Large Igneous Provinces: a target for combined IODP-ICDP projects

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Abstract

Questions surrounding the formation of large igneous provinces, their economic aspects, and their influence on the environment are best addressed through programs that combine on-shore and off-shore drilling. Continental flood basalts and oceanic plateaus probably are manifestations of the same geodynamic processes, but their composition, structure and impact on the environment are strongly influenced by differences between continental and oceanic lithosphere and by differing interactions with the atmosphere and oceans.

Major issues to be resolved include: (1) the total volume of magma within a province, the rate at which it erupted, and the manner this flux varied in the course of the eruption; (2) the nature of the mantle source, the conditions of partial melting, the mechanism of transfer of magma from source to surface, the effects of interaction with lithosphere and crust; (3) relationships between tectonic processes and flood volcanism; (4) relationships between the emplacement of volcanic provinces and the origin or maturation of petroleum deposits, and the mechanism of formation of magmatic sulfide ore deposits; (5) the relationship between flood volcanism and ocean circulation, oceanic anoxic events, climate change, and mass extinctions.

Many of these issues can be resolved through investigation of samples taken in outcrop of continental flood basalts or obducted sections of oceanic plateaus, but such sections are incomplete; continental drilling is needed to obtain more complete sections that include soft rocks that outcrop poorly but provide crucial samples. Most extant oceanic plateaus can only be sampled through oceanic drilling.

Three possible provinces for joint IODP-ICDP programs are (1) the North Atlantic Magmatic province where oceanic drilling is needed to sample volcanic rifted margins off Greenland and Norway and continental drilling is required to sample

volcanic sequences and associated intrusions in Greenland, Iceland and Ireland; (2) the Caribbean oceanic plateau where continental drilling will sample obducted sections and oceanic drilling the *in situ* extrusive and intrusive rocks; and (3) the Ontong Java Plateau where oceanic drilling will sample the extant plateau and onshore drilling will investigate obducted sections and lavas beneath atolls surmounting the plateau. Other provinces such as the Kerguelen Plateau-Broken Ridge, Parana-Etendeka province, Karoo-Ferrar province, Central Atlantic Magmatic province, and flood basalts in Australia and India are also possible.

Introduction: IODP and ICDP

The two international programs of scientific drilling have almost always operated independently, for a number of historical and practical reasons. IODP and its predecessors require one or more expensive drilling platforms.. To operate the platforms year-round requires considerable financial support from national agencies, and a complicated administrative structure has been developed to conduct and oversee drilling operations. Although the choice of drilling sites is science driven, the planning and operation of the programs is very strongly influenced by the need to coordinate the ships' programs, and also by their limitations and specific capacities.

Continental drilling, in contrast, has not been tied to specific drilling platforms. Targets are selected on a scientific basis, ICDP provides only partial support, and the realization of the drilling program is the responsibility of the principal investigator(s) of each individual program. Although the ICDP operations support group provides considerable advice and expertise, the principal investigator and his team is required to find the funds needed to complete the program, to choose the drill rig, and to oversee the logistics of the operation. The need to obtain complementary funding has meant that many drilling projects are supported by diverse organizations, not only governmental, but often from industry as well.

Shortfalls in government funding since the start of IODP in 2003, and the likelihood that that the situation will persist, has meant that IODP has had to seek additional funding sources. Such diversification in funding will likely continue in any new program. Furthermore, operation of two major drill ships as well as mission specific platforms has resulted in IODP operations becoming more like those of ICDP.

With this introduction we will investigate the scientific and logistical justification for joint IODP-ICDP programs.

Off-shore and on-shore drilling.

IODP-ODP-DSDP drilling has traditionally focussed on purely oceanic targets, with considerable success. In most cases such an emphasis is entirely justified, for scientific as well as logistic reasons. The mid-ocean ridge system is almost entirely oceanic and where the rifts propagate onto land, as at Afar or Iceland, the tectonic and petrological context is very different. Drilling of sediment sequences for stratigraphic or climate-related purposes requires the sampling of in-situ sequences which have few direct equivalents on land. In cases where investigation of on-land equivalents of these sequences is called for, sampling of outcrops usually provides adequate material.

