Formation of hydrothermal pits and the role of seamounts in the Guatemala Basin (Equatorial East Pacific) from heat flow, seismic, and core studies

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Abstract We acquired seismic and heat flow data and collected sediment cores in three areas in the Guatemala Basin (Cocos Plate, Eastern Pacific) to investigate the process by which depressions (pits) in the sedimentary cover on young oceanic crust were formed. Median heat flow of 55 mW/m² for the three areas is about half of the expected conductive cooling value. The heat deficit is caused by massive recharge of cold seawater into the upper crust through seamounts which is inferred from depressed heat flow in the vicinity of seamounts. Heat flow inside of pits is always elevated, in some cases up to three times (max. 300 mW/m²) relative to background. None of the geochemical pore water profiles from cores inside and outside of the pits show any evidence of active fluid flow inside the pits. All three areas originated within the high productivity equatorial zone and moved northwest over the past 15 to 18 Ma. Pits found in the working areas are likely relict dissolution structures formed by diffuse hydrothermal venting in a zone of high biogenic carbonate production which were sealed when they moved north. It is likely that these pits were discharge sites of “hydrothermal siphons” where recharging seamounts could feed cold seawater via the upper crust to several discharging pits. Probably pit density on the whole Cocos Plate is similar to the three working areas and which may explain the huge heat deficit of the Cocos Plate.

1. Introduction

It is well documented that measured sea floor heat flow at mid-ocean ridge flanks is systematically lower than predicted by conductive cooling models of the oceanic lithosphere (Hasterok [2013] and references therein). This heat deficit on ridge flanks is attributed to an incomplete or thin sediment cover which allows a direct exchange of energy and mass between ocean and upper crust. Once the sediment cover is continuous and the hydraulic impedance of the sediment layer is above a critical threshold advective exchange between ocean and crust is significantly reduced [Spinelli et al., 2004]. Investigations on the well-sedimented ridge flank in the Cascadia Basin revealed that seamounts may act as places where seawater flows into the upper crust (recharge) or where at the base of the seamount hydrothermally heated fluid escapes (discharge) but local recharge and discharge at one and the same seamount is also possible [Fisher, 2005]. Harris et al. [2004] showed that seamounts play a significant role for the exchange of fluids and heat between crust and ocean. Fisher [2005] summarized this concept of off-axis hydrothermal circulation and termed it “hydrothermal siphon.”

A compilation of measured sea floor heat flow and sediment thickness for the Cocos Plate (Eastern Pacific) reveals that the plate is cooled down substantially before it is subducted at the Middle American Trench [Heesemann et al., 2009]. The reason for this dramatic heat deficit is attributed to the numerous seamounts populating the plate which most likely provide pathways for cold seawater entering the upper crust. Detailed heat flow measurements on the Cocos plate in the vicinity of seamounts which support this hypothesis are concentrated in an area off Nicoya Peninsula (Costa Rica) [Hutnak et al., 2007, 2008]. However, observations made as early as 1981 by Mayer [1981] now point to an additional cooling effect which may be related to the hydrothermal siphon model. Mayer [1981] observed more or less circular depressions in the sediment cover mapped in some equatorial areas of the central Pacific. His observations remained unnoticed until Michaud et al. [2005] and Moore et al. [2007] also reported these depressions in their publications, again in equatorial areas but much farther east compared to Mayer’s findings. Moore et al. [2007]...
associated these pits with hydrothermal discharge over basement highs where pathways were created by differential compaction and/or fracturing. They mention that dissolution of carbonates may also play a role in the formation of the pits. Bekins et al. (2007) developed a conceptual model, linking seamounts to the formation of hydrothermal pits: cold seawater penetrates the uppermost crust (Layer 2A) and is gradually heated up on its way down. Due to its retrograde solubility, calcite should precipitate in the pore space as seawater is heated. The precipitation of secondary calcite was observed in cores of nearby ODP drillholes such as 504B, 896A, and 1256D [Alt, 2004]. At some distance away from the seamount upwelling of warm water may happen if permeability or basement structure allows. The undersaturated seawater with respect to calcite comes in contact with carbonate rich sediments and dissolves some or all carbonates thereby creating the pit. Bekins et al. (2007) claim that their model is compatible with existing observations of permeabilities in Layer 2A, one of the main controlling parameters of the proposed fluid circulation.

