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Hydrothermal activity and the evolution of the seismic properties of upper oceanic crust

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Abstract. In order to investigate the impact of off-axis hydrothermal circulation on changes of the seismic properties of upper oceanic crust (layer 2A), we performed an extensive geophysical survey on the eastern flank of the East Pacific Rise at 14°S. Seismic refraction and heat flow data were obtained along a 720-km-long and 25 to 40-km wide corridor, covering thinly sedimented seafloor created since 8.5 Ma. The seismic data yield a seismic velocity of ~2.9 km/s at the top of 0.5-m.y.-old basement rocks. Within about 8 m.y. the velocity increases gradually to a value of mature oceanic crust (~4.3 km/s). Heat flow data, derived from 43 in situ thermal conductivity and 86 geothermal gradient measurements, suggest that an open hydrothermal circulation system persists for at least 6-7 m.y. In crust older than 7 Ma, regional heat flow is close to values predicted by plate cooling models, suggesting that hydrothermal circulation is going to cease. Considering published dating of alteration minerals, it appears that the permeability of uppermost oceanic crust has decreased to values insufficient to promote a vigorous hydrothermal circulation within 10-15 m.y. This idea may explain why seismic velocities in the Pacific ocean have not changed significantly in igneous crust older than 8-10 Ma. In regions where juvenile and consistently hot crust is buried rapidly by sediments the evolution of the seismic properties is quite different; velocities increase rapidly and reach values of mature oceanic crust within 1-2 m.y. We therefore favor a model where basement temperature is governing the evolution of the seismic properties of upper oceanic crust [*Stephen and Harding*, 1983; *Rohr*, 1994].

Introduction

In young insignificantly sedimented crust, values of heat flow are widely scattered and fall below those expected for cooling solely by thermal conduction. This heat flow discrepancy is thought to reflect the transport of significant amounts of heat at the seabed by circulating fluids [*Lister*, 1972]. Results of this circulation are exhibited most spectacularly at the ridge crests where venting of fluids at temperatures of 350° to 400°C occurs. On ridge flanks the heat loss from cooling of the lithosphere drives circulation in the porous upper layers of oceanic crust. Here, at much lower temperatures, the vigor of hydrothermal circulation is reduced, but because of the vast areas of the seafloor where such circulation can occur, the majority of hydrothermal heat flux is off-axis [*Stein and Stein*, 1994].

The circulation of seawater through basalts and sediments plays a key role in the development of the physical and chemical nature of the upper crust. *Houtz and Ewing* [1976] recognized that hydrothermalism is an evolutionary process that affects the seismic properties of the volcanic edifice, called layer 2A [*Talwani et al.*, 1971]. They proposed that compressional wave velocities increase over a time spanning tens of millions of years. The most likely explanation for the increasing velocities is decreasing porosities of extruded basalts due to the filling of voids and cracks with hydrothermally generated minerals, a byproduct of off-axis hydrothermal circulation [e.g., *Jacobson*, 1992]. However, over the last two decades little progress has been made in refining and understanding the interaction between hydrothermal activity and the evolution of the seismic properties. A recent re-examination of the data from *Houtz and Ewing* [1976] and *Houtz* [1976] shows that some of their interpretations are compromised either by basement topography [*Diebold and Carlson*, 1993] or by assumptions in their interpretation methods [*Carlson and Jacobson*, 1994]. More recent studies have found that upper crustal structure is indeed a function of plate age; seismic velocities increase from approximately

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2.2 km/s near mid-ocean ridges by a factor of 2 within less than 10 m.y. [*Purdy*, 1987; *Rohr*, 1994; *Grevemeyer and Weigel*, 1996, 1997; *Carlson*, 1998].

The mechanisms which affect the vigor of hydrothermal circulation, and hence changes in upper crustal seismic structure, have long been of interest. In a model of *Anderson and Hobart* [1976] the fluid flow into the crust is restricted when the basement is buried with 150-200 m of sediment. A second possibility, suggested by *Anderson et al.* [1977], is that the volume of water passing through the crustal rocks is reduced with age by decreased porosity and hence permeability of the crust due to hydrothermal deposition of secondary minerals. In this case the reduction in hydrothermal heat flux should correlate with variations in crustal seismic velocity. However, both increased sediment cover and reduced crustal permeability may contribute to restrict the fluid flow into the volcanic edifice [e.g. *Jacobson*, 1992].

Only one recent study indicates that there is a strong correlation between the hydrothermal regime and the increase in seismic velocities in layer 2A east of the Juan de Fuca Ridge [*Rohr*, 1994]. *Rohr* [1994] proposed that seismic velocities increase as the crust is sealed by sediment and basement temperature rises. While in most ocean basins burial of basement occurs over several tens of millions of years, the eastern flank of the Juan de Fuca Ridge is covered rapidly by turbidite sediments from the adjacent North America continental margin. In turn this may produce a unique hydrogeological regime. Aboard the research vessel *Sonne* we investigated both upper crustal seismic structure and the heat transfer on the flank of a spreading ridge with thin sediment cover: the East Pacific Rise (EPR) at 14°S.

Geological Background

In 1995 a joint University of Hamburg and University of Bremen program, called 'Exchange between Crust and Ocean' (EXCO), was conducted on the southern East Pacific Rise (SEPR) to characterize the structure and hydrogeology of young insignificantly sedimented crust on a "superfast" rate spreading center. South of the Garrett fracture zone, the SEPR is uncharacteristically devoid of any transform fault boundaries for nearly 1150 km [*Lonsdale*, 1989]. We selected a 720-km long and 25 to 40-km-wide tectonic corridor on the eastern flank (i.e., the Nazca plate) which intersects the ridge axis 60 km south of the Garrett transform between 14°S and a minor ridge axis discontinuity at 14°27'S [*Weigel et al.*, 1996; *Grevemeyer et al.*, 1997]. Magnetic data from the survey allow a unambiguous identification of the sequences of reversals. Modeling of the data suggests that over the last 8.5 m.y. the Nazca plate was spreading with an average rate of 85 mm/yr [*Grevemeyer et al.*, 1997].

At the ridge crest, the axis morphology is characterized by a prominent bathymetric high with smooth flanks and a relatively flat summit [*Lonsdale*, 1989; *Scheirer and Macdonald*, 1993]. Seismic reflection imaging provides evidence for an axial magma chamber (AMC) reflector [*Detrick et al.*, 1993; *Kent et al.*, 1994]. Both the blocky crestal ridge and the prominent AMC reflector are consistent with a magmatically active ridge segment [*Detrick et al.*, 1993; *Scheirer and Macdonald*, 1993]. The accretion process at this portion of the EPR is very uniform along axis [*Detrick et al.*, 1993; *Kent et al.*, 1994], and the thickness of extruded basalts (i.e., layer 2A) doubles within 1-2 km of the ridge axis from 200-250 m to 500-600 m and remains nearly constant off-axis [*Kent et al.*, 1994].

