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The Prospectivity of Hotspot Volcanic Islands for Geothermal Exploration

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ABSTRACT

The majority (>90%) of the World's geothermal developments have been associated with volcanism adjacent to subduction zones at crustal plate boundaries. However the increased level of international interest in utilising geothermal resources for power generation, has directed attention to hotspot volcanic islands that are remote from subducting plate boundaries. This has been driven by the very successful development of geothermal resources in Iceland and Hawaii at so-called hotspots.

Over the past twenty years the origin and mechanisms of hotspot volcanics and mantle plumes has become a specialised field of study. In order to better assess the geothermal prospectivity of hotspot volcanic islands the questions must be asked - what other field associations, field relationships, chemical, mineralogical or petrological characteristics might be useful in such early assessments? What roles do size and age, magma type, and hydrological setting play in providing a suitable setting for high temperature geothermal systems? Seven hotspot islands are reviewed in the paper. They include Iceland, Hawaii, the Azores, Ascension, the Canary Islands, Samoa and Tahiti.

There are also strong economic drivers to encourage the development of such indigenous island resources for base load electricity supply on islands that are otherwise dependant on imported fuel oil.

1. INTRODUCTION

With the increased level of international interest in utilising geothermal resources for power generation, greater attention is being given to the exploration of hotspot volcanic islands for their geothermal potential. On a world-wide scale, a large proportion of developed geothermal fields are located adjacent to subduction zones at crustal plate boundaries. The so-called Ring of Fire around the Pacific Ocean host a large proportion of the World's currently developed systems. However, in Iceland, Hawaii and the Azores high temperature geothermal systems are hosted on hotspot volcanic islands whose dominant rock type is mantle derived basalt. However, there is also some evidence of more acidic magmas at these locations.

This paper does not discuss systems associated with subduction zones. It specifically addresses the prospectivity of hotspot volcanic islands.

Evidence is presented from hotspot literature and current geothermal exploration and development on a selection of hotspot volcanic islands. Variables that are considered include:

- The magnitude, age and depth of hotspot and associated mantle plume
- Magma composition
- Geological and structural setting
- Hydrological setting
- Surface features

Hotspot islands selected for this review are Iceland, Hawaii, the Azores, Ascension, and the Canary Islands, when there have already been some successful exploration and/or developments taking place. In addition some background information is provided on Samoa and Tahiti which are located above the margin of the Pacific Superplume and may be a good target for future exploration.

2. REVIEW OF HOTSPOT LITERATURE

The origin of hotspots is a controversial topic. Wilson (1983) proposed at least 60. Some have tens of volcanoes associate with them. For example the Louisville hotspot has over 80 related volcanoes. Morgan (1971, 1972) proposed that deep mantle plumes created in the lowermost mantle are the source of some hotspots: most notably those having linear chains of extinct volcanoes which are thought to have formed on lithospheric plates, and which migrated as the plates drifted over them. Hawaii and its connected seamount chain are the most conspicuous example. It was also proposed that hotspot volcanoes could alternately have formed by tensional cracking of the lithosphere (Turcotte and Oxburgh, 1973).

Courtillot et al. (2003) identified 49 hotspots throughout the World of less than 1 My in age, and proposed five criteria to characterise them. He proposed that plumes originating from deep in the mantle should have these criteria whereas shallower sourced hotspots should not. These criteria are:

(1) presence of a linear chain of volcanoes (track) with monotonous age progression,

(2) a flood basalt at the origin of this track,

(3) a large buoyancy flux (a strong plume acendancy rate) which he put at > 10^3 kg/sec, which would result in slow cooling rates during ascendance.

(4) consistently high ratios of the three to four isotopes of helium, and

(5) a significant low shear wave velocity (VS) in the underlying mantle.

