Fluid flow through active mud dome Mound Culebra offshore Nicoya Peninsula, Costa Rica: evidence from heat flow surveying

Ingo Grevemeyer\textsuperscript{a,b,c,*}, Achim J. Kopf\textsuperscript{b}, Noemi Fekete\textsuperscript{c}, Norbert Kaul\textsuperscript{b}, Heinrich W. Villinger\textsuperscript{b}, Martin Heesemann\textsuperscript{b}, Klaus Wallmann\textsuperscript{a,c}, Volkhard Spieß\textsuperscript{b}, Hans-Hermann Gennerich\textsuperscript{b}, Meino Müller\textsuperscript{b}, Wilhelm Weinrebe\textsuperscript{a,c}

\textsuperscript{a}IFM-GEOMAR, Leibniz Institut für Meereswissenschaften, Wischhofstraße 1-3, 24148 Kiel, Germany
\textsuperscript{b}Fachbereich Geowissenschaften, Universität Bremen, Klagenfurter Straße, 28359 Bremen, Germany
\textsuperscript{c}SFB 574, Christian-Albrechts Universität zu Kiel, Wischhofstraße 1-3, 24148 Kiel, Germany

Received 19 March 2003; received in revised form 22 March 2004; accepted 7 April 2004

Abstract

Mud extrusion is frequently observed as a dewatering phenomenon in compressional tectonic settings such as subduction zones. Along the Middle American Trench, several of these features have been recently discovered. This paper presents a heat flow study of actively venting Mound Culebra, offshore Nicoya Peninsula, and is complemented by data from geophysical surveys and coring. The mud diapir is characterised by methane emission and authigenic carbonate formation at its crest, and is composed of overconsolidated scaly clays and clast-bearing muds. Compared with the conductive background heat flow, the flux through the mud dome is elevated by 10–20 mW/m\textsuperscript{2}, possibly related to advection of heat by fluids rising from greater depth. Decreased chlorinity in the pore waters from gravity cores may support a deep-seated fluid origin. Geothermal measurements across the mound and temperature measurements made with outriggers on gravity corers were corrected for the effects of thermal refraction, forced by the topography of the mound. Corrected values roughly correlate with the topography, suggesting advection of heat by fluids rising through the mound, thereby generating the prominent methane anomaly over the dome and nurturing vent biota. However, elevated values occur also to the southeast of the mound. We believe that the overconsolidated clays and carbonates on the crest form an almost impermeable lid. Fluids rising from depth underneath the dome are therefore partially channelled towards the flanks of the mound.

© 2004 Elsevier B.V. All rights reserved.

Keywords: heat flow; dewatering; fluid flow; mud diapir; subduction zone; Costa Rica

1. Introduction

Mud volcanism is a global phenomenon that has been studied for almost 200 years (e.g., Goad, 1816; Abich, 1857). Mud domes are most abundant along convergent margins (Higgins and Saunders, 1974; Kopf, 2002) and are related to the extrusion of fluid-rich, fine-grained sediments. The upward migration of mud through a lithologic succession is mainly driven by buoyancy, but processes like gas and fluid flow, petroleum formation and seismic activity may act as additional triggers (Kopf, 2002). In subduction zones, porous fluid-rich sediments accumulate in
deep-sea trenches at high rates and then undergo deformation during which liquids and volatiles are expelled due to increasing compactional stress and temperature. Studies of geophysical data and samples of mud volcanoes have considerably improved the understanding of the mechanics, driving forces and evolution of these features through the most recent Earth history (e.g., Brown, 1990). In addition, deep ocean drilling and submersible studies shed crucial light on eruption, emission of volatiles and potential hazard originating from violent mud extrusion (e.g., Kopf, 2002). Although quantification of fluid and mud discharge of mud volcanoes is not easy due to the short-lived nature of individual discharge events and relative inaccessibility on the seafloor, first-order estimates regarding flux rates have recently been attempted for various features and regions (e.g., Henry et al., 1996; Kopf and Behrmann, 2000). When put into a broader context, such estimates indicate that mud extrusion contributes significantly to fluid back-flux from the lithosphere to the hydrosphere. Along wide parts of large accretionary prisms (like the Barbados or Mediterranean Ridges), hundreds of mud volcanoes can cause fluid expulsion at rates exceeding those at the frontal part of the prism (see discussion in Kopf et al., 2001). Such fluids are believed to play a crucial role in heat transfer. However, temporal and spatial variability in the heat and fluid fluxes during the life cycle of mud domes complicates an assessment, primarily because heat flow data from active mud volcanoes are scarce.

