Geofile Online

SEPTEMBER 2006
526

TIM EDDIS

HOT SPOTS IN PLATE TECTONICS – EVOLUTION OF A THEORY

Introduction

Plate tectonic theory has come a long way in its relatively short history. Building on Alfred Wegener's observations on continental drift, it was only in the 1960s that seismologists and geophysicists obtained sufficient scientific data to establish the underlying mechanics of Earth movement (broadly vindicating Wegener's ideas). In the succeeding 40 years it has since been widely accepted that the globe's oceanic crust (65% of the Earth's surface) and continental crust (35% of the Earth's surface) are buoyed along on an extremely viscous mass of molten rock (comprising the upper mantle, often described as 'plastic' in its flow characteristics); and that underlying convection currents are the main motive force for the movement of tectonic plates (Figure 1). And yet, while the circumstantial and scientific evidence for plate tectonic theory is almost overwhelming (see Further Reading), there is one aspect that remains potentially problematic – explaining the origins of the world's hot spot volcanism (Figure 2).

Background

The *Dictionary of Physical Geography* defines a hot spot as:

> 'A small area of the Earth's crust where an unusually high heat flow is associated with volcanic activity. Of approximately 125 hot spots thought to have been active over the past 10 million years most are located well away from plate boundaries.'

Figure 1: Cross-section of the Earth

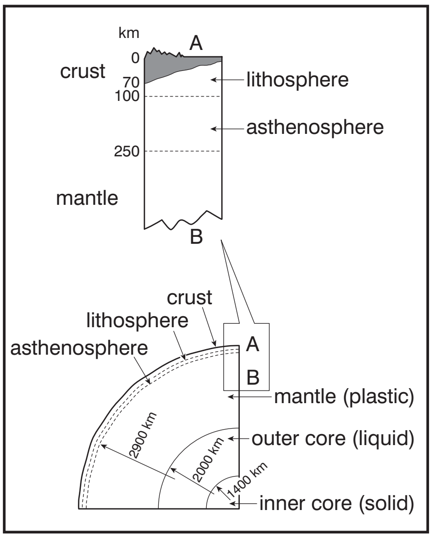
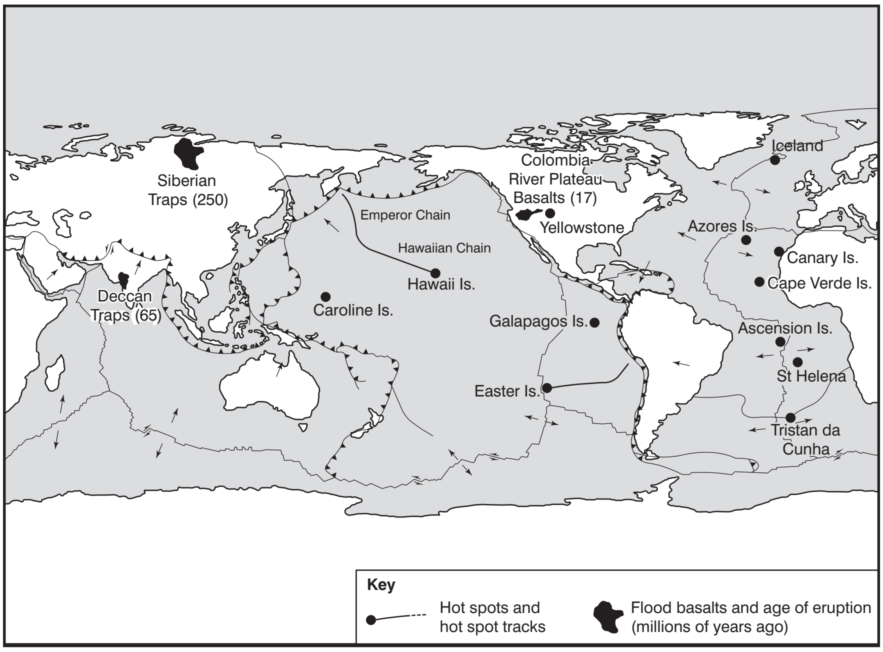


