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High resolution temperature measurements in the borehole Yaxcopoil-1, Mexico

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Abstract–Within the frame of the International Continental Deep Drilling Program (ICDP) and as a part of the Chicxulub Scientific Drilling Project (CSDP), high resolution temperature measurements were performed in the borehole Yaxcopoil-1 (Yax-1). The temperature was logged to the depth of 858 m seven times between March 6–19, 2002, starting 10 days after the hole was shut in and mud circulation ceased. Successive logs revealed only small temperature variations in time and space, indicating a fast temperature recovery to almost undisturbed conditions prior to the first log. From these logs, a mean temperature gradient of ~37 mK/m was determined below the uppermost 250 m. Another temperature log was recorded on May 24, 2003 (15 months after the shut in) to a depth of 895 m. The obtained temperature profile is very similar to the 2002 profile, with an insignificantly higher mean gradient below 250 m that may indicate a long-term return to the pre-drilling temperature. The temperature in the uppermost part of the hole bears signs of considerable influence of a convective contribution to the vertical thermal heat transfer. The depth extent of the convection seems to have deepened from 150 m in March 2002 to 230 m in May 2003. Based on the observed temperature gradient and the rock types encountered in the borehole above 670 m, the conducted heat flow is expected to be in the range 65–80 mW/m^2.

INTRODUCTION

Geothermal measurements in sediments of the Caribbean Sea and the Gulf of Mexico (Epp et al. 1970; Khutorskoy et al. 1990) yielded surface conductive heat flow values mainly between 20 and 50 mW/m^2. These values were determined from measured thermal gradients and in situ conductivities of sediments within the first 10 and 2.5 meters, respectively. Khutorskoy et al. (1990) concluded from their measurements and model calculations that the sea bottom relief had a predominant effect over other factors in the observed scatter of heat flow determinations in the Gulf of Mexico. No measurements were made on the Campeche Bank, a platform shelf with water depths between 100 and 200 m that extends to the west of the Yucatán peninsula. Heat flow values of 39–64 mW/m^2 have been reported by Čermák et al. (1984, 1991) from the western part of Cuba located about 500 km to the northeast of the Chicxulub crater. Similar values were measured in the Yucatán basin by Erickson et al. (1972), but a substantially higher heat flow value of 88 mW/m^2 was reported from the Cayman Trough (Erickson et al. 1972).

Heat flow determinations on land on the Yucatán peninsula were obtained by Matsui et al. (1998) who performed temperature measurements in 50 m and 100 m deep boreholes drilled across the crater for an explosion seismic survey. They observed that the heat flow was ~60 mW/m^2 near the crater center and gradually fell to <20 mW/m^2 outside the crater rim.

The first heat flow determinations using temperature measurements in deep boreholes in the Yucatán were reported by Flores-Marquez et al. (1999). They derived a map of the estimated surface heat flow in the north-western part of the peninsula from temperature measurements in eight boreholes, drilled by the Universidad Nacional Autónoma de México (UNAM), with a depth range of between 63 m (UNAM-4) and 703 m (UNAM-7). See Fig. 1 for the position of the UNAM boreholes and the Yaxcopoil-1 (Yax-1) borehole drilled within the frame of the CSDP program. The heat flow map, shown in Fig. 13 of Flores-Marquez et al. (1999), displays two minima: one in between the UNAM-1 and -5 boreholes and the other one between the UNAM-3 and -6 boreholes. From this map, a surface heat flow of ~55 mW/m^2