In the vicinity of Nicoya Peninsula, Costa Rica, published heat flow surveying suggests that the downgoing lithosphere is colder than what has to be expected due to its age and sediment cover. It has been argued that a vigorous hydrogeological circulation system is mining heat (Langseth and Silver, 1996; Silver et al., 2000). Fluid flow is suspected to occur laterally, either by flow towards the trench or vertically through the margin wedge. Potential sites for vertical flow are dome-like features on the slope, which have been initially interpreted as mud volcanoes (Shipley et al., 1990; Zuleger et al., 1996; Bohrmann et al., 2002; Mörz et al., in press).

In this article, we present results from a transect of heat flow measurements across the prominent Mound Culebra mud dome offshore Nicoya Peninsula to reveal its local pattern of heat and fluid flux. In addition, a heat flow transect across the middle continental slope was obtained to yield the overall thermal state of the downgoing plate and margin wedge. This information is essential to determine the regional conductive heat flow through the margin, and hence a background reference for the Mound Culebra transect. Results will be compared with those from other mud volcano settings, and will be discussed in the context of geophysical data, structural observations and physical properties (density, porosity, thermal conductivity) of muds cored during leg 2 of cruise M54 with RV Meteor in summer 2002.

2. Geological background

West of Costa Rica and Nicaragua, late Oligocene to early Miocene oceanic crust of the Cocos Plate undergoes rapid (9.1 cm/year, DeMets et al., 1994) subduction along the Middle America Trench (Fig. 1). Recent drilling confirmed the fore-arc wedge to be of igneous origin, reflecting a non-accretionary scenario having followed subduction erosion (Kimura et al., 1997; Vannucchi et al., 2001). A ~ 400-m-thick sedimentary succession is underthrusting the igneous forearc wedge, which itself is covered by deformed slope sediments. Only a tiny thrust wedge is observed in the toe area of the overriding plate (von Huene et al., 2000; Kimura et al., 1997). Dewatering mechanisms in the frontal thrust wedge, the deformed slope sediments, the faulted igneous margin wedge, and the underthrust sediments play a crucial role in the understanding of the tectonic development of the margin (Hinz et al., 1996). Moreover, gas hydrate processes (and namely their dissociation), as suggested from the presence of BSRs (Bottom Simulating Reflectors) on seismic profiles (Pecher et al., 1998) and drillcore recovery (Kimura et al., 1997), may play a considerable role in fluid budget calculations along and across the active continental margin of Middle America.

The upper forearc off Costa Rica and Nicaragua has been investigated during numerous geophysical surveys, some of which observed mud volcanism (Shipley et al., 1990; Stoffia et al., 1991; Bohrmann et al., 2002). Recent results from deep sea drilling indicate that the frontal wedge of the overriding plate is of non-accretionary origin (Kimura et al., 1997), so that the mud volcanoes on the sediment apron
overlying the igneous forearc wedge are either shallow dewatering products, or relate to deep-seated faults. The mud domes are numerous offshore Costa Rica and Nicaragua (H. Sahling, personal communication), generally cone-shaped, and do not exceed 1 km in diameter (Bohrmann et al., 2002; Mörz et al., in press).

Fluid venting has been documented on the Costa Rica forearc wedge, although not directly at the toe of the small accretionary structure (McAdoo et al., 1996). Instead, fluid venting was most abundant where normal faults and mud domes are observed at the seafloor some tens of kilometers behind the deformation front (Bohrmann et al., 2002; Hensen et al., 2003). These vents were typically accompanied by cold vent fauna (Kahn et al., 1996; Bohrmann et al., 2002). In addition, active seepage at landslides and headwall scarps related to seamount subduction releases fluids and gas into the ocean (Bohrmann et al., 2002). Enigmatic low heat flow of 8–14 mW/m² was detected offshore Nicoya Peninsula along the drilling transect of Ocean Drilling Program (ODP) Leg 170 and Leg 205, which is by a factor of 6 lower than what would be expected from sediment-covered crust of this age (Langseth and Silver, 1996; Silver et al., 2000). Unusual effective hydrothermal cooling is envisaged as explanation for the low-temperature crust, most likely via advection of heat by fluid flow through abundant faults, the latter perhaps originating from bending of the downgoing slab.