Figure 2: Hot spot distribution



The chain of volcanic peaks comprising the Hawaiian Islands and the volcanic and associated hydrothermal activity of the Yellowstone region in Wyoming provide two examples of currently active hot spots that fit the definition. There are some exceptions to the general rule – Iceland, for example, is formed by an unusually active hot spot situated directly below the mid-Atlantic ridge. An understanding of hot spots can also be used to explain relict features that, nevertheless, have profound geomorphological (and perhaps historical) significance. One such example is the Deccan Traps in NW India, a layered mass of flood basalt up to 2,000 metres thick and covering an area of 500,000 sq km. It is known that these lavas erupted approximately 65 million years ago, and some commentators believe that the enormous amounts of ash and gases that were ejected into the atmosphere in such a large event would have had a global impact on the climate, perhaps even contributing to the extinction of dinosaurs at approximately the same time.

There is still some debate as to how hot spots are formed. In part, this stems from the fact that direct observation of the interior of the Earth simply isn't possible, and that most evidence relies on the interpretation of how seismic waves travel through the mantle. Even the deepest drilling project has probed only 12 km or so into the crust (the Kola Superdeep Borehole in Russia), at which depth the drill bit was threatening to melt in temperatures of 180° C or more. Nevertheless, the available information would seem to indicate the existence of regions of superheating within the mantle where strong convection currents raise mantle plumes, or broad domes of plastic rock up to 1,000 km across. These plumes push upwards to the surface in much the same way that the blobs of translucent wax rise in a lava lamp. On nearing the surface the plastic mantle plume encounters significantly lower pressures and becomes molten; and in certain circumstances this molten rock will pierce the rigid (oceanic or continental) crust above. Where a hot spot coincides with the crustal weakness of a divergent margin, then the outpourings of lava can be significant, as was the case with the Deccan Traps and continues to be the case with Iceland today (situated, as it is, some 2.5 km above the prevailing summit of the mid ocean ridge and covering 100,000 sq. km).

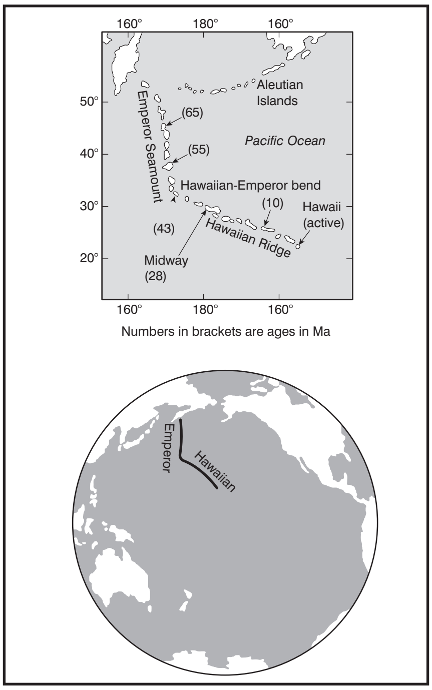
Hot spot theory was first proposed by J. Tuzo Wilson in 1963, and dozens of subsequent studies appeared to support his idea of deep origin, relatively stable, heat sources to account for volcanism that could not be otherwise neatly explained by plate tectonic theory. Even somewhat unexpected sources of evidence seemed to bear out his conclusions – for example, satellite imagery which can show the swelling of the crust in the broad region around a hot spot. In this way it is known that Iceland and the Hawaiian Islands, for example, are atop more generalised 'bulges' in the oceanic crust which are much larger than the volcanic islands themselves, just as would be expected above a large mantle plume.

More recently, however, there have been suggestions in the scientific community that Wilson's beguilingly neat theory should come under greater scrutiny. Of particular concern are several aspects of hot spot 'proof' that might not stand up to further analysis.

Static hot spots

The classic explanation for the bend in the Hawaiian Island and Emperor Seamount chain is that the Pacific Plate changed direction approximately 45 million years ago; however, modelling actual plate movements over time suggests that a change in plate direction alone cannot explain the bend; and that the plume itself must have shifted location. This latter conclusion has been supported by studies of palaeomagnetic and radiometric age data from ocean cores taken in the vicinity of the Emperor Seamount.