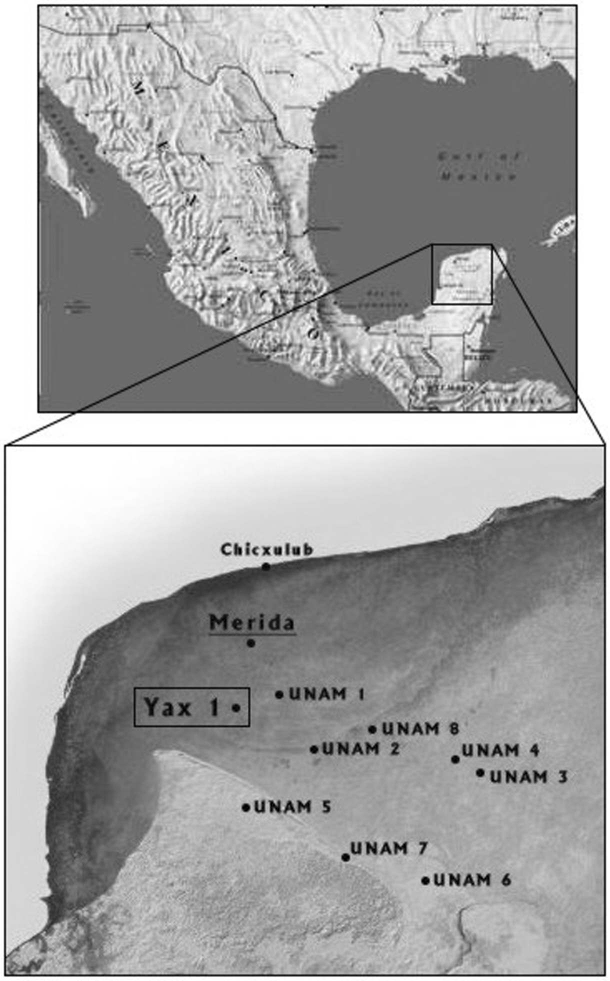

Fig. 1. Location map of the Yucatán peninsula (modified from JPL Planetary Photojournal image #PIA03379) with the position of the boreholes UNAM 1–8 and Yax-1.

would be expected for the position of the Yax-1 borehole. It is, however, conspicuous that in Table 3 of Flores-Marquez et al. (1999) the surface heat flow values for the UNAM-2 and -5 boreholes are 61.67 and 71.90 mW/m^2, respectively, although, from the pattern of their heat flow isolines, one would expect smaller values. A heat flow maximum appears along the line connecting the UNAM-7 and -8 drill holes, which have heat flow values of 64.62 and 85.20 mW/m^2, respectively (Table 3 of Flores-Marquez et al. [1999]). The last and highest value was, however, derived from a borehole that is only 101 m deep and is likely to be strongly affected by convective cells, rainfall, and groundwater movements. The computed surface mean heat flow is 64 ± 8 mW/m^2. The thermal model for the Chicxulub basin presented in Flores-Marquez et al. (1999) shows significant lateral temperature variations down to the depth of 6 km as a consequence of an enhanced fluid flow at a depth of 1–5 km in the Cretaceous and the Chichen Itza formations. The implication is that strong local variations of temperature gradient and heat flow occur because of local variations in permeability of these formations.

It has been proposed by Steinich et al. (1996) that, from the region of this heat flow maximum, groundwater flows in the NE and NW directions along the semicircle of cenotes (sinkholes), thus, causing modifications of the normal temperature field in the Yucatán basin. Other interpretations of temperature measurements in cenotes with regard to the groundwater circulation in the near surface karst formations on the Yucatán peninsula have been reported by Beddows et al. (2002) who found evidence that fresh and saline water flows are decoupled at the halocline, whereas Stoessel et al. (2002) believe that cold water from the Caribbean Sea enters the coastal limestone at depths of a few hundred meters, heats up, rises buoyantly in vertical fractures, and flows back to the coast below the halocline, where heat and saline water is mixed into the overlying fresh water by entrainment.

Popov et al. (2004) determined the thermal conductivity, thermal diffusivity, volumetric heat capacity, specific heat capacity, and the porosity on 120 dry and water-saturated cores from the depth of 404–666 m of the borehole Yax-1. A non-destructive, non-contact optical scanning technology was used for thermal property measurements including thermal anisotropy and inhomogeneity. The rocks within this section are carbonaceous siltstones and limestones. The porosity ranges from 1.7 to 37%. The thermal conductivity and diffusivity ranges were determined correspondingly as 0.65–2.69 W/(m K) and (0.69–1.44) × 10^{-6} m^2/s for dry samples and 1.57–2.73 W/(m K) and (0.59–1.56) × 10^{-6} m^2/s for water-saturated samples. The thermal anisotropy coefficient does not exceed 1.22 for dry samples (1.06 on average) and 1.13 for water-saturated samples (1.02 on average). In most cases, anisotropy was found to be related to rock fracturing (Popov et al. 2004). Vertical variations of thermal properties along the section are significant (up to 40%) even within short intervals of depth (10–15 m). Only within the depth interval of 535–570 m are the thermal properties more stable (see Fig. 2 of Popov et al. [2004]). Using data that is representative of the thermal properties, they divide the formation into three zones (404–533 m, 534– 576 m, and 577–666 m). The thermal conductivity correlates well with porosity, and a negative correlation exists with regression coefficient of 0.98 for dry cores and 0.88 for water-saturated cores. The thermal diffusivity does not change significantly after water-saturation of rock samples, which can be explained by the high porosity of these rocks. A combination of experimental data on thermal conductivity for dry and water-saturated rocks and a theoretical model of effective thermal conductivity for heterogeneous media have been used to calculate the thermal conductivity of the mineral skeleton and a pore aspect ratio for every core under study (Popov et al. 2004). The skeleton thermal conductivity ranges were determined as 2.3–2.8 W/(m K) and the pore aspect ratio ranges as 0.03–0.23 along the section. Supplementary