Data and Interpretation

Geothermal Measurements

In situ thermal gradient and conductivity measurements were made with a violin bow "Lister probe" [*Hyndman et al.*, 1979; *Lister*, 1979]. The temperature gradient is measured by up to 11 thermistors mounted in a lance that penetrates 3 m into the sedimented seafloor. In situ conductivity measurements are made at 43 locations by monitoring the decay of a calibrated heat pulse. Thermal gradient, thermal conductivity, and the heat flux are determined using an approach of *Villinger and Davis* [1987]. In order to assess the regional decrease of heat flow with age as well as the known, highly variable local values, we attempted to determine heat flow at age intervals of roughly 0.5 m.y., that is, at 45-km intervals (Figure 1). Regional stations consisted of up to nine penetrations on short profiles parallel and normal to the ridge axis. To assess the correlation between seafloor relief and heat flow, we placed 20 penetrations along a profile covering 1.5- to 1.7-m.y.-old seafloor. The spacing between penetrations was 1000 m. At the end of the survey, 16 locations comprising a total number of 86 penetrations were explored. Figure 2 shows the heat flow values as a function of plate age. The heat flow values range from 60 to 470 mW/m^2 and show significant variations, both along isochrons and with age. In general, almost all values lie below the trend predicted by the plate cooling model, suggesting that significant amounts of heat are being removed by hydrothermal circulation. However, even in the case of very high heat flux on crust ≤ 1 Ma and a sediment thickness of less than 10-20 m, no signs of advective fluid flow can be detected [*Kaul et al.*, 1996]. But the scatter decreases for ages greater than 6 Ma and the observed heat flux approaches the conductive-cooling curve on ~7-m.y.-old seafloor.

Existing published heat flow measurements [*von Herzen and Uyeda*, 1963; *Langseth et al.*, 1965; *Anderson et al.*, 1978] (referred to as old data set in the following discussion) on the EPR are mostly about 200 km north or south of the EXCO heat flow transect with some overlap. Both data sets (old and new) show the typical behavior of heat flow on ridge flanks: the large heat flow variations close to the ridge decrease with increasing crustal age, as expected. However, there are two important differences between the published and the new data sets. First, the spacing of individual measurements in the old data sets is generally of the order of 50 to 100 km, compared to 1000 m in our study. Therefore they do not allow us to infer local variability due to variations of sediment thickness or local recharge/discharge of water. Second, heat flow values of the old data sets are based on thermal conductivities measured on core samples with needle probes [*von Herzen and Uyeda*, 1963; *Langseth et al.*, 1965; *Anderson et al.*, 1978]. These thermal conductivities are about 20–25% lower than our in situ values [*Kaul et al.*, 1996], a discrepancy that cannot be explained by temperature or pressure effects alone. It is, however, very likely that the needle probe measurements suffered from systematic errors of unknown cause. In situ thermal conductivities measured with the Lister probe on previous cruises agree very well

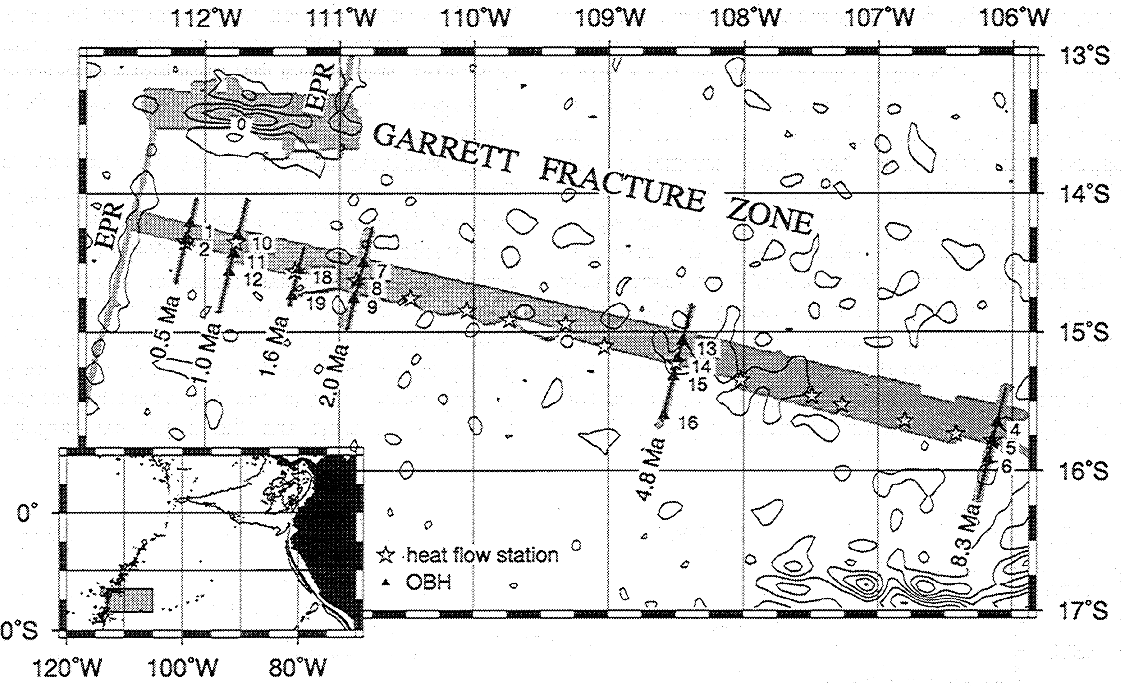

Figure 1. The EXCO study area on the southern East Pacific Rise at 14°S. Complete bathymetric coverage is indicated by gray shading. Stars mark the 16 heat flow stations, triangles are OBH positions, and the seismic refraction lines are shown along with seafloor ages from *Grevemeyer et al.* [1997]. Contour lines are satellite-derived gravity anomalies [*Smith and Sandwell*, 1995].

with measured values on cores [*Davis et al.*, 1997]. Therefore we are confident that our in situ thermal conductivities are correct within their inherent error limits of ± 3%.

In order to better understand the thermal regime along the investigation corridor, we correlated the heat flow values with the topography. Previous investigations indicated that fluid circulation is controlled by basement topography [e.g., *Davis and Villinger*, 1992; *Johnson et al.*, 1993; *Fisher et al.*, 1994], with higher heat flow at summits of abyssal hills and lower values in the valleys. However, measurements in the vicinity of normal faults that bound the valleys indicate that faults also serve as conduits for both discharge and recharge [*Davis and Villinger*, 1992; *Johnson et al.*, 1993].

