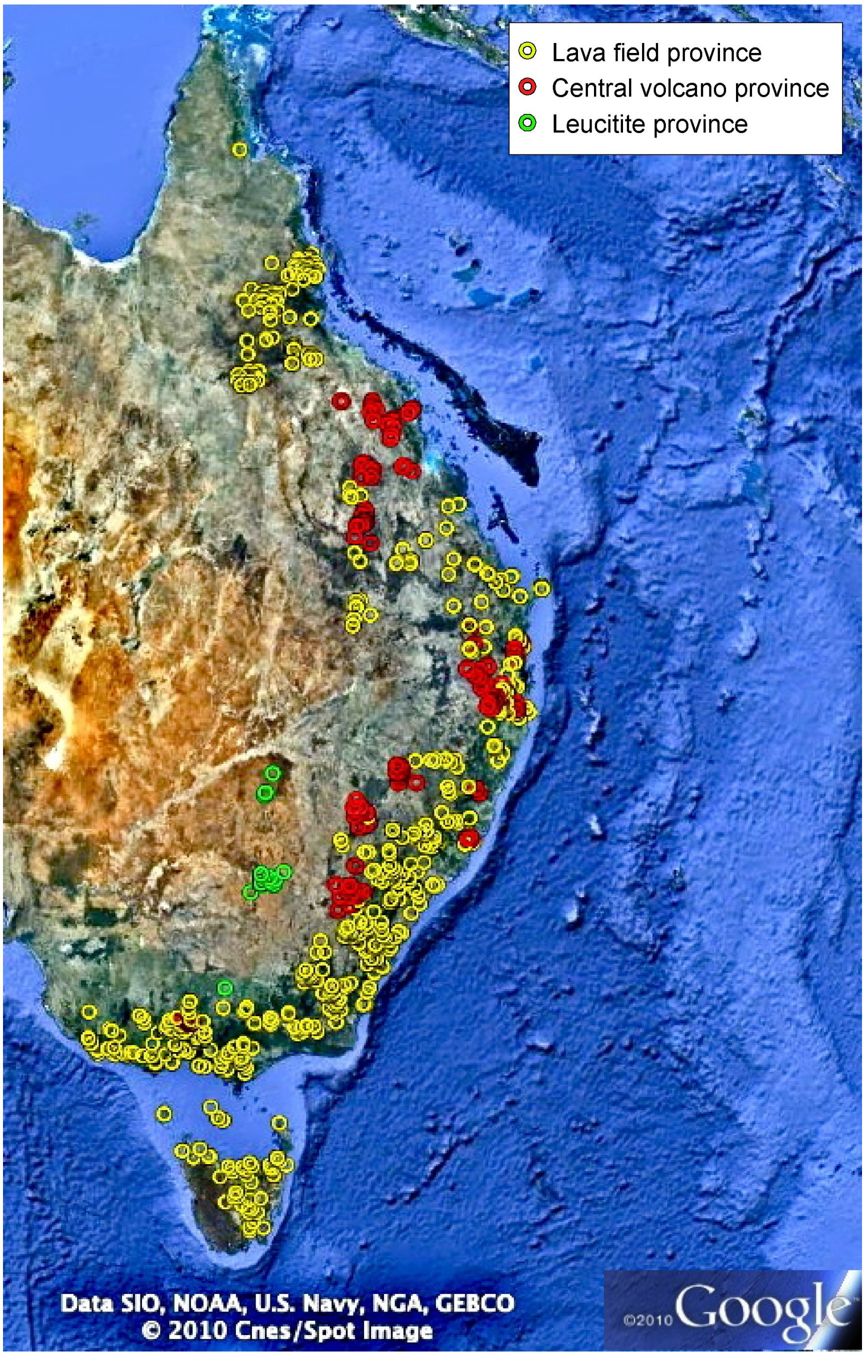
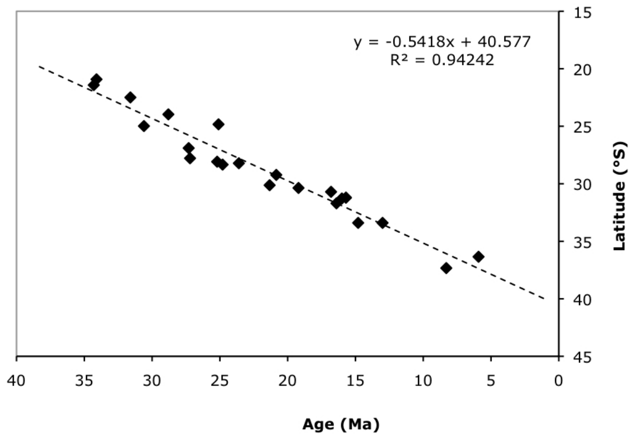