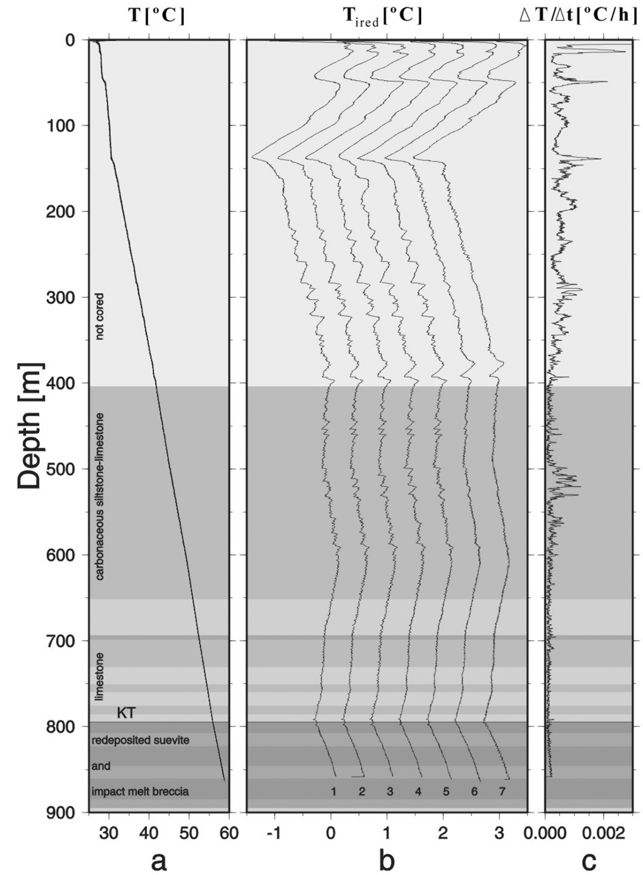

Fig. 2. Temperature measurements in the borehole Yax-1 in March 2002 and derived temperature variations: a) seven measured temperature profiles (°C), start times of logging, see Table 1; b) corresponding temperature profiles reduced by T*(z) = 27 + 0.03666 z, (°C), z (m), (to avoid overlaps, later logs were shifted by 0.5 °C with respect to the foregoing one), vertical direction corresponds to temperature gradient of 36.66 mK/m; c) mean hourly rate of temporal temperature variation |ΔT/Δt| during the measurement period (°C/h).

petrophysical measurements (acoustic velocity, electrical conductivity, and permeability) on twelve representative samples of the collection, performed at the Institute of Applied Geosciences, TU Berlin, complete this investigation. Bulk permeabilities were found to be rather small (below 10 mD) despite the high porosity of the Tertiary limestones. From these results, we conclude that the hydraulic properties of this formation are probably dominated by macroscopic karst effects.

TEMPERATURE LOGGING IN 2002

When a borehole is drilled, the temperature in the borehole and in the neighboring rocks gets disturbed, depending on the amplitude and duration of the disturbance, on the distance of the rocks from the hole and on the hydrological conditions. When the drilling operations stop, the source of the thermal disturbance is switched off and, if the thermal transport is purely conductive, the existing disturbance fades away by transient diffusion propagating in space and time. In order to study this thermal restoration process, we ran several temperature logs directly after shut in of the mud circulation. As the temporal variations of temperature are the largest directly after shut in, the logs should provide the best data on the in situ thermal diffusivity and related rock properties.

If the temperature gradient is biased by a convective part in the vertical heat transport the product of the gradient with the thermal conductivity does not yield the true value for the corresponding heat flow density. Therefore, this heat flow value should be called apparent or specified as conductive.

Drilling operations in the borehole Yax-1, situated at 20° 45′N, 89°43′W (see Fig. 1), ran from November 9th 2001 until February 25th 2002, with an interruption on January 21st that lasted 17 days. The final depth reached was 1510.6 m. Details about the scientific objectives, the drilling operations, and preliminary results are described in Dressler et al. (2003). The borehole is cased until the depth of 980.8 m and has a diameter of 3.5" (89 mm). Ten days after shut in, thermal logging measurements were started by the Geophysical Institute Karlsruhe in cooperation with the Instituto de Geofisica UNAM, Mexico City and the Geoforschungszentrum Potsdam (GFZ), Germany. Seven temperature logs were recorded from the ground surface down to 858.3 m depth by the thermal logging tool LogIn TS40/100 with a sampling rate of 1 or 2 s and a logging speed between 1.53 and 2.95 m/min (see Table 1 for start times of measurements after shut in). The logging tool has a resolution of 1 mK. It was calibrated in the temperature range 5–95 °C in a heat bath using a Hewlett-Packard Quartz Thermometer 2804A with an accuracy of ±0.02 °C and an ambient stability of ±0.03 °C in the temperature range 0–55 °C.