Unfortunately, seismic reflection and 4-kHz profiling often provided only poor images of the sedimentation pattern, which may indicate that the sediment thickness is at several locations below the resolution of the experimental setup. The data are often plagued with reflections and diffractions from seafloor features such as abrupt fault scarps, collapsed lava tubes, small hills, and troughs. Moreover, out-of-plane scattering from a rough seafloor may contribute to the noise in the reflection profiles. These scattered seafloor events indicate that the basement is only thinly buried with sediments. Nonetheless, seismic reflection, refraction, and 4-kHz data can be used to provide an initial assessment of the overall sedimentation pattern, suggesting that the sediment thickness for 0.5- to 1.0-, 1.5- to 5.0-, and 8.3-m.y.-old crust is in the order of ≤ 10 m, 20-50 m, and 10-30 m, respectively. Immediately to the south, fault scarps are very well preserved in Seabeam 2000 sidescan data [*Cormier et al.*, 1997]. The fact that fault scarps a few hundred meters high are very clearly imaged out to 4 Ma suggests that sediment cover is at most a few tens of meters at this age (M.-H. Cormier, personal communication, 1997). Therefore we concluded that seafloor topography derived from swath-mapping bathymetry is a good approximation of the basement topography.

In agreement with previous studies, our results show that circulation of hydrothermal fluids is controlled by the base-

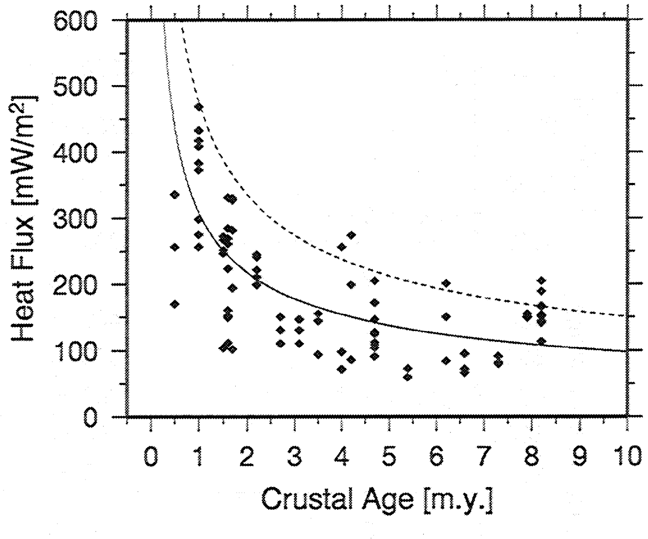

Figure 2. Heat flow data obtained along the EXCO corridor. In crust younger than 7 Ma, measurements of heat flow are widely scattered and fall below those predicted by plate cooling models (broken line: plate cooling model [*Parson and Sclater*, 1977]; solid line: composite heat flux model with hydrothermal cooling [*Pelayo et al.*, 1994]). At 7 Ma heat flow approaches values of the plate cooling model, suggesting that hydrothermal heat flux has largely ceased.

ment topography (Figure 3). In general, basement highs are associated with high heat flow values while graben structures display low values. Although measurements on the summits of two abyssal hills at 1.5-1.7 Ma are coarsely spaced and the local variations in heat flow may not be well resolved, we suggest that two local heat flow anomalies near 111.37°W and 111.26°W may correlate with high permeability pathways, through which the recharge of seawater occurs (Figure 3). Indeed, heat flow values roughly decrease from 260 to 105 mW/m^2 and from 340 to 90 mW/m^2, respectively, while basement topography remains nearly unchanged at both locations. Similar observations are made on profiles along isochrons. Thus two different forms of hydrothermal circulation may occur within oceanic crust, which are controlled by (1) the "background" permeability, producing a heat flow pattern which roughly mimics the topography, and (2) high-permeability conduits, providing local heat flow anomalies. We believe that such high-permeability pathways can support low-temperature off-axis vents which may occur elsewhere.

Of particular interest is that the observed regional heat flow approaches the trend of the plate cooling model [*Parson and Sclater*, 1977] at about 7- to 8-m.y.-old crust. Recent studies [*Stein and Stein*, 1994] claim that the sealing age for the Pacific ocean is reached at a crustal age of about 65 m.y. According to *Stein and Stein* [1994], the sealing age is defined as the age where the observed heat flow approximately equals the heat flow predicted by a purely conductive cooling model, that is, the age where hydrothermal circulation between crust and the ocean has largely ceased. In

