

Widespread seawater circulation in 18–22 Ma oceanic crust: Impact on heat flow and sediment geochemistry

Thomas Kuhn¹, G.J.M. Versteegh², H. Villinger³, I. Dohrmann², C. Heller¹, A. Koschinsky⁴, N. Kaul³, S. Ritter^{2,5}, A.V. Wegorzewski¹, and S. Kasten²

¹Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, 30655 Hannover, Germany

²Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI), Am Handelshafen 12, D-27570 Bremerhaven, Germany

³Department of Geosciences, University of Bremen, P.O. Box 330440, 28334 Bremen, Germany

⁴Department of Physics & Earth Sciences, Jacobs University Bremen, Campus Ring 1, 28759 Bremen, Germany

⁵Institute of Earth Sciences, Heidelberg University, Im Neuenheimer Feld 234, 69120 Heidelberg, Germany

ABSTRACT

On the basis of heat-flow measurements, seismic mapping, and sediment pore-water analysis, we demonstrate widespread and efficient ventilation of the 18–22 Ma oceanic crust of the northeast equatorial Pacific Ocean. Recharge and discharge appear to be associated with basement outcrops, including seamounts and north-south-trending faults, along which sediment cover thins out and volcanic rocks are exposed. Low-temperature hydrothermal circulation through the volcanic crust leads to the reduction of heat flow through overlying sediments, with measured heat-flow values that are well below those expected from conductive cooling curves for lithosphere of this age. Typically, dissolved pore-water oxygen decreases from the sediment surface downward, reaching minimum values at mid-depth and rising again in the lower part of the cores investigated, clearly indicating oxygen-rich seawater circulation through the oceanic crust underneath the sediments. If the residence time of the circulating fluids in the upper crust is short or the fluid flux is large, oxic conditions may be preserved, and oxygen can diffuse upwards into the sediments. This process, leading to widespread oxic conditions in the near-basement sediments, may cause the oxidation of residual reduced material stored in the deeper sediments, resulting in downward fluxes of the reaction products into the basement and from there back into the oceans. Considering the widespread existence of this type of off-axis ventilation, the net effect of the resulting return flow of reaction products on biogeochemical cycles and element fluxes (e.g., carbon and nitrogen) may be very large.

INTRODUCTION

One of the important processes by which Earth loses internal heat is through cooling of the oceanic lithosphere (Sclater, 2003). At the axis of mid-ocean ridges without sediment cover, heat loss occurs due to focused or diffuse hydrothermal discharge. Farther away from the axis, on lithosphere older than ca. 1 Ma, heat-flow measurements in deep-sea sediments generally display values that are lower and more heterogeneous than those expected from conductive lithospheric cooling models (Hasterok et al., 2011, and references therein). These measurements indicate that hydrothermal fluids remove significant amounts of heat from the oceanic lithosphere in off-axis settings up to an age of ca. 65 Ma on average (Stein and Stein, 1992; Hasterok et al., 2011). Off-axis seamounts and other basement outcrops that protrude through low-permeability sediments offer important pathways for the transport of heat and fluids (Fisher, 2005).

The conclusion of Baker et al. (1991) that seawater circulates in the upper crust of the equatorial Pacific Ocean was predominantly based on the interpretation of pore-water profiles from

Deep Sea Drilling Project (DSDP) boreholes. They backed their conclusion by referring to six low heat-flow values from the same area (Sclater et al., 1976). Pore-water evidence for seawater circulation in oceanic basement was also presented by Mewes et al. (2016) for a transect of sediment cores retrieved at the flank of a seamount in the northeast equatorial Pacific Ocean. Here, we present the first comprehensive investigation including bathymetry, seismic, heat-flow, sedimentary pore-water, and solid-phase data in a typical ridge-flank setting (Fig. 1). We find compelling evidence for suppressed heat flow over a broad region resulting from advective heat extraction through numerous basement exposures at seamounts and faults.