Based on these criteria Courtillot (2003) identified only seven so-called 'primary hot spots' which he considered to have a very deep origin (three in the Pacific and four in the Indo-Atlantic hemisphere. They include Hawaii, Easter and Louisville in the Pacific hemisphere and Iceland, Afar, Reunion and Tristan in the Indo-Atlantic hemisphere.

Samoa was considered to be close to classifying as a primary hotspot but lacked the presence of flood basalts.

Anderson (2005) acknowledged both shallow and deep origins but believed that Courtillot's criteria ignored the significance of shallow processes (stress, plate tectonics, so-called fertility (compositional) variations along with an asthenosphere that is close to its melting point. Anderson concluded that most hotspots are not caused by mantle plumes from deep boundary layers: but that such volcanism is controlled by lithostatic architecture, stress and fabric rather than concentrated jets of deep mantle material. Location was therefore controlled by stress and fabric. Volume was controlled by fertility (composition, volatile content and solidus) of the mantle, small scale convection, plate thickness, plate stress and to a lesser extent temperature.

Zhao (2007) presented an extensive series of whole mantle tomographic images of 60 of the World's hotspots. His study showed good general agreement with the conceptual diagram of Nataf (2000) (Figure 1) where the dashed lines show the 410 and 660 km discontinuities and the top of the D″ layer above the core–mantle boundary (CMB).

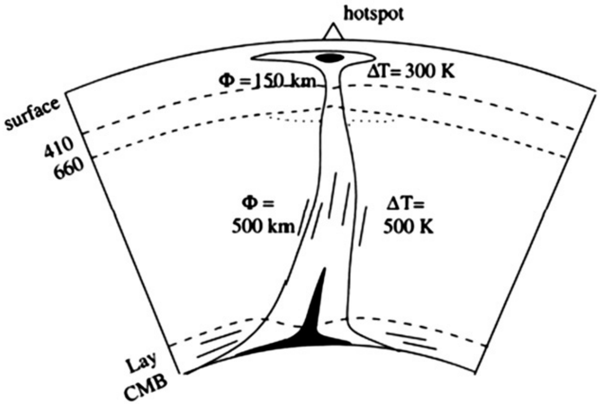

Figure 1. Conceptual mantle plume (after Natev, 2000)The black parts denote melts. Short lines in the mid lower mantle and the D″ layer show the preferential alignment of minerals, which could induce seismic anisotropy.

Zhao (2007) undertook lateral resolution of the tomographic images to about 400–600 km under the oceanic hotspots providing some deeper evidence of their origin. Twelve plume-like, continuous low-velocity (low-V) anomalies in both the upper and lower mantle are visible. Zhao (2007) classified these hotspots as grade 1 or 2. These included Hawaii, Tahiti, Iceland, Cape Verde and Reunion, hotspots, suggesting that these were whole-mantle plumes originating from the core–mantle boundary (CMB). Figures 2 and 3 present his tomographic images for Hawaii and Iceland.

Tomographic images for Samoa, Ascension, Azores and the Canary Islands also show tomographic patterns indicating mantle plume derived low velocity zones in parts of the mantle. These hotspots were classified from 2-3 by Zhao (2007).

In most cases, the seismic images under the hotspots are complex, particularly around the mantle transition zone. A thin low-V layer is visible right beneath or just above the 660-km discontinuity which was considered by Zhao (2007) to reflect possible accumulation of plume materials in the top part of the lower mantle or the bottom of the upper mantle. The variety of behaviours of the low-V anomalies under hotspots reflects strong lateral variations in temperature and viscosity of the mantle, which control the generation and ascent of mantle plumes as well as the flow pattern of mantle convection.