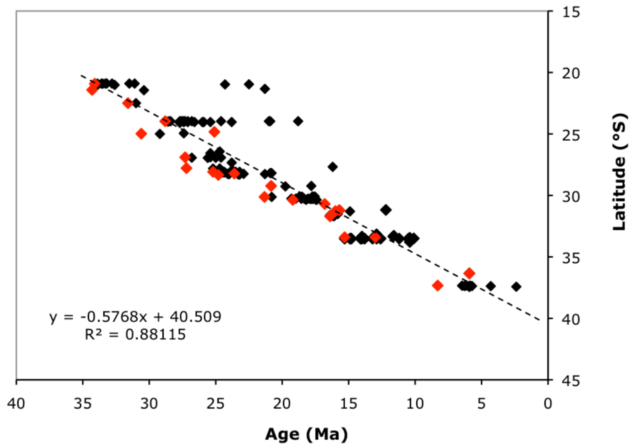
Fig. 1. Locations of Cainozoic volcanic rocks dated by K-Ar, compiled by (Gibson 2007) plotted on Google Earth. The trails of the Tasmantid seamounts can be seen to the east.

The central volcano and leucitite provinces form a hotspot trail with a well-defined age-latitude relationship (Wellman & McDougall 1974; Duncan & McDougall 1989). The oldest of the central volcano provinces is the Hillsborough Province in central Queensland, with an average age of 33.2 Ma (Duncan & McDougall 1989). Ages decrease with latitude, with the youngest felsic volcanism being the Macdon-Trentham Province of Victoria with an age of 6 – 7 Ma (Price *et al.* 2003). The oldest felsic samples from the Hillsborough and Macedon-Trentham Provinces are 34.1 ± 0.8 Ma (McDougall & Slessar 1972) and 8.3 ± 0.1 Ma (Gibson 2007) respectively. There is a distance of 1865 km between these two locations, giving an overall migration rate of 72.3 ± 2.5 mm/yr. Wellman & McDougall (1974) and Duncan & McDougall (1989) used the mean age of analysed samples for each province to derive average migration rates of 66 ± 5 mm/yr and 65 ± 3 mm/yr respectively. The predicted latitude for the present location of the hotspot, derived from the oldest felsic age in each province, is 40.6°S (Fig. 2a), which is close to the 40.8°S calculated by (Wellman & McDougall 1974) using the mean ages. Using the oldest sample for each province may provide a better indication of the relative location of the hotspot over time and avoids possible sampling bias, whereby the numbers of samples of a particular age may give an undue weighting in the calculation of the mean. Furthermore, although Wellman & McDougall (1974) claim that a southward younging can be observed within certain provinces, such as Peak Range, Nandewar and Warrumbungle, the data compiled by Gibson (2007) show a step-wise age-latitude plot, with each province having a much more restricted latitude range than that predicted by the continuous movement of the lithosphere over a stationary hotspot (Fig. 2b). This implies that magma from the sub-lithospheric hotspot source migrates into the lithosphere and is carried along with the lithosphere until the connection with the hotspot plume is broken and the next province commences at a higher latitude.

The central volcano provinces are predominantly basaltic, but include felsic lava flows or intrusions. The provinces are centred around a central vent or cluster of vents. The leucitite provinces contain mafic, high-K minor intrusives. They are petrologically and spatially distinct, being restricted to three aligned provinces in central N.S.W. and northern Victoria. The lava field provinces are exclusively basaltic. They contain abundant vents that are dispersed throughout the province, with widespread lava flows. Flows are generally relatively thin, but valley-filling flows can produce basalts in excess of 100 m thick. All of the north Queensland provinces are of the lava field type and are centred around the Great Divide.



(a)



(b)

Fig. 2. Age:latitude relationship for the central volcano and leucitite provinces. (a) Oldest sample from each province. (b) All dated samples, showing the step-wise relationship between provinces. Red points are the oldest samples for each province.

The trend of the apparent hotspot locations agrees with the northward migration of the Australian plate. A postulated trend (Fig. 3a) from the oldest (Hillsborough) to youngest (Macedon-Trentham) central volcanic provinces, passes through the leucitite province in central New South Wales and is close to the current movement of the Australian plate, as determined by Global Positioning System measurements (Jet Propulsion Laboratory 2010). Such a trend, however, does not align with the trend of the Tasmantid seamounts to the east, which have a near north-south alignment (Fig. 1). A similar, north-south trend (Fig. 3b) of the central volcanic provinces would align the N.S.W. leucitite volcanics with the co-magmatic Cosgrove leucitite in north-central Victoria (Birch 1978), but leaves the Macedon-Trentham Province considerably to the west of the central volcanics trend. The divergence of the current movement of the Australian plate, as determined by GPS measurements, from the long-term trend, may be due to recent rotation of the Australian plate. A more easterly movement is thought to have started approximately 6 million years ago, due to the interaction of the Ontong Java Plateau with the Australia plate, which still continues today (Wessel & Kroenke 2000). Fig. 3c gives possible trends for an initial northerly migration of the Australian plate, with a more recent easterly movement.

