Scientific Seamount Drilling

Report of a JOI-USSAC Sponsored Workshop

Lamont-Doherty Geological Observatory

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INTRODUCTION

Submerged oceanic volcanoes or seamounts are the most numerous volcanoes on earth. Interest in their origin, evolution and tectonic significance has accelerated in the last decade because seamounts are linked directly to many important scientific questions of interest to the geoscience community. A sampling of these diverse questions can be gleaned from: 1) a symposium and special issue of the *Journal of Geophysical Research* on seamounts (volume 89, no. B13, 1984), 2) special sessions on seamounts at meetings of the American Geophysical Union (Fall 1984 and Fall 1985) with an AGU Monograph resulting from the Fall 1985 session, 3) special session on seamounts at the Winter 1985 meeting of the American Society of Limnology and Oceanography (ASLO) and 4) special symposium on seamounts to be held at the Vancouver 1987 meeting of the International Union of Geodesy and Geophysics (IUGG) under the sponsorship of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI).

The largest of seamounts emerge to form active volcanic islands like Hawaii which may then subside to form coral atolls or guyots. Studies of oceanic volcanic islands and their inactive drowned successors have, of course, been traditionally active and continue to be of great interest. More recent recognition of the scientific importance of the much more common smaller seamounts plus the development of new tools facilitating their study add impetus to seamount studies and partly accounts for a renewed focus on their origin and evolution. At the same time, accelerated progress in the area of geodynamics is partly due to modern studies involving seamounts. As mechanical loads and indicators of deep thermal perturbations in midplate regions, seamounts provide valuable natural laboratories for the study of the thermo-mechanical properties and response of the ocean lithosphere. Likewise, at active ridge crests and fracture zones, seamounts provide important evidence for conditions and processes in these very active regions. Like volcanism at active plate boundaries, midplate seamount volcanism supplies fundamental insight into problems of magma generation, ascent and eruption that are linked via geochemical characteristics to Earth's origin and differentiation over the last 4.5 billion years.

The purpose of the workshop we report on here was to discuss the outstanding scientific questions concerning the study of seamounts. More specifically, an attempt was made to identify those important questions which require scientific drilling in the framework of the Ocean Drilling Program. In this report, we summarize those scientific questions that we believe can best be addressed by scientific seamount drilling.

SCIENTIFIC SEAMOUNT DRILLING — HISTORICAL PERSPECTIVE

Prior to the inception of the Deep Sea Drilling Project (DSDP) in the late 60's, seamount drilling was confined to fairly shallow drilling of a few oceanic volcanic islands and atolls carried out for non-scientific purposes. Among the scientific questions listed as high priorities for DSDP/IPOD were two seamount-related programs: 1) petrologic history of a hot spot and 2) igneous stratigraphy of isolated seamounts. The first objective was only partly successful, but was attempted several times: 1) Hawaiian-Emperor chain: Leg 19 (Site 192), Leg 32 (Sites 308, 309) and leg 55 (Sites 430-433, eleven holes); 2) Line Islands: Leg 33; 3) New England Seamounts: Leg 43 (Sites 382 and 385); 4) the Walvis ridge: Leg 39 (Site 359) and 5) assorted sites on aseismic ridges. In contrast, drilling of isolated volcanoes, not members of linear chains, was attempted only twice: 1) Horizon guyot (Site 171) during Leg 17, and 2) Ita Maitai guyot (Sites 200, 201 and 202) during Leg 20. Thus, while seamount drilling has, in general, been sadly neglected (only 24 of 625 sites: 3.2% of holes drilled), drilling of isolated seamounts is in an even sadder state (0.6% of holes drilled) considering their scientific importance and the fact that they are the most common type of volcano on the planet.

It is gratifying that more recent appraisals of the importance of scientific seamount drilling concur with the earlier ones of IPOD. For example, the Conference on Scientific Ocean Drilling (COSOD) report stresses the scientific importance of seamount drilling (both large midplate volcanoes and small near-ridge ones) for the questions of: 1) mantle inhomogeneity and mantle evolution, 2) formation of overly thick crust and flood-type volcanism, 3) structure, petrology and geochemistry of transform faults and fracture zone offsets, 4) the origin of intraplate volcanism and 5) dynamics of magma chambers and formation of oceanic crust. In addition, near-ridge seamounts and their hydrothermal activity represent significant components of two top priority COSOD objectives: mid-ocean ridge magma generation and the configuration, chemistry and dynamics of hydrothermal systems.

The Scientific Seamount Drilling Workshop builds upon these previous recommendations by the community. In particular, the workshop focused on the important scientific questions that would benefit significantly from drilling. Participants were aware that seamounts occur in many different tectonic settings, that they occur as chains, groups and isolated from others, can be erupted upon ocean lithosphere of any age and vary widely in size, shape, rock type, lava chemistry and other characteristics. Much information is needed to explain this great diversity and its significance, so our discussion focused primarily on identifying important scientific questions which could be significantly advanced by drilling in conjunction with other types of on-going study.

MAJOR PROBLEMS RECOMMENDED FOR STUDY BY SEAMOUNT DRILLING

For purposes of discussion, participants were divided into three working groups. Each group agreed on the same two principal priorities and listed several other important problems. We first discuss the two topics which received the widest consensus among the groups: 1) Thermo-mechanical characteristics of the ocean lithosphere and 2) internal composition of a typical seamount.