Figure 3: Hawaii and Emperor Seamount Chain



Numbers in brackets are ages in Ma

Lithology

Analysis of rocks from the Icelandic crust shows that they formed at a temperature lower than would be expected from a superheated mantle plume.

Simulations

Computer modelling is, as yet, unable to demonstrate how a plume could account for the significant volumes of lava that are found in basalt fields of the Deccan Traps.

Depth of plume

Insufficient evidence exists to show that mantle plumes emanate from deep within the Earth at the core-mantle boundary, as the theorists would suggest.

Alternative theory

In 2003 G. Foulger wrote in a debate on the Geological Society website that the number of modifications and elaborations necessary to make the hot spot theory apply in all cases was a 'sign of a hypothesis in trouble' (http://geolsoc.org.uk), and that there are valid grounds for challenging it. Instead, she proposes that a viable explanation for anomalous volcanism (incorporating all the current exemplars of hot spot activity) could be found by looking at weaknesses that exist in the tectonic plates themselves. It is argued that all plates will have 'scars' from former collisions or divergence, and that larger plates such as the Pacific will be stretched towards the centre as the edges are pulled down into subduction zones. When these more vulnerable parts of the crust pass over slabs of previously subducted material that melt easily in conditions of lowered pressure, the stage is set for volcanic activity on a scale and of a type observed at what are now known as hot spots.

Whichever theory provides the correct explanation for the volcanic activity experienced remote from plate boundaries (or in unexpected volumes as in Iceland), there can be no doubt as to the geographical importance of the igneous activity that has taken place there.

Hawaiian Islands

Hawaii is the 50th of the United States and takes its name from the largest island (called Hawaii or the Big Island), but comprises 19 islands and atolls in total (Figure 3). The islands are all volcanic in origin and show a distinct trend in age the further you travel from the Big Island, where the only active volcanoes in the state are to be found. One of these volcanoes, Kilauea, has been constantly erupting since 1983; while 30 km offshore the Loihi Seamount promises to reach sea level within the next 100,000 years. The basaltic lava flows associated with these volcanoes prove to be more of an inconvenience than a significant hazard, and examples of a'a and pahoehoe lava flows, as well as lava tubes and other volcanic phenomena, are widespread and accepted as part of the landscape.

The benign volcanism of the Hawaiian Islands has created conditions that are of considerable interest to the geographer:

Scientific research

Because Hawaii is almost 4,000 km from the nearest continental landmass it offers ideal conditions for astronomical and atmospheric observations, far from localised pollution sources. In this way the Scripps Institution of Oceanography's Mauna Loa observatory has been able to log increasing global levels of carbon dioxide since the 1950s (Figure 4), making a valuable contribution to our understanding of the enhanced greenhouse effect (webcam views from Mauna Loa can be seen at : http://www.mlo.noaa.gov/LiveCam/FcamMK.htm). The constant eruption since 1983 of Kilauea (the name translates as 'much spewing') has also afforded geophysicists the opportunity to study the chemistry and composition of molten rock, thereby furthering our understanding of extrusive igneous activity.

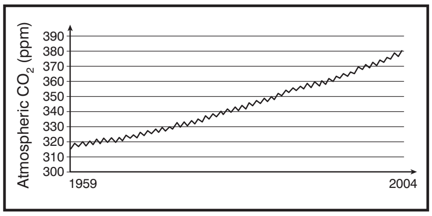
Strategic significance

Quite apart from the fact that, without volcanism, Hawaii wouldn't exist at all, the islands play an important role in US geopolitics. At one time they were a major staging point for trade, and Pearl Harbor continues to be the home port of the US Pacific Fleet.