In contrast to the central volcano provinces, the lava field provinces show little apparent correlation of age to their latitude. A plot of all Cainozoic K-Ar ages for eastern Australia (Gibson 2007) is shown in Fig. 4.

The McBride Basalt Province

The McBride Province is one of nine lava field provinces in north Queensland. The provinces are closely aligned to the Great Divide, which may suggest a relationship between volcanism and uplift. Wyatt & Webb (1970), however, noted that basalts in the Chudleigh, Sturgeon and Nulla Provinces, to the south of the McBride Province, flowed away from the divide down preexisting drainages. The divide must therefore have occupied its present position prior to the development of these provinces. But some post-eruption uplift is also evidenced by the rejuvenation of drainages at rates that are much greater than that of the regional denudation (Wyatt & Webb 1970).

The McBride Province covers approximately 5500 km^2 and contains some 164 eruption centres (Griffin 1977). It forms a topographical dome, with flows generally radiating away from the central area (Fig. 5). The highest point is Undara crater, which is located on the Great Divide, at an elevation of 1020 m above sea level (a.s.l.). The periphery of the main body of flows has an elevation of 500 – 600 m a.s.l., with the most distal flows having elevations of around 400 m a.s.l. Although it is possible that the total thickness of basalt is up to 500 m, basalts adjacent to granitic inliers, 17 km west of Undara crater, have a surface elevation of around 650 m a.s.l., so it appears that the province is located on a preexisting regional dome, similar to that on which the Chudleigh, Sturgeon and Nulla Provinces are centred. There is a relatively constant slope of the basalts from the 700 m elevation to Undara crater, however, suggesting that the basalt pile may well be over 300 m thick.

The oldest flows in the McBride Province have K-Ar dates of 8.0 Ma (Griffin & McDougall 1975, recalculated to IUGS constants by Gibson 2007). The bulk of the eruptions, however, have occurred within the last 2.7 Ma. There have been spasmodic, but essentially continuous eruptions since that time, with the youngest centre being Kinrara, 22 km southeast of Undara crater. Kinrara has a K-Ar age of 52 ka (Griffin & McDougall 1975), but this age