Thermal and Mechanical Properties of Oceanic Lithosphere

Studies of flexural loading at seamounts have provided important information on the thermal and mechanical properties of oceanic lithosphere. Seamounts, for example, have provided the key data for our understanding of the relationship between elastic thickness and plate age. Recently, seamount loading studies have been used to estimate the effects of thermal perturbations on plate structure such as those associated with mantle hotspots.

In many respects, seamounts provide ideal locations for the study of the thermal and mechanical properties of the lithosphere. They are located in a variety of tectonic settings including the interior of plates away from the complexities of plate boundaries. Furthermore, they represent "discreet" loads on the plates over relatively short times. As a result, seamount studies have yielded key parameters for geodynamic models of basin evolution and mountain building.

Recently, a multichannel seismic study was carried out in the vicinity of Hawaii in order to better constrain the flexure model. Although the seismic structure deduced in this study (e.g., Figs. 1, 2) generally supported the flexure model, several differences between the observed and expected structure were encountered. These included: 1) a slightly lower elastic thickness, 2) an overthickened crust, 3) relatively thin crust beneath the volcano, and 4) relatively small P and S wave velocities in the upper 1 km of oceanic crust near the flexural node. These observations indicate that the seismic, thermal and elastic properties of oceanic lithosphere may be fundamentally altered by the process of volcano building.

One of the most interesting results to come from the seismic study was to show that flexural moats around seamounts may be infilled by thick sequences of gently dipping, poor to well stratified material (Fig. 3). Theoretical modeling studies show that the patterns of moat strata may provide key information on the form of stress relaxation in oceanic lithosphere and on the extent of heating by a mantle. Unfortunately, the seismic data cannot yet be used to constrain a particular type of model because the nature and age of material infilling the moat is at present unknown.

We believe that the moat infill contains key information on the history of vertical movements during seamount formation. Furthermore, they provide an "inverted" stratigraphy of the structure of a seamount (Fig. 4).

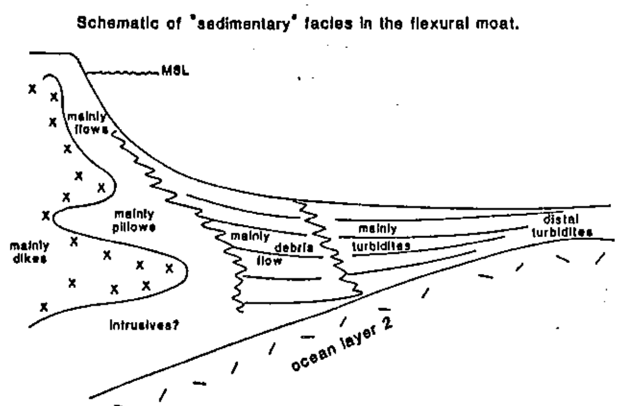


Figure 4. Schematic diagram of an insular moat showing the expected sedimentary and volcanic facies.

Participants in the workshop agreed widely that a drilling program aimed at understanding vertical movements is a very high priority because it offers promise of fundamental new insights on the thermo-mechanical behavior of oceanic lithosphere.