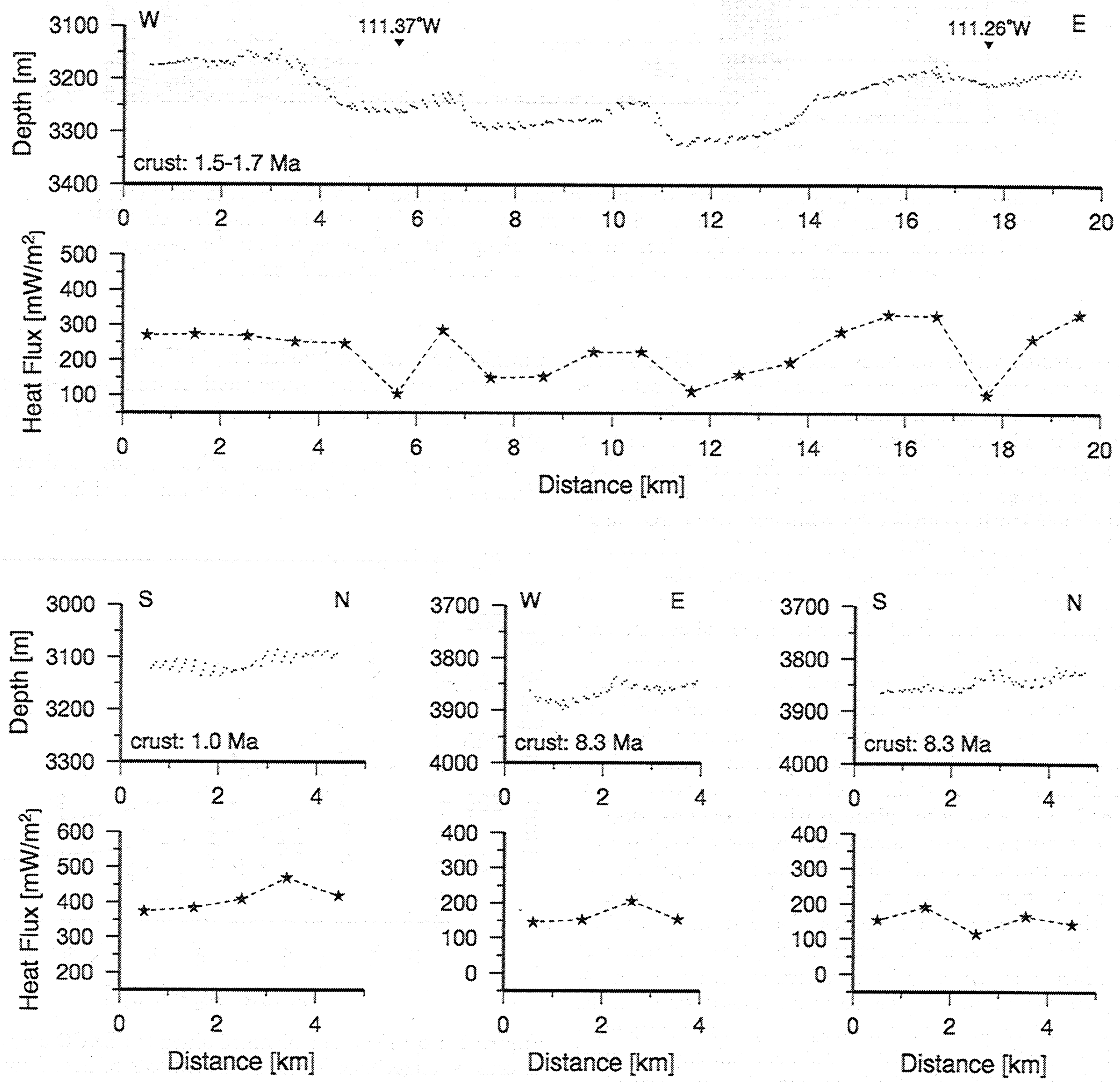

Figure 3. Correlation between heat flow values and topography. Topography is a 1000-m wide swath derived from multibeam bathymetry. The measurements indicate that topographic forcing is responsible for long wavelength variations, with high heat flow at abyssal hill summits and low values in abyssal hill troughs. However, local heat flow anomalies near 111.37°W and 111.26°W suggest that high permeability pathways serve as conduits for hydrothermal fluids.

addition to the simple plate cooling curve of *Parson and Sclater* [1977], Figure 2 shows the composite heat flow model of *Pelayo et al.* [1994]. This model incorporates hydrothermal cooling. For crust older than 7 m.y. our measurements yielded values well above the composite model. Thus hydrothermal heat flux at the SEPR is comparatively lower than predicted by global heat flow data. Moreover, because dating of alteration products suggested that most of the minerals form within 10-15 m.y. [e.g., *Peterson et al.*, 1986; *Hart et al.*, 1994], it seems to be very unlikely that the sealing age will be reached at seafloor of 65 Ma (see discussion below).

In a region of insufficient sediment blanketing, the transition to a predominantly conductive thermal regime is inherently affected by the permeability structure of uppermost oceanic crust. According to the observed regional heat flow pattern, it thus appears that crustal evolution has reduced upper crustal permeability to a value insufficient to support a vigorous hydrothermal circulation system. The off-axis hydrogeological regime, however, is also affected by basement topography and basal heat flow [*Davis and Villinger*, 1992; *Johnson et al.*, 1993; *Fisher et al.*, 1994]. In a statistical study, *Grevemeyer et al.* [1997] estimated the rms height of abyssal hills in the EXCO corridor. With an rms height of only 40 m the seafloor is remarkably smooth where the heat flow approaches the plate cooling model. In terms of numerical simulations a decreasing basement relief produces a reduction in the discrepancy between observed and predicted heat flux [*Fisher et al.*, 1994]. Thus heat flow values on ~8-m.y.-old crust may reflect both reduced upper crustal permeability and the impact of a smooth basement. Moreover, even a thin sediment layer over older crust may cause enough conductive refraction at the seafloor to mask the variations in seafloor heat flow associated with off-axis hydrothermal convection [*Fisher et al.*, 1994].

Seismic Experiment

To sample variations in upper crustal velocity structure, six 50- to 100-km-long refraction lines were shot over 0.5- to 8.3-m.y.-old seafloor (Figure 1). The source was a single 32-litre airgun operating at a pressure of 13.8 MPa. A shot spacing of 180 m was used on all profiles except for the 8.3 Ma line, which was shot at 250 m spacing. The navigation along the seismic lines and instrument drop point positioning was controlled by the Global Positioning System. The receiver were digital recording ocean-bottom hydrophones (OBHs) from the GEOMAR [*Flüh and Bialas*, 1996]. The hydrophone data were stored at 200 samples per second onto digital audio tapes. In total, 17 OBHs provided data useful for geophysical interpretation. The receiver locations were further constrained using water path arrival times from airgun shots. The sound speed model used for this approach was based on conductivity-temperature-depth measurements obtained on 8.5-m.y.-old crust. The timing and positioning uncertainties inherent in refraction data are estimated to be less than 12 ms.

Recently, *Douglas et al.* [1997] have shown that three main factors determine how accurately any particular onset of a seismic arrival is read: (1) magnification and time scale of the display, (2) signal-to-noise ratio, and (3) the form of the pulse radiated by the source. Figure 4 shows typical seismograms recorded on the seafloor sensors. To provide only wavelengths much shorter than the typical thickness of layer 2A, seismograms were bandpass filtered from 20-50 Hz. The low ambient noise level and the good quality of waveforms made picking of the first breaks relatively straightforward. Compared to the strong amplitudes of the water wave, refracted arrivals corresponding to ray path entirely within the basement layer can readily be identified ahead of the water wave. Most arrivals from layer 2A could be picked to ± 8 ms. Arrivals from layer 2B and upper layer 3 have larger errors of ± 10-40 ms, because of the lower signal-to-nose ratio at larger offsets. When combined with positioning uncertainties of ± 12 ms, estimated errors in observed first-arrival travel times vary from about ± 20 ms to ± 50 ms.

To refine previous estimates of upper crustal seismic structure [*Grevemeyer and Weigel*, 1997] the travel time data were calculated using a two-dimensional ray-tracing algorithm [*Zelt and Smith*, 1992]. We applied a combination of forward modeling and inversion. A structural model was constructed using a "top-down" approach, modeling the velocity and depth to each layer before moving down to the next. To place additional constraints on the velocity gradients, synthetic seismograms were calculated [*Zelt and Ellis*, 1988]. Both the ray-tracing and the synthetic seismogram modeling code are based on asymptotic ray theory [*Cerveny et al.*, 1977]. All lines were modeled so that the calculated and observed first-arrival travel times match as close as possible within the error limits. To assess the quality of modeling, we used the rms travel time and the chi-square parameter. These parameters quantify the fit between the observed and computed arrival times [*Zelt and Smith*, 1992]. Amplitudes were fit subjectively matching the principal variations in the seismic records [*Grevemeyer et al.*, 1998].

