

The origin and occurrence of Large Igneous Provinces on Earth and Mars.

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1. Introduction

This essay attempts to illustrate the possible origin and the occurrence Large Igneous Provinces (LIPs) on Earth and Mars. To do this the specification of a LIP must be defined. To address the origin (processes of formation) and occurrence of LIPs on Earth and Mars the geographical distribution of LIPs must be determined and where possible the relationship with LIP surface distribution and mantle state like Low Velocity Zones (LVZs) and Ultra Low Velocity Zones (ULVZs) addressed, as well as histories regarding the specific LIP zones where possible. Well studied LIPs like the North Atlantic Igneous Province, Deccan Volcanic Province, Ontong Java Plateau and the Tharsis province will be used in this essay to explain the origin and occurrence of LIPs on the neighboring planetary bodies.

1.1 What are LIPs?

LIPs are found on both continental and oceanic lithosphere and have been defined as massive volumes of basaltic magma (sometimes with subsidiary picrites and rhyolites) as extrusive (flood lavas) and intrusive (plutonic bodies, giant dyke swarms) bodies emplaced by processes other than plate-tectonics (but can initiate) (*Ernst et al. 2005*). Generally LIPs have no strict definition (*Stuart et al. 1996*) (www.largeigneousprovinces.org).

The minimum geographical distribution of LIPs is 0.1 Mkm². Most Cenozoic and Mesozoic continental flood basalts (LIPs) are 2-4 Mkm², whereas the exposed Ontong Java plateau covers 6 Mkm². Taking into account the Ontong Java plutons it becomes 44.4 Mkm² (*Ernst et al. 2005*).

On Earth LIPs are emplaced within <10 Ma, with an accelerated period of volcanism occurring for 1-2 Ma. There is currently no determined time scale for Martian LIPs. The common idea is that continental LIPs have a two phase development, post/syn-rift and pre-rift. Where pre-rift signifies a plume head arrival beneath the lithosphere, displays doming of the lithosphere and some volcanism. Post/syn-rift signifies the development of a spreading ridge and the majority of volcanism, this is thought to take 1-10 Ma to form from plume head arrival to active spreading ridge (*Ernst et al. 2005*).

2 Mars as planetary body

Mars is the fourth planet from the Sun and the seventh largest. It has a diameter of ~7,000 km which is ~half the size of Earth (www.solarviews.com). Due to the size of Mars relative to Earth and according to the rules of thermodynamics it must have heated up and cooled quicker. Mars geological timescale to date (Fig 1) has only three eras and no periods, as there's very little in the way of periodic indicators to date, for example no fossils found yet and no radiometric dating!!

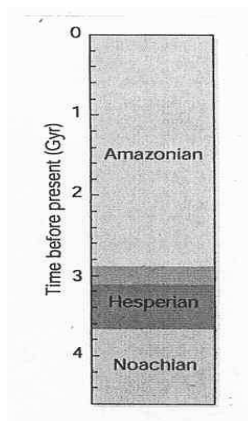


Fig 1 Martian geological time scale inferred from mapped stratigraphy. (Zuber, 2001)

The interior of Mars is inferred from satellite data reading the gravity and magnetic anomalies, orbital geophysics, topography and Martian meteorite analysis (Zuber, 2001);(Berkta & Fei, 1997) Fig 2 is a proposed cross-section of Mars, showing the crust, upper and lower mantle, CMB and core.

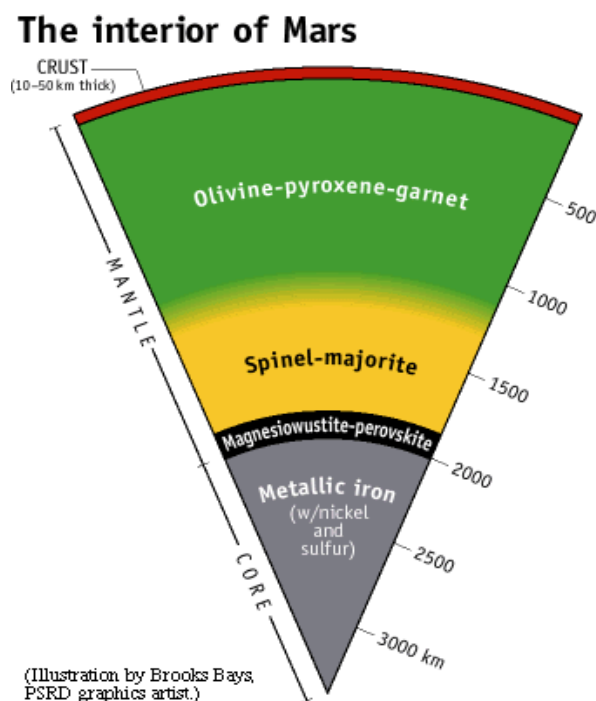


Fig 2 Proposed interior of Mars. (Berkta & Fei, 1997)

Mars has a relatively low density to that of the Earth, something in the region of one-tenth (Anderson, 1989). Mars has no global magnetic field at present, but magnetized igneous rocks (palaeomagnetism) in the crust imply that at some point in early Martian history there was a global magnetic field produced by a core magnetic dynamo.