Table 1. Dates of temperature measurements in March 2002.

Measurement number	Date March 2002	Time after shut in (h)
1	6	253
2	7	272
3	8	296
4	10	345
5	12	393
6	15	463
7	19	561

Figure 2 shows the lithology, the measured temperature logs, reduced temperatures profiles, and the mean temporal temperature variation during the measurement period as a function of depth from the ground surface downward. The background indicates the lithology as described by Dressler (personal communication) in the field laboratory. The leftmost curves are the seven measured temperature logs which at this scale are almost identical, so that they are represented by one more or less thick line in Fig. 2a. To make variations between these individual profiles more apparent, we have plotted reduced temperature profiles in Fig. 2b. A linear temperature-depth variation $T^*(z) = 27.00 + 0.03666\,z$ °C, z in m, which was derived from the lower part of the temperature profile T_7 by linear regression, was extrapolated to the surface and subtracted from the measured temperature profiles. After removal of this linear trend the reduced temperature is: $T_{ired}(z) = T_i(z) - T^*(z)$. To avoid overlaps, each log has been shifted by 0.5 °C with respect to the foregoing one. The profiles reveal a rich structural variability and a close correlation between each other, but it is also apparent that the first five profiles show more short-scale variability than the two last ones.

The greatest structural variability of the reduced temperature profiles occur in the upper 400 m of the borehole from which no core samples were recovered, but which is of considerable importance for the assessment of groundwater resources. The profiles are clearly well-correlated here, and large variations in the temperature and the temperature gradient with depth indicate a considerable influence of a convective contribution to the vertical thermal heat transfer. It is not possible to determine a reliable value for the temperature gradient between the surface and the depth of 150 m. Below the depth of ~150 m to ~350 m, the mean gradient is ~43 mK/m. The temperature step at about 50 m may be indicative of at least two different groundwater systems in the upper karst. Below 150 m, the heat transport is mainly conductive with certain exceptions where intense fracturing may be present. It should also be noted that during the drilling operations big fluid losses were encountered above 400 m.

In the Yax-1 borehole, the first Chicxulub impact suevites are encountered at 794.63 m (Dressler et al. 2003), whereas the first Tertiary fossils are observed at 794.11 m, leading Keller et al. (2004) to interpret this location as the K-T boundary. We expected strong variations of the temperature gradient above the K-T boundary due to vertical fluid motions in these highly permeable layers. As a matter of fact, we observed only small temperature variations in time and space between successive logs (Figs. 2a and 2b), indicating that the temperature in the borehole must have already recovered to almost undisturbed conditions during the ten days between shut in and the first temperature measurement or even before. This may be a consequence of a considerable convective component in the heat transfer at least in the upper part of the borehole.

In the reduced temperature profiles (Fig. 2b), even small changes of the temperature gradient are easily detectable. For example in the range 404–666 m depth, which is described as carbonaceous siltstone/limestone, three layers with approximately constant but slightly different slopes of the reduced temperature (404–495 m, 495–605 m, 605–666 m) appear in the T_7 profile. At the K-T boundary, the change in temperature gradient correlates clearly with the change in lithology. This effect is almost certainly caused by a corresponding change in thermal conductivity between the Tertiary carbonaceous siltstone/limestone and the impact suevites. A closer look at the variations of the reduced temperatures near 500 m shows a temperature front propagating upwards from 510 m to 490 m during the observation period. This is only imaginable if this change of temperature is caused by fluid flow from below. We conclude that our temperature-depth variations may be used to help identify variations of the thermal conductivity and/or contributions of convective heat flow to the total heat flow in the upper 400 m part of the borehole, where no cores have been taken.