The modeling yielded a velocity structure which closely matches the seismic structure of layer 2 found along the EPR [e.g., *Kent et al.*, 1994; *Christeson et al.*, 1997]. The upper crust consists of a surficial low-velocity layer 2A (400-700 m thick) underlain by layer 2B with velocities >5.2-5.6 km/s. Compared to results obtained from expanding spread profiles (ESP) [e.g., *Harding et al.*, 1989; *Vera et al.*, 1990] and from on-bottom seismic experiments [*Christeson et al.*, 1994a] our velocity-depth profiles are comparatively simple. While our modeling suggests that the layer 2A-2B boundary is consistent with a simple discontinuity, those experiments revealed a steep gradient or a step-like high-gradient region [*Christeson et al.*, 1996]. However, the experimental setups have been quite different. As shown by some recent studies [e.g., *Herber et al.*, 1997], the noise of previous shots reverbrates much longer in the water column when the spectrum of the source is dominated by low frequencies. The dominant frequencies of OBH, ESP, and on-bottom seismic experiments are generally < 10 Hz, ~30 Hz, and ~60 Hz, respectively. Therefore the shot spacing of the OBH experiment was larger and hence the spatial resolution of seismic data is reduced. Moreover, lower frequencies produced longer wavetrains in seismic record sections. Thus they tend to mask second arrivals. ESP experiments, for example, often use second arrivals to model upper crustal structure.

A major goal of our study was to resolve the age-dependent structure of layer 2A. Figure 5 shows the ray paths of OBH 7 through upper oceanic crust. Generally the OBHs were able to detect rays turning entirely within layer 2A.

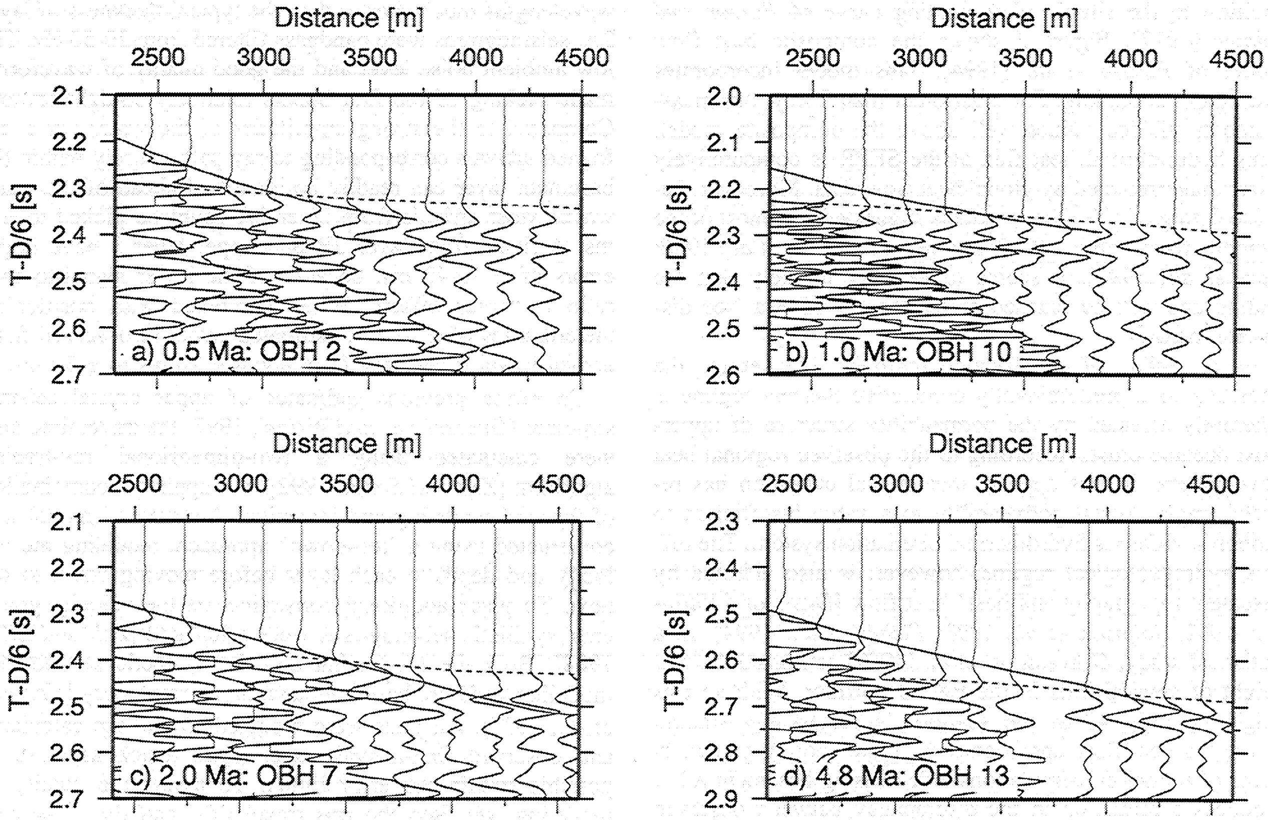

Figure 4. Hydrophone data from airgun shots from (a) OBH 2, (b) OBH 10, (c) OBH 7, and (d) OBH 13 on 0.5-, 1.0-, 2.0-, and 4.8-m.y.-old seafloor, respectively. Seismograms are 20-50 Hz bandpass filtered. Large amplitudes are clipped for display purposes. Also shown are calculated travel times of layer 2A (solid line) and 2B (broken line).

However, the experimental setup was limited in its ability to detect and resolve the velocity structure in the uppermost 50-100 m. To put constraints on this region, we assume a single velocity gradient in layer 2A. Off-axis, this is a good approximation for the uppermost 200-300 m [e.g., *Vera et al.*, 1990]. In order to estimate uncertainties in our layer 2 velocity structure and thickness, we used a damped least squares inversion of travel time data [*Zelt and Smith*, 1992]. This analysis indicates an error of ± 0.1 km/s for the seismic velocities and suggests that the thickness of the layers is calculated with uncertainties of approximately 15-20%.