The chemistry of the fluids obtained from Alvin push cores reveal significant differences between vent-related sediments and slope apron samples (Zuleger et al., 1996). Sediment pore waters squeezed from cold vent areas and mud volcanoes indicate possible admixing of fluid from greater depth. Vice versa, interstitial waters of deposits from the sedimentary cover of the margin wedge show variations in sulfate and alkalinity, which are typical of material rich in organic matter, as it has been shown from deep drilling in the area (Hesse et al., 1985). Interstitial water compositions from ODP Leg 170 core material suggest mixing of deep fluids, gas
hydrate water and pore water (Kimura et al., 1997; Kopf et al., 2000).

3. Geology and structure of Mound Culebra

Detailed bathymetric charts of Mound Culebra have been obtained by RV Sonne using a Simrad EM120 swath mapping echosounder (Weinrebe and Flueh, 2002). The mound has an oval shape (~1500 m SW–NE-oriented long axis, ~700 m NW–SE-oriented short axis) and is topographically about 115 m higher than the surrounding seafloor (Fig. 2a). Its crest is situated at 86°18.3′W/10°17.8′N at a water depth of 1508 m and may juxtapose a normal fault through the forearc (Mörz et al., in press). Backscatter intensities are highest on the crestal plateau and the NE-flank (Fig. 2b). Ocean bottom video surveying suggests that high backscatter regions are characterised by authigenic carbonate precipitation, while the steep flanks are covered with soft sediments. A prominent methane anomaly over the mound, authigenic carbonate formation at its crest and typical cold seep fauna indicate that the feature is actively venting (Mau et al., 2003; Mörz et al., in press).

High-resolution multichannel seismic data were acquired during leg 1 of RV Meteor cruise M54 by the University of Bremen using a 600-m-long streamer and an airgun array with a total volume of 4.1 l. Fig. 3 displays a time-migrated seismic section, which is roughly orientated along the heat flow profile. The seafloor reflection is sharp and of high amplitude except on the steep flanks of the mound. The first 0.3 s TWT below the seafloor are characterised by distinct, subparallel reflectors that are often discontinuous. Reflectors show abrupt amplitude variations, and appear folded or tilted. Beneath the northwestern flank, the shallow strata are bent upwards and amplitudes decrease sharply towards the centre of the mound. Underneath the highly reflective package is a unit of low reflectivity and low continuity, with only few small high-amplitude patches. At approximately 0.6 s TWT below the seafloor, a sharp, reversed-polarity bottom simulating reflector is imaged, shoaling towards the mound, bending beneath its flanks. The BSR seems to be absent under the centre of the dome, although structural complexity, free gas or pronounced velocity anomalies may deteriorate the seismic image. It also displays local amplitude variations, as for example sudden decreases in amplitude near CDPs 2200, 2360 or southwest of 2400. Furthermore, fine scale seafloor topography, e.g., near CDP 2370, is not perfectly matched by the morphology of the BSR, indicating a smooth subseafloor temperature field.

4. Methods

4.1. Geothermal measurements

Geothermal measurements were made with a violin bow design “Lister probe” (Hyndman et al., 1979; Lister, 1979). This probe obtains the geothermal gradient from 11 thermistors mounted in a lance that penetrates 3 m into a sedimented seabed. After penetration, the frictional heating decays while the probe remains in the seafloor for 7 min. Equilibrium temperatures are calculated by extrapolating the decay of the frictional heating pulse (Hartmann and Villinger, 2002). At every other station, in situ conductivity measurements were made by applying a 20-s pulse of electric current along heater wires within the lance. The thermal decay of this calibrated heat pulse allows to estimate the conductivity at the location of in situ temperature measurements. Data from the individual thermistors were monitored in real time using a coaxial cable connecting the probe with the ship. In addition to measurements with the Lister probe, thermal gradients were measured by outriggers (Pfender and Villinger, 2002) mounted on some of the gravity corers. Thermal conductivities from the cores have been measured using needle probes (von Herzen and Maxwell, 1959), which were inserted into undisturbed areas of split cores recovered from the seafloor. All individual temperature and conductivity measurements were inverted to obtain surface heat flow. The complete processing sequence to obtain surface heat flow is described elsewhere (Hartmann and Villinger, 2002).