The Bekins model can be tested by observations as the down-flow of cold seawater at seamounts should result in a halo of diminished sea floor heat flow around them and thus an elevated heat flow inside the pits. Moreover, pore water profiles of cores taken inside pits should show indications of advective fluid transport if present. This strategy to test the Bekins-model formed the basis for an investigation of numerous pits and seamounts in the Guatemala Basin (Cocos Plate, Eastern Pacific; see Figure 1a) observed in the published seismic site survey data for ODP Leg 206 [Wilson et al., 2003a].

In this area, detailed investigations of swath mapping, multichannel reflection seismics, gravity, and magnetics were carried out during the course of a site survey for the deep crustal hole begun on ODP Leg 206. The comprehensive dataset allowed detailed planning and efficient selection of areas for this study. In addition two ODP sites (site 844 and 1256; Shipboard Scientific Party [1992] and Shipboard Scientific Party [2003]) are located within the working area GUATB-01 and GUATB-03, allowing dating of prominent seismic reflectors, which are present over the whole area. Based on the published data [Wilson et al., 2003a], we selected sites where we used swath mapping, sediment echosounding and single channel seismics (SCS) to survey profiles across pits and to confirm their location. Subsequently, sea floor heat flow measurements were made. Additional sediment coring inside and outside of the pits provides pore water samples. This strategy was followed in all three working areas.

The cruise SO207 on the German research vessel RV SONNE took place in the summer of 2010 (Caldera to Caldera, Costa Rica; June 21, 2010–July 13, 2010, see Figure 1). Details of the cruise can be found in the cruise report [Villinger et al., 2011].

2. Methods

2.1. Research Area

The investigation areas (GUATB-01 to GUATB-03; Wilson et al., 2003b, see Figure 1) are located about 750 km southwest of Costa Rica in the Guatemala Basin on the Cocos Plate. The crust of the Guatemala Basin originated from the East Pacific Rise (EPR) and was formed at a full spreading rate of 200 to 220 mm/a [Wilson et al., 2003a] resulting in crustal ages of 18 Ma in working area GUATB-01 to 15 Ma in area GUATB-03. Present-day water depth in all three working areas is around 3600 m. Seismic lines published in Wilson et al. [2003b] in all working areas show characteristic pits (e.g., Line EW9903) which in hindsight can also be identified in the bathymetry. Therefore, we restricted our available working time to these known features without exploring outside of the three already presurveyed areas. Two large seamounts in working area GUATB-01 and GUATB-02 and one between them were investigated to test the hypothesis of the cold seawater inflow into the upper crust via seamounts with pits in their close vicinity. ODP site 844 (ODP Leg 138; Shipboard Scientific Party [1992]) located in GUATB-01 and ODP site 1256 (ODP Leg 206; Shipboard Scientific Party [2003]) in GUATB-03 were used as references in order to date sedimentary seismic reflectors and to calibrate a velocity-depth model for the determination of the true sediment thickness.

The drilling results from ODP Site 844 [Shipboard Scientific Party, 1992] and Site 1256 [Shipboard Scientific Party, 2003] show that the sediment cover can be divided into two lithological units, the upper one (Hole 844B: 0–68 mbsf; Hole 1256B: 0–41 mbsf) consisting of clay and biogenic silica-rich ooze, the lower one (Hole 844B: 68–291 mbsf; Hole 1256B: 41–251 mbsf) predominantly of biogenic carbonate. Hole 1256D has been deepened in subsequent IODP legs and has reached now a depth of 1507 mbsf [Teagle et al., 2012]. Heat flow based on downhole temperature measurements in the sedimentary section of Hole 1256 is 113
mW/m² [Wilson et al., 2003a] which is very close to the expected heat flow from conductive lithospheric cooling models [Hasterok, 2013]. This agrees well with the observation, that alteration of the upper crust is minor compared to DSDP/ODP Hole 504B [Shipboard Scientific Party, 2003] indicating that minor amounts of fluids circulated within the upper crust and therefore no significant heat mining took place.

2.2. Acoustic Measurements and Heat Flow Survey

The instrumentation used for acoustic measurements and heat flow survey are described here very briefly. Details can be found in the supporting information.