STUDY AREA AND METHODS

The study area is located in the equatorial northeast Pacific Ocean ~900 nautical miles (1700 km) southwest of Manzanillo, Mexico, and it belongs to the German license area for the exploration of manganese nodules granted by the International Seabed Authority in 2006 (Fig. 1; refer to www.isa.org.jm for an updated map

with all license areas). Magnetic data indicate a crustal age of 18–22 Ma (Barckhausen et al., 2013). Water depths are 1460–4680 m, with an average of 4240 m (Rühlemann et al., 2011). The seafloor is characterized by deep-sea plains interspersed with NNW-SSE-oriented horst and graben structures that are several kilometers wide, tens of kilometers long, and 100–300 m high (Rühlemann et al., 2011; Fig. 1). Many extinct volcanoes (seamounts) rise a few hundred meters to almost 3000 m over the surrounding abyssal plains. They are 3–30 km in diameter and seem to appear in clusters with an east-west-trending orientation (Rühlemann et al., 2011; Fig. 1).

During cruise SO-240 (May–June 2015) on the German research vessel *SONNE*, 636 km of single-channel seismic profiles were run perpendicular and parallel to the ridge and graben structures using one 3.4 L GI air gun and a 100-m-long, 16 channel streamer (Kuhn et al., 2015; Fig. 1). Apart from identifying tectonic structures of the upper crust, the seismic data were used to assess sediment thickness, with a resolution limit of 10 m due to the low main frequency of the air gun signal. High-resolution bathymetric data using the hull-mounted EM 122 multibeam echosounder system and internal sediment structures using the subbottom profiler ParaSound P70 were recorded together with the seismic data. Heat flow (Bremen heat-flow probe; Villinger et al., 2010) was mapped on 14 profiles (109 individual measurements), all collocated on seismic and ParaSound profiles. Long piston (KL) and gravity cores (SL; up to 13.5 m) were taken at locations of heat-flow anomalies (Fig. 1; Table DR1 in the GSA Data Repository¹). Oxygen in the retrieved sediments was determined onboard using amperometric Clark-type O₂ sensors according to the procedure described

¹GSA Data Repository item 2017261, sediment permeability and thickness, seismic and heat flow data, sediment and pore-water geochemistry, and a side-scan sonar image indicating mass wasting, is available online at <http://www.geosociety.org/datarepository/2017/> or on request from editing@geosociety.org.