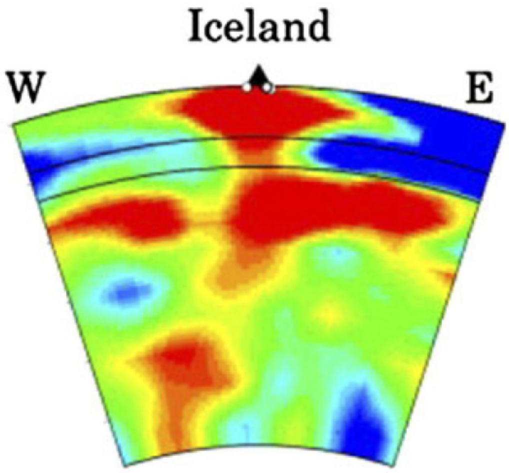

Figure 2. Tomographic image Iceland (Zhao, 2007)

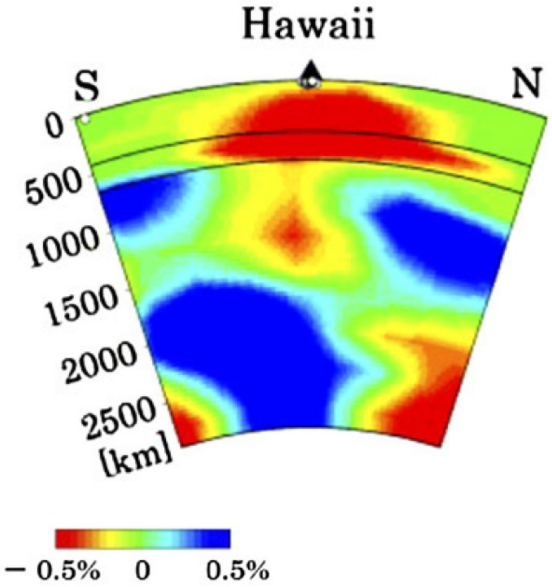

Figure 3. Tomographic image Hawaii (Zhao, 2007)

The Pacific superplume: Under the South Pacific superswell where six hotspots (Samoa, Tahiti, Pitcairn, MacDonald, Easter, and Marquesas) are located, a huge slow anomaly (>2000 km wide) is visible in the entire mantle (Figure 4). The centre of the superplume is located directly beneath Tahiti (Society Island) and the Marquesas. Four other hotspot volcanic islands (including Samoa) are located at the edges of the superplume.

3. GEOLOGY AND HYDROLOGY OF ISLAND HOTSPOTS

3.1 Magma Composition

The basalt magma which dominates hotspot volcanics has a low viscosity so that it can force its way through the overlying crust quite quickly (speeds of 5 kilometres per hour have been estimated). An important aspect of this style of volcanism is that there is no crustal magma reservoir present between eruptions so there is no continuous source of heat to drive geothermal systems.

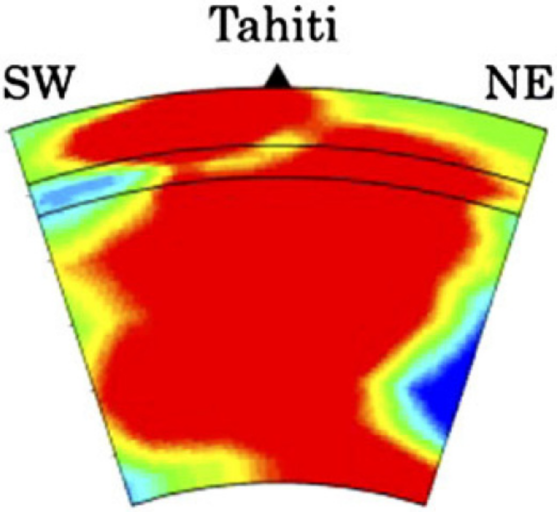

Figure 4 Tomographic image of the Pacific Superplume under Tahiti (Zhao 2007)

In terms of juvenile' or 'primary' water content of magma, subduction related melts derive from crustal material that contains water. The water lowers melting point, causing melting and buoyancy in the subducting slab and overlying crust. Such subducted waters may eventually be recycled and contribute fluid to hydrothermal systems in island arc settings, but will be absent at hot spots.