Figure 1. Overview of the SeamountFlux working areas including locations of seismic profiles, heat flow measurements and core locations. (a) Location of the three working areas south-west of Costa Rica in the Guatemala Basin which were investigated during a site survey for an ODP deep crustal drillhole [Wilson et al., 2003b]. The names of the working areas GUATB-01 to GUATB-03 were chosen according to Wilson et al. [2003b]. (b–d) Detailed maps of the working areas GUATB-01, GUATB-02 and GUATB-03. White solid lines are multi-channel seismic (MSC) profiles shown in detail in Wilson et al. [2003b]. Yellow solid lines are single channel seismic (SCS) profiles shot during the SeamountFlux cruise. Red solid circles are locations of heat flow measurements made during the SeamountFlux cruise. ODP sites 844 (Figure 1b) and 1256 (Figure 1d) served as a reference for the interpretation of the seismic data. The color scale is the same as in Figure 1a. Green open stars mark locations where sediment cores were taken. A black circle in Figure 1b marks the location of the largest pit found in the three working areas.
On board of RV SONNE the multi-beam echo sounding system KONGSBERG EM120 is used for deep-sea bathymetric surveys. A sediment echo sounding system is permanently installed in the ship's hull. It is a parametric system which has a footprint diameter of 7% of the water depth and therefore has a superior lateral resolution compared to conventional 3.5 kHz systems. Data are stored digitally for later processing and display. The single channel seismic system used consisted of a GI gun (210 inch³, 3.4 liters) as seismic source and a 100 m active length 16 channel analogue streamer. The data were digitized and stored in SEGY.

During the cruise, we exclusively used the 6 m long Bremen heat flow probe [Villinger et al., 2010, 2011]. The heat probe is constructed in the classical violin bow design [Hyndman et al., 1979; Hartmann and Villinger, 2002; Villinger et al., 2010] with 21 thermistors distributed over a total length of 6 m in a sensor tube. It also contains a heater wire for in situ thermal conductivity measurements [Lister, 1979]. Data are stored in the probe but also transmitted via coax cable on board in real time, where the data are visualized and stored on a PC. The duration of a measurement including transit at a lateral spacing of about 1 km is on the order of 1–1.5 h. Precise positioning of the probe at the seafloor using the ultra-short baseline system Posidonia was only possible for two profiles (HF1030 and HF1032) due to technical problems thereafter. For all subsequent measurements, a constant offset of 110 m behind the ship relative to the ship’s position was applied based on the experience gained from the two profiles where we had precise probe positions. However, navigational errors of the probe for individual penetrations could be around 50–100 m. The basic processing steps of raw heat flow measurements are outlined in Hyndman et al. [1979]. Details can be found in Villinger et al. [2010]. Final heat flow values were calculated by using the in situ measured thermal conductivity.

All heat flow profiles except one are superimposed on colocated seismic profiles. As basement relief often correlates with observed heat flow [Elderfield et al., 2004] calculated temperatures at sediment-basement boundary will help to distinguish purely conductive from conductive-advective processes in the upper crust [Fisher and Harris, 2010]. Temperatures are calculated based on

\[ T(z^*) = T_0 + q \int_0^{z^*} \frac{dz}{k(z)} \]

with \( z^* \) as the depth of sediment-basement boundary, \( T_0 \) as bottom water temperature, \( q \) as measured sea floor heat flow and \( k(z) \) as thermal conductivity profile from sea floor to the sediment-basement boundary. Two-way-traveltime to basement was picked on all profiles and converted to depth using a constant velocity \( V_p = 1721 \) m/s. This value is based on results from ODP drillholes 844 and 1256 and crosschecked with our seismic profiles over the drill sites. To simplify the calculation of temperature at the sediment-basement interface we divided the sediment column in two parts, one upper section (\( z_u \)) above the carbonate-rich sediments with a thermal conductivity of \( k_u = 0.8 \) W/m K and a lower section (\( z_l \)) with carbonate-rich sediments with \( k_l = 1.09 \) W/m K [Shipboard Scientific Party, 1992; Shipboard Scientific Party 2003]. The bottom water temperature was assumed to be \( T_0 = 2 \) C in all working areas. Therefore, the calculation of the temperatures at the sediment-basement interface simplifies to

\[ T(z^*) = T_0 + q \left( \frac{z_u}{k_u} + \frac{z^* - z_u}{k_l} \right) \]  

These simplifications may introduce errors into the calculated temperatures at the sediment-basement interface due to the lack of more detailed information on the physical properties of the sediments except for the locations in close vicinity of the drill holes. However, these systematic errors are most likely constant along short profiles and will therefore only lead to a shift in the calculated temperatures but leave lateral variations unaffected.

Thermal conductivity measurements were made on split core sections (archive half) with a commercially available thermal conductivity instrument KD2PRO (www.decagon.com). The split cores were measured on board after they equilibrated to ambient temperatures in the laboratory. As the sediment was very homogeneous only two measurements per core section (normally about 1 m long) were made. Results are shown in supporting information.