2.1 Earth as planetary body

Earth is the third planet from the sun, the fifth largest and the densest solid body in our solar system; it has a diameter of ~13, 000 km (www.solarviews.com). The Earth generates heat from two main sources, the 1st is heat trapped from the planets formation and 2nd from the decay of unstable radioactive isotopes in the lower mantle (*Middlemost, 1997*). The mantle makes up more than two thirds of the Earths mass, with the core taking up just under a third and the crust being <1% shown in Fig 1 (*Middlemost, 1997*). The surface of the Earth is tectonically active causing zones of upper mantle to become enriched by subducted volatiles such as water. The core is cooling and increasing in size as it does, one method of cooling is heat transfer through the mantle to the surface by plumes which initiates volcanism (*Middlemost, 1997*).

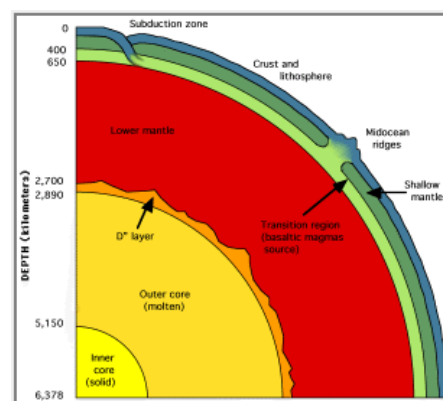


Fig 3 The conceptual interior of Earth (www.solarviews.com)

3- LIPs on Mars

The Martian crust has a hemispherical divide, the south is relatively thick, cratered, old and elevated the north is relatively thin, depressed and young (*Zhong & Zuber, 2001*)

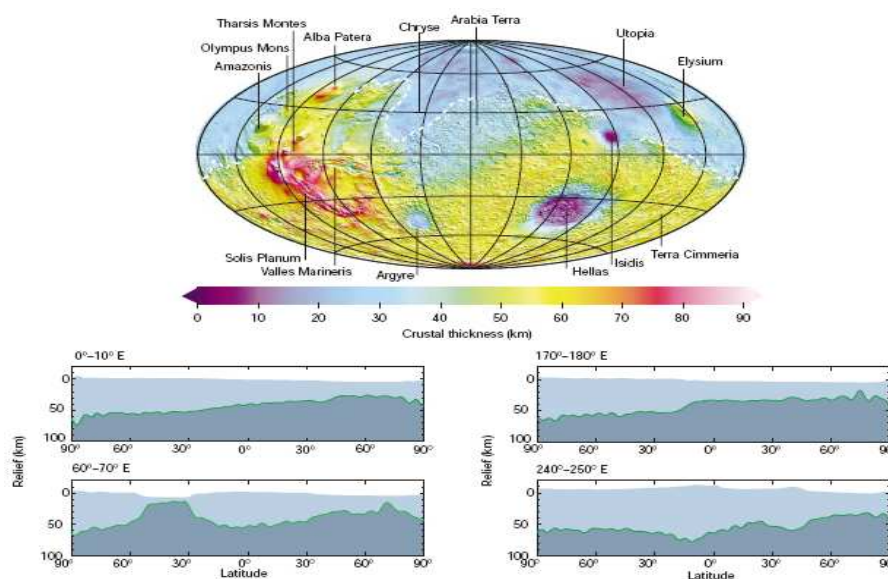


Fig 4 Crustal thickness of Mars with mantle depth. Localities of some volcanoes (large enough to be LIPs) geographically. (*Zuber, 2001*)

The geographic distribution of several volcanoes on Mars, with some indication of lithospheric thickness is shown in Fig 4. The definition of a LIP is not so useful when dealing with Mars, as many individual volcanoes on the Martian surface are large enough to be classed as LIPs (*Montesi, 2000*). Such as Olympus Mons which is the largest volcano in the solar system. It is also larger than the largest LIP known on Earth the OJP. (*Zuber, 2005*).

Presently Mars is a single plate planet with no active plate tectonics. (*Solomon et al. 2005*) The mantle of Mars is covered by a single plate (*Weizman et al. 2000*). Although Mars is ~half the size of Earth it has volcanoes which are 10-100 times larger than volcanoes found on Earth (*www.solarviews.com*). Mars was most volcanically (and possibly tectonically) active within the first billion years of its formation, by the end of the Noachian (at ~3.8 Ga) much of the volcanism was concentrated in the Tharsis province, which covers >25% of the surface, which is thought to have developed as centre of volcanic activity post-hemispheric crustal thickness divide (*Solomon et al, 2005*).

3.1- Olympus Mons

Mars is also home to the solar systems largest volcano, the giant Olympus Mons. It is located NW of the Tharsis province, and is large enough to be a LIP in its own right. With an elevation of 24 km, a width of 550 km, the slopes dip is only ~2-5° it is like a giant Hawaiian volcano. Three times the height of Everest and as large as the whole Hawaiian volcanic chain. (*www.solarviews.com*).

3.2- The Elysium Planitia province

The Elysium Planitia province is the second largest LIP on Mars. A dome in the lithosphere (indicating plume related) which is 1700 km by 2400 km in width containing several volcanoes is observed. The largest volcano in this province is Elysium Mons with dimensions of 420 km by 500 km by 700 km with elevation of 13 km (*www.solarviews.com*).

3.3- The Tharsis province

The Tharsis province is the largest igneous province on Mars covering one-third of the planet's surface. Its bulged surface reaches an elevation of 11 km (*Mege & Masson, 1996a*). The Tharsis province displays distinct episodes of magmatic/tectonic activity which decreases with time. Fault rift systems and vertical uplift due to plume manifestation also observed. Early explosive activity which progressively evolved into fissure-fed eruptions. The Tharsis province volcanism is also thought to have caused short (10's thousands year cycles) hydrological cycles in the northern hemisphere. (*Anderson et al, 2004*). The Tharsis province contains several volcanoes, impressive examples include three shield volcanoes forming a chain are known as the Tharsis Montes (Ascraeus Mons, Pavonis Mons and Arsia Mons) range in size from 350-450 km wide and elevation of ~15 km above the surrounding plains. (*www.solarviews.com*).

