Fisher, A., Davis, E.E., and Escutia, C. (Eds.), 2000
Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 168

1. AN INTRODUCTION TO THE SCIENTIFIC RESULTS OF LEG 168[1]

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LEG 168 DRILLING TRANSECT

Hydrothermal circulation through the oceanic crust is known to carry a significant portion of the heat from cooling lithospheric plates, to exert a strong influence on the chemistry of the oceans, and to modify the composition of oceanic crust before it is recycled by subduction. Among the objectives of Ocean Drilling Program (ODP) Leg 168 were (1) elucidation of the fundamental physics and fluid chemistry of ridge flank hydrothermal circulation and (2) documentation of consequent alteration of the upper igneous crust and sediments that host the flow in a young ridge flank setting. This was accomplished with a transect of sites on the eastern flank of the northern Juan de Fuca Ridge drilled into crust ranging in age from 0.8 to 3.6 Ma (Fig. 1).

In most ocean basins, burial of the igneous crust and the resultant hydrologic isolation of permeable basement takes place over tens of millions of years; on the eastern Juan de Fuca Ridge flank, burial is accelerated as a consequence of the proximity of the ridge to the abundant supply of turbidite sediments shed from the adjacent North American continental margin during the Pleistocene. The arrangement of Leg 168 drill sites along an east-to-west transect spanned a range of crustal ages, sediment thicknesses, and thermal and chemical states in basement (Fig. 1), allowing an assessment of current conditions and how conditions may have changed over time. Sites at the western end of the transect were closest to the spreading axis and the position of sediment/igneous-basement onlap and showed the greatest extent of hydrothermal cooling and the least amount of rock and fluid alteration. In contrast, sites at the eastern end of the transect revealed considerably greater rock and fluid alteration. Penetration into the basement section beneath the sediments was intentionally shallow during Leg 168; primary attention was given to lateral variations in basement fluid composition, formation temperatures, fluid pressures, and alteration. Deeper penetration and experiments were reserved as goals for later drilling.

Results based on Leg 168 shipboard studies are summarized in the Leg 168 *Initial Reports* volume (Shipboard Scientific Party, 1997) and in a short summary article (Davis et al., 1997). Because of recent changes in ODP publications policy, many papers containing results from Leg 168 appear in journals rather than this volume. In the rest of this introduction we highlight results of post-cruise research, with an emphasis on hydrogeologic processes and papers that appear outside this volume.

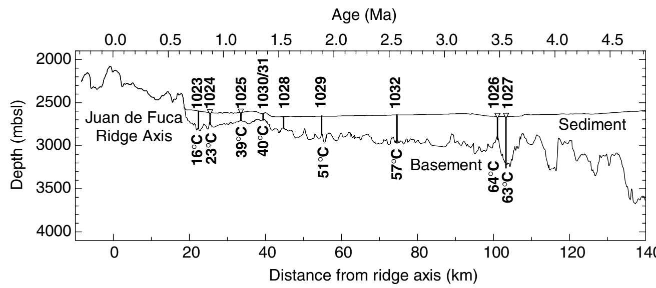

Figure 1. Section through Leg 168 drilling sites showing seafloor and basement topography and crustal age. The profile, derived from seismic reflection data, crosses the ridge at 48°N and is oriented at N107°E, perpendicular to the strike of the ridge crest. Triangles indicate locations of reentry cones and borehole observatories (CORKs), and temperatures are those measured directly at the sediment/basement interface or estimated from extrapolation of profiles measured in overlying sediments.

LONG-DISTANCE TRANSPORT IN THE UPPER IGNEOUS CRUST

The working model for hydrothermal circulation used to plan Leg 168 is one in which permeable extrusive igneous rocks are between low-permeability deeper crustal rocks and low-permeability sediments. The physical nature of layering and basement exposure is readily apparent from extensive seismic surveying along the Leg 168 transect (Rosenberger et al., Chap. 2, this volume), as are age variations with distance from the spreading ridge (Shipboard Scientific Party, 1997; Su et al., Chap. 4, this volume). Cold, unaltered seawater enters the crust where basement is exposed at the seafloor and is heated and reacts as it flows through the rock. Buoyancy-driven fluid flow is confined within igneous basement, except where permeable rock is exposed at the seafloor and fluid exchange between the crust and the ocean can occur. This model served well, and both initial drilling results and subsequent studies provided excellent quantitative constraints on the nature of shallow, ridge flank circulation (e.g., Davis et al., 1999; Elderfield et al., 1999).