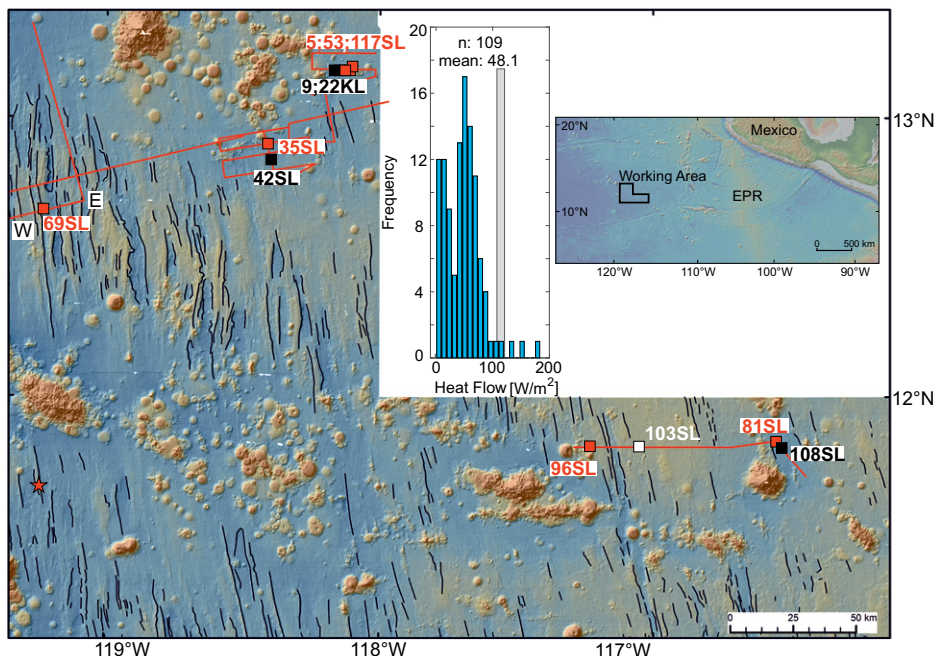


Figure 1. Bathymetry of study area based on EM 120 multibeam echosounder system data from previous cruises in northeast equatorial Pacific Ocean (Rühlemann et al., 2011). Black lines—lineaments detected in bathymetry; red lines—seismic profiles; red squares—sediment cores that are oxic throughout; black squares—cores with a suboxic zone at depth (see Fig. 3); W and E indicate the location of the seismic profile of Figure 2; red star—position of Figure DR6 (see text footnote 1). Permeability measurements were carried out on sediments from core 103SL. Insets: Location of study area ~900 nautical miles (1700 km) southwest off Mexico; EPR—East Pacific Rise. Histogram shows all heat-flow measurements from this study with mean value (48.1 mW/m²) and range of lithospheric cooling predictions for 18–22 Ma oceanic crust (gray bar; Hasterok, 2013).

by Ziebis et al. (2012) and Mewes et al. (2014, 2016). Pore-water samples were retrieved by Rhizon samplers, diluted 1:10 and acidified with suprapure 1 M HNO₃, and stored at 4 °C until analysis of dissolved manganese (Mn²⁺) at the home laboratory at the Alfred Wegener Institute (Bremerhaven, Germany) using inductively coupled plasma–optical emission spectrometry (ICP-OES). For more technical details, see Kuhn et al. (2015).

Permeability of the deep-sea sediments was measured by constant-flow tests with a “Column TestStand” based on the German standard DIN 19683-9 (see Fig. DR1 and the Data Repository). Sediment down-core porosity was also measured to check for compaction according to the procedure described by Mewes et al. (2014).

RESULTS

Hydro-Acoustic and Heat-Flow Data

The hydro-acoustic mapping (bathymetry, subbottom profiler, seismics) showed sediment thicknesses between 0 m and 100 m, with an average of 48 m (refer to Fig. DR2). Low to zero sediment thickness was detected at several locations along the NNW-SSE–trending ridges (Fig. 1). The basaltic basement may outcrop at these sites or is covered by less than 10 m of sediment (Fig. 2). Due to the small-scale roughness of the seafloor bathymetry, even ParaSound could not resolve <10 m sediment cover. Seismic data revealed intense small-scale tectonics in the acoustic basement (layer 2A; Fig. 2). Except for a few isolated high values, the mean heat flow of 48.1 mW/m² is well below the ~108–119 mW/m² predicted for 18–22 Ma conductively cooling oceanic crust (see Figs. DR3 and DR4, and data in the Data Repository; Hasterok, 2013),

and it also only ~2/3 of mean values reported for this crustal age (Fisher, 2005). The few heat-flow values above the predicted value for conductive cooling are either related to faults in the basaltic basement (69SL; Fig. 2) or are close to a seamount (117SL; Fig. 3). *In situ* thermal conductivities are rather uniform (0.83 W/Km; Fig. DR4), because the sediment composition in all study areas is very homogeneous. They consist of a mixture of siliceous ooze and deep-sea clay, except for stations 69SL and 117SL, where

carbonate-rich sediments were found at greater down-core depth (Fig. DR5; Kuhn et al., 2015).

Pore-Water Geochemistry

In long sediment cores close to seamounts and close to larger fractures in the basaltic crust, sediments are oxic throughout, with O₂ concentrations decreasing downward from the core top and upward from the bottom of the cores toward the middle part (53SL, 81SL, and 117SL in Fig. 3; 5SL, 35SL, 69SL, and 96SL in Fig. DR6). The