3.4- Conflicting ideas regarding the formation of the Tharsis province

The development of the Tharsis province is conceptionally thought to be the result of a plume impacting the Martian lithosphere causing the 11km domal uplift and supporting volcanism. (*Mege & Masson, 1996a*);(*Montesi, 2000*);(*Weizman et al. 2000*);(*Zhong & Roberts, 2003*);(*Anderson et al. 2004*).

With one plate acting as a cap over the Martian mantle and no recycling of extruded material the mantle convection would be considerably sluggish (*Montesi, 2000*), inhibiting plume generation. Yet distinct episodes of early magmatic/tectonic activity that declines with time from early explosive volcanism evolving into steady growth of fissures, shield and cone volcanoes (*Anderson et al. 2004*). This is consistent with the arrival of a plume (relative to Earths plumes- 'super-plume') head beneath the lithosphere in the Tharsis province and establishing a LIP. The plume beneath the Tharsis province would have had to be stationary for >2 Ga and active, cyclic delamination of Martian lithosphere into the plume head combined with addition of heat from the cooling core could provide a negative feedback system required to maintain such sustained volcanism over long periods of time (*Weizman et al. 2000*). With the immense size for a plume required to satisfy the Tharsis province cooling would take a few Ga. During the late stages of cooling the diminishing plume would still be able to feed volcanism for younger volcanoes such as Olympus Mons (*Zhong & Roberts, 2003*). One proposal for the amount of volcanoes with close proximity is that a 'super-plume' branches off at the head into several smaller 'normal sized' plumes. This is argued as the case for concentric dykes surrounding volcanoes such as Pavonis Mons and Arsia Mons where the concentric dykes have been interpreted as a reflection of plume head dimensions (*Montesi, 2000*).

There are problems with the plume model for the Tharsis province genesis. The size of the plume required is large enough cause a bulge that covers a 3rd of the Martian surface. As Mars is ~half the Earth and the latter doesn't have any plumes near this scale, even with active tectonics which increases plume formation. The development of a plume to this scale and surviving >2 Ga is doubtful (*Menge & Masson, 1996b*). Also Isotropic evidence doesn't suggest mantle mixing has occurred and computer models show that a plume would contribute only a fraction of the topographic elevation visible today. Calculations have shown that an impact of a meteorite (with right size and velocity) could initiate upwellings that survive in a stable fixed position for the entirety of Martian evolution and play a role in aeroid evolution. Impact doesn't require convection or CMB upwellings (*Reese et al. 2004*).

4- LIPs on Earth

Fig 5 shows the geographic distribution of LIPs on Earth with mantle state (LVZs) (*Ernst et al. 2005*). It can be seen that most LIPs on Earth are sited above LVZs, indicating either hot (relative to surrounding) material is either generated there or transported from an internal source (thermal-boundary layers, D") as an upwelling, or 'plume' which feeds the volcanism responsible for forming a LIP. The other idea is that the material has been decompressed lowering its shear modulus.

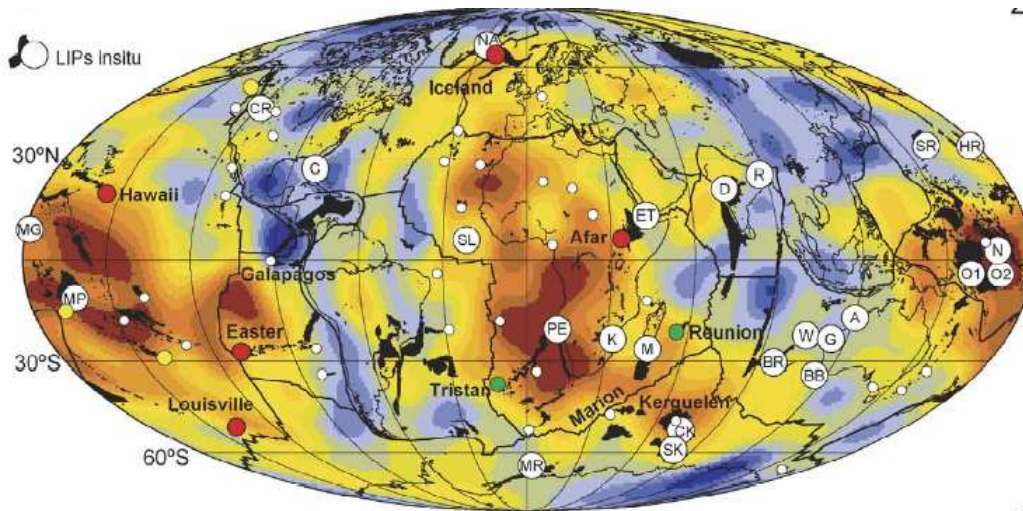


Fig 5 Distribution of LIPs, current plate boundaries and 44 hot-spots (white circles). (Importantly NA= NAIP, O1 & O2 = OJP and D= DVP. The OJP is in two parts as it has been separated by plate tectonic activity. Red, green and yellow dots represent hot-spots with a proposed deep mantle origin. The base of the map is a tomographic model of D'' ~2800 km deep. Blue is relatively fast shear wave speed and red is slow. (Burke & Torsvik, 2004)

The generation of LIPs are observed throughout Earth's history dating back to Archaean >2.5 Ga. Although the majority of well studied LIPs are from the Mesozoic and Cenozoic as surface weathering processes and plate tectonics have all but destroyed older LIPs (Burke & Torsvik, 2004). The destroyed LIPs reveal their feeder dykes, like the McKenzie dyke swarm in N.America (Fig 6)



Fig 5 Proterozoic LIP weathered away exposing its plumbing system.