We investigated the measured gradients to search for direct evidence for heat advection and hence fluid
flow. Fluid migration at rates of a few centimetres per year will generate nonlinear temperature–depth profiles (Bredehoeft and Papadopulos, 1965). However, even at the site of the deepest penetration on the crest of Mound Culebra, the temperature–depth trend is linear over the measured 3.6 m; thus, it does not
provide any evidence for advective heat transfer (Fig. 2c). It is important to note that advection rates of less than \( f_1 \) cm/year cannot be discriminated from pure conductive heat transfer by thermal measurements. Nevertheless, elevated heat flow patches may still indicate locations of fluid outflow.

Measured heat flow values are supplemented by heat flow derived from the occurrence of natural gas hydrates; thus, bottom simulating reflectors. The temperature at BSR depth is expected to be controlled by a system of seawater and methane (Dickens and Quinby-Hunt, 1994; Grevemeyer and Villinger, 2001). Thermal gradients from heat probe measurements are generally higher than BSR-derived gradients, indicating that the thermal conductivity increases with depth. To calibrate BSR-derived heat flow values (e.g., Grevemeyer and Villinger, 2001), we used constraints from the measured gradients and thermal conductivities. For the surface heat flow, a one-to-one relationship between BSR-derived and measured data was achieved by using a thermal conductivity that is 0.1 W/mK higher than the reference values measured in the first 3 m of the seafloor, i.e., \( f_0.95 \) W/mK. BSR-derived heat flow was used to yield the regional heat flow along the seismic reflection line BGR99_39 (Ranero et al., 2003) shot across the continental slope adjacent to Mound Culebra (Fig. 1) and along line GeoB02-430 across the mud dome.

4.2. Complementary geophysical investigations and coring

To gain a better understanding of the extrusive nature of the mud mound, gravity and push coring were carried out. These cores were then examined for structural features and sampled for physical properties measurement (porosity, wet bulk density and grain density on discrete samples) and pore water analyses, e.g., Cl\(^-\).

5. Results and discussion

5.1. Background heat flow and heat loss

On the middle continental slope in the vicinity of Mound Culebra, a regional transect was surveyed to yield the regional conductive heat flow through the margin wedge. The regional heat flow trend is defined by both measured and BSR-derived heat flow. To yield the thermal state of the incoming plate, a reference station was place seaward of the trench axis (Fig. 1). Values are scattered about the expected lithospheric heat flow (Fig. 4), indicating an average heat loss of the incoming plate, which roughly correlates with the expected heat flow anomaly of a 24-Myr-old plate. This observation indicates significantly different heat flow pattern than that obtained to the...
south offshore Central Nicoya Peninsula, where—with respect to the age of the oceanic lithosphere—heat flow on the incoming oceanic plate is reported to be too low. This heat flow is interpreted to indicate vigorous mining of heat by hydrothermal flow of cold seawater through the permeable lava pile of the incoming Cocos plate (Silver et al., 2000). In consequence, the thermal state of the downgoing plate and hence of the margin wedge off Nicoya is affected (Harris and Wang, 2002). However, in accordance with our measurements, recent surveys on the incoming plate indicate profound changes of the thermal state parallel to the trench axis (Fisher et al., 2003), with higher heat flow to the northwest of Nicoya Peninsula. With respect to the thermal state of the incoming plate in the vicinity of Mound Culebra, a simple conductive cooling model with age-dependent basal heat flow seems to be appropriate.