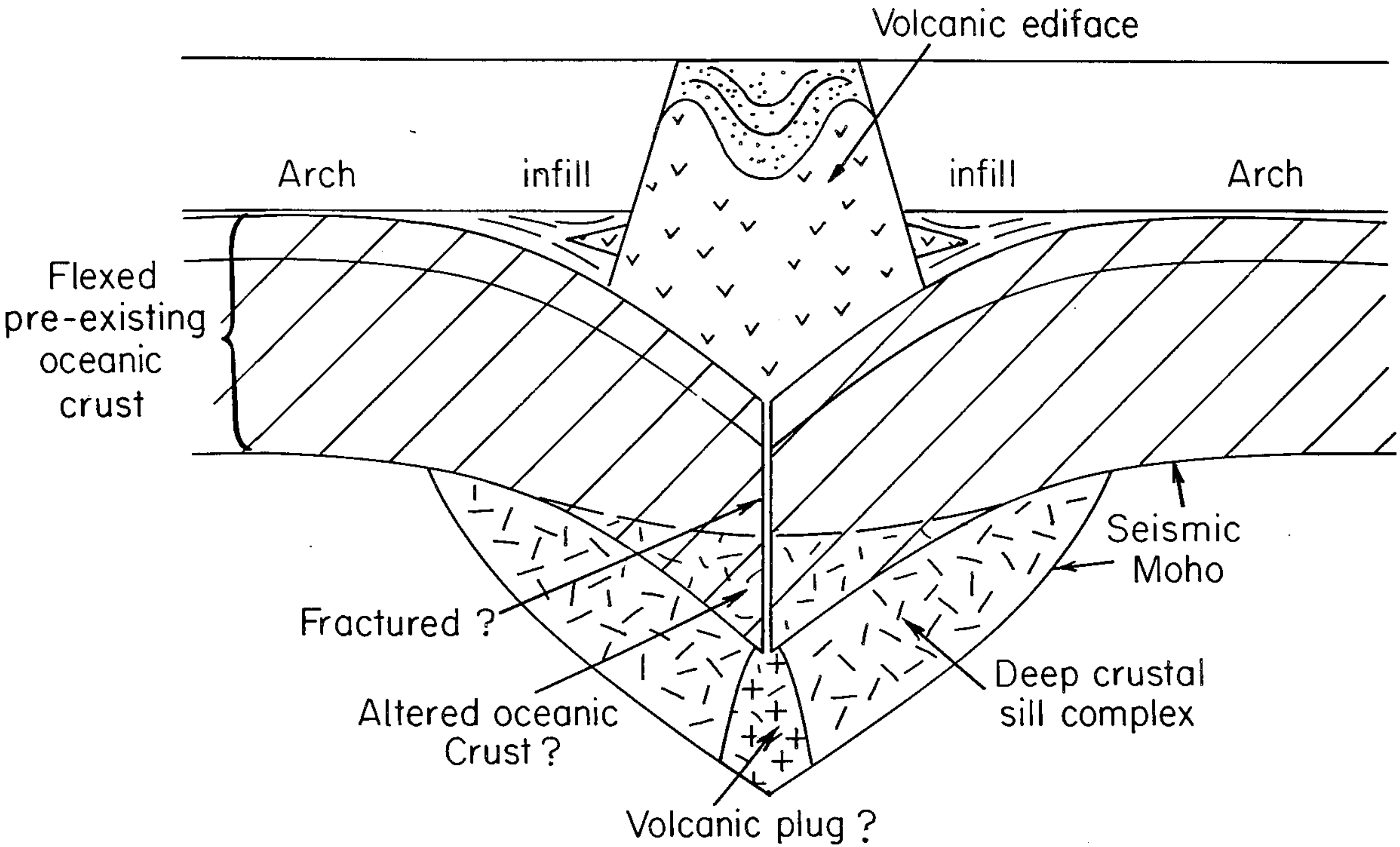


Figure 1. Crustal structure beneath Hawaii deduced from a recent multichannel seismic study.