The MacKenzie dyke swarm 1270 Ma, Alaska. (Ernst *et al.* 2005)

LIPs on Earth occur throughout geological history as shown in Fig 7 and do not seem to be controlled by latitude or longitudinal positioning (fig 5). In the last 150 Ma (the best record of LIPs due to preservation) there has been 1 LIP per ~10 Ma, but this figure is not rigid as LIPs show gaps and concentrations in the geological record. Destruction of LIPs due to plate-tectonics and weathering processes inhibit the record (Ernst *et al.*, 2005). The occurrence of LIP clusters in the geological record has a strong link with super-continent dispersal, at least 5 LIPs are linked with the break-up of Gondwanaland and several linked with Rodinia (Ernst *et al.*, 2005) and the role of the NAIP in initiating the formation of a spreading ridge which separates the Eurasian plate and the North American plate which formed the Atlantic ocean (Fitton *et al.* 1997).

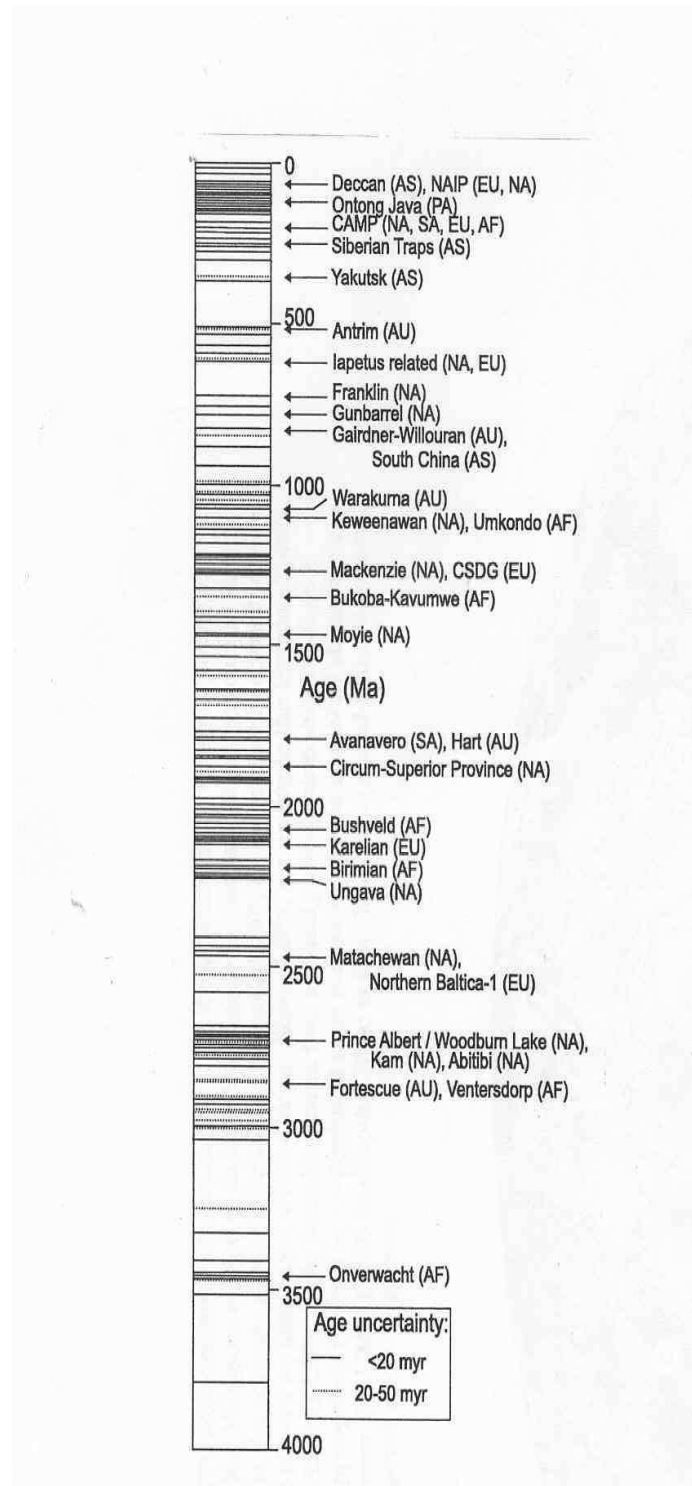


Fig 7. Recorded occurrence of LIPs through time from ~4 Ga. Note the reduction in LIPs recorded from 2.5 Ga to 4 Ga. This is thought to be due to weathering on the surface and not an increase in LIP generation through time. Letters in brackets show current location. NA= North America, Eu= Europe, AS= Asian Sea, AF= Africa, AU= Australia and PA= Pacific ocean. (*Ernst et al. 2004*)

4.1- The North Atlantic Igneous Province (NAIP)