To relate the surface heat flow through the margin wedge to the thermal properties of the downgoing lithosphere, heat flow was modelled using a two-dimensional analytical approximation to conduction through the upper plate and advection of heat into the subduction zone by the slab (Molnar and England, 1990). In general, frictional heating in the subduction zone thrust fault could be an important source of heat (e.g., Peacock, 1996). However, shear tests on clays sampled in the trench indicate that the coefficient of friction along the shallow decollement is low ($\mu \sim 0.2–0.25$; Kopf and Brown, unpublished data) and has been neglected. Thus, surface heat flow $q$ is given by $q = q_0/S$, where $q_0$ is the flow related to the cooling lithosphere, and $S = \sqrt{z_f \sin \delta / \kappa}$ is a denominator that accounts for advection of the descending lithosphere, where $z_f$ is the depth to the plate interface, $\nu = 9.1$ cm/yr is the convergence rate, $\delta = 13^\circ$ is the dip angle of the subducting plate and $\kappa = 1.1 \times 10^{-6}$ m$^2$/s is the thermal diffusivity of fore-arc crust. The dip angle of the downgoing plate is derived from seismic refraction studies (Ye et al., 1996; Walter et al., 2000), the convergence rate is from the NUVEL-1A model (DeMets et al., 1994) and the age of the incoming lithosphere (Barckhausen et al., 2001) is in agreement with the measured basal heat flow $q_0 = 104$ mW/m$^2$ (Fig. 4).

The conductive model derived from these parameters approximates the measured and BSR-derived heat flow trend across the slope (Fig. 4). Both the modelled heat flow and BSR-derived data indicate a regional surface heat flow of 25–30 mW/m$^2$ for Mound Culebra. Over the dome and adjacent to the feature, observations indicate values about 10–20 mW/m$^2$ (i.e., 30–80%) higher than the regional heat flow, and hence indicate additional sources of heat, possibly related to fluid flow through the margin wedge.

Unfortunately, only a few other mud domes and volcanoes have been investigated to yield their heat loss. In terms of thermal significance, the most spectacular mounds are located seaward of the deformation front of the Barbados accretionary prism (Henry et al., 1996; Sumner and Westbrook, 2001). Heat flow values on some of the features are well above 1000 mW/m$^2$. Similarly high values have been found on the Håkon Mosby mud volcano (Eldholm et al., 1999) in the Norwegian–Greenland Sea. However, these features may not be representative for the majority of mud domes at convergent margins. For example, in the vicinity of mud volcanoes investigated on the Mediterranean Ridge, heat flow roughly mimics the regional heat flow pattern, though values tend to increase towards the mounds (Camerlenghi et al., 1995).

Geochemical data from pore fluids sampled in Costa Rican mud domes suggest that the thermal regime in the vicinity of Mound Culebra may reflect fluids escaping out of the subduction zone along normal faults. The heat and fluid supply is therefore most
likely related to diagenetic and metamorphic reactions in the subduction zone (Hensen et al., 2003); thus, it may indicate fluid return flow out of the deep subduction zone (Moore and Vrolijk, 1992; Kopf et al., 2001). Evidence for deep fluids is perhaps found by decreased chlorinity in the pore waters from the gravity cores recovered from the lower flanks of Mound Culebra. Chlorinity decreases from seawater background concentration of 550 to \(\sim\) 510 mmol/l within 8 m. Reduced chlorinity may indicate the dissociation of gas hydrate. However, chlorinity may also indicate water release either from clay mineral dehydration (Colten-Bradley, 1987) or tectonic dewatering (Fitts and Brown, 1999). For mud domes offshore Central Costa Rica, Hensen et al. (2003) show that chloride anomalies are due to fluids rising from greater depth. Further evidence for fluids rising from greater depth has been found on other mounds off Nicoya Peninsula by Zuleger et al. (1996).

The significance of Mound Culebra and the other mud domes on the total advective heat transfer through the Costa Rican margin is difficult to assess. Although Mound Culebra is venting fluids and transferring heat advectively into the ocean, the magnitude of its heat flow anomaly suggests that the total energy loss over the whole feature is only moderate at present time, especially if we compare it to mud volcanoes seaward of the deep sea trench off Barbados (Henry et al., 1996) and off Norway (Eldholm et al., 1999). The fact that most of the mud domes offshore Nicoya Peninsula show little (and possibly episodic) activity is supported by observations made from dives with Alvin (Zuleger et al., 1996).