At the depth of 666–858 m, the temperature gradient varies approximately continuously down to 760 m where a para-conglomerate layer is located (Fig. 2b). Between 760–794 m, the gradient is ~4.1 mK/m smaller, whereas in the region below the K-T boundary, the gradient is ~6.6 mK/m greater than the mean gradient 36.7 mK/m. This is a step in the gradient from 32.6 to 43.3 mK/m, and represents the most prominent variation of the temperature gradient below the depth of 250 m. In the suevitic layer, a small curvature is remarkable and it indicates that radioactive heat production might be affecting the observed temperature profile. In support of this, the K- and U-logs recorded by the technical service of the Geoforschungszentrum Potsdam (Dressler et al. [2003]) show an increase in intensity in the same depth range.

In Fig. 2c, the temporal variability of the temperature profiles during the measurement period of two weeks, i.e. the mean hourly rate of temperature change $|\Delta T/\Delta t|$, is displayed as a function of depth. It exhibits "outbursts," especially in the upper, non-cored part of the borehole and in the carbonaceous cored part, i.e., in the karst limestones and carbonaceous siltstones, but there is also a smaller outburst at the K-T boundary. The rate of temperature change calculated from the successive temperature logs is likely to reveal permeable regions, and some of them are probably concentrated at lithological boundaries. In the upper 400 m depth range, the mean hourly temperature variation exhibits especially high values at about 50 and 140 m, and also near the surface at about 10 m. Broader peaks appear in the ranges 180 to 200 m, 280 to 300 m and 320 to 340 m. Here, we expect the largest convective contributions to the vertical heat flow. At the depth of 404–666 m, the temporal variation $|\Delta T/\Delta t|$ shows an impressive maximum between 500 and 540 m depth with an indentation at 530 m. A secondary peak appears at 560 m. This depth interval must contain fractures that allow fluid flow to change the purely conductive temperature recovery to the undisturbed state. Below this depth range, the temporal temperature changes are very small, only some peaks indicate a higher permeability near the depths of 690, 710, and 790 m. An enhanced permeability also occurs at the K-T boundary and in the first layer of suevite between 794 and 808 m. These peaks are likely to be indicative of an additional influence of convective heat transport caused by fluid motions.

Fig. 3 shows averaged values over 5 m of the thermal

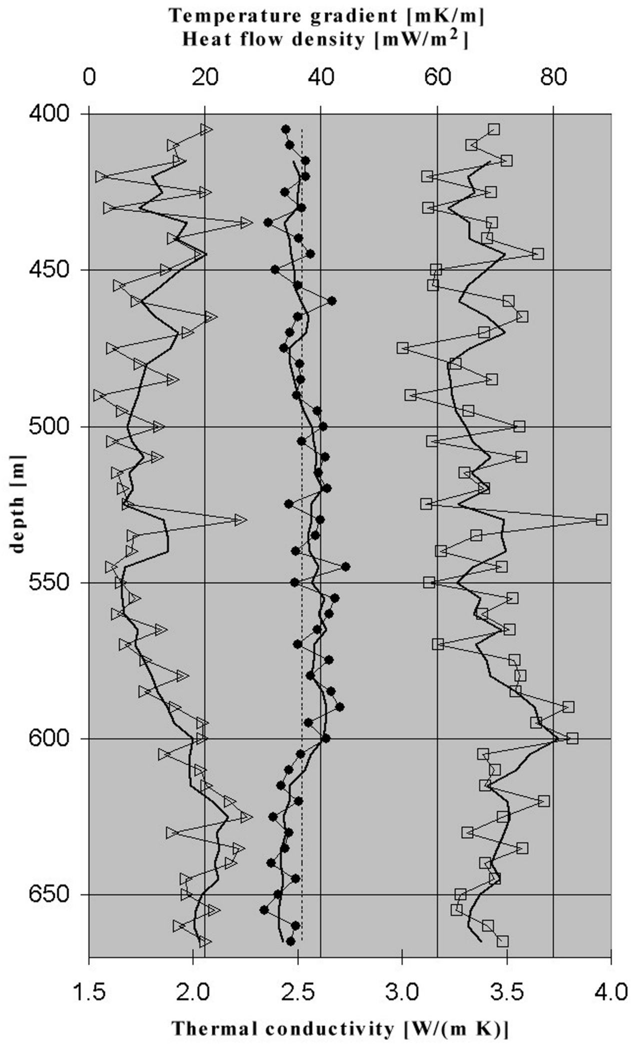

Fig. 3. Five-meter averaged values of thermal conductivity measured on saturated core samples (W/[m K]) (open triangles, lower scale), thermal gradient (mK/m) (filled circles, upper scale, hatched vertical line corresponds to mean gradient 36.66 mK/m used for temperature reduction), and apparent heat flow density (mW/m^2) (open squares, upper scale) for the depth range 404–666 m (Popov, personal communication). Continuous curves show 20 m running mean of the corresponding values.