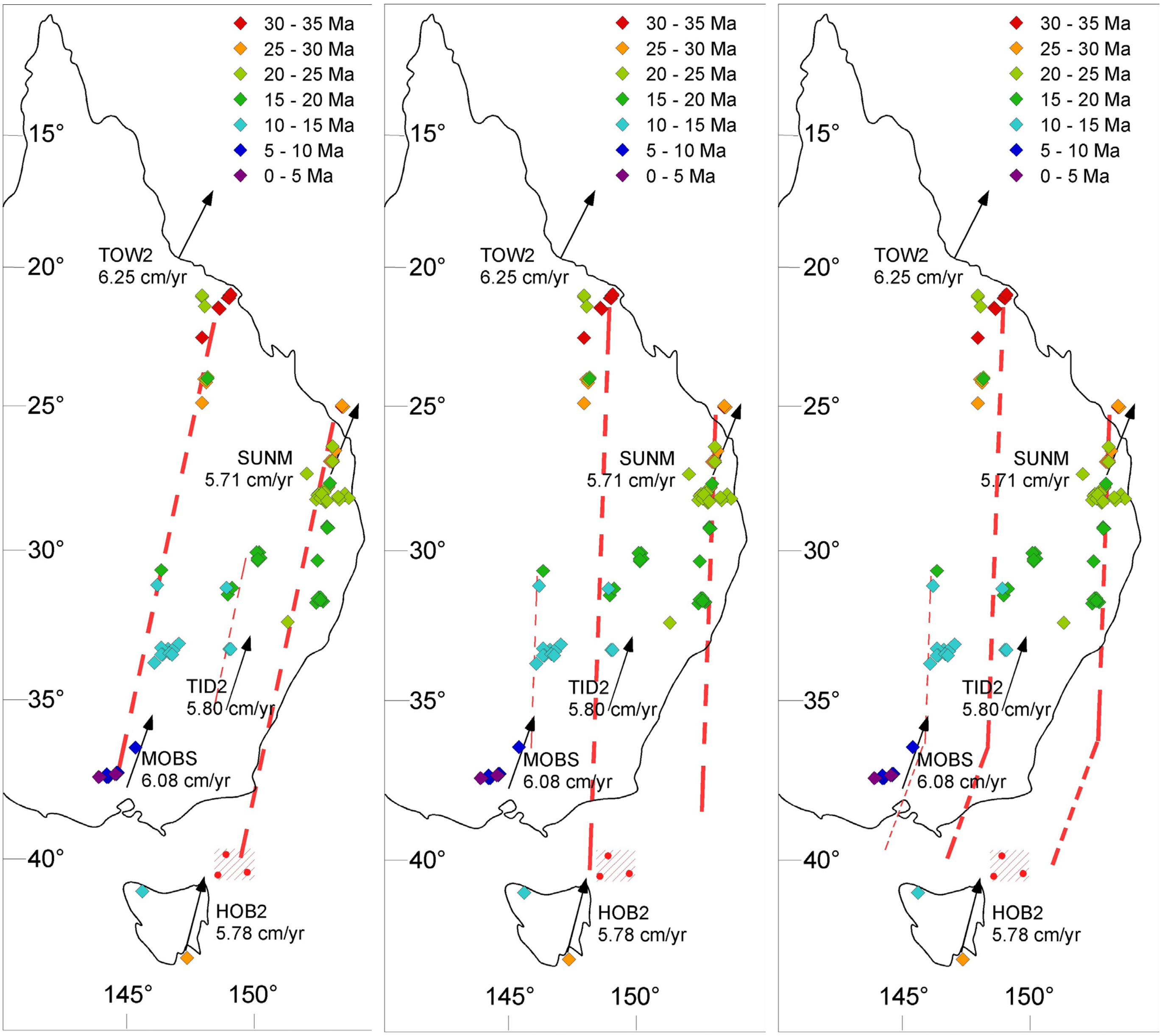


Fig. 3. Postulated trends in the Australian plate, from central volcano and leucitite province ages. (a) Trend defined from linking the oldest and youngest central volcano provinces. (b) Northward trend, similar to that of the Tasmantid seamount chain (Fig. 1). (c) Northward trend, followed by an easterly rotation 6 million years ago. Dots and hashed region off northeast Tasmania is a zone of recent earthquakes (Wellman 1989). Maps are drawn to a transverse Mercator projection, to preserve directions as straight lines. Arrows show the direction of movement of the Australian plate (Jet Propulsion Laboratory 2010).

may be regarded as a maximum age. The degree of preservation of the Kinrara basalts is similar to that of the Toomba flow, in the Nulla province, which is only 18 ka (Stephenson *et al.* 1978). The McBride Province has a similar age range to the Chudleigh, Sturgeon and Nulla provinces to the south and to the Atherton province to the north. As intermittent volcanism has been occurring for at least the last 5 million years, it is probable that eruptions will continue into the future, although volcanism appears to be waning (Whitehead *et al.* 2007).

Undara Basalts

The Undara lava flows cover an area of 1510 km^2 (Stephenson *et al.* 1998). K-Ar dates taken from Undara crater and from "The Wall", 54 km to the northwest, have identical ages of 0.20 Ma (Griffin & McDougall 1975, recalculated to IUGS constants by Gibson 2007). Most of the lavas flowed to the west and north, with one flow to the east. Lava tubes developed in the flows to the west, northwest and north. Caves exist up to 30 km from the crater, where the gradient is greater than 0.7°. Numerous structures formed by lava inflation occur, including a prominent lava rise ridge known as "The Wall" (Atkinson *et al.* 1975), which starts 60 km down flow from Undara crater and extends for another 40 km.

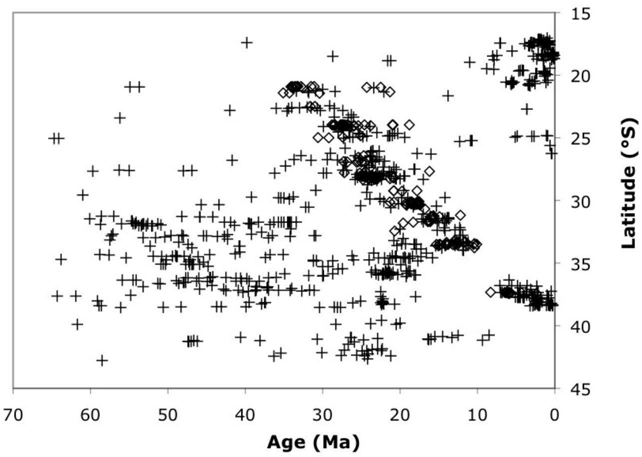


Fig. 4. Age:latitude relationship for Cainozoic igneous rocks of eastern Australia. Samples from central volcano and leucitie provinces are shown as diamonds, all others as crosses.

Undara crater lies close to the centre of the McBride Province and marks the highest elevation of the province. The crater has a low rim about 330 m in diameter that rises about 20 m above the surrounding land. The crater is about 60 m deep and drops steeply to a floor about 190 m across. This low cone is the only source that has been identified for the extensive Undara lava fields.