2.3. Porewater Geochemistry

The strategy of the sedimentological and geochemical investigation was to collect sediment cores from inside and outside of the pits and to compare their sediment and pore water composition. The sediments...
collected inside the pits were expected to exhibit dissolution features and a lower $\text{CaCO}_3$ content (e.g., Bekins et al. [2007]), which should be reflected in the chemical composition of the corresponding pore waters. Thus, alkalinity, pH, and Ca concentration were measured to investigate calcite/aragonite saturation. The element Cl is used to evaluate seawater content of the pore waters and Mg concentrations are deemed useful to indicate hydrothermal processes in the basement (e.g., Pichler et al. [1999]). Details can be found in the supporting information.

Sediment cores of up to 12 m length were retrieved by gravity corer for the collection of pore water and sediment samples. When possible, the gravity core sampling position was monitored using the ship’s Posidonia USBL positioning system. Upon retrieval, the cores were cut lengthwise and divided into a working and archival half. The cores were described from a largely sedimentological standpoint before a suite of standard sampling of porewater and sediments took place. Subsequent onshore laboratory analysis comprised calcium carbonate ($\text{CaCO}_3$) and total organic carbon (TOC) content determination as well as examinations of the surface texture of planktic foraminifera by scanning electron microscope (e.g., Dittert and Henrich [2000]).

3. Results

Figure 1 shows the location of the published multichannel seismic lines [Wilson et al., 2003b], the single channel seismic lines acquired during SO207 and the locations of heat flow measurements and coring sites. During the seismic surveys, bathymetric and sediment echo sounding measurements were run in parallel. Locations of gravity cores and heat flow measurements are given in supporting information.

3.1. Bathymetric and Seismic Survey of Pits

A statistical analysis of the bathymetric data in our working areas shows a clear preferred orientation of ridges and troughs striking NW/SE ($\sim$140°) which is more or less parallel to the isochrons (and the spreading axis) as shown in Meschede and Barckhausen [2000]. In total, we found 51 pits within the three working areas by analyzing the new high-resolution bathymetry from the SO207 cruise together with the site survey data [Wilson et al., 2003a]. The shape of the pits ranges from circular to elongated (Figure 2) with an orientation of the long axis in a few cases roughly parallel to the spreading axis. However, the number of pits found is too small to infer a statistically significant conclusion from that fact. About 50% of them have a surface area between 0.5 and 1 km$^2$, a median volume of about $2*10^7$ m$^3$ and a depth between 50 and 90 m relative to the depth of the sea floor around the pit (see Figure 3). Only a few pits are deeper than 100 m. These dimensions are smaller than the ones reported west of the East Pacific Rise axis by Moore et al. [2007]. The total area covered by the pits in our working area is on the order of 0.1% of the total mapped area.

The single channel seismic data show a well stratified sediment cover of up to 300 m thickness in all three working areas. The sediment-basement boundary is easily identifiable as seen on Figure 4 allowing calculation of temperatures at the top of the basement at locations of our heat flow measurements. Seismic lines from this survey and the presite survey cross the existing ODP drillhole locations in the working areas and therefore dating of horizons and calibration of velocities for depth calculations is possible. A pronounced reflector at roughly 75 m (GUATB01) to 100 m (GUATB03) depth marks the cessation of mainly carbonate rich sedimentation about 10.5 Ma ago as shown by results from drilling at ODP Site 844 [Shipboard Scientific Party, 1992] and 1256 [Shipboard Scientific Party, 2003].

Most of the pits found within the three working areas were surveyed seismically. Cross lines (Figure 4) of the largest pit found (for location see Figure 1b) illustrate two features observed at almost every pit: i) Basement is elevated relative to the surrounding basement topography; in the case of the pit shown in Figure 4 it is located above a more or less circular basement edifice; elongated pits are most likely on top of basement ridges. ii) Sedimentary structures inside the pits are difficult or impossible to image due to their small size compared to the footprint diameter of the seismic signal. The same is true for the sediment echosounding records. Only the largest pits allow tracing (see Figure 4) some reflectors across them.

3.2. Heat Flow

3.2.1. General Remarks

All but one heat flow profile is located on seismic lines as seen in Figures 1b–1d. The 143 successful measurements are all of good to excellent quality even in the case of extremely low heat flow. The statistics of all thermal in situ measurements is shown in Figures 5a and 5b.
Figure 2. Examples of pit shapes. The four detailed maps show the most frequently seen pit shapes in the working areas. Shapes are from (a) almost perfectly circular to (b) elongated and (c) with different orientation and (d) as a series of pits.