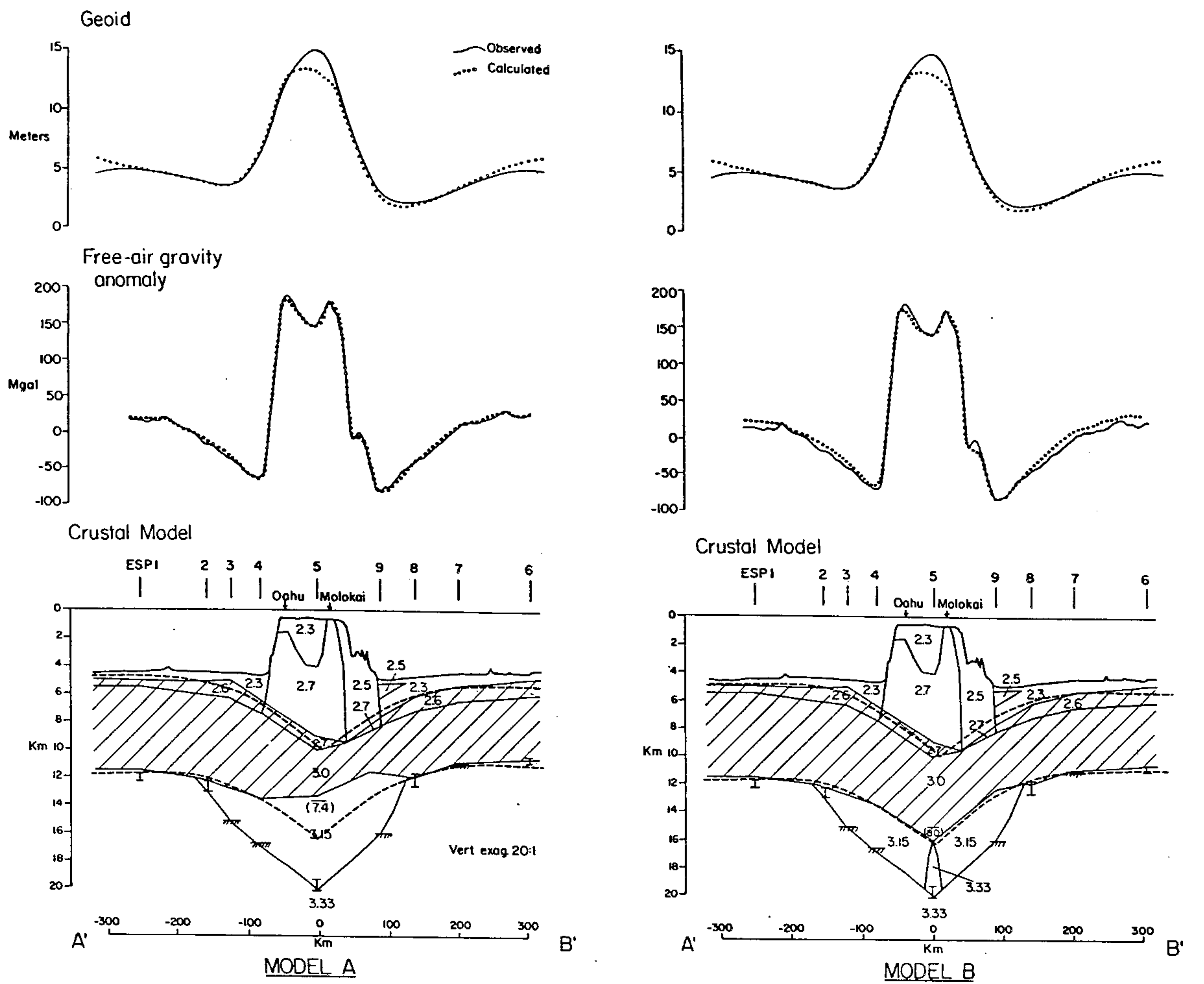
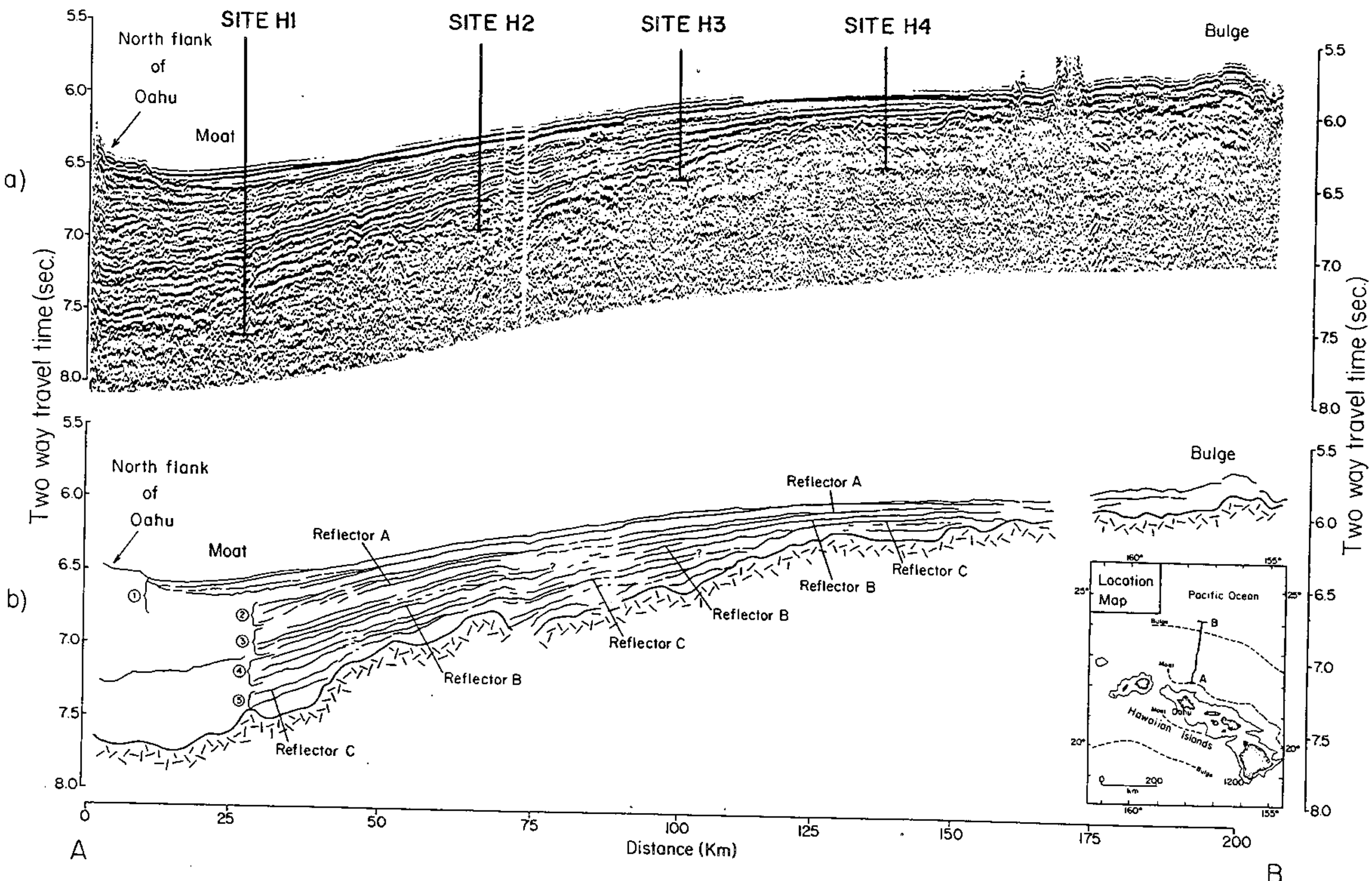


Figure 2. Free-air gravity anomaly and model structures with labeled densities.

Figure 3. Multi-channel data (a) and interpretation (b) of flexural moat north of Oahu showing suggested drill sites.