Undara crater is unusual in that it occurs at the top of a regional dome rather than being the summit of a discernible volcano. Although any lava pile from a single vent may essentially be equated to forming a shield volcano, the gradients radiating out to 5 km from Undara crater range from only 0.7° to 1.4°, which is considerably less than those of typical shield volcanoes. Mauna Loa, for example, has slopes ranging from around 7°- 9° and Skjaldbreiour ("broad shield" in Icelandic) has slopes of around 6°-7°. The existence of such a small cone perched on top of several hundred metres of basalt, suggests that the present Undara crater is simply the last manifestation of the vent that produced the Undara lava field.

Flows from Undara extend up to 160 km from the vent. The north Queensland basalt provinces contain many flows of considerable length, with twenty flows being known to extend for over 50 km (Stephenson 2005). These lengths were achieved despite a low regional gradient of 0.2°- 0.4° for the distal portions of many of the flows. The lavas were not unusual with regards to their composition, eruption temperature or viscosity (Stephenson *et al.* 1998). Notably, however, modelled temperatures suggest that there was very little cooling of the lavas down the length of the flows and there is little change in the basalt texture from the proximal to

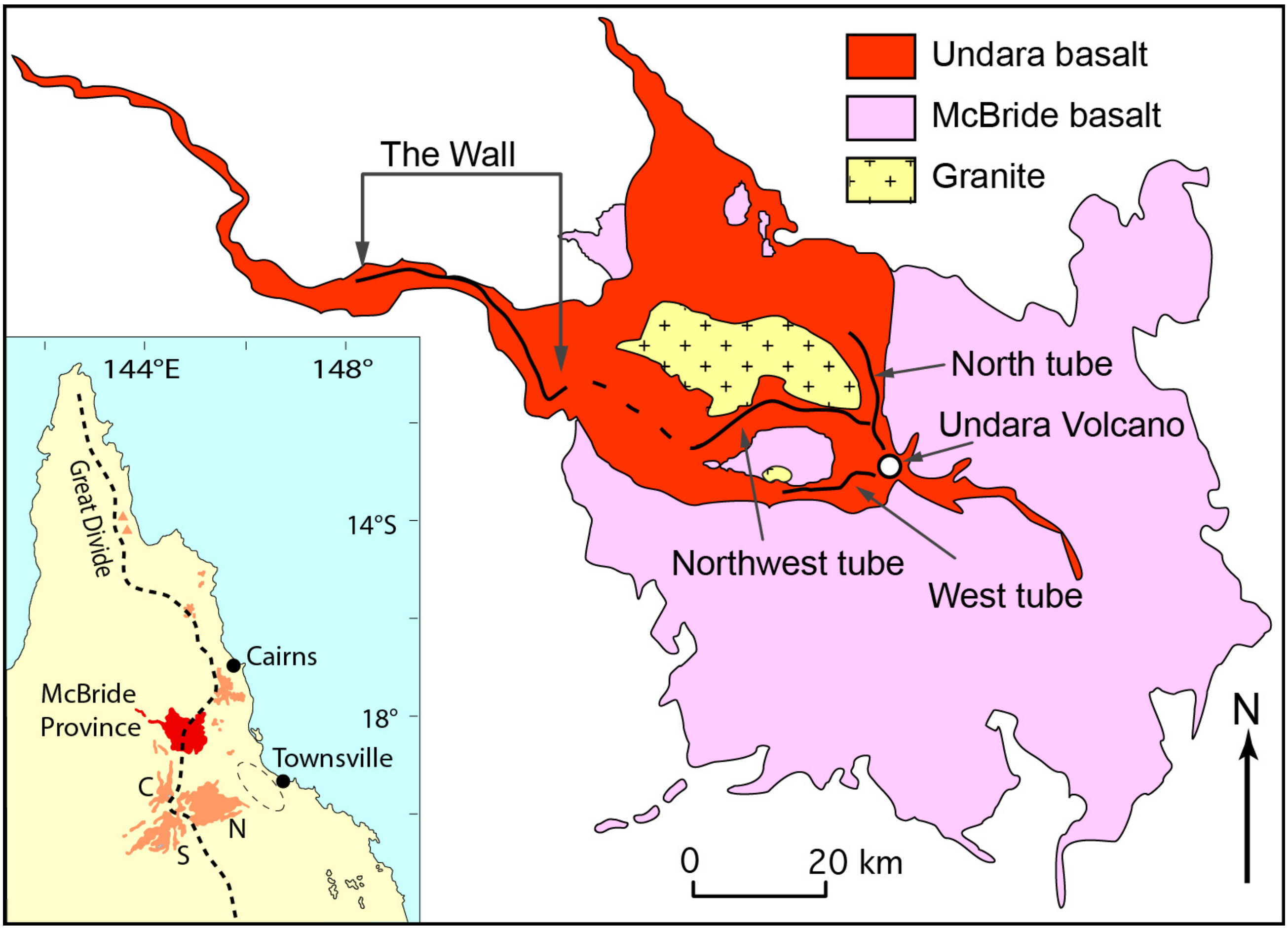


Fig. 5. Outline of the McBride Basalt Province, showing the extent of the Undara basalts and major lava tube lines. Inset: Basalt provinces of north Queensland. C – Chudleigh, N – Nulla, S – Sturgeon.