In New Zealand, the subduction located volcanics that host geothermal systems are, viscous andesite and rhyolite magmas whose compositions reflect processes such as partial melting or mixing of magma remelted crustal material/anatexis.

Evidence of intermediate or acid volcanism at hotspots was sought during the literature search.

3.2 Hydrological settings and Surface features

Worldwide exploration of geothermal systems associated with volcanism adjacent to subduction zones at crustal plate boundaries has led to a fairly well defined series of surface features which guide surface exploration.

Although there is less experience in exploring on hotspot volcanic islands, with the exception of Iceland, there frequently seems to be an absence or lack of well defined surface features.

By comparison to island arc geothermal systems, hotspot islands show less surface springs or weaker surface indicators of geothermal activity. This may be due to a combination of several factors including: (i) the absence of a shallow magma chamber, (ii) permeability, and (iii) the absence of 'juvenile' or 'primary' water in hotspot magma.

In terms of permeability, hotspot volcanic islands are commonly composed of fragmental volcanics with high permeability and steep terrain. Accordingly, surface waters are conducted freely to lower elevations and the water table in these settings is usually only meters above sea level. Deep thermal waters may be capped by older weathered lava flows or masked by lateral flow of overlying cold groundwater.

Not all water on volcanic islands flows directly to low elevations however. Groundwater is common at higher elevations in both Hawaii and Tenerife, where dykes can provide impermeable barriers to flows along faults.

4.0 EVIDENCE FROM SELECTED HOTSPOTS

4.1 Hawaii

In Hawaii, Teplow et al. (2009) has reported dacitic dikes in a recent borehole at Puna. A dacite melt was encountered during routine commercial drilling operations of injection well KS-13 at the Puna Geothermal Venture wellfield on the Big Island of Hawaii. The KS-13 drill hole, drilled in 2005, is located along a segment of the Kilauea Lower East Rift Zone which erupted basalt flows from rift-parallel fissures in 1955. During the drilling of KS-13 a 75-metre interval of microdiorite containing brown glass inclusions was penetrated at a depth of 2415 m. At a depth of 2488 m a melt of dacitic composition was encountered. The melt flowed up the wellbore and was repeatedly re-drilled over a depth interval of ~8 m, producing several kilograms of clear, colourless vitric cuttings at the surface.

Hawaii, (currently 35MW geothermal generation installed and potential of 250MW), has few surface thermal springs. Fumaroles are present.

4.2 Iceland

Although Iceland is predominantly basaltic there are several recorded occurrences of more silicic magmas. The largest is in central Iceland where Gunnarsson et al. (1998**)** reported that the Torfajökull volcano contained the largest volume of exposed silicic extrusives in Iceland (~225 km^3). erupting from a family of fissures 1–2.5 km apart within or just outside a large caldera (12×18 km). The silicic lavas were composed of five chemically distinct units. and were considered to have evolved by the extraction and collection of small parcels of silicic melt from originally heterogeneous basaltic crustal rock through heterogeneous melting and wall rock collapse (solidification front instability, SFI). Chemically, this occurred as a two-stage process of crystal fractionation. Gunnarsson et al (1998) considered that the accumulation of high-temperature basaltic magmas at shallow depths beneath the Icelandic rift zones and major central volcanoes, coupled with unique tectonic conditions, allowed large-scale reprocessing and recycling of hydrothermally altered Icelandic crust. The end result was a compositionally bimodal proto-continental crust.

Iceland has a long and extensive history of exploitation of hot springs for direct use as well as the more recent exploitation of their high temperature systems. Fumaroles are present.

4.3 The Azores

The Azores are predominantly basaltic, but on Terciera Collis (1982) describes some silicic volcanism. Terciera Island is one of nine islands of the Azores which are located at a triple junction between the North American, Eurasian and African Plates.

Collis (1982) reports evidence of active hydrothermal systems including weak fumaroles and areas of hot ground. No hot springs are evident but there is evidence of some rifting and caldera collapse which may be useful indicators of zone of high permeability for fluid flow.