Figure 3. Statistics of pits found in working areas GUATB-01 to GUATB-03 (box-and-whisker plot). The box contains all values from the 1. quartile to the 3. quartile with the median shown as horizontal solid red line. The whiskers encompass 95% of all values. Red crosses indicate outliers.

In situ thermal conductivity measurements were only done at every third location in order to save time. The compilation of all in situ measurements (Figure 5b) shows that the thermal conductivity of the upper 5 to 6 m of sediment is very uniform with a mean of 0.783 W/m K and a standard deviation of 0.03 W/m K which is equivalent to ±4% and most likely represents the absolute error of the in situ thermal conductivity measurements. In situ measured thermal conductivities agree very well with thermal conductivities measured on the uppermost core sections from ODP Sites 844 and 1256 (Shipboard Scientific Party [1992] and Shipboard Scientific Party [2003]).
The median heat flow, determined from temperature gradients and in situ thermal conductivities, has a value of 55 mW/m². The error of the calculated heat flow values mainly resulting from errors of thermal conductivity measurements is on the order of ±5%. Expected heat flow for the three working areas based on conductive lithospheric cooling varies between 131 mW/m² in GUATB-03 and 119 mW/m² in GUATB-01 [Hasterok, 2013]. In the following we will use a mean value of 125 mW/m² as reference.

3.2.2. Heat Flow Results Around Seamounts

Four heat flow profiles were measured in close vicinity of seamounts in areas GUATB-01, GUATB-02, and at one seamount between these working areas (for locations see Figure 1). Profile HF1039 (Figure 6) runs from the location of ODP Site 844 toward a seamount. Figure 6 shows the location of measurements, heat flow and calculated temperatures at the sediment basement boundary. Estimated temperatures at sediment-basement interface are based on measured heat flow and calculated according to equation (1). Expected heat flow according to lithospheric cooling models at this site is ~119 mW/m² [Hasterok, 2013]. That means that measured heat flow is about an order of magnitude smaller than expected. We interpret this observation as a strong indication for a recharging seamount thereby cooling the upper crust very efficiently to almost bottom water temperatures of 1.88°C as can be seen by the estimated temperatures at the sediment-basement boundary. No temperature measurements were made in ODP Hole 844B to compare our results with.

A second example of measurements at a seamount is shown in Figure 7. At the eastern end of profile HF1035 heat flow is with values 20 mW/m² again very low, rises as one approaches the seamount to a maximum value of 97 mW/m² but drops again to 21 to 35 mW/m² at the foot of it. Two measurements inside the caldera are with 13.4 and 14.2 mW/m² almost one order of magnitude smaller than expected conductive lithospheric heat flow.

One other example will be discussed in the next section together with measurements inside of pits and one more example is shown in the supporting information.

3.2.3. Heat Flow Profiles Across Pits

Profile HF1030 (location see Figure 6a; results see Figure 8) starts out about 5 km north of a seamount and runs across a series of pits which line up in a direction which is roughly parallel to the ridge orientation. At the westemmost end is the largest pit found in all...
Heat flow was investigated in more detail inside the largest pit accompanied by extensive sediment coring (Figure 9). All values measured at the flat bottom of the pit are well above 100 mW/m². Heat flow was observed in GUATB-03 on Profile HF1034 (see Figure 10), southeast of ODP Site 1256. Superimposed on a broad heat flow minimum with values close to 2 mW/m² we find a pronounced heat flow high with values close to 114 mW/m² inside of a pit. This value is by chance almost identical to heat flow determined in ODP Hole 1256B [Shipboard Scientific Party, 2003] with a value of 113 mW/m². More examples of profiles across pits can be found in supporting information.

3.2.4. Heat Flow Profiles Across Basement Ridges

Two profiles (HF1034 and HF1036; for location see Figure 1) cross basement ridges as seen in the detailed bathymetry. Figure 10 shows that northeast of the ~60 m high ridge heat flow is slightly elevated above background. The same observation can be made on Profile HF 1036 (see supporting information).

3.3. Sediments

In total 23 cores were taken in three working areas. Of those 12 were from the inside of pits, 4 on the slopes of pits and 7 from the outside (for core locations see supporting information and Figures 1b–1d). At one pit in GUATB-01 cores were collected along a transect starting on the outside and stepping down the slope toward the center of the pit.