Such an experiment is, at least conceptually, site independent though, of course, data constraints of uplift/subsidence history, loading and ages of volcanism are necessary to plan a fruitful drilling effort. Presently, the Hawaiian moat and swell are attractive sites because the wealth of existing data can be used for detailed planning and site selection. Hawaii has the further advantage of a relatively simple and well-known thermal history; it is the best known, well-behaved hotspot. Drilling the moat would, of course, also provide direct evidence of the petrologic and volcanic development of Hawaii during the crucial stage of emergence. Figure 3 shows a possible pattern of sites recommended for such a program.

While Hawaii represents an attractive, simple case, other volcanic chains with more complex thermal and loading histories are also important because their study by drilling can increase our understanding of the causes of multiple eruptive events as well as the related thermo-mechanical properties of the lithosphere. Large regions of the Pacific, for example, are known to have been thermally rejuvenated at least once. This is manifested by anomalous (reset) subsidence histories and volcanism. Complex examples of such phenomena offer the opportunity to study the consequences of such rejuvenation and thereby constrain the possible cause. Several reasonably well-studied potential sites for such drilling programs are the Marquesas swell, the Marshalls and the Austral Island chain.

Internal Composition and Structure of a Typical Seamount

Knowing the internal composition and structure of a typical oceanic volcano or seamount would provide very valuable information for inferring the origin and evolution of seamounts. In addition, such data would provide important constraints on magma generation, ascent mechanisms, timing of eruptive and intrusive activity and fundamental information about deep sea volcanic and hydrothermal phenomena. To date, the internal structure of seamounts has had to be inferred very indirectly from their morphology and modelling of potential field measurements such as gravity and magnetics. Drilling is the only means of obtaining direct information. Once in hand, however, these drill results could be used to greatly enhance the value of potential field measurements and should provide a definitive test of several competing hypotheses for the volcanic and petrologic development of seamounts.

It is known that many seamounts contain petrologically and isotopically diverse lavas and drilling would provide important information on the chronology of such eruptive products. Such data would provide valuable constraints for testing competing models of mantle heterogeneity and thus provide constraints on the early differentiation history of the earth, mantle convection schemes and absolute depths of melt formation.

The vast majority of seamounts, typically 0.5-1.5 km high, form near active mid-ocean ridge crests. Subsequently, seamounts are added to oceanic lithosphere in diminished number (but large size) as the plate cools. Figure 5 shows a typical example of a small seamount near the East Pacific Rise and Figures 6 and 7 show a seamount formed near the East Pacific Rise (EPR) which evolved from tholeiitic mid-ocean ridge basalt (MORB) to alkalic composition more typical of oceanic island basalt (OIB) as it drifted away from the EPR. These sorts of volcanoes are typical seamounts and are attractive drill targets because a single deep drill hole could penetrate the entire edifice into the underlying oceanic crust. Such volcanoes are thought to evolve from very tiny volcanoes that are roughly circular or polygonal in plan form to roughly circular edifices with broad flat summits by evolution of the conduit system. In the early stages they are fed from points or multiple linear vents which later evolve to magmatic conduits shaped like inverted cones. Drilling through a single seamount of this type would provide a definitive test of this hypothesis. In addition, such a drilling program would provide a wealth of direct information on seamount hydrothermal activity (Fig. 7), caldera formation and filling, importance of intrusive versus extrusive activity, magma chamber size, shape, replenishment and longevity, petrologic and geochemical evolution, density and magnetic properties of seamount rocks and information on the styles of deep sea eruptions and how these vary with water depth. Participants in the workshop rated such a drilling program as a top priority.

Such a program could focus on a typical small seamount near an active mid-ocean ridge but alternatively could be sited on an ancient ridge-generated volcano. For example, a very attractive possibility is to choose a small, old volcano capped by either pelagic sediment or a coral reef such as some volcanoes in the Marshall Islands. Small size is the only important constraint because small size enables complete penetration and sampling of the seamount's interior. Another alternative is to carry out such a program on a typical large (usually