ICDP drilling has normally focussed on specific targets that have few or no direct equivalents in ocean basins. Examples include major seismogenic structures such as the San Andreas and New Zealand Alpine Faults, lakes in a wide variety of climatic and topographic settings, and meteorite impact craters. The Hawaiian drill hole, a decade-long project, would have been logistically difficult and prohibitively expensive if conducted from a drill ship for which costs are many times greater than those of an on-shore drilling rig.

A successful example of a joint IODP-ICDP project is the New Jersey Coastal Plain Drilling Project which drilled sedimentary sequences at a modern continental margin in order to obtain a continuous sedimentary record of past sea level changes. The on-shore and off-shore segments of several volcanic provinces represent a similar target.

Large Igneous Provinces

A Large Igneous Province or LIP is defined as a large volume of magmatic rock (typically basalt but including rhyolite) that erupted over a short geological time interval in a setting not associated with normal plate tectonic magmatism. Examples on continents are known as (continental) flood basalts or traps; examples in oceans are known as oceanic plateaus. Magmas erupted in the two settings have different compositions due to contamination with continental lithosphere of the continental basalts; the oceanic varieties therefore provide better probes of the composition of their mantle sources. Yet extant oceanic plateaus are difficult to access, especially their lower parts. Previous oceanic drilling has only penetrated the uppermost fraction of extant oceanic plateaus.

The origin of LIP magmas is controversial; most earth scientists accept that they form through melting in a large deep-seated mantle plume but a small (vocal) minority calls on shallower sources related to plate configuration or plate movements. Further discussion surrounds the broader questions of the emplacement of LIPs and plate tectonics – whether the two processes are totally independent, whether plumes trigger continental rifting, or whether flood volcanism is linked directly or indirectly to pre-existing plate margins. These issues could be addressed through combined continental and oceanic drilling at sites such as the examples described below. The list is not exhaustive and other examples such as the Kerguelen plateau and on-shore equivalents on Australia and India or the Central Atlantic Magmatic Province could also be considered.

Three examples of combined on-shore and off-shore drilling projects

(1) The North Atlantic Magmatic Province. The magmatism started about 62 Ma ago with continental flood volcanism on Baffin Island, Greenland, Ireland and Scotland, continued as the ocean opened around 55 Ma and persists on Iceland to the present day. The site therefore represents an excellent locality to study co-evolution of the mantle source and tectonic processes, as has been done in previous ocean drilling (e.g. Legs 38, 48, 49, 81, 104, 152, 163). Since then several broader issues related to LIP emplacement have become apparent, including their influence on ocean circulation, their effects on the Earth's climate, and their role in the formation of economic mineral deposits.

Wright & Miller (Paleoceanography, 11, 157-170, 1996) and Poore et al. (Geochem. Geophys. Geosystems, 7, Q06010, doi:10.1029/2005GC001085, 2006) have shown that global Neogene ocean circulation has been strongly influenced by the flow of northern component water over the Greenland-Iceland-Scotland ridge and that this flow might have been moderated by temperature fluctuations in the Iceland plume represented by the V-shaped ridges south of Iceland. This hypothesis can be tested through a combination of offshore drilling on the V-shaped ridges and intervening troughs and onshore work in Iceland, including completed and projected deep boreholes.

Svensen et al. (2004, *Nature*, 429, 542-545) have shown that the emplacement of North Atlantic magmatic intrusions into sedimentary sequences released large amounts of greenhouse gases, a process that appears to have caused Paleocene-Eocene global warming. The same intrusions in the Voring basin off the coast of Norway have influenced the evolution of petroleum deposits, enhancing maturation in some cases, degrading the deposits in others. Four decades of petroleum exploration has made the North Atlantic one of the best studied of all LIPs and has provided excellent 3D seismic images of lavas, intrusions and sediments. Finally some of the world's richest ore deposits, the Ni-Cu sulfides of Noril'sk in Russia, formed through magma-sediment interaction in a setting similar to that of the North Atlantic magmatic province.