Agriculture

The combination of mild tropical climate, high annual rainfall totals and decomposed volcanic rock has

Figure 4: Atmospheric carbon dioxide levels, 1959-2004. A clear trend of increasing concentration of carbon dioxide in the atmosphere since 1959 is shown by this data from Mauna Loa (rising from 315ppmv to 379ppmv in 2004). The cyclic fluctuation is caused by the seasonal variation in the growth of vegetation in the Northern Hemisphere.



produced extremely fertile soils in parts of the islands. Hawaii's vast sugar and pineapple plantations are testament to the importance of the primary sector (agriculture accounts for 47% of the state's land area), augmented by the production of nursery plants, coffee and macadamia nuts.

Biogeography

Hawaii's extreme isolation meant that colonisation of the islands by new species took many thousands of years. One estimate suggests that new species became established in Hawaii (under their own power, or blown by storms) only once every 35,000 years. Evolutionary adaptation and selection resulted in plants and animals that were highly adapted to the environment that they encountered, and there are many species that are now unique to the islands. Considerable variation in flora and fauna has been further encouraged by the close proximity of diverse biomes (from tropical rainforest at sea level to high alpine deserts on the volcano flanks).

Figure 5: Taro production. The taro/kalo, also known as the 'potato of the tropics', was once the staple crop of the indigenous Hawaiians. Labour intensive wet-planted kalo (cultivated in a fashion similar to padi rice), such as still exists in pockets on the islands, provided a good source of vitamins and protein and was also known for its medicinal value.

One of the major biological concerns about Hawaii is the introduction of non-native animals that has accompanied recent human colonisation. With native species ill-prepared to compete with invasive aliens, the state Department of Land and Natural Resources claims that 'hundreds or possibly thousands of unique species are already extinct', with hundreds more critically endangered.

Tourism

Hawaii is ideally positioned to benefit from domestic US tourism. Offering a tropical climate, few security concerns, and a familiar currency, it is little surprise that over 65% of the islands' visitors come from the continental United States. The second largest group, at an average of 20% of visitors, comes from Japan. The tourism sector accounts for more than 25% of the local economy and is a significant source of employment. Such dependence on one industry leaves the state vulnerable to changes in consumer trends and the global economy, but tourism in Hawaii has shown remarkable resilience over time – not least due to the unique volcanic landscape that the islands offer.

Yellowstone National Park

Yellowstone National Park forms the core of the Greater Yellowstone Ecosystem, which is one of the largest intact temperate zone ecosystems on Earth. It also sits atop a colossal chamber of molten rock which is under incredibly high pressure. The last significant eruption to occur here was 650,000 years ago, at which time a caldera 30 miles wide by 45 miles long was formed, and much of the western United States was covered in pyroclastic material (enough material was ejected – 1,000 cubic km – to cover the entire country in a layer 12 cm thick).

The United States Geological Survey (http://www.usgs.gov) explains how the hot spot underneath the North American plate has built up an

Figure 6: A 2-metre high Haleakala silversword – a highly adapted species. The Haleakala silversword is a remarkable plant that grows only at higher altitudes on the flanks of the Haleakala Crater on the island of Maui. The sword-shaped leaves have silvery hairs that reflect light and heat and insulate the plants from the strong solar rays and dryness in the area. They are similar to the Yucca plant, in that they live for many years and then bloom at the end of their lifespan. The plants can live for 30 to 40 years, so it is fairly rare to see a silversword in bloom.

accumulation of magma near the base of the plate, where it has melted rocks from the lower regions of the crust. These melts, in turn, rise closer to the surface to form large reservoirs of potentially explosive rhyolite magma. And it is rhyolitic magma which has caused the episodic cataclysms noted in the geological record (with apparently regular eruptions at 2.1 million years ago, 1.3 million years ago and 650,000 years ago).

The potential destruction that would follow an equivalent eruption at Yellowstone today has excited the interest of hazards expert Bill McGuire of University College London. As part of his global geomorphological risk assessment, and especially in light of unusual hydrothermal activity noted in and around Yellowstone in 2003, he predicted that a similar-sized event could bring about a volcanic winter, with global temperatures dropping by as much as 10° C as sunlight was blocked by thick volcanic clouds. This would prevent plants from photosynthesising, disrupting food chains and could even lead to man's extinction. The USGS agrees that, at some unspecified point in the future, another eruption is inevitable. Such an occurrence would bring with it 'global consequences that are beyond human experience and impossible to anticipate fully'. Given that the USGS estimates the force of Yellowstone's last eruption at 10,000 times as powerful as that of Mount Saint Helens in 1980, the threat is certainly worth monitoring.