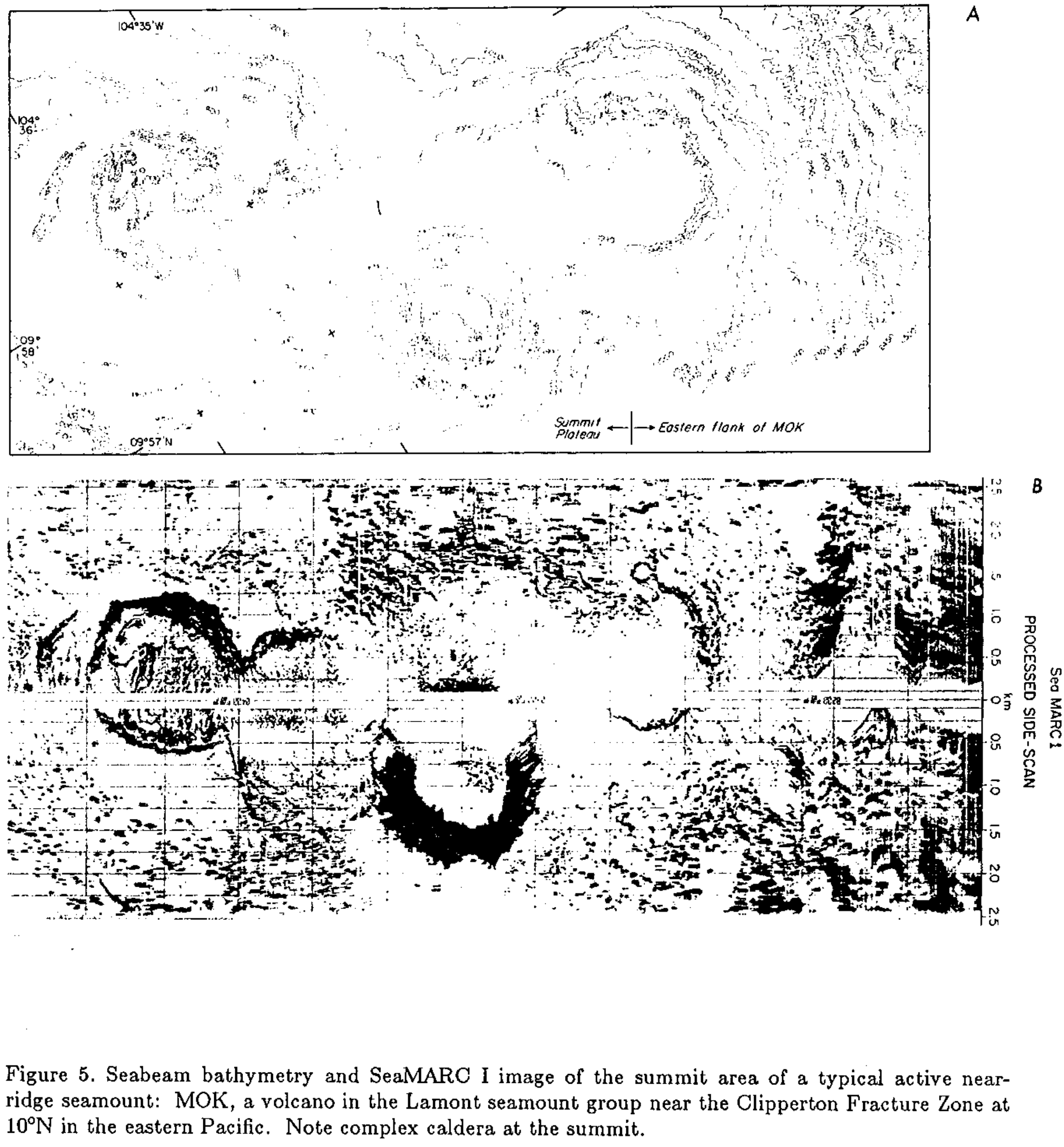


Figure 5. Seabeam bathymetry and SeaMARC I image of the summit area of a typical active near-ridge seamount: MOK, a volcano in the Lamont seamount group near the Clipperton Fracture Zone at 10°N in the eastern Pacific. Note complex caldera at the summit.