### 5.2. Hydrogeological implications

Heat flow data have been obtained along a north-west–south-east striking line across Mound Culebra and by outriggers during coring elsewhere on the dome. Away from the mound and on its flanks, all measurements were successful. On the crest, however, the probe or the gravity corers were not always able to penetrate the seafloor, possibly related to massive carbonates outcropping at the seafloor (Fig. 2b). However, the data show a systematic trend along the survey line and increase from local background values of \(\sim\) 34 mW/m² at approximately 2 km distance from the mound to \(\sim\) 40–50 mW/m² at the foot and steep slope (Figs. 2a and 5b). This trend is consistent with the upward curvature of the BSR as it approaches the mound (Fig. 3). In total, four successful penetrations were made on the crest. Surprisingly, heat flow on the mound and uppermost slope drops back to approximately local background flux. The only exception is a single site where outriggers made successful measurements. Heat flow is with 41.5 mW/m² well above the local background flux, suggesting that the anomaly may be caused by both conductive and advective effects.

However, topographic features on the seafloor may cause significant deviation of the conductive background flux by refraction of heat (Lachenbruch, 1968). We therefore calculate the impact of topography on the heat flow across Mound Culebra using a simple numerical model. Constraints from the numerical approach are in excellent agreement with an assessment based on analytical solutions provided by Lachenbruch (1968). The topography of the mound has indeed a profound effect on heat flow pattern, as it focuses and defocuses heat flow, with an elevated flux near the foot of the mound and decreased flux on the mound itself (Fig. 5). After correcting the heat flow for the effects of topography, heat flow over Mound Culebra roughly approximates the topographic relief with background values of 34 mW/m² to the northwest and elevated values of up to 58 mW/m² on the top. Values higher than the background flux may indicate advective transfer of heat through the mound. Fluid advection is supported by the formation of authigenic carbonate crusts (Fig. 2b), carbonate chimneys (Fig. 6; Mörz et al., in press), and methane venting on top of Mound Culebra (Mau et al., 2003) and methane plumes over other mounds offshore Costa Rica (Bohrmann et al., 2002). Additionally, recovered core material and deep-tow video tracks across Mound Culebra (Mörz et al., in press) show vent fauna and therefore support advective gas and fluid flow through Costa Rican mud domes.

It is interesting to note that BSR-derived heat flow to the northwest of the mound matches exactly with the measured surface heat flow, while measured heat flow to the southeast is elevated by 5–8 mW/m² with respect to the BSR-derived data (Fig. 5). On the accretionary prism of Vancouver Island, Davis et al. (1990) relate the discrepancy between higher values of measured heat flow and lower values of BSR-
Fig. 5. Heat flow along the transect shown in Fig. 2a. (bottom) Topographic relief; (middle) observed heat flow over the mound (solid dots: measured heat flow; circles: BSR-derived heat flow) and the computed focusing and defocusing produced by the topography (broken line). The correction term of heat flow is expressed as heat flow fraction; thus, values normalised to the basal heat flow. (top) Corrected heat flow.

Fig. 6. Lithology of core M54-27, taken on the top of Mound Culebra.
derived heat flow to the advection of heat by fluid flow between the BSR and the seafloor. We therefore suggest that the region to the southeast of Mound Culebra, which is offset from the crestal plateau by \( \sim 1 \) km, may reflect seepage of fluids at the base of the mud dome.