Previous OBH studies often did not resolve velocities of layer 2A. In general, these studies used explosive charges and suffered from a too large shot spacing. To sample layer 2A, we need a close shot spacing, though water depth, layer 2A thickness, and velocity will affect whether a layer 2A or layer 2B refraction will emerge from the water wave. On zero-age crust, only two OBH studies detected arrivals turning within layer 2A [*Cudrak and Clowes*, 1993; *McDonald et al.*, 1994]. Those studies benefitted from the shallow crestal depth of the Juan de Fuca Ridge off Vancouver Island. Our study, however, benefitted from an increase in layer 2A velocity with age. This effect is evident in Figure 4. Because of the increase of seismic velocities in the uppermost crust, the layer 2A-2B takeover point is shifted toward larger offsets. In addition, the thickness of layer 2A varies by as much as 500 m (Figure 6), promoting layer 2A arrivals at locations with a thick lava pile. Similar variations have been observed at the SEPR at 17°S [*Bazin et al.*, 1998], where a thick layer 2 is associated with crust affected by migration paths of overlapping spreading centers. Our survey provided the thickest crust in areas characterized by a rough seafloor topography [*Grevemeyer et al.*, 1997], which may represent discordant zones associated with fossil overlapping spreading centers.

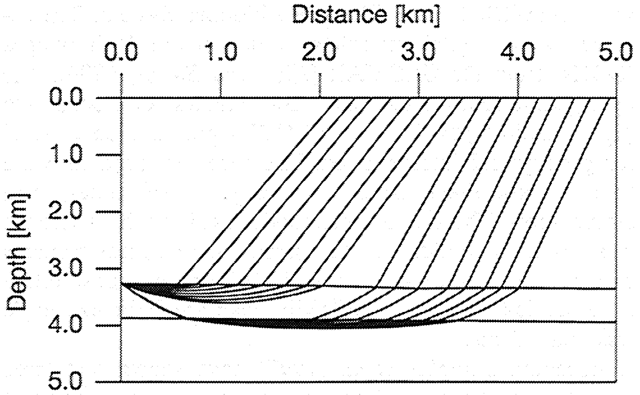

Figure 5. Ray paths of airgun shots of OBH 7 used for forward modeling and inversion of travel time data shown in Figure 4c. Note that the experiment was able to detect rays turning entirely within layer 2A.

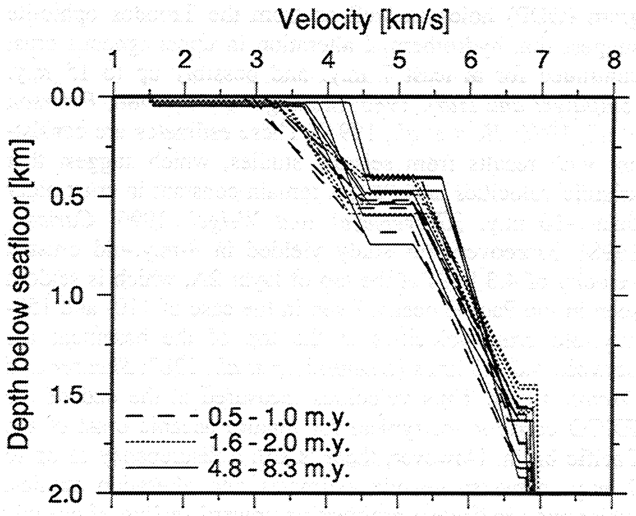

Figure 6. Compressional velocity-depth models of upper oceanic crust obtained from forward modeling and inversion of 17 OBH split profiles on 0.5- to 8.3-m.y.-old crust.

In total 17 split profiles provided data from the surficial low-velocity layer. The modeling revealed that the velocity at the top of layer 2A increases gradually from ~2.9 km/s in 0.5-m.y.-old crust to a value of 4.3 km/s (Figure 7). Moreover, the data indicate a decrease of the vertical velocity gradient in layer 2A with age. A similar observation was made by *Purdy* [1987] on the western flank of the Mid-Atlantic Ridge. This observation could be interpreted in terms of a progressive upward sealing of oceanic crust by secondary minerals, as suggested by *Peterson et al.* [1986]. However, there might be a trade off between gradient and attenuation, which is high for layer 2A over young crust [*Christeson et al.*, 1994b]. Therefore velocity gradients of upper oceanic crust might be tenuous.

At the ridge crest of the SEPR at 14°S, wide aperture profiles (WAP) yielded a velocity of 2.35 km/s at the top of the volcanic basement [*Tolstoy et al.,* 1997], suggesting that layer 2A velocities rapidly increase close to the ridge axis (~0.8-1 km/s per 1 m.y.) and slowly thereafter (0.1-0.2 km/s per 1 m.y.). Along with our new data a compilation of seismic velocity determinations is shown in Figure 7. Because marine seismologists have shown the presence of horizontal anisotropy in upper oceanic crust [*Stephen*, 1985; *McDonald et al.*, 1994], we included only those values obtained shooting parallel to the ridge axis direction. We compiled velocities derived from ESP [*Harding et al.*, 1989; *Vera et al.*, 1990], WAP [*Tolstoy et al.*, 1997], vertical seismic profiling (VSP) [*Stephen*, 1985] and on-bottom seismic experiments [*Christeson et al.*, 1994a]. Although only one VSP experiment from Deep Sea Drilling Project (DSDP) Hole 504B [*Stephen*, 1985] is available on off-axis crust, the data are in good agreement with our estimates. This observation suggests that the trend found on the SEPR might be common for large areas of the Pacific ocean. It is interesting to note also that data from the Atlantic ocean [*Purdy*, 1987] support the same trend (Figure 7). Profound differences between the emplacement process of extrusives at slow- and fast-spreading ridges have been observed [e.g., *Bonatti and Harrison*, 1988]. However, according to the trend found here, it seems reasonable to hypothesize that the accretion process does not affect the age-dependent structure of oceanic crust. Clearly, much more data from the ridge flanks will be needed to understand the evolution of the seismic properties in more detail, though a recent statistical investigation of 102 published velocity determinations of upper oceanic crust [*Carlson*, 1998] provides an excellent agreement with the data shown in Figure 7. We therefore argue that there is a global trend for upper crustal structure versus age.