The three working areas showed no distinct change in sediment composition. The lithology was chiefly...
comprised of slightly to extensively bioturbated clayey nannofossil ooze and nannofossil silty clay. Sandy ash and calcareous layers were found in several cores, as well as a few manganese concretions. A few white clayey calcareous layers were cored in GUATB-02.

The overall CaCO$_3$ content in the sediments varied from 0 wt % up to 85 wt %. The high CaCO$_3$ content in some samples was due to the presence of white calcareous sediment layers. There was no discernible difference between sediments from the inside or outside of the pits. The foraminifera tests exhibited a well-preserved form and surface textures in all chosen samples (Figure 11).

3.4. Pore Water Geochemistry

In all three working areas, the pore water concentrations of Ca, Mg, and Cl showed minor variations; however, they did not display any trend, nor did the variation deviate much beyond the analytical uncertainty (Figure 12; details see supporting information).

To investigate if there were subtle changes associated with pits, samples were collected along a transect from the outside to the inside of a large pit in GUATB-01 (Figure 9). The vertical pore water profiles for Mg or Ca did not indicate a systematic difference along the transect, neither vertically nor

Figure 8. Results of heat flow measurements on profile HF1030 superimposed on seismic section across a series of pits (working area GUATB-01; for location of profile see Figure 6a). Start of the SE to NW oriented profile is about 3 km north of a seamount. Estimated temperatures (filled red circles) at sediment-basement interface are based on measured heat flow (filled blue circles) and calculated according to equation (1). Expected heat flow based on lithospheric cooling models at this site is on the order of 119 mW/m$^2$ [Hasterok, 2013]. The deepest and widest pit at a distance of about 10 km from start of profile was investigated in detail and crossed by another seismic line (green vertical line) oriented perpendicular to this profile.

Figure 9. Heat flow and gravity core locations at a large pit in working area GUATB-01. The colored filled circles represent measured heat flow values (for scale see color bar) and black filled circles are locations of gravity cores. Core locations can be found in supporting information.
laterally (Figure 13a). A calculation of aragonite and calcite saturation indices showed that with four exceptions for aragonite, both minerals were saturated (see supporting information). This observation was corroborated by the absence of a systematic relationship between CaCO$_3$ content and saturation index of calcite (Figure 13b).

4. Discussion

The analysis of bathymetry, sediment-echo sounding, and seismic records shows that most of the pits are associated with basement highs. Shape and orientation of the pits support the assumption that they were formed by hydrothermal venting when they were close to the ridge axis. In addition, a significant part of the carbonate-rich sequence is missing inside the pits. Median heat flow of 55 mW/m² is less than about half of the value of about 130 mW/m² which would be expected from conductive lithospheric cooling models [Hasterok, 2013]. In some locations heat flow is even almost one magnitude smaller than the expected lithospheric heat flow thus confirming the existence of a vigorous hydrothermal circulation system in the upper crust.

All measured heat flow profiles toward seamounts in our working areas show a pronounced decrease toward the seamount which indicates that they act as recharge sites of cold seawater into the upper crust (see Figures 6–8). This is a well-known phenomenon at some seamounts and described in the literature [Villinger et al., 2002; Fisher et al., 2003; Fisher, 2005; Fisher and Harris, 2010]. It should be noted that very low heat flow values found on one long profile in working area GUATB-03 (see Figure 10) are obviously not connected to a recharging seamount. However, the lack of more measurements in the close vicinity of the profile makes an explanation impossible. Another example of heat flow measurements close to a seamount in working area GUATB-02 can be found in supporting information.

All heat flow measurements made in pits are elevated by up to a factor of three relative to background values measured outside of the pits in their close vicinity. This is even true in the case of profile HF1034 where the heat flow signal of the pit is superimposed on a large negative anomaly (Figure 10). Maximum values in pits reach 300 mW/m² resulting in temperatures at the sediment-basement interface of up to 80°C. This is a clear indication for the hydrothermal origin of the pits. Local variation inside a pit could only be measured in the biggest one as shown in Figure 9. An explanation of these quite large variations is not possible as the
subsurface could not be imaged well enough with ship-based instrumentation. A purely conductive and radially symmetric model of a pit shows that heat flow increase inside pits cannot be explained by variation of sediment thickness inside the pits alone. This model also supports the interpretation of high sediment-basement interface temperatures as being of hydrothermal origin. For details see supporting information.