Perhaps the most surprising result of Leg 168 was the lateral distance over which the hydrothermal circulation in the igneous crust provides hydrologic communication beneath the relatively continuous sediment cover on the ridge flank. Thermal and geochemical evidence for large-scale transport was found at the time of drilling (Shipboard Scientific Party, 1997). Systematic increases in heat flow and basement temperatures with distance from basement outcrop (Pribnow et al., in press; Fig. 1) showed a clear influence of ventilated circulation as far as 20 km from the point of sediment onlap, and sulfate concentrations in basement waters indicated influence of seawater recharge over the full length of the drilling transect (Shipboard Scientific Party, 1997). Even at sites over 80 km from the area of extensive basement outcrop near the ridge, sulfate concentrations were found to have declined only to half seawater values, despite the diffusive loss into the sediment section where sulfate is consumed by bacteria. Shore-based studies confirmed this scale of influence and allowed estimates of lateral fluid flow on the order of meters per year (Davis et al., 1999; Elderfield et al., 1999; Wheat et al., 2000). Radiocarbon dating of large-volume water samples showed that nowhere along the transect was water >8 ka in age (Elderfield et al., 1999), even at the extreme eastern end of the transect, farthest from the spreading axis.

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NATURE OF LOCAL CONVECTION

Drilling at the oldest two Leg 168 sites targeted a buried basement ridge and adjacent valley, where it had been inferred that buoyancy-driven fluid circulation was sufficiently vigorous so as to have thermally homogenized the sediment/basement contact. Temperatures measured close to the sediment/basement contact during Leg 168 supported this hypothesis, and these results were confirmed by seafloor observatories (CORKs) installed during Leg 168 that permitted basement fluid temperatures and pressures to be determined long after drilling disturbances had dissipated (Davis and Becker, 1998). Basement temperatures at the two sites (1026 and 1027) were found to be virtually identical (Fig. 1), despite a contrast in sediment thickness of 2.5:1. Permeabilities required to sustain such small temperature differences were inferred to be very high, consistent with borehole observations based on packer pumping experiments (Becker and Fisher, 2000) and open-hole flow-rate determinations (Fisher et al., 1997). Local rates of fluid flow also must be high, on the order of meters per year or more, as inferred for the area to the west.

Basement fluids appear to be compositionally homogeneous on a lateral scale of kilometers, but are different within distinct regions along the drilling transect. Basement water collected from Site 1026 is nearly identical in composition to basement waters collected from basement edifices roughly 7 km north and south of the site (Mottl et al., 1998; Wheat et al., in press). A subtle lateral compositional gradient between the outcrops suggests that along-strike flow, not resolved by the cross-strike drilling transect, also may be important in this area (Wheat et al., in press). Basement pore fluids are extensively altered but relatively young within the basement below Sites 1026, 1030, and 1031. This observation suggests that there may be different sources of recharge along the Leg 168 transect and that a simple model of fluid flow from west to east can not explain all observations.

Experience gained through Leg 168 drilling and postdrilling observations have led to new opportunities for crustal fluid sampling. For example, a clear relationship has emerged between hydrologic structure and local fluid pressure: fluid pressures in buried basement edifices consistently exceed local hydrostatic pressure (Davis and Becker, 1998), allowing large volumes of formation water to be produced at the seafloor (Fisher et al., 1997). This phenomenon has been exploited for both geochemical and biological sampling (e.g., Mottl et al., 1998; Mottl et al., Chap. 9, this volume; Elderfield et al., 1999; Wheat et al., in press). Average formation pressures generated through thermal buoyancy are relatively small, and in some instances, tidally generated pressure differentials create occasional overpressures even where the average formation pressure is subhydrostatic (Davis et al., 1999). And finally, in cases where fluids cannot be naturally produced, in situ fluid samplers, a technology recently developed and successfully tested in Leg 168 holes, can provide continuous time-series samples of crustal fluids.