Discussion

The data compiled in Figure 7 have in common that the basement is not isolated from the seawater by a thick sediment sequence. *Grevemeyer and Weigel* [1997] suggest that the two-stage evolution of seismic properties of layer 2A (rapidly at young ages, gradually thereafter) is caused by the ridge crest and ridge flank hydrothermal circulation system. Changes in physical properties are believed to be caused by seawater-rock interactions, which are controlled by the water/rock ratio, and by the temperature of reaction. In general, the higher the temperature, the faster and greater the extent of the reaction. This implies that the high temperature axial system, with its rapidly circulating hydrothermal fluids, is accompanied by a comparatively large amount of hydrothermal alteration and sealing of open void spaces. In the ridge flank system, the chemical reactivity is reduced at the much lower temperatures. Several studies indicate that most of the

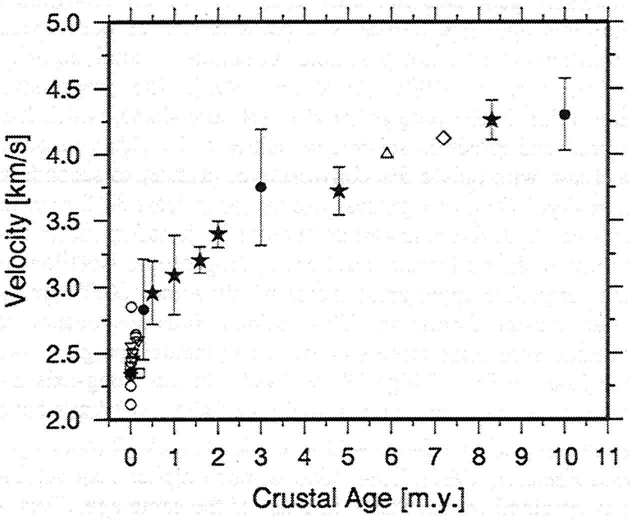

Figure 7. Upper crustal or layer 2A velocity as a function of basement age. We characterize layer 2A by its velocity at the top of the layer. Along with our new results (stars), we show velocities derived from wide aperture profiles (solid diamond) [*Tolstoy et al.*, 1997], expanding spread profiles (squares and inverted triangles) [*Harding et al.*, 1989; *Vera et al.*, 1990], and on-bottom seismic measurements (open circles) [*Christeson et al.*, 1994a]. These data are from the East Pacific Rise. In addition, we included vertical seismic profiling measurements from Deep Sea Drilling Project hole 504B (triangle) [*Stephen*, 1985] and from an on-bottom seismic experiment on the Mid-Atlantic Ridge (open diamond) [*Purdy*, 1987]. Solid circles are mean values from a global statistical analysis of seismic velocity data from layer 2A [*Carlson*, 1998].

hydrothermal alteration occurs within the first 3 m.y. [e.g., *Thompson*, 1983]. Because the rate of crustal crack filling depends on the availability of alteration minerals and on the vigor of hydrothermal circulation, plugging of pore spaces and changes in the seismic velocity structure occur slowly away from the ridge crest and cease in a closed system.

Temperature can influence the compressional wave velocity of basalts [e.g., *Sato et al.*, 1989], but it has a small effect (<5%) until solidus temperatures are reached. Thus near mid-ocean ridges, temperature variations will not be detected by compressional waves, except in the vicinity of an axial magma chamber. While basement temperature has no considerable impact on changes of the seismic properties, seafloor observations from the Juan de Fuca Ridge may explain the rapid increase of velocities close to the ridge axis by tectonic processes. Seafloor gravity data obtained from the submersible *Alvin* [*Holmes and Johnson*, 1993] show an abrupt increase in density and hence velocity of the upper 200 m of crust within ~150,000 years. This density change is interpreted as a systematic reduction in bulk porosity of the upper crustal section, from 23% for the axial ridge to 10% for the flanking abyssal hills. *Holmes and Johnson* [1993] suggest that the most likely cause of this dramatic decrease in porosity is elimination of large-scale voids known to be present at volcanically active ridges [*Francheteau et al.*, 1979]. Large-scale porosity, like hollow pillows and lava tubes, may collapse as the lithosphere moves away from the ridge axis.

The most reasonable cause for the off-axis increase of seismic velocity is filling of open void spaces with hydrothermally generated minerals. It is now widely recognized that this age dependence is a consequence of pore space modification and not a simple reduction of total porosity [*Wilkens et al.*, 1991; *Jacobson*, 1992]. The progressive deposition in the pore space changes pore shape, which has a profound effect on seismic velocities and yields a velocity increase with only a 5% conversion of primary to secondary porosity. While this process occurs for at least 8-10 m.y. in an open hydrothermal system (Figure 7), it occurs rather abruptly when burial and resultant hydrogeologic isolation of the permeable upper crust occurs within some 100,000 years after crustal formation. This unique situation occurs at oceanic spreading centers close to continental margins, like the Juan de Fuca Ridge [*Rohr*, 1994]. In the along-axis direction, seismic refraction velocities of about 4.3 km/s have been sampled in 1.5-m.y.-old volcanic bedrock [*Rosenberger and Fechner*, 1997]. This value is much higher than velocities obtained on the SEPR in crust of the same age. Thus it appears that the accumulation of sediments inherently affects the thermal regime and hence the evolution of seismic properties [*Stephen and Harding*, 1983; *Rohr*, 1994] (see discussion below).

To constrain the timescale of hydrothermal activity from seismic velocity estimates and heat flow data, an independent line of evidence is required. Although precise dating of alteration history is generally unavailable, a great deal of information exists regarding the composition of the altered upper crust. K/Ar and ^{87}Rb/^{86}Sr dating of celadonites, a near-final stage low temperature alteration mineral, provided an initial assessment on the time interval within which alteration, and hence the evolution of seismic properties, can occur. Results from several DSDP and Ocean Drilling Program (ODP) holes as well as from the Troodos ophiolite suggest that hydrothermal alteration in upper igneous crust continued for at least 7 m.y. and possibly up to 15 m.y. [*Staudigel and Hart*, 1985; *Staudigel et al.*, 1986; *Peterson et al.*, 1986; *Hart et al.*, 1994]. These estimates are consistent with results from seismic studies, which suggest that seismic velocities in layer 2A remain constant in crust older than ~10 m.y. [*Grevemeyer and Weigel*, 1996; *Carlson*, 1998]. Moreover, our study yielded in 8-m.y.-old crust a velocity of 4.3 km/s at the top of layer 2A, which is seldom seen in the Pacific ocean. Even in the case of 110- and 157-m.y.-old crust velocities at the top of the basement are between 4.0-4.3 km/s [*Duennebier et al.*, 1987; *Shearer and Orcutt*, 1986]. Thus velocities measured at the end of the EXCO corridor are typical for mature oceanic crust of the Pacific basin. However, there is still a discrepancy of up to 7 m.y. between seismic estimates and alteration studies, which may indicate a progressive upward sealing of oceanic crust by secondary minerals [*Peterson et al.*, 1986]. As discussed above, changes in the physical properties in the uppermost 50-100 m would not be detected by seismic refraction technique using surface shots. On the other hand, it could be discussed in terms of a model presented by *Wilkens et al.* [1991]. Their model suggested a pore space modification with crustal age, where first small-aspect ratio pore spaces are filled and then large-aspect ratio voids. Because calculations indicated that seismic velocities increase more rapidly by closing the smaller voids than by filling the larger ones, the closure of large aspect ratio void spaces in older crust does not affect seismic velocities significantly.