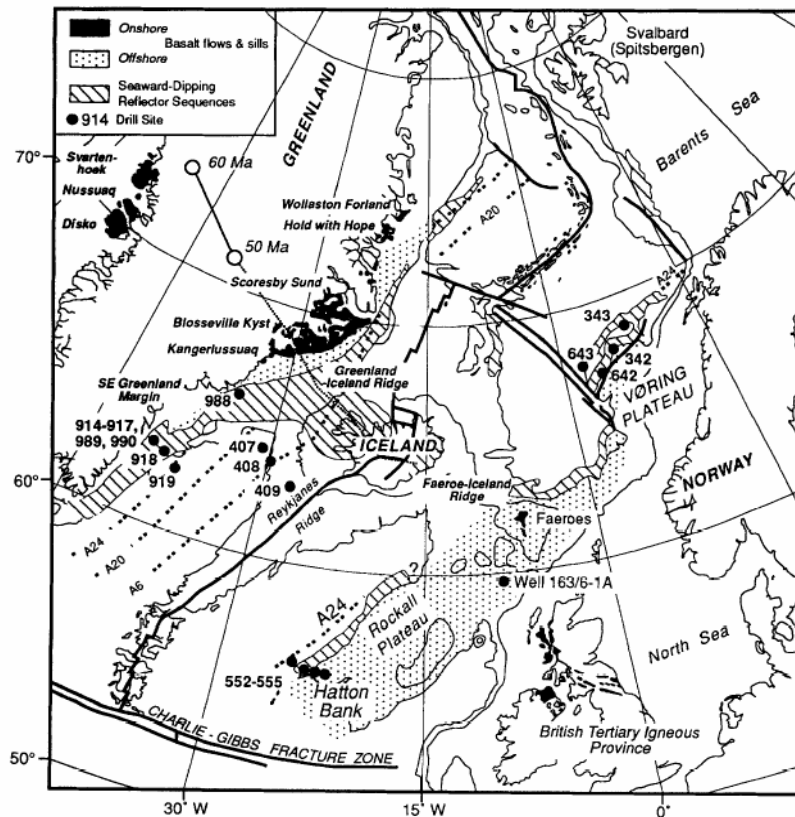


Fig 8. The present day settings of the NAIP showing onshore and off shore tertiary igneous rocks. (Fitton *et al.* 1997)

The NAIP (Fig 8) is associated with the Iceland plume head arrival beneath thinned (due to extension) lithosphere causing the formation of a spreading ridge (~63 Ma) (Mid Atlantic Ridge-MAR) and the growth of the North Atlantic ocean with subsequent development of Iceland. Basalts from the NAIP can be correlated with E&W Greenland, Iceland, NW Scotland and NE Ireland, these basalts are ~60-54 Ma (early tertiary). (Stuart *et al.* 2000).

4.2- Conflicting ideas on the formation of the NAIP

The origin of the NAIP is commonly put down to the arrival of a plume head beneath (Fig 9) tectonically thinned lithosphere causing flood volcanism pre-ridge formation (Fitton *et al.* 1997) (Stuart *et al.* 2000). Some other authors have suggested otherwise, (Foulger *et al.* 2004) (Foulger & Anderson 2004) suggesting that; subducted Iapetus oceanic crust trapped in the Laurasian continental mantle lithosphere within the collision zone associated with the Caledonian suture, is then recycled into a melt zone locally beneath the Atlantic ridge causing a crust-peridotite mixture resulting in excess melt, model shown in Fig 10. This could have caused the flood volcanism in the NAIP.

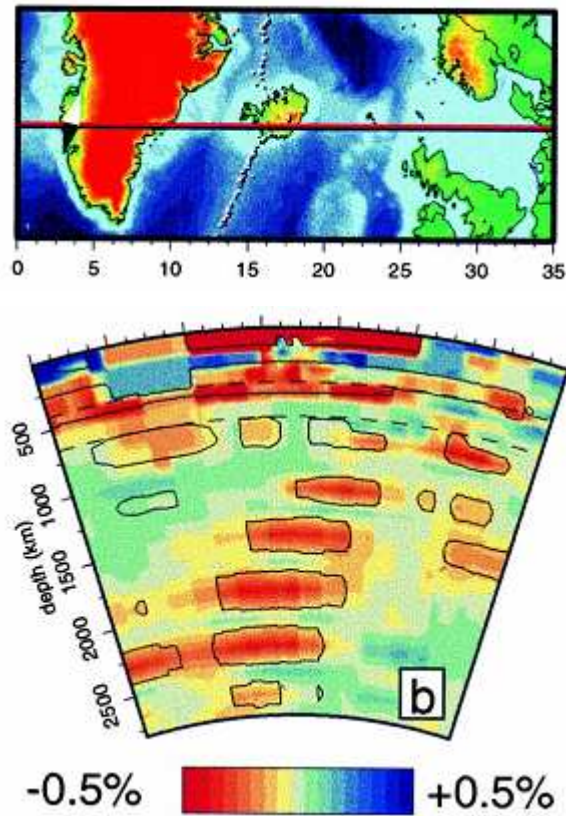


Fig 9 A tomographic section through the NAIP cutting across Iceland. The red colour represents low shear modulus to green and green to blue. (*Bijwaard & Spakman, 1999*).