distal flows. Several factors are believed to have aided the development of the long flows, including—

- the continuity of the eruption
- the existence of drainage channels that were dry or contained low water levels
- the flow of lava along insulated conduit systems
- repeated breakouts from static flow fronts to sustain flow advance (Stephenson *et al.* 1998)

Lava Tubes

The term "lava tube" is commonly used in everyday language, with the "Thurston Lava Tube" of Hawaii being a well-known example. In the geological and speleological literature, however, the term has been used for a variety of features (Halliday 2008). Here, the term "lava tube" is restricted to a locally channelised flow of lava that flowed sub-surface, creating an approximately cylindrical structure. The formation of an open space, by either the down-cutting or partial drainage of the flowing lava, is termed a "lava tube cave". It is proposed that any other type of cavity within solidified lava flows be termed "lava caves". All other sub-surface passages of lava that lead to the incremental lengthening of lava flows, are here termed "lava conduits".

The concentration of lava into a lava tube can lead to the thermal erosion of the underlying rock. Observations of flowing lava tubes in Hawaii showed the lowering of the tubes by an estimated 15 m over a nine month period (Swanson 1973). Pinkerton *et al.* (1990) calculated erosion rates of between 6 cm/day and 22 cm/day for the 1984 Mauna Loa eruption, based on the thermal properties of the basalts, the channel dimensions and discharge and viscosity data. Direct measurements of the depth of an active lava tube by were undertaken by Kauahikaua *et al.* (1998) over a two month period, where an average erosion rate of 10 cm/day was obtained, after which the rate of erosion lowered substantially. The surface of the stream receded to 5.2 m below the surface, with the depth of the lava stream being measured as 0.7 m when it was close enough to the surface for measurements to be taken. The velocity of the lava was measured at around 2.5 m/s. The surface gradient was 2.7° in the upstream direction and 3.4° downstream.

Over 60 lava tube caves and arches have been discovered in the Undara lava field (Atkinson & Atkinson 1995). The caves are preserved within Undara Volcanic National Park but only a few caves along the northwest tube line are open to the public. These caves may be viewed on guided tours, run by commercial tour operators that have been certified by the Queensland Parks and Wildlife Service. No caves are freely accessible to the public.

The northwest tube line extends for 30 km from Undara crater. Lava tube caves are generally large structures, averaging around 14 m wide and up to

Fig. 6. View of "The Wall", in the Undara lava field.
Photo taken from approximately 18° 5.1'S, 144° 4.9'E, looking to the north.

19.5 m high. The longest is Bayliss Cave, which runs for 1.3 km (Atkinson & Atkinson 1995). The caves display features that are typical of formation from thermal erosion by the lava, including benches and flow lines, although wall linings frequently conceal these features. In "The Archway", a series of 5 flow sub-units can be seen in the 14 m high walls, defined by vesicular, pahoehoe surfaces. The lava lines, benches and sub-units seen in the cave walls are consistent with their derivation from the thermal erosion of a confined lava tube. The gradient along the northwest tube line averages 0.7°, which is greater than the 0.5 ° required to allow drainage (Hatheway & Herring 1970).

The tube line closely follows a line of surface depressions, which continue beyond the last known cave. No access to the caves can be obtained from the depressions, which appear to be derived from a separate flow. Caves are accessed by narrower and steeper depressions, formed by cave collapses.

Lava Inflation structures

Lava inflation occurs when pressure from the liquid lava produces a swelling of the solidified crust (Walker 1991). They are thus distinguished from pressure ridges where lateral compression forms a buckling of the crust. Lava inflation structures can occur as point form structures (tumuli), as plateaux (lava rises), or as long, narrow ridges (lava rise ridges). Regions of lava flows that fail to inflate and hence indicate the original level of the flow prior to inflation, are termed lava rise pits. Observation of the Kalapana flow in Hawaii showed a flow 150 m across, that was initially less than 0.5 m thick, became inflated to greater than 10 m thick over 22 days (Kauahikaua *et al.* 1998).

"The Wall" at Undara is interpreted as a lava rise ridge (Fig. 6). It is 40 km long but generally less than 200 m wide. The Wall is breached in several places, but is effectively continuous. It rises up to 20 m above the surrounding lava field to the south, but has lower relief on the northern edge, where a later flow has apparently banked up against it (Stephenson & Whitehead 1996). The gradient over the length of the Wall is less than 0.09°.