Hot Spot Hazards

It has been shown that hot spots are widely distributed across the Earth, and that hot spot activity has been experienced throughout the geological record. In the more recent past, as human settlements have become more dispersed and therefore in greater proximity to hot spots, these naturally occurring processes have come to represent a significant natural hazard, owing to the potential threat that they now pose to life and property. The magnitude of the hazard posed varies from place to place, and the human response has been correspondingly diverse.

The Volcanic Explosivity Index (VEI) attempts to classify the destructive force of a volcano, ranging from a VEI of 0 ('non-explosive') to the maximum of 8 ('very large . colossal'), and suggests that the frequency of a given event declines with its magnitude. Thus a VEI 0 volcano erupts on an almost daily basis, and the human response to this is usually avoidance. Occasionally human settlement might be exposed to a threat when a long dormant volcano springs to life. In such circumstances there have been some successful attempts to divert lavas from properties (Mt Etna in Sicily, 1983), but more frequently the most cost-efficient course of action is to yield to the advancing lava flows. This was certainly the case when Kilauea began to erupt in 1983 and engulfed a number of villages on the southern flanks of the volcano. In any case, the hazard posed to people is extremely limited due to the predictability of the eruption – to the extent that intrepid visitors can even choose to walk to the current lava channels (though the US National Park Service advises against it). This level and type of hazard, with its associated human responses, is most typically associated with hot spots.

A volcano (or volcanic system) with a VEI of 8, such as underlies Yellowstone, entails very different priorities. Here the 'return period' of each eruptive event is measured in hundreds of thousands of years, with consequences that are measured in global, rather than local, terms. It is also statistically unlikely that Yellowstone will erupt in the near future (despite the fact that it is 'overdue' according to the frequency of past events), and so the most cost-efficient course of action is to ignore the hazard altogether. Encouraging a state of hazard preparedness might be considered a sensible course of action; but the costs of making this effective, combined with the fact that most people have much more pressing concerns, means that the US government does not consider this a sensible use of funds. Geothermal activity throughout the western United States is therefore seen as something to be exploited – for tourism, for heating, for agriculture and aquaculture – rather than to be avoided for the risk posed.

Conclusion

Hot spot theory has provided a valuable 'final piece to the puzzle' in our overall understanding of plate tectonics. However, there are some scientists who are now seeking to challenge the governing paradigm, arguing for alternative explanations in the light of new evidence. No doubt there will continue to be discoveries that push forward our detailed understanding of the global distribution of volcanoes, and perhaps hot spot theory will be finally proved or disproved in due course. Until this time J. Tuzo Wilson's ideas are likely to dominate the agenda, as man seeks to learn more about this restless planet.

Further reading

A. Jones (2006) 'Seismic/Eruption: A program for the visualization of seismicity and volcanic activity in space and time', http://www.geol.binghamton.edu/faculty/jones.

G. Nagle (2005) 'Island Arcs', **Geofile** unit 492.

L. Newstead (2004) 'Geological Slant on Plates', **Geofile** unit 477.

D. Thomas & A. Goudie (2000) *Dictionary of Physical Geography*, Blackwell.

http://en.wikipedia.org/wiki/Main_Page.

http://www.mantleplumes.org.

http://www.nps.gov/yell/.

http://www.sciencemag.org/cgi/content/abstract/301/5636/1064.

http://vulcan.wr.usgs.gov/Volcanoes/Yellowstone/Publications/OFR95-59/OFR95-59.html.

FOCUS QUESTIONS

1. Using examples, compare and contrast oceanic and continental hot spot activity.

2. What steps can be taken to reduce the hazards posed by hot spot volcanoes?

3. Describe the advantages and disadvantages of hot spot volcanism for the residents of Iceland.