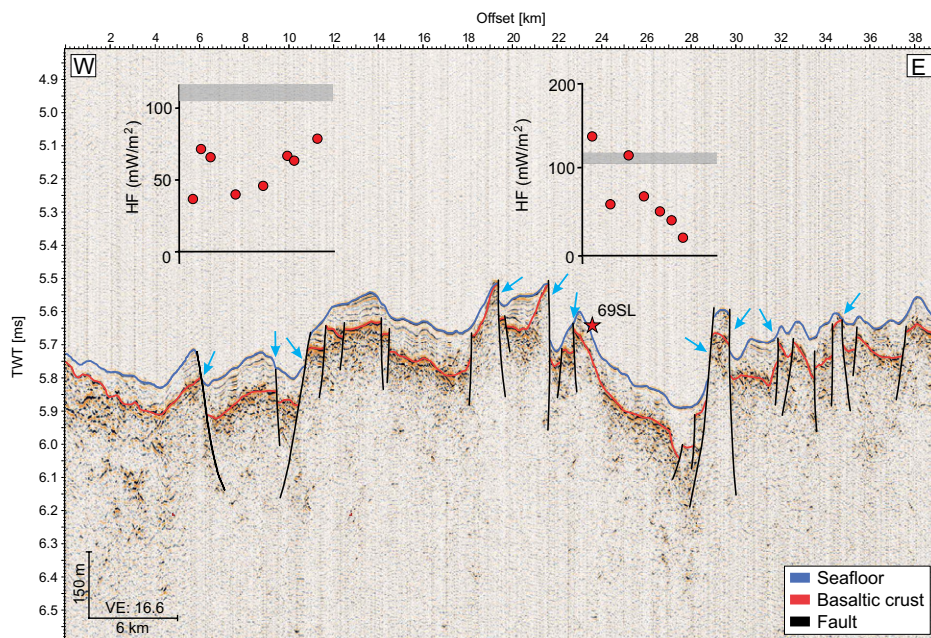


Figure 2. Processed seismic profile with suggested fault structures and heat-flow profiles. At some faults, basaltic basement is exposed to seafloor, enabling a direct hydrological link between seawater and permeable basaltic crust (blue arrows). Horizontal gray bars indicate range of lithospheric cooling predictions for 18–22 Ma oceanic crust (Hasterok, 2013). VE—vertical exaggeration, TWT—two-way travelttime (R. Singh, 2017, personal commun.).

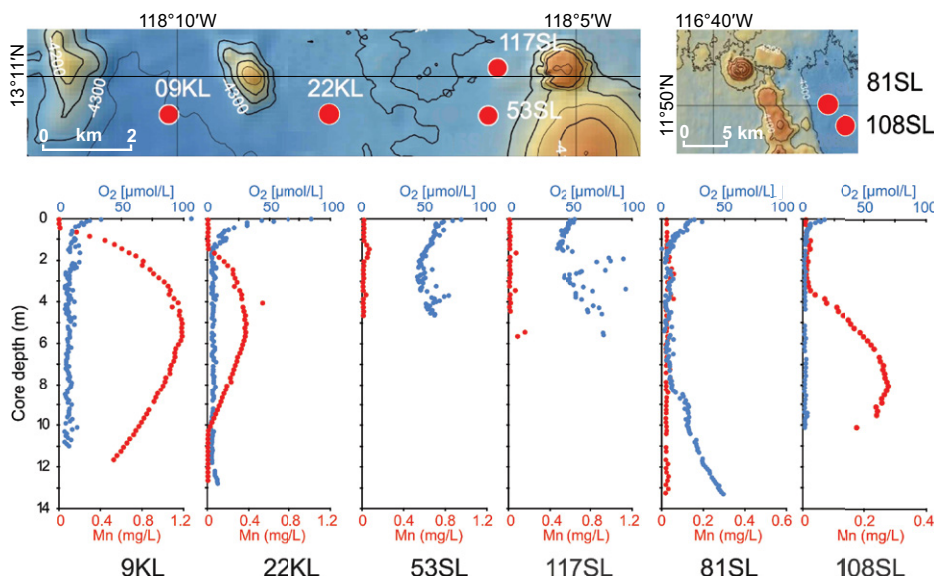


Figure 3. Pore-water concentration profiles of O_2 and Mn^{2+} along a near-seamount, east-west transect (9KL-117SL), as well as at a site above a fracture in basaltic crust (81SL) and a site without such a fracture (108SL). See Figure 1 for location of cores. Isobaths denote 100 m depth intervals.

sediments overlying the basaltic crust are ~10 m thick at sites 53SL and 117SL. Farther away from these locations and with increasing sediment thickness (~20 m), the concentrations of O_2 in the central parts of the retrieved cores decrease until these eventually are oxygen-free, i.e., suboxic (22KL in Fig. 3). In these oxygen-free sediment intervals, dissolved manganese (Mn^{2+}) is present at the highest concentrations. With further increasing sediment thickness, the retrieved sediments do not contain any dissolved O_2 in their bottom part; however, the downward-decreasing pore-water Mn^{2+} concentrations clearly indicate that O_2 is present deeper in the sediment (9KL and 108SL in Fig. 3). Comparison of pore-water O_2 and Mn^{2+} profiles for sediments taken above or near faults that extend from the basaltic crust into the lower part of the sediment package (69SL, 81SL) with nearby sediments from similar sites but without such an underlying fault (09KL, 22KL, 108SL) shows that O_2 penetrates much further from the basement upwards into the sediments where faults are present (Fig. 3).