The Wall is believed to have formed by lava being confined to a stream bed and that subsequently underwent inflation. Similar structures are found in the Toomba flow of the Nulla province to the south (Whitehead & Stephenson 1998). The Toomba flow is only 13 ka (Stephenson *et al.* 1978) and features such as inflation clefts and banded and striated surfaces that characterize inflation structures, are still well preserved on the lava rise ridges (Fig. 7). Such features are not apparent in The Wall, although the remnants of a lava inflation cleft may be preserved near the termination of The Wall (illustrated in Atkinson & Atkinson

(a)

(b)

Fig. 7. (a) Lava inflation cleft on the edge of a lava rise ridge in the Toomba basalt field. (b) Banding within the lava inflation cleft, caused by incremental opening of the cleft. Scale bar is 1 m.

1995, pp. 50-51). The Wall has been suggested as an analogue to basaltic ridges that can be seen on the moon (Atkinson 1992). As lunar flows could not have been confined to fluvial channels, the lunar ridges may be pressure ridges, rather than lava inflation ridges.

In several places on the Wall there are roughly circular depressions, up to 100 m across. Similar depressions occur in many places within the Undara basalt flows. Notably, aligned depressions occur close to the north and northwest lava tube lines. Possible interpretations of these depressions are as collapsed lava ponds or collapsed tubes (Atkinson *et al.* 1975), shattered rock rings (Kauahikaua *et al.* 1998) or as lava rise pits (Stephenson *et al.* 1998).

The depressions are regarded as being analogous to the lava rise pits of the Toomba lava field (Stephenson & Whitehead 1996). At Toomba, the depressions are commonly 20 m deep and 50 m to 100 m long, with pahoehoe preserved on the floor and the steeply sloping sides (Fig. 8). Most of the depressions contain tapering cavities within the walls, commonly close to the level of the floor. These cavities are large, sub-horizontal lava clefts and contain sagging lava wedges with banded and striated surfaces (Fig. 9). These features are diagnostic of lava inflation (Walker 2009). No evidence of lava tube entrances were found in any of the depressions.

Similarly, at Undara, no cave entrances are to be found from the depressions. Where the depressions lie over the line of a lava tube cave, no collapse is apparent in the cave beneath, which may have indicated a collapse feature (Stephenson & Whitehead 1996). Rather, the depressions appear to act as a constraint to the tubes, which bifurcate around the depressions. This is consistent with there being a region that acted as a barrier to the flow of lava. Where lava tubes were formed, the tubes deviated around the obstruction. Where broad lava conduits led to the inflation of the surface, the solidified section of the flow failed to inflate, leading to the development of lava inflation pits.

Lava inflation versus thermal erosion

Lava inflation structures may occur throughout lava fields, both close to the volcano, where gradients are generally steepest, and in the distal portions, which generally contain the lowest gradients. Lava tube caves, however, are restricted to regions of higher gradient, above the 0.5° required for tube drainage (Hatheway & Herring 1970). There is a fundamental dichotomy between the processes required to form lava inflation and thermal erosion. For inflationary structures to form, lava conduits must underlie the entire structure that is undergoing inflation. The lava conduit must be filled, leading to hydrostatic pressure which forces the surface of the lava flow to rise above its original level. Any breakage of the surface would lead to a squeeze-up of lava from below. Intuitively, the formation of lava inflation structures would require the lava to be advancing relatively slowly. Conversely,