Due to limited navigational accuracy of the heat probe using USBL it is not possible to confirm or disprove Fisher’s findings of elevated heat flow on top of basement ridges. If one assumes that the position of the heat probe for our measurement across a basement ridge (see Figure 10 and supporting information) is correct, then heat flow is not elevated on the ridge itself but adjacent to the ridge and may be associated with fluid flow at the bounding faults of the ridge.

None of the pore water geochemical profiles from gravity cores taken in pits in the three working areas show any indication of present active vertical fluid flow. In addition, the pristine surfaces of foraminifera make ongoing solution very unlikely. These observations lead to the conclusion that the pits carry a heat flow signal that points to a hydrothermal origin but that there is presently no active venting going on.

The process of how pits were formed becomes understandable by backtracking the present pit locations, i.e., backtracking to zero crustal age. The rate of movement and direction relative to the hotspot reference frame was calculated for each working area based on Gripp and Gordon [2002]. Fifteen to 18 Ma ago all three working areas were within the East Pacific equatorial high productivity zone [Antoine et al., 1996] where large amounts of mostly biogenic carbonate sediments were deposited (see Figure 14).

Figure 11. Scanning electron microscope image of a Foraminifera in core GeoB 14619 from a depth of 6.71 m. This image is representative for the occurrence of Foraminifera found in all cores. The zoomed area shows the surface at a larger magnification (8000X). Even at that magnification there are no discernible dissolution features.

Figure 12. Ca, Mg, and Cl concentration for all pore water samples collected in the three working areas (GUATB-01, GUATB-02, and GUATB-03) during the cruise.
It is well-known from ridge studies that the bare rock environment of young oceanic crust (Schultz and Elderfield [1997]; Mottl et al. [1998]) is an area of intensive focused and widespread diffuse venting. Warm to hot hydrothermal fluids exit the sea floor with fluid velocities on the order of centimeters per second to meters per year [Schultz and Elderfield, 1997]. Due to their buoyancy, these fluids will rise preferentially vertically. Places of diffuse venting are most likely located on basement highs, either small “seamounts” or basement ridges. Hydrothermal fluid chemistry leads to a partial dissolution of the biogenic carbonate rich sediments at the vent site, either through the direct pH effect of acidic fluids, or indirectly through transfer of sulfurous components [Lutz et al., 1994]. In addition, the upflow of fluid might affect sediment consolidation and/or grain size [see discussion in Giambalvo et al., 2000] although these authors focus on hemipelagic sediments. Larger and thus heavier biogenic particles (foraminifera) may be sedimented despite the

![Figure 13. Pore water profiles across pits. (a) Depth profiles for Ca and Mg concentration as well as the aragonite saturation index (SI) for pore water samples from those cores collected along the transect stepping from the outside down the slope into the center of the large pit in GUATB-01 (see Figure 9). The data from outside of the pit is added as black filled circles in the profiles of the slope and inside. (b) Calcium carbonate (CaCO₃) content for sediments (filled gray diamonds) and corresponding pore waters from cores from the outside (green filled triangle) down the slope (blue filled square) into the center of the large pit (red filled diamond) in GUATB-01. The colored ellipses show the 90% confidence interval.](image-url)
hydrothermal upflow but due to the coarse-grained composition of the deposited sediments their permeability is comparatively high and therefore these sediments do not seal the vent sites efficiently. Both effects lead to a deficit in the total sediment cover over diffuse vent sites and finally to the formation of pits. As the plate moves northward the three working areas leave the area of high biogenic productivity and normal pelagic sedimentation of deep sea clays dominates. By that time the biogenic carbonate sediment layer might have become less permeable and the magnitude of fluid flow as well as its temperature may have decreased considerably. That allows the sedimentation of fine-grained deep sea clays which eventually stop fluid flow completely due to their low permeability. The depressions in the sedimentary cover which are observed today are a relict and an indicator of a previously diffuse vent site of warm to hot hydrothermal fluid.

The process described above is supported by the following observations: (i) most of the pits are on basement ridges or isolated basement highs ("small seamounts"), (ii) some of the pits have an elongated elliptical shape where the long axis parallels the ridge orientation, (iii) some pits are strung in a line approximately parallel to the prevailing ridge orientation, (iv) geochemical pore water analysis does not indicate any fluid flow, (v) recovered foraminifera do not show any indication of dissolution, and (vi) last the strong heat flow anomaly associated with every pit, where measurements were taken is a clear indicator of a hydrothermal origin. It is very likely that these pits were discharge sites of a "hydrothermal siphon" where one recharging seamount could feed its cold water to several discharging pits depending on the permeability structure of the upper crust and the recharging seamount.