It is also interesting to discuss the heat flow data in terms of alteration studies. As we demonstrated above, changes in seismic velocities occur within 8- to 10-m.y.-old crust, and hydrothermal alteration continued for about 7-15 m.y. Global heat flow estimates, however, suggested that hydrothermal circulation removes a significant amount of heat for up to 65 m.y. [*Stein and Stein*, 1994]. Hydrothermal heat transfer is generally associated with hydrothermal alteration of crustal rocks and hence the formation of alteration products. A discrepancy between the time scale for hydrothermal circulation from global heat flow and alteration studies is evident. The new heat flow data presented in this paper are well below the plate cooling model and are scattered about the composite heat flux model of *Pelayo et al.* [1994] for crust younger than 7 m.y. For crust older than 7 m.y., however, we observe a quite different behavior. The data show some scatter about the theoretical curve of the plate cooling model of *Parson and Sclater* [1977], and all observations are well above the composite model. We therefore suggest that the observed heat flow approach values predicted by the plate cooling model, though sediments may capture heat that the plate is giving off by convection [*Fisher et al.*, 1994]. However, because most of the alteration minerals form within 7 to 15 m.y., it might be reasonable to suggest that crustal evolution has changed the physical properties of ~15-m.y. old upper oceanic crust to values insufficient to allow a vigorous hydrothermal circulation.

To initiate thermal convection in a porous layer, the geothermal gradient and permeability must exceed critical values. Constraints from ophiolites and ODP/DSDP drill sites indicate a final porosity of 4-8% in uppermost oceanic crust [*Gillis and Sapp*, 1997], and hence the presence of permeability. However, the rock fabric and the heat loss of the earth may not support hydrothermal activity in oceanic crust everywhere. The regional trend of heat flow (Figure 2) and the dating of celadonites [*Staudigel and Hart*, 1985; *Peterson et al.*, 1986; *Staudigel et al.*, 1986; *Hart et al.*, 1994] indicate that a vigorous hydrothermal circulation system persisted for at least 7 m.y., and may cease in ~15-m.y.-old crustal rocks. If so, permeability in 10- to 15-m.y.-old basement rocks might be insufficient to promote hydrothermal circulation. The prediction of permeability itself is difficult and tenuous. The work of *Anderson et al.* [1985] and *Evans* [1994], however, provide an initial assessment. On-axis, upper crustal permeability is ~6 x 10^{-12} m^2, decreasing to ~7 x 10^{-14} m^2 within 6 m.y. Seismic velocities for crust of the same age are 2.2 km/s and 4.0 km/s, respectively (Figure 7). Thus an increase of seismic velocity by hydrothermal sealing of upper crustal porosity is associated with decreasing permeability. Consequently, it might be reasonable to hypothesize that an increase to 4.3 km/s may indicate a permeability of some 10^{-14} m^2, or less.

These results demonstrate that in thinly sedimented areas plugging of crustal pore spaces generally extends to at least 7 Ma, and possibly up to 15 Ma. In regions with significant sediment cover, however, the evolution of crustal porosity is quite different. While in an open circulation system the crust is cooled by the convection of seawater, burial of basement rocks reduces the hydrothermal flow through the crust, and in turn, temperatures in the crust increase. Alteration of basalts is intensified with increasing temperature, and hence the formation of metamorphic minerals is accelerated. Consistently, under such conditions, sealing of open void spaces by secondary minerals and hence reduction of porosity is enhanced. *Stephen and Harding* [1983] proposed this mechanism to explain high velocities in young upper oceanic crust in the Gulf of California (crustal age ~1 Ma). The same mechanism was proposed by *Rohr* [1994] to explain seismic results from the Juan de Fuca Ridge. At the Juan de Fuca Ridge, some recent seismic refraction measurements sampled velocities in the along-axis direction [*Rosenberger and Fechner*, 1997]. Velocities of about 4.3 km/s occur in 1.5- to 2.0-m.y.-old basement rocks. A similar value occurs at the insignificantly sedimented SEPR after 8 m.y. of crustal evolution. Therefore our measurements clearly support the idea that basement temperature, itself a function of basal heat flow, sediment thickness, and sediment permeability, governs the evolution of the seismic properties of upper oceanic crust [*Stephen and Harding*, 1983; *Rohr*, 1994]. However, upper oceanic crust is composed of basalts. Massive, nonvesicular basalt has a compressional wave velocity of about 7 km/s [*Wilkens et al.*, 1988]. The reason for the large difference, of course, is that extrusives of layer 2A are vesicular, fractured, and brecciated and formed into flow units with selvages, interpillow voids, and other porosity [e.g., *Wilkens et al.*, 1991]. This discrepancy indicates that even in mature and sealed oceanic crust, porosity at various scales is still present.

Summary and Conclusions

We present new heat flow and seismic refraction measurements from thinly sedimented seafloor created over the last 8.5 m.y. at the "superfast" spreading East Pacific Rise south of the Garrett fracture zone. The primary objective of the work is to understand the processes that control and affect the hydrogeology and the evolution of the structure of upper oceanic crust as seafloor ages. A number of conclusions can be reached:

1) In crust younger than 6-7 Ma, heat flow values are widely scattered and fall below those expected for cooling solely by thermal conduction.

2) Hydrothermal circulation is generally controlled by the "background" permeability, yielding a heat flow pattern which roughly mimics the topography. However, high permeability conduits can produce local heat flow anomalies.

3) For crust older than 6 Ma the scatter among heat flow values decreases and the regional heat flux approaches values predicted by plate cooling models on 7- to 8-m.y.-old crust. Alteration studies indicate that crustal evolution continued for at least 7 m.y. and possibly up to 15 m.y. [e.g., *Peterson et al.*, 1986; *Hart et al.*, 1994]. We therefore suggest that within 10-15 m.y. hydrothermal alteration decreases upper crustal permeability to values insufficient to promote a vigorous hydrothermal activity in upper oceanic crust.

4) Two-dimensional modeling of 17 OBH split profiles reveals a two-stage evolution of seismic velocities in layer 2A: rapidly at young ages ($\leq$ 0.5 Ma) and gradually thereafter. In young crust, both hydrothermal precipitation of secondary minerals and tectonism may contribute to reduce porosity in the extrusive section of oceanic crust. Off-axis, seismic velocities increase because open void spaces are filled with hydrothermally generated minerals.

5) Layer 2A velocities increase gradually to values of mature oceanic crust within 8-10 m.y. Thereafter the impact of hydrothermal circulation on the evolution of the seismic properties is negligible. In regions where young crust is rapidly buried with sediment, however, seismic velocities increase within only 1-2 m.y. to values of mature crust and remain constant in older seafloor. It therefore appears that basement temperature is the sole factor governing the off-axis evolution of the porosity structure of upper oceanic crust [*Stephen and Harding*, 1983; *Rohr*, 1994].

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