4.4 The Canary islands

The Canarian Archipelago, is one of the major volcanic island groups in the Atlantic Ocean basin, consists of seven major islands (Lanzarote and Fuerteventura to the east; Gran Canaria, Tenerife, and Gomera in the centre; and Hierro and La Palma in the west. Schmincke, and Sumita (1998) reconstructed the volcanic evolution of Gran Canaria from apron sediments: synthesis of an ocean drilling project and encountered a range of compositions from basalts to rhyolites.

In Tenerife there are no known surface thermal springs, but fumaroles are present. Groundwater flow on Tenerife is strongly influenced in the vertical direction by nearly impermeable deposits, such as the debris avalanche deposits known as the mortalón, and in lateral directions by the extensive dyke system along the rift zones.

4.5 Ascension

Studies on Ascension by Nielson and Stiger (1996) and Adams (1996) confirmed a high proportion of pyroclastic deposits relative to lava flows (based on exposure). The central and eastern parts of the island predominantly comprise pyroclastic deposits (both mafic and silicic) and trachyte lava flows and domes. The rest of the island predominantly comprises scoria cones and mafic lava flows, some of which have a thin veneer of pyroclastic deposits. K-Ar whole rock age dates (mostly for trachyte) suggest that the oldest exposed rocks are about 1 million years old. A deep (3126 m) geothermal exploration well (Ascension #1) records much of the history of the formation of the island Below 1966 m, the sequence is largely mafic; felsic rocks mostly occur only above 887 m depth.

On Ascension Island there are no known surface thermal springs, but fumaroles are present.

4.6 Tahiti and Samoa

These islands are located in above (Tahiti) and on the margins of (Samoa) the Pacific Superplume.

On Tahiti there is evidence of plutonic rocks in the Tahiti-Nui caldera (Bardintzeff et al.,1988). In French Polynesia geothermal upwelling within a lagoon is described by Rougerie et al. (1992) which is indicative of elevated thermal gradients. No data was found on thermal features or geothermal exploration.

Kear and Wood (1959) provided a detailed description of the geology of Western Samoa. Savai'i island is a basaltic shield volcano with eruptions known in historical times. The island has numerous volcanic centres from older eruption sites.

On Samoa there are no known geothermal surface features. However, Layman Associates (2003) report possible warm temperatures (27-31°C) in coastal boreholes on Savai'i. Therefore, despite the recent volcanism there is no direct evidence for the existence of a hot reservoir at depth. Layman Associates (2003) suggests that deep thermal waters may be capped by older weathered lava flows or masked by lateral flow of overlying cold groundwater.

4. SUMMARY

4.1 The role of Mantle Plumes

Although the plume literature confirms the presence of deep mantle plumes beneath all of the geothermal targets discussed in this paper, we believe the near surface processes may play a more significant role in developing suitable hosts for geothermal exploration. Therefore evidence of near surface processes such as mixing, reprocessing, partial melting and the presence of plutonic or felsic magmas should be used as exploration criteria.

4.2 Felsic units

In this study we have confirmed the presence of more acidic units (dacites, rhyolites and trachytes) in Iceland, Hawaii, Azores, Ascension the Canary Islands and Tahiti. They may provide the slowly cooling plutons that would be the heat source for geothermal systems.

Their origin may be from the reprocessing of earlier basaltic materials (e.g., Gunnarson et al, 1998) especially on islands where sustained magmatism allows reprocessing of the existing volcanic/plutonic pile. Greater attention to petrographic studies maybe worthwhile to look for evidence of xenoliths of felsic material.

4.3 Age

Age of the volcanics is definitely a key criterion. Perhaps targets younger than several hundred thousand years should receive higher priority for exploration?

4.4 Summary compilation of data

The evidence compiled from this review is presented in Table 1 which includes:

- classifications by Courtillot (2003)
- classification by Zhao (2007).
- selected geological, geophysical data
- exploration and development data.