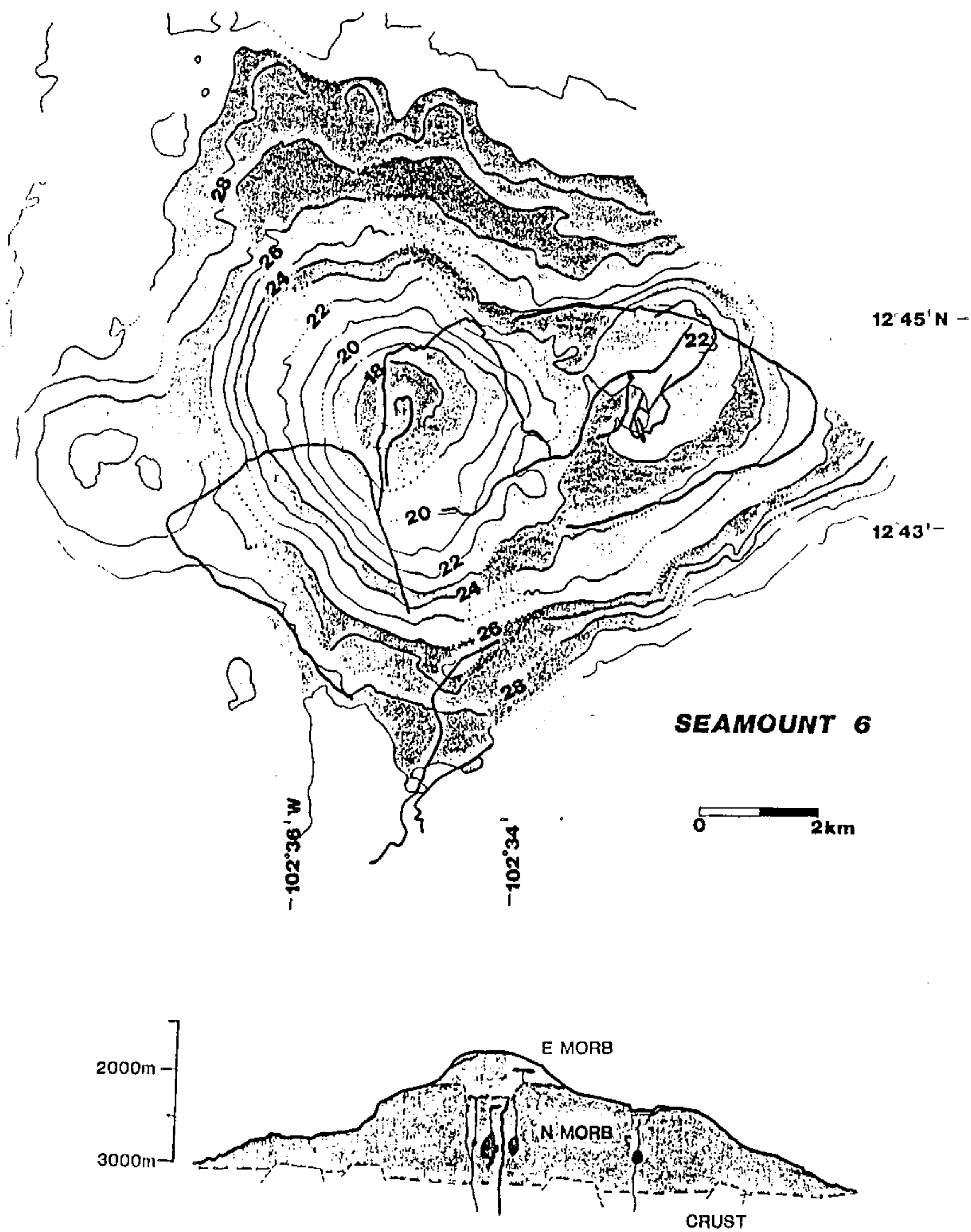


Figure 6. Seabeam bathymetry of seamount 6, a typical near-ridge seamount built just east of the East Pacific Rise on ocean crust 3.5 Ma in age. Dark lines on map show ALVIN dive tracks and ANGUS photo traverses. cross section (2.6 vert. exag.) is west to east and shows the inferred geology based on ALVIN study and dredge results.

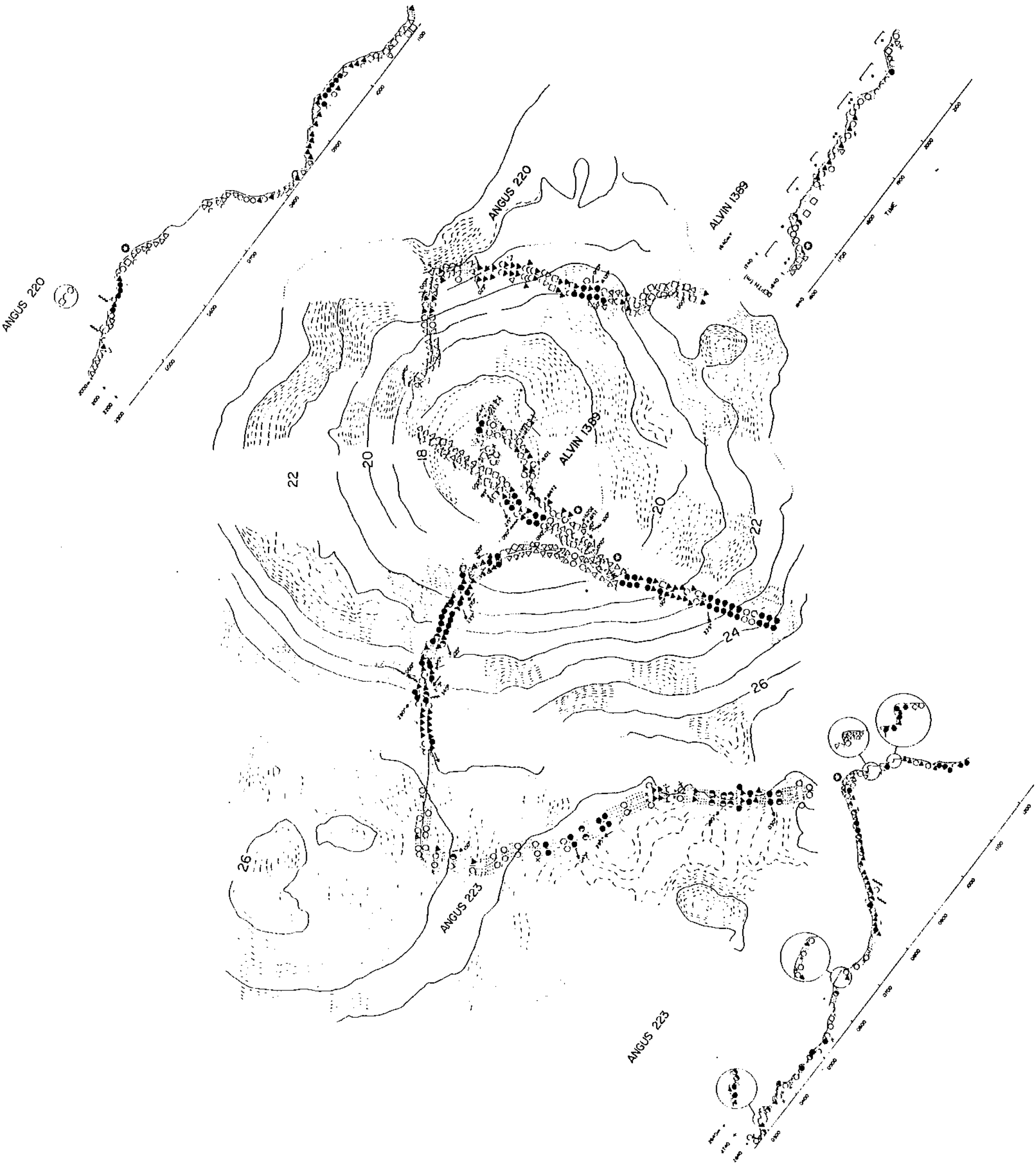


Figure 7. Geology of the summit of seamount 6 inferred from ALVIN dive observation, interpretation of ANGUS photographs and extensive laboratory study of volcanic rocks.