Models of mud mounds generally suggest that warm fluids migrate upwards within an ascending mud diapir, causing venting on its top. However, because elevated values are not confined to the mound alone, fluid flow might be diverted. A series of gravity and push cores allow us to characterise the nature and origin of the mound. The cores at the foot of Mound Culebra recovered undisturbed silty clays, which have been interpreted as background sedimentation in the area. Thermal conductivity of the silty clays is low \( (k = 0.73-0.8 \text{ W/mK}) \), indicating a relatively high porosity (e.g., Grevemeyer and Villinger, 2001). At the flank, the recovered material was intensely deformed, showing scaly fabrics, hydrofractures due to pore fluid overpressure (Behrmann, 1991), and striations on polished surfaces. Thermal conductivity increases \( (k = 0.77-0.85 \text{ W/mK}) \), indicating a reduction of the porosity. Given the shallow depths of the cores, lower porosity and induration suggest that the material is slightly overconsolidated. The same is true for sediment obtained from the crestal cores. Here, muds are highly deformed and have collected mudstone clasts and carbonate fragments during ascent (Fig. 6). Brecciation and hydrofracturation allow soupy silts to migrate along \( \sim 1 \)-cm-wide conduits to accommodate for the elevated pore pressures. Authigenic carbonate crusts of considerable thickness (in places exceeding 20 cm so that coring was impossible) cover the mound and indicate that methane gas or methane-rich fluids are emitted in the central area (Mötz et al., in press). Thermal conductivity increases further on the crest (maximum of \( k = 1.17 \text{ W/mK} \) measured on the most intensely deformed scaly clays). Porosity of core material is between 50% and 60%. Therefore, physical properties show a systematic change across the mound, from watery muds away from the mound to overconsolidated muds on the flanks and competent clasts and authigenic carbonate on the crest (see also Mötz et al., in press). We therefore suggest that the overconsolidated clays and carbonates may form an almost impermeable lid that may affect the transfer of rising volatiles. As a consequence, fluid migration from depth may be diverted in some areas. While some volatiles (and namely the methane gas) ascend and emit at discrete crestal vent sites (see high heat flow value on the crest; Fig. 2a), a significant portion of the fluid is channelled along the base of the mud mound, where it may seep at slow rates out of the seafloor at the foot of the dome.

Based on our observations, a conceptual model for the evolution of Mound Culebra is summarised schematically in Fig. 7. During an initial phase, a

---

**Fig. 7.** Schematic cross section through Mound Culebra showing fluids rising along fractures and other high-permeability pathways through the mound (1), forming vent sites on top of Mound Culebra. In some areas, however, fluid migration from depth may be diverted (2) as a result of low permeability of indurated scaly clays (see text for discussion).
mud diapir started to ascend in the upper portion of the forearc. The mud now forming Mound Culebra has been most likely mobilised in the lowermost part of the sedimentary apron (i.e., ~1000-m depth) because the underlying forearc wedge consists of nonsedimentary, igneous material (Hinz et al., 1996; Kimura et al., 1997). The fluids, triggering ascent of the mud, may have originated at greater depth, possibly as deep as the plate boundary thrust (Moore and Vrolijk, 1992). These fluids may have migrated upwards along permeable faults cutting through the margin wedge (Hensen et al., 2003) before they helped create a density inversion in the slope apron sediment. Methane from depth may have further lowered the density of the mud (e.g., Hedberg, 1974). The liquefied mud then started to rise slowly as a diapir (rather than vigorously as a diatreme; see Brown, 1990), as indicated by the intensely deformed and dewatered scaly clays recovered by coring. Similar material has been found in diapiric mélanges elsewhere and has been interpreted as the product of maximised strains where the mud diapir is in contact with the surrounding host rock (Kopf, 2002). After having pierced the seafloor, fluid supply may have been shut off (at least temporarily), as suggested by the absence of mud debris flows at the crest and flanks. With time, the deformed scaly clays may have consolidated even further, so that the feature now acts as a plug to ascending fluids. As a consequence, fluid pressure transients rose to cause hydrofracture, this way creating pathways and small conduits for liquefied muds and gas to reach the crest. Such episodically active fluid flow is suggested from both heat flow data and evidence in the cores. The bulk portion of the dome, however, consists of muds of low porosity (~50%) and permeability. In addition to flow through the subvertical conduits in the cores, we propose that a considerable amount of fluid escapes beneath the plug and is conducted along the foot of the dome (Fig. 7). Here, slightly decreased chlorinity in the pore waters may support a deep origin of the fluid, perhaps related to clay mineral dehydation (Colten-Bradley, 1987; Hensen et al., 2003). Further research on both the muds and the fluids is required to assess the exact depths of their mobilisation and to date the rise and piercement of the mud mass.

Acknowledgements

We are grateful to scientists, masters and crews of research cruises SO163 and M54 for having provided support, information and discussion. Thanks also to Bernd Heesemann and Julia Schneider for assistance during the heat flow deployments. Marion Pfender assisted in calculating topographic corrections. Reviews of B. della Vedova, A. Camerlenghi, and G. Westbrook are appreciated. This study was funded by the Deutsche Forschungsgemeinschaft through grant Vi 133/7-1 to University of Bremen and the SFB 574 “Volatiles and fluids in subduction zones” at Christian-Albrechts University, Kiel. SFB 574 contribution no. 45.

References