The tomographic studies of hotspot island volcanic islands have demonstrated that most are associated with large deep mantle plumes with associated large volume discharges and prolonged and continuous activity. However, tomography should not be used in isolation to rank geothermal prospects.

In all cases intermediate or acid volcanic or plutonic bodies are associated with the more typical mantle-derived basalts. These dacites and rhyolites are likely to have originated by the reprocessing of basalts (involving partial melting and/or differentiation processes) during the prolonged periods of magmatic activity.

5. CONCLUSIONS

If the currently explored/exploited hotspot volcanic islands are to be used as a template for future exploration of hotspot volcanic islands the following criteria may provide a useful guide to prioritising exploration targets:

1. **Age of the magmatic activity**: Dating prospective targets would be a relatively low cost exploration tool for prioritising exploration targets. The younger the volcanism the better.

2. **Size and Depth of the Mantle Plume**: Depth of the mantle plume maybe less relevant than near surface processes. However, we would favour evidence of recent volcanism and an extended period of volcanic activity to promote both heat and development of more silicic bodies.

3. **Size:** Of the most recently active hotspot volcanic islands, those having large topographic signatures (above the sea floor) are more likely to have larger buoyancy fluxes and more residual heat.

4. **Surface Features:** Current evidence from many hotspot volcanic islands indicates that the thermal features we have learned to expect at island arc settings may be weak or absent. Prioritising exploration prospectivity on the basis of surface features (which are typical of island-arc geothermal systems) may not be a good idea. Greater attention may need to be paid to identifying higher than normal thermal gradients. Perhaps temperature gradient drilling may be useful at an early stage.

5. **Petrographic studies:**

   Greater attention needs to be paid to mapping volcanic units and determining if felsic units are present. Undertaking petrographic studies of volcanic material to look for evidence of xenoliths of intermediate or acidic magmatic material may provide evidence of felsic materials at depth.. A similar recommendation has been made for exploration of continental hotspots by Demisse (2008).

6. **Pacific Exploration:** Based on these criteria, prospective hotspot Pacific volcanic islands could include those islands located over the Pacific Superplume. These include Tahiti, Easter Island, Marquesas, Macdonald, Pitcairn, and Samoa.

REFERENCES

Adams, M. C. (1996): Chemistry of fluids from Ascension 1, a deep geothermal well on Ascension Island, South Atlantic Ocean. *Geothermics* 25: 561–579.

Anderson, D.L. (2005): Scoring Hotspots: The plume and plate paradisms. In Plates, Plume and Paradisms: G.R. Folger, Natland,J.H., Presnall, D.C., Anderson D.L. *Special Paper 388, Geol. Soc. America*, pp 31-45.

Ásmundsson, R.K.(2008): South Pacific Islands Geothermal energy for electricity production. Icelandic International Development Agency.

Bardintzeff, J.M., Bellon. H., Bonin.B., Brousse. R. McBirney, A.R. (1988): Plutonic rocks from Tahiti-Nui caldera (Society Archipelago, French Polynesia): a petrological, geochemical and mineralogical study. *Journal of volcanology and geothermal research:* v 35 1-2, pp. 31-55.

Collis, S.K. (1982): Geology of the PicoAlto geothermal prospect Terciara Island, Azores*: Proc. 4th N.Z. Geothermal Workshop* pp 381-383.

Courtillot, V. (2003): Three distinct types of hotspots in the Earth's mantle. *Earth and Planetary Science Letters* 205, 295-308.

Demisse, G. (2008): Magmatic Association of Hydrothermal Activity in the Northern and Central Sectors of the East African Rift System (EARS): Abstract of presentation at *the 2nd African Rift Geothermal Conference*, Entebbe November 2008.