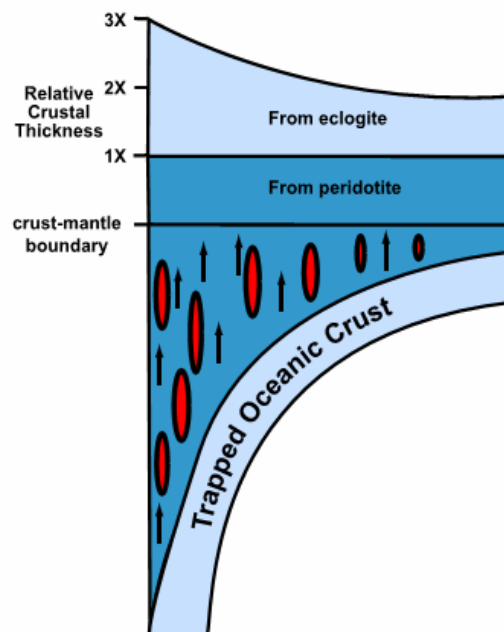


Fig 10 This is a proposed model for re-melted subducted oceanic crust . Two types of melt are possible which yield different volumes of material, mantle peridotite and eclogite. (*Foulger et al. 2004*)

Seismic tomography shows a near vertical LVZ (subducted slabs show High Velocity Zones) extending from Iceland and possibly all the way to D'' (Fig 10)(*Bijwaard & Spakman, 1999*), which is interpreted to show a 'deep mantle plume' which is responsible for the formation of the NAIP as a normal result of conductive core cooling., of coarse, others such as *Foulger et al.(2004)* interpret this to be evidence for subducted oceanic crust. This debate is still unresolved (which includes more than the two authors cited above).

4.3- The Ontong Java Plateau (OJP)

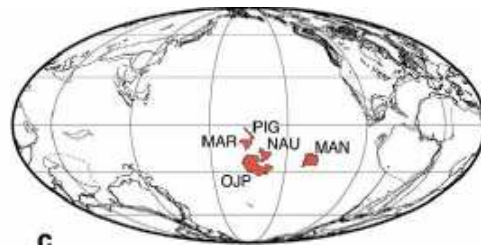


Fig 11 Map showing the location of the OJP with respect to the Pacific ocean. (*Ingle & Coffin, 2004*)

The OJP is the largest LIP known on Earth, and is located in a near central position of the Pacific ocean (Fig 11). The OJP is roughly the same size as Alaska (USA), covering an area of at least 6 Mkm². The main eruptive stage was 122 Ma (early cretaceous) with smaller eruptions 62 & 34 MA (early & mid tertiary), with a maximum crustal thickness of ~30km (*Ely & Neal, 2003*). Beneath the OJB is a low velocity root descending ~300 km into the mantle (*Ingle & Coffin, 2003*). This LIP is not associated with continental break-up (plate tectonics) (*Burke & Torsvik, 2004*).

4.4- Conflicting ideas on the formation of the OJP

There is great confusion over the origin of the OJP. Conflicting models have been put forward to explain the formation of the worlds largest LIP. These include cataclysmic melting in the inflated/decompressed heads of newly risen plumes or a 'super-plume' and large meteorite/asteroid impact (*Tejada et al. 2004*).

The plume or 'super-plume' theory has a few problems regarding the OJP formation. There is a lack of a post-plateau seamount chain caused by a moving continent over a fixed plume, lack of any active plumes with which to link to the OJP and post-eruptive subsidence of the plateau appears to have been much less than expected for oceanic lithosphere post-plume or 'super-plume' (*Tejada et al. 2004*). Seismic tomography shows a 300km tail from the OJP into the upper mantle (*Ingle & Coffin, 2004*). There is still however evidence for plume activity in a geochemical sense, the OJP basalts contain enough concentrations of Platinum Group Elements (PGE) to indicate an outer-core origin transported by a deep mantle plume from D'' (*Ely & Neal, 2003*). This is not final, as 168Os/188Os ratios can not be derived. The 107Ar/109Ar ratios have not yet been determined, which would tip the balance one way or another regarding the plume idea for OJP origin.

The PGEs can be explained by other processes other than plumes, Impact of a large and fast enough (>10 km diameter at 20 km/s) Chondritic meteorite. This would remove ~60 km overburden in an area in excess of 200km, causing decompression melting and possibly a ~300 km tail (Fig 12). The mantle root could be ‘replacement’ material in-filling the vaporized and uplifted (due to buoyancy) overlying material. This is based on the S-wave velocity change being -5%, which ‘if’ representative of temperature would indicate a ~700°C temperature gradient between the root of the OJP and the surrounding mantle, enough to cause volcanism now. Decompressed material sufficiently reduces its shear modulus relative to the surrounding material giving the 5% reduction in S-wave speed. There is also an absence of large impact craters in oceanic lithosphere post-Jurassic times possibly due to the formation of LIPs which auto-obliterate craters (*Ingle & Coffin, 2005*)