To understand better the formation of this and other volcanic provinces, their economic resources, and their effects on the environment requires a better knowledge of the way magma flows through the intrusive complexes that underlie the volcanic series. We need to understand where the magma flux was concentrated and how this flux varied during the evolution of the province. The majority of volcanic rocks that erupted after rifting are now submerged and can be sampled only through oceanic drilling; the intrusions, however, are best accessed on land. To obtain information on magma flux requires detailed geochronology, volcanology and petrology on continuous volcanic sections; some of these are accessible in outcrop but to obtain more complete sections requires drilling. To investigate how magma interacts with sediment requires detailed study of contact aureoles; again, some material is available in outcrop but drilling is needed to obtain more complete profiles.

The North Atlantic magmatic province therefore represents a site where a complex and protracted episode of magmatism and mantle-lithosphere interaction could be investigated through coordinated continental and oceanic drilling. The event had a major influence on global environment and the study has important implications for past climate changes. Associated petroleum and ore deposits should attract support from industry.

(2) **The Caribbean oceanic plateau**. Unlike many other oceanic plateaus, which are located on the ocean floor and are not readily accessible, parts of the Caribbean plateau have been obducted onto the Central and South American continent. Large thrust sheets containing volcanic rocks from various levels of the original plateau are found in sites from Guatemala to Ecuador, and as far east as Haiti, Curacao and Trinidad. Some of these appear to have come from the lower portions of the plateau providing unique access to this part of the magmatic edifice. Included in these portions are picrites and komatiites which represent the hottest magmas to have erupted since the Precambrian and provide invaluable information about conditions in the modern mantle. Associated with slices of the oceanic plateau are pieces of the Cretaceous volcanic arc that formed as the subduction zone jumped to the SW during

collision between the plateau and the American continent. These obducted fragments therefore record a complex history of mantle and tectonic processes. Of additional significance is the correlation of the timing of Caribbean flood volcanism with ocean anoxic event 2, which is responsible for several important petroleum producing marine sedimentary formations (e.g., La Luna).

Reading this record is difficult for two main reasons. First, it has been scrambled by the irregular manner in which portions of the plateau and volcanic arc were thrust onto the continent. Second, the rocks are exposed to hot humid climates that has affected all surface outcrops. To obtain complete sections of fresh lavas will require targeted drilling.

A joint program of oceanic and continental drilling would involve the following. (1) sampling of segments in the Caribbean basin, as described in lapsed proposal Full560 to the ODP; (2) drilling in shallow water surrounding Gorgona Island to investigate the tectonic setting of the komatiites of the island and perhaps to recover new samples of these unique rocks; (3) targeted drilling of obducted segments in Curaçao, Costa Rica and parts of Colombia to obtain more complete sections and fresh samples of these rocks.

(3) The Ontong Java Plateau. Magmatic activity forming three enormous Pacific plateaus (Ontong Java, Manihiki and Hikurangi) peaked at ~122 Ma and coincided with Oceanic Anoxic Event 1a. Models for the origin of the Ontong Java Plateau such as a surfacing plume head, bolide impact, or mantle metling related to plate configuration cannot account for all of the observations made for the world's largest igneous province. To develop models that satisfy existing data, new samples of Lower Cretaceous sediment and basement both on and off the plateau are required. Basement rocks, especially from the Plateau's eastern salient, beneath atolls surmounting the plateau, and obducted sections in the Solomon Islands, are key to understanding of origin and evolution of the plateau. In particular, temperature and thermal conductivity measurements are needed to determine heat flow that will test whether the mantle root beneath the Plateau is thermal or chemical in nature. Basement and sediment sections are needed to quantify subsidence of the plateaus at each site and therefore evaluate anomalous subsidence.

Coring of lower Cretaceous sediment, including syn-plateau sections from off-plateau sites, will be vital in establishing whether paleoenvironmental changes are contemporaneous (or not) with plateau formation. If contemporaneous, sedimentary and paleoclimatic records in syn-plateau sections are key to assessing the environmental effects of oceanic plateau formation.

Comprehensive off-shore and on-shore drilling of the plateau, in islands, atolls, reefs, and seamounts surmounting the plateaus as well as in syn-sedimentary sections in the neighboring ocean basin and in obducted sections is required to advance our knowledge of the origins, magmatic chronology, and environmental impacts of oceanic plateaus.