Gunnarsson, B., Marsh, B.D., Taylor, H.P. Jr (1998): Generation of Icelandic rhyolites: silicic lavas from the Torfajökull central volcano. *Jour. of Volcanology and Geothermal Research*. Vol. 83, 1-2, July 1998, 1-45.

Kear, D. and Wood, B.L. (1959): The geology and hydrology of Western Samoa. N*.Z. D.S.I.R. Geol. Survey Bulletin* n.s. 63.

Layman Energy Consultants Inc (2003): Preliminary feasibility study for a geothermal electric power project. Island of Savai'i. Independent State of Samoa. Presented to the Ministry of Public Works and the Electric Power Corporation, Apia, Samoa.

Morgan, W., (1971): Convection plumes in the lower mantle. Nature 230, 42–43.
Morgan, W., (1972): Deep motions and deep mantle convection. *Geological Society of America, Memoirs* 132, 7–22.

Nataf, H., (2000): Seismic imaging of mantle plumes. *Annual Review of Earth and Planetary Sciences* 28, 391–417.

Rougerie, F., Fagerstom, J.A. Andrie,C. (1992): Geothermal endo-upwelling: a solution to the reef nutrient paradox? *Continental Shelf Research*, Vol. 12, no. 7, pp. 785-798.

Schmincke, H. U,. Sumita, M. (1998): Volcanic evolution of Gran Canaria reconstructed from apron sediments: synthesis of Vicap project drilling. *Proc. of the Ocean Drilling Program, Scientific Results,* Vol. 157 Weaver, P.P.E.,
Schmincke, H.-U., Firth, J.V., and Duffield, W. (Eds.).

Stieltjes, L. (1985): Statistical and probabilistic approach volcanic hazards for location of geothermal wells and plant in Fournaise active volcano (Reunion Island), *Int Symp on Geothermal Energy. GRC*. p 541□545.

Turcotte, D.L., Oxburgh, E.R. (1973): Mid plate tectonics, *Nature* 244, pp 337-339.

Teplow, W., Marsh, B., Hulen, J., Spielman, P., Kaleikini, M., Fitch, D., Rickard, W. (2009): Dacite melt at the Puna geothermal fVenture wellfield, Big island of Hawaii. *In press, GRC Council Proceedings* 2009.

Wilson, J., (1963): A possible origin of the Hawaiian islands. *Canadian Journal of Physics* 41, 863–870.

Zhou, D. (2007): Seismic images under 60 hotspots: Search for mantle plumes, *Gondwana Research* 12, 335–355.

Table 1 Summary of data for selected hotspot volcanic islands

Hotspot Island	Mantle plume extent / Classification by Zhao (2007)	Classification by Courtillot (2003)	Magma Types / Age	Thermal features	Geothermal Development
Hawaii	Whole mantle / 1	4	Basalt, Dacite dikes / Historical and current	Few hot springs but numerous fumaroles	35MW plant installed. 250MW potential
Iceland	Whole mantle / 1	4	Mafic and felsic / Historical and current	Numerous hotsprings and fumaroles	570MW plant installed, 6000MW potential
Ascension	Upper mantle, transition zone (410-660km depth), lower mantle / 3	0	Mafic and felsic / 1000 yrs	Fumaroles are present	No development, but exploration drilling has been undertaken
Azores	Upper mantle, transition zone (410-660km depth), lower mantle / 2	1	Mafic and felsic / Historical	Hot ground with weak fumarolic activity	28MW installed, 200MW potential
Canary Islands	Transition zone (410-660km depth), upper part of lower mantle, lower mantle / 3	2	Various compositions: basalts to rhyolites / Historical and current	Fumaroles present at Teide summit, but no thermal springs	No development
Samoa	Upper mantle, transition zone (410-660km depth), upper part of lower mantle / 3	4	Basalt / 100yrs	No known thermal features	No development
Tahiti	Upper mantle, transition zone (410-660km depth), upper part of lower mantle / 3	4	Basalt Plutonic rocks Tahiti-Nui caldera	No data	No developments