SCALING AND EVOLUTION OF BASEMENT PROPERTIES

Basement permeabilities were found to be high during both open-hole flow and packer experiments, roughly consistent with modeling results, but significant differences in apparent permeabilities suggest that there may be a scale dependence of these properties (Fisher et al., 1997; Davis and Becker, 1999; Davis et al., 1999; Davis et al., in press; Becker and Fisher, 2000). In addition, when Leg 168 packer data from the uppermost basement were combined with measurements from elsewhere around the world, a consistent permeability-age trend was identified (Becker and Fisher, 2000). Differences in basement permeability inferred using different methods and assumptions may indicate that a large fraction of the fluid flux through oceanic basement is concentrated within a small volume of rock (Fisher and Becker, 2000), an interpretation consistent with the heterogeneous nature of basement alteration (Marescotti et al., Chap. 10, this volume; Hunter et al., 1999).

SEDIMENT AND BASEMENT ALTERATION: CONSEQUENCES OF FLUID FLOW

The sediments covering igneous basement along the Leg 168 transect are a mixture of hemipelagic mud (closest to basement, particularly above local basement highs) and turbidites (Underwood and Hoke, Chap. 5; Cavin et al., Chap. 6; both this volume). Sediments within the shallowest part of the section vary in texture depending on proximity to distributary channels. Correlation between sediment physical properties and seismic profiles allows extrapolation of interpretations laterally away from ODP boreholes (Sun, Chap. 3, this volume).

Fluid seepage through shallow sediments was evident from pore water profiles at Sites 1030 and 1031 (Shipboard Scientific Party, 1997). Sediments at these sites were found to have anomalous seismic properties (Zühlsdorff et al., 1999) when compared to sediments from equivalent depths at adjacent sites, but subsequent laboratory testing revealed variations in primary lithology that could account for differences in chemical and physical properties (Inoue, 1999; Giambalvo et al., 2000) and little direct evidence for sediment alteration caused by fluid seepage, except immediately above basement (Su et al., Chap. 4, this volume; Bautier et al., in press). Pore waters at Sites 1030 and 1031 appear to be maintained at a state close to equilibrium with their host sediment (Monnin et al., Chap. 8, this volume). Alteration within ridge flank sediments depends strongly on the reactivity of organic carbon (Rudniki et al., in press).

Low-temperature alteration within upper basement is ubiquitous along the Leg 168 transect, with extent and intensity increasing along with age and temperature from west to east (Hunter et al., 1998; Hunter et al., 1999; Marescotti, et al., Chap. 10; Porter et al., Chap. 12; both this volume). Secondary clays in veins, vesicles, and replacing olivine and glass account for several percent to 10%–20% of the recovered rock by volume and represent the earliest alteration products. A later alteration stage is characterized by calcium carbonate (calcite and aragonite) in veins and vesicles. A general progression from hydrologically open, oxidizing alteration to hydrologically isolated, reducing alteration is evident in the penetrative alteration and vein mineralogy (Marescotti et al., Chap. 10; Porter et al., Chap. 12; both this volume; Hunter et al., 1999). The minor and trace element chemistry of low-temperature secondary minerals such as calcite and aragonite provide information about hydrothermal fluid chemistry and the budgets for a number of elements (Yatabe et al., Chap. 11, this volume). Alteration is consistent with a thermal history in which the rocks have never seen temperatures greater than those at present (Marescotti et al., Chap. 10, this volume).

MICROBIAL ACTIVITY

Bacterial concentrations are present though most of the sediment section at Site 1027 but decrease by one to two orders of magnitude in the first 20 m below the seafloor (Mather and Parkes, Chap. 13, this volume). Concentrations rise again at the base of the sediment section, where sulfate associated with partially altered seawater diffuses up from basement. Amino acids also are most abundant within shallow Leg 168 sediments but decrease in concentration rapidly with depth (Andersson et al., 2000). Within basement rocks, microbes were observed on fractured surfaces of volcanic breccia cored at Site 1026 (Fisk et al., Chap. 14, this volume). Filtered formation water from this same site had low cell abundance, suggesting that there is not a large microbial population in the formation water sampled at this site.

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Date of initial receipt: 24 February 2000
Date of acceptance: 10 March 2000
Ms 168SR-001