In addition to the backtracked locations of GUATB-01, GUATB-02, and GUATB-03, Figure 14 shows also the backtracked locations of the other areas where pits have been observed [Mayer, 1981; Michaud et al., 2005; Pöllke et al., 2008]. All areas but the one of Mayer [1981] originate in locations within the high productivity area close to the equator. Therefore, it is very likely that the pits in these areas were formed in the same way as described above. Due to their small size, hydrothermal pits are very difficult or impossible to identify in global bathymetric data sets, even with the highest resolution of 15 arcseconds (SRTM15_PLUS, http://topex.ucsd.edu/marine_topo/). In addition, only a seismic profile across a pit allows an unambiguous identification. Detailed microbathymetry surveys using ROVs or AUVs might show additional small scale
depressions which cannot be detected by ship’s swath bathymetry surveys. Based on the available observations it is a well-justified assumption that pits are present in all areas which originated within the equatorial high-productivity area.

5. Conclusion

We acquired seismic and heat flow data in three areas in the Guatemala Basin to investigate the process by which depressions (pits) in the sedimentary cover on young oceanic crust were formed. In particular, we wanted to test the hypothesis published by Bekins [Bekins et al., 2007] if these depressions are locations with active hydrothermal fluid venting. A published data set from an ODP presite survey of the investigation areas allowed concentrating our seismic and heat flow surveys as well as sediment sampling on previously identified pits. The analysis of geophysical data and geochemistry of porewaters of cored sediments allow to make the following conclusions.

The median of all heat flow measurements is 55 mW/m$^2$ which is about half of the value one would expect from lithospheric conductive cooling models [Hasterok, 2013]. The heat deficit is caused by massive recharge of cold seawater into the upper crust through seamounts which is inferred from depressed heat flow in the vicinity of seamounts in the investigation areas. In some locations heat flow is even almost one magnitude smaller than the expected lithospheric heat flow thus confirming the existence of a vigorous hydrothermal circulation system in the upper crust.

Analysis of bathymetry, sediment-echo sounding and seismic records show that most pits are associated with basement highs and that a significant amount of the carbonate-rich sediments inside the pits are missing. Heat flow inside of pits is always elevated, in some cases up to three times relative to the values in the close vicinity. Maximum values reach 300 mW/m$^2$ resulting in temperatures at the sediment basement interface of up to 80 °C. This is a clear indication for the hydrothermal origin of the pits. None of the geochemical pore water profiles from cores inside and outside of the pits show any evidence of presently active fluid flow.

All three areas where pits were investigated originated within the high productivity equatorial zone and moved northwest over a time span of 15 to 18 Ma to their current location. At active venting sites close to the ridge and on ridge flanks sedimentation was partially inhibited due to the upflowing fluid and due to partial dissolution of carbonates. Once the areas moved out of the high productivity zone, pelagic sediments sealed the fluid flow zone and a pit as a depression in the sedimentary cover remains. At the same time, fluid flow becomes less vigorous as the crust ages which may also contribute to the sealing process.

In conclusion pits found in the working areas GUATB-01 to GUATB-03 (Guatemala Basin) are most likely relic structures formed by diffuse hydrothermal venting in an area of high biogenic carbonate production which were sealed when they moved north. It is very likely that these pits were discharge sites of “hydrothermal siphons” where recharging seamounts could feed cold seawater via the upper crust to several discharging pits. Pit density on the whole Cocos Plate is probably similar to the one in the three working areas which may explain the huge heat deficit of the Cocos Plate [Heesemann et al., 2009].

Pits found in other areas of the equatorial Pacific were probably formed by the same process but this inference remains to be tested by heat flow surveys and geochemical pore water analysis in those areas described by Mayer [1981], Michaud et al. [2005], Moore et al. [2007], or Pálík et al. [2008]. However, only drilling through one of these pits would help to reconstruct the complete process of its formation.

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Seismic and bathymetry data can be found at PANGAEA (https://www.pangaea.de/) by searching for data base entries related to cruise SO207. Tables with core locations, all heat flow data, geochemical data and additional figures are provided in supporting information. Monika Wiebe kindly provided the results of model calculations shown in Figure 6 (supporting information). We thank the officers and crew of R/V Sonne for their expert handling of our equipment, mainly our heat probe. We are very grateful for very helpful comments by K. Becker and D. Hasterok which improved our manuscript considerably. This project was funded by the German Federal Ministry of Education and Research (BMBF; Grant03G0207A). No real or perceived conflicts of interests for any of the authors exists.

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