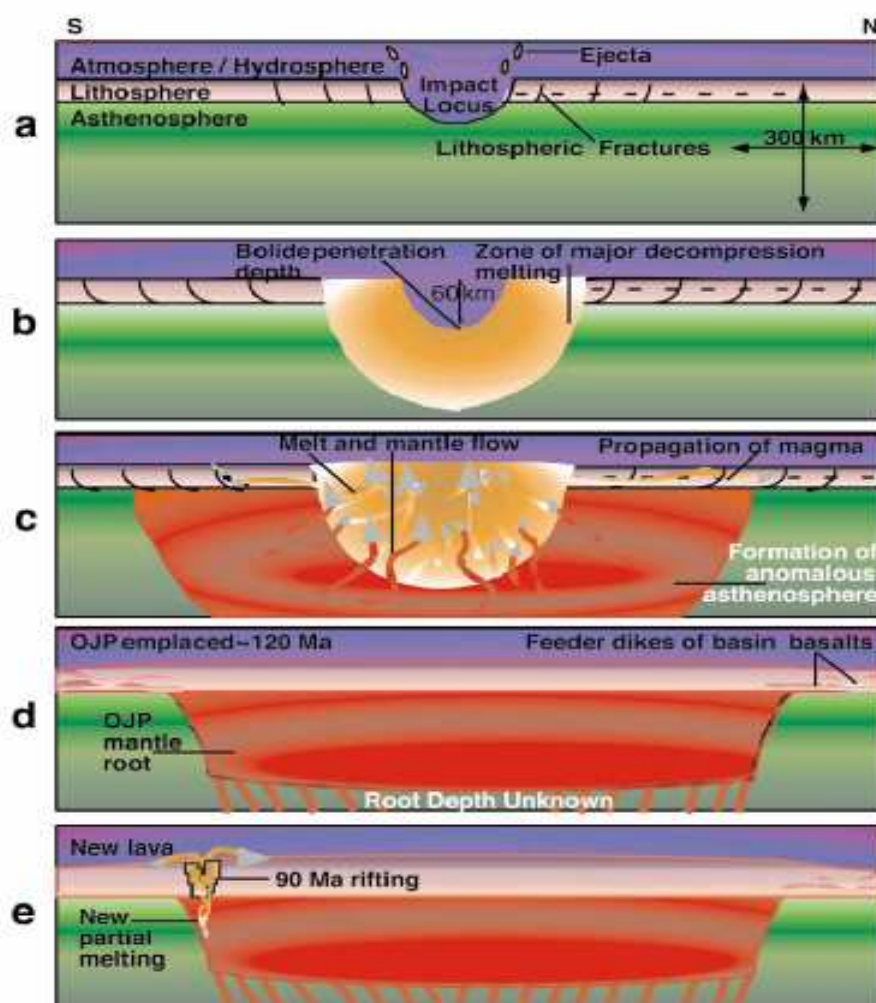


Fig 12. Conceptual model of impact generated volcanism of OJP. a) Moment of impact, hydrosphere and oceanic lithosphere are displaced. Asthenosphere penetrated. b) Maximum penetration, decompression melting starts. c) Crater auto-obliterated by up-welling of magma. Lithospheric fractures form dykes. d) ~120 Ma, the OJP at end of emplacement, pink layer is new crust. e) 90 Ma tectonism causing more decompression melt and rifting occurs. Scale is maintained throughout. (*Ingle & Coffin, 2004*)

4.5- The Deccan Traps or Deccan Volcanic Province (DVP)

The DVP is located in India (south and central) extending into the Arabian Sea (Fig 13). The DVP basalts were extruded ~65 Ma at the time of the K-T boundary. The activity is thought to have occurred rapidly in <1 million years spanning with areal extent of 0.5 Mkm (*Ravi Kumar & Mohan, 2005*). The DVP is traversed by the Cambay triple junction (Fig 13) of rifting, indicating that the DVP could be caused by plate tectonic activity decompressing the upper mantle and not causing it like the NAIP.