Permeability of the Sediments

Permeability was measured on whole rounds of one sediment core at six different depths (103SL, Fig. 1). Permeability ranged between $1.4 \times 10^{-14} m^2$ and $7.8 \times 10^{-14} m^2$ (Fig. DR1), which is in the typical range of siliceous-rich sediments (Spinelli et al., 2004). The porosity of the sediments measured on several cores from the study area is rather constant (~85%), indicating that there was no or negligible compaction.

DISCUSSION

In intraplate settings, fluids may flow laterally through the basaltic basement at rates of 0.1–10 m/yr if permeability is in the range

of 10^{-12} to $10^{-11} m^2$ (Fisher and Becker, 2000). Deep-sea sediments generally have a low permeability ($<10^{-14} m^2$; Spinelli et al., 2004), preventing large-scale vertical fluid advection through them. Therefore, basement outcrops and high basement permeability are necessary to permit seawater to recharge and discharge the basaltic basement. Seamounts, which protrude through low-permeability sediments, serve as conduits enabling the transport of fluids into the basaltic basement in off-axis settings (Fisher et al., 2003; Villinger et al., 2017). In model studies, small-sized seamounts (with a radius of several hundred meters and a radius/height ratio <0.5) can act either as fluid recharge or discharge sites at a crustal heat flow of 50–150 mW/m², whereas large seamounts tend to form convection cells within their seamount structure (Kawada et al., 2011; Winslow and Fisher, 2015).

Our heat-flow data, well below the values of pure conductive cooling, indicate that cold bottom water enters the basaltic crust and extracts heat. All cores from the vicinity of small seamounts (after criteria of Kawada et al., 2011) have dissolved O_2 and Mn^{2+} concentration profiles indicating the flow of seawater in the basaltic crust underneath the sediments at these locations.

However, seawater recharge was not restricted to seamounts; it could also be detected near basaltic outcrops on the NNW-SSE-trending ridges (Figs. 1 and 2), suggesting spatially widespread heat extraction in the study area (Fisher et al., 2001; Hutnak and Fisher, 2007).

The near-surface sediments (upper 10–15 m) of the study area mainly consist of a mixture of siliceous ooze and pelagic clay (Fig. DR5). Because porosity and composition are rather constant, the hydraulic impedance (i.e., the permeability) is mainly dependent on sediment

thickness. At an average thickness of 40 m, mixtures of siliceous ooze and pelagic clay will have impedance values between $1 \times 10^{-15} m^{-1}$ (pure siliceous ooze) and $1 \times 10^{-16} m^{-1}$ (pure pelagic clay; Spinelli et al., 2004). Given these conditions, advective flow through the sediments may be inhibited, and lateral fluid flow may dominate in the permeable basaltic crust underneath. At sites with very thin sediment cover and/or faults along which the basaltic basement is exposed, seawater recharge and discharge may happen. This assumption is consistent with the local geological conditions of our study area (Fig. 2; Fig. DR3) and with the diffusion of O_2 from the basement into the overlying sediments evidenced by all our sediment cores. Recharge and discharge at basement outcrops extract heat from the upper crust, resulting in temperatures a few degrees above bottom water temperature, which limits chemical reactions of the circulating fluid with the basaltic basement. Therefore, the fluids are oxic throughout, and upward O_2 diffusion into the sediments occurs. Fluid seepage may only be possible through very thin sediments (<10 m), as none of the pore water profiles indicates advective fluid flow through thicker sediments.