Figure 8. Hydrothermal activity near the southwest wall of Axial seamount's caldera (Juan de Fuca ridge). The pale milky fluid in the photograph is emitted near the base of a chimney that conducts fluid up to 330°C (courtesy S. Hammond).

hotspot generated) volcano. Such edifices have morphologies clearly dominated by flank eruptions along subradial rift zones and provide an interesting contrast with smaller volcanoes that typically lack rift zones of this type or possess only poorly developed examples. A drilling program on such a volcano would require more holes to be successful and the entire edifice could only be penetrated at the distal flanks. Finally, yet another alternative is to carry out a drilling program at a youthful and active small volcano which could either be at the young end of a hotspot chain, like Loihi Seamount or Teahitia, or situated directly on an active mid-ocean ridge, like the Axial Seamount at Juan de Fuca. Drilling programs sited at either sort of volcano would accomplish most of the objectives for this highly recommended priority provided drilling conditions allowed deep penetration and good core recovery.

ADDITIONAL IMPORTANT PROBLEMS

Drilling through a small typical seamount to determine its internal anatomy and drilling of flexural moats to determine the thermo-mechanical nature of the oceanic lithosphere were both widely agreed upon as the highest priorities for scientific seamount drilling. In addition, however, several other important problems which could be successfully addressed by seamount drilling were also discussed at the workshop.

Mid-ocean ridge seamounts: drilling of seamounts near mid-ocean ridges is an important complement to drilling programs aimed at understanding mid-ocean ridges. Seamounts can provide important information about ridge crest activity because though they form mostly near ridge offsets (edges of spreading segments) they also form near the topographically elevated centers of spreading cells. Seamount drilling thus provides important information on melt formation, migration and storage at the edges of rising melt diapirs and crustal magma chambers. Seamount formation and growth near active ridges may result from the interplay of episodic melt intrusion with episodic tectonic spreading. If so, then seamount stratigraphy recoverable by drilling may preserve a valuable record of this episodic behavior unavailable at a single location elsewhere along the ridge.

Magmatism in plate interiors: The nature of melt production and ascent beneath plate interiors is a problem of fundamental importance. A drilling program on small or large mid-plate seamounts could provide important constraints by supplying important data on the chemistry and timing of eruptions.

Hotspot chains: Many hot spot chains do not exhibit the simple age progression of the Hawaiian-Emperor chains. Furthermore, the rate of melt production and/or eruption can vary widely along a single chain and among different hotspots. Drilling, in combination with other geologic, geophysical and geochemical studies can provide key data needed to understand the causes of such variations.

Drilling has an important role for a variety of other important, seamount-related problems. In most of these cases, drilling is not necessarily the most important component of targeted study but is nevertheless a key tool. These problems include: 1) geographical and temporal patterns of mantle heterogeneity, 2) past plate motions as inferred from the paleomagnetism of seamounts and 3) the role of seamount lavas (both fresh and altered) and hydrothermal products to geochemical cycles involving subduction.

DRILLING

The objectives favored by participants in the workshop can be successfully completed with present drilling technology and the drilling and logging capabilities on ODP's *Resolution*. From experience gained during ODP Legs 106 and 109 it is clear that spudding in of the drill string, even in young volcanic terranes, is not a serious problem. However, it is also clear that penetration rate and core recovery of rubbly rocks typical of young volcanic areas can be improved. For scientific seamount drilling, this limitation is not serious as volcanoes old enough to have their rubbly zones cemented by secondary and hydrothermal minerals are abundantly available. As with other ODP holes, utility of the hole for logging and instrumentation is highly recommended and could prove very valuable.

SUMMARY

Participants in the Workshop on Scientific Seamount Drilling (SSD) agreed on two top priorities for drilling:

1) Insular or seamount sediment-filled moats, swells and flanks [e.g., Hawaii, Marquesas, Australs]

- subsidence/uplift history
- thermo-mechanical properties of the lithosphere
- petrologic and volcanic evolution of hotspot volcanoes

2) Anatomy of a seamount

- origin and evolution of seamounts
- petrologic and geochemical evolution of seamounts
- test models of morphologic and volcanic development
- seamount hydrothermal activity
- provide samples for density and magnetic properties measurements

Such a program could be carried out on or near:

1) a young, small seamount
2) an old, small seamount with a pelagic or reef cap
3) an active hotspot seamount
4) an older, large hotspot seamount
5) an active ridge crest seamount

In addition, the participants identified several other problems that could be fruitfully approached with drilling. These include:

- mid-ocean ridge seamounts
- magmatism in plate interiors
- hotspot volcanoes and chains.