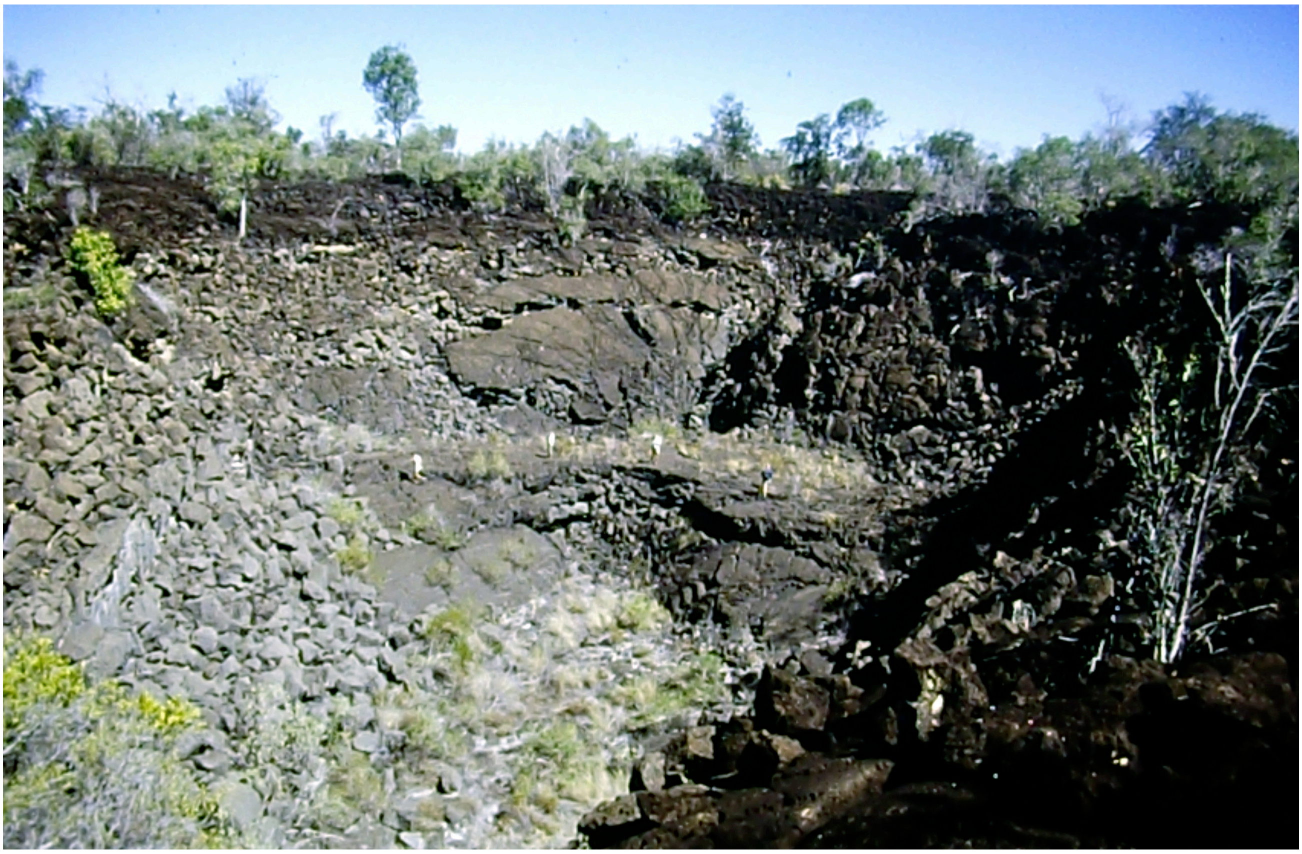
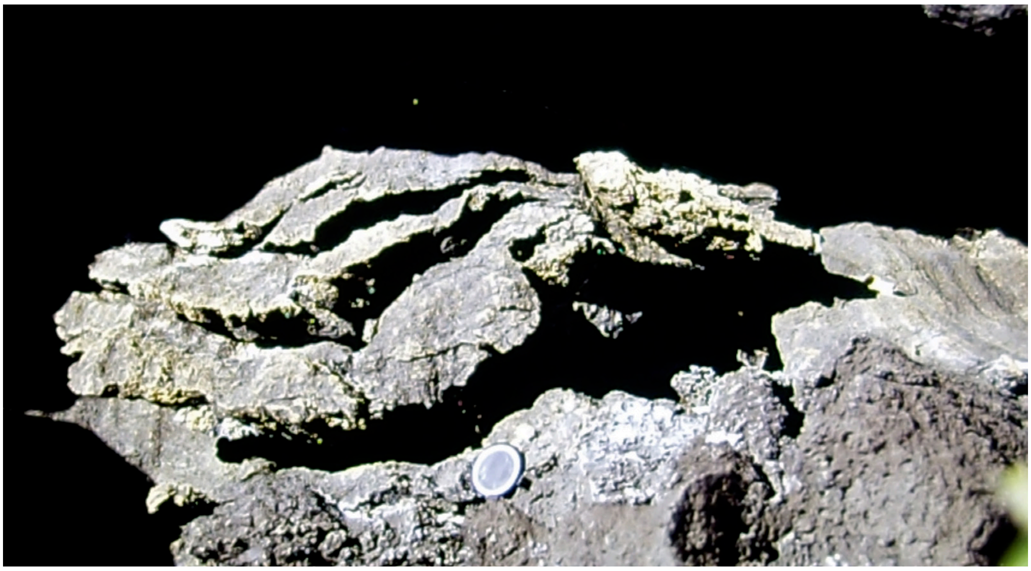


Fig. 8. Lava inflation pit in the Toomba basalt flow.

for thermal erosion to occur, the lava must be channelled along a confined stream and be freely flowing. Lowering of the lava stream leads to an unsupported roof, which can lead to the formation of skylights by roof collapse.

At Undara, although the aligned depressions, which are here interpreted as lava inflation pits, and the lava tube caves are in close proximity, the contrasting methods of formation mean that they must have been formed from different flows. In the more distal regions, where The Wall occurs, gradients are too low for the formation of lava tube caves. The depressions in The Wall are here interpreted as lava inflation pits, by comparison with similar features in the younger and better-preserved Toomba flow, rather than collapse features.

(a)



(b)

Fig. 9. Lava wedges, Toomba. (a) Vertical lava wedge in a lava inflation cleft, formed by horizontal movement as the cleft opened. (b) Horizontal lava wedges at the base of a lava inflation pit, indicating vertical movement as the sides of the pit inflated.

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