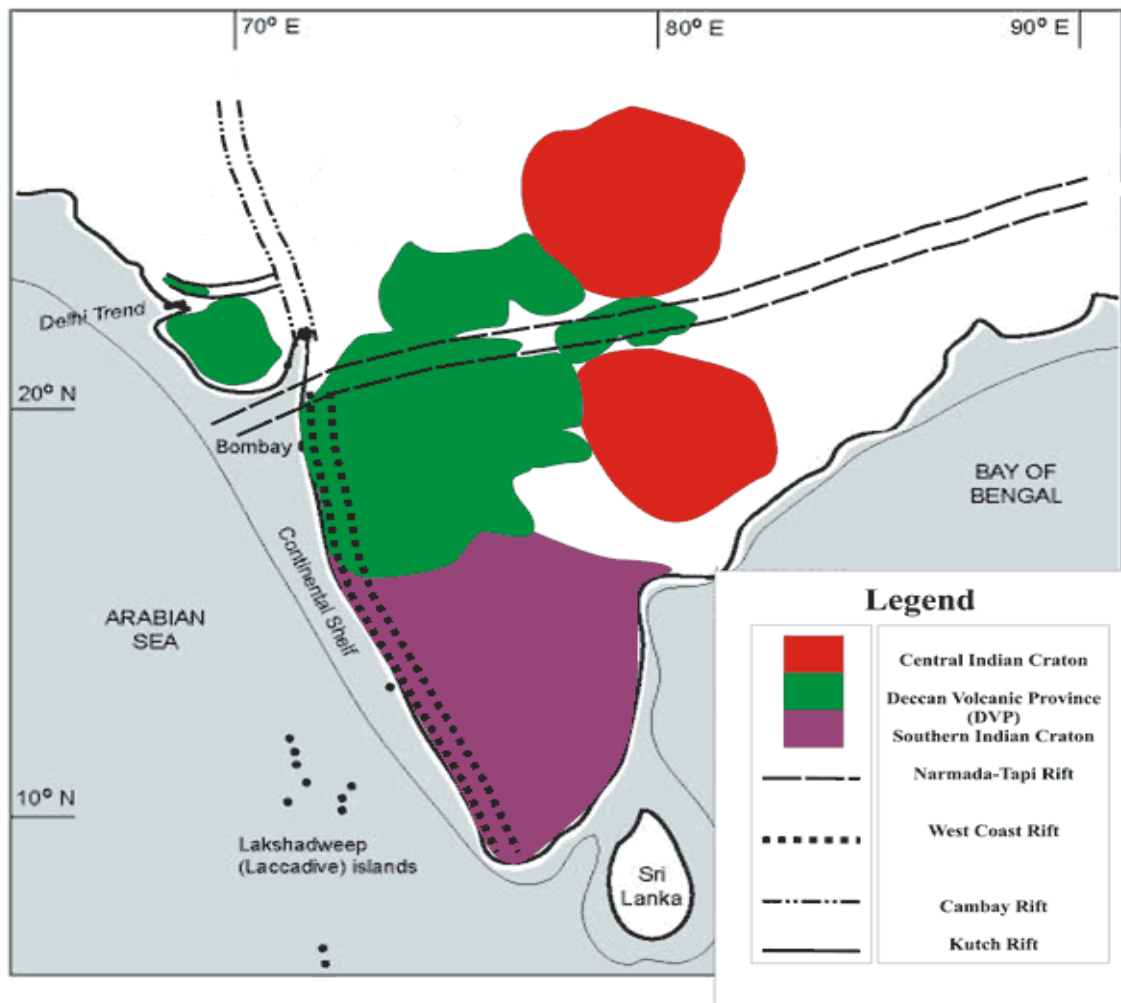


Fig 13 Geological map of the DVP showing the Cambay triple junction. (*Sheth & Chandrasekharam, 1997*)

4.6- Conflicting ideas on the formation of the DVP

The DVP is one of the world's best exposed LIPs (>70% land exposure) yet still its genesis remains poorly understood (*Rejan et al. 2005*). The common conception is that the Reunion plume causing the DVP as India migrated north on separation from Gondwanaland (*Sheth & Chandrasekharam, 1997*) ~65 Ma. In *The Deccan beyond the plume hypothesis (2005)* Sheth argues that plate-tectonics and lithospheric delamination can explain the DVP. This is backed up as the Reunion plume being situated 21°S, and the DVP having been erupted at 30°S. The Reunion plume is fixed, the migration of magma

laterally beneath the lithosphere from 21°S to 30°S is doubtful, and there is no evidence of whole mantle roll to argue migration either. But the $^3\text{He}/^4\text{He}$ are high enough to suggest (conceptionally) deep mantle plume magmas in the DVP basalts.

The large volumes of melt with such a high eruption rate indicates rapid decompression with a high rate of melting and a direct, secure plumbing system from magma source (chamber) to surface (*Rejan et al. 2005*).

Slightly hotter mantle (+100°C), relatively lower solidus of delaminated lithosphere to surrounding mantle (-100°C) and focusing the magma beneath a (tectonic) triple-junction could cause sufficient melt for a LIP (*Anderson, 2005*). Fig 13 shows that the DVP is situated in an area with a tectonic triple junction of rifts. There is no known plume available to support the volcanism at the DVP (*Sheath, 2005*).

So based on evidence for the origin of the DVP, a magma chamber situated in the lithosphere beneath India since 460 Ma erupting steadily pre-DVP and mostly crystallizing (cooling). During India's northerly migration from Gondwanaland ~190 Ma. Delamination of the lithosphere then occurred, this increased fertility of the magma chamber, decompression and thinning of the lithosphere, this sequence of events would give rise to the formation of the DVP according to the Lithospheric Delamination theory (*Rejan et al. 2005*)

5- Evaluation

It can be concluded that-

- There is a sketchy but systematic occurrence of LIPs throughout Earth's history (~1 per ~10 Ma). LIPs on Earth form all over the global surface, so it appears that there are no geographical constraints for LIP generation on Earth.
- Lack of credible data means no legible pattern of occurrence through time can be concluded for Martian LIPs, but most activity appears to have occurred ~2-4 Ga. Although geographical constraints seem apparent as most of Martian volcanism is concentrated around its equator, and generally focused in and around the Tharsis province (accept the Elysium Planitia province). Which is odd as the thin northern crust seems best suited for initiation of volcanism relative to the thick south as thin or thinned lithosphere is easier to penetrate relative to thick lithosphere.
- There is no conventional origin (process of formation) for LIPs. The origin of a LIP is dependant on the LIP in question. But there is a correlation with LIPs and LVZs/ULVZs indicating a ~direct relationship.

For example-

1. The NAIP, based on seismic tomography, plate tectonics and isotropic evidence is put down to the Iceland plume (although the origin of the Iceland plume [mantle up-welling] is arguable as to source of material, never the less it is still a plume). This LIP is associated to the formation of the mid-Atlantic spreading ridge. But palaeo-plate tectonics shows that there was a subduction zone present so the model for re-melted sub-ducted oceanic crust is still attractive and can not be overlooked.

2. The Ontong Java plateau is interesting as isotropic data, argues for both deep mantle plume and the impact of a large Chondritic meteorite (due to PGEs). Seismic tomography picks up a tail only 300km deep which could be the tail end of an old plume or decompressed upper mantle due to the impact theory. This depends on the LVZ being a chemical or physical difference. As a chemical difference would argue for a mantle plume transporting material from deeper in the Earth (assuming that the plume is a thermo-chemical upwelling and not just thermal upwelling), and a physical difference would argue for decompressed upper mantle material with the same composition as the surrounding upper mantle material which displays a lower shear modulus due to decompression.
3. The origin of the Deccan traps is generally not well understood despite being one of the best exposed. Its genesis is still being worked out/debated among planetary/igneous geologists on two sides, the plume and those who won't take plume for an answer.
4. For the Tharsis province until more credible data is accumulated, i.e. seismic tomography, isotope data and more research, the plume model seems best suited. Although the Impact generated magmatism theory is attractive, and plausible as Mars is theoretically too small for such a large plume as proposed.

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