A prerequisite for fluid advection through the basaltic basement outside the influence of seamounts is a very thin sediment cover and/or outcropping basaltic crust. Obviously, there are several locations on the NNW-SSE ridges where this prerequisite is fulfilled. The reason for the low and variable sediment thickness over those ridges might be a combination of strong near-bottom currents and active tectonics. Numerous faults on the NNW-SSE ridges were identified by our seismic data (Fig. 2). Near-bottom current activity has been detected using sidescan sonar during previous cruises (Wiedicke-Hombach, 2010, personal commun.; Fig. DR7) and is further supported by the presence of hiatuses in the sediment cover of the study area (Mewes et al., 2014).

Our interpretation of the geophysical data is consistent with the pore-water geochemistry. In areas of low heat flow and thin sediment cover, the sediments are oxic throughout (53SL, 117SL in Fig. 3). In these sediments, dissolved O_2 concentrations are high at the top and the bottom of the retrieved sediments and lower in-between. Such pore-water profiles can be explained by downward O_2 diffusion from oxygen-rich seawater as well as upward O_2 diffusion from oxygen-rich water migrating through the basaltic basement (Mewes et al., 2016; Mogollón et al., 2016; Ziebis et al., 2012).

With increasing sediment thickness, the O_2 gradients get less steep, resulting in a slower diffusive flux. In combination with ongoing O_2 consumption, this eventually leads to a suboxic zone with Mn reduction (and denitrification) separating the upper and lower oxic zones in the sediment column (22KL in Fig. 3). If sediment thickness further increases, the suboxic

zone expands downward, eventually reaching beyond the core bottom, so that only the downward-decreasing pore-water Mn²⁺ concentrations indicate the presence of O₂ deeper in the sediment (9KL, 108SL in Fig. 3). The observation that O₂ diffuses further upward in the sediments near faults that reach from the basement into the sediments (81SL in Fig. 3) demonstrates that faulting facilitates upward transport of O₂. The consumption of O₂ by reduced phases within the sediments may release nitrate and inorganic carbon to the pore-water, where they subsequently diffuse downward into the basement. In this way, the reaction of oxygen within the sediments also contributes to changes in fluid composition (Orcutt et al., 2013) and the percolating fluids in the basement may act as a transport pathway of these oxidation products back to the ocean.

The heat-flow values, which are slightly higher than the theoretical values of conductive cooling at the locations of cores 69SL (Fig. 2) and 117SL (Figs. 1 and 3), cannot be explained by a decrease in sediment thickness but suggest that temperatures at the sediment-basement interface are elevated relative to temperatures at this depth in the close vicinity. However, we did not find a single site with extremely high heat flow.

CONCLUSIONS

Our study at a typical, 18–22 Ma ridge flank adds a comprehensive data set of seismic, heat-flow, sediment pore-water, and solid-phase data to the global observations of heat and mass transfer on ridge flanks. Despite the limited areal coverage of our survey, we are confident that the clear signals for vigorous hydrothermal circulation in the upper crust are representative for a large area of the western flank of the East Pacific Rise comprising tens of thousands of square kilometers. If the residence time of the fluids in the upper crust is short or the fluid flux is large, the fluids would remain oxic, and O₂ could diffuse upwards into the overlying sediments and react with them. This would result in diffusive downward transport of oxidized reaction products (CO₂, NO₂) from the sediment into the basement fluid, and with this fluid, these products would be transported back into the water column.

To date, the exchange of elements and substances between sediment and ocean water has been thought to be a direct exchange between ocean and sediment operating from above. However, there seems to be a similar, albeit “indirect,” exchange that affects the sediments from below and operates via the fluids percolating through the ocean crust. This “indirect” ventilation is important for remobilization of the residual reduced material in the deep sediments and for bringing it back into the ocean.

ACKNOWLEDGMENTS

We thank captain Lutz Mallon and the crew of the German research vessel *SONNE* for the excellent cooperation and the pleasant atmosphere during cruise

SO-240. A. Lamparter from the Federal Institute for Geosciences and Natural Resources (BGR) carried out the permeability measurements, for which we are grateful. The manuscript was improved by comments from A. Fisher, L. Coogan, and an anonymous reviewer. This work was funded by the German Federal Ministry of Education and Research (BMBF) under grant 03G0240A-D, and by internal funding from BGR and the Helmholtz Association.

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Manuscript received 23 February 2017
Revised manuscript received 4 May 2017
Manuscript accepted 4 May 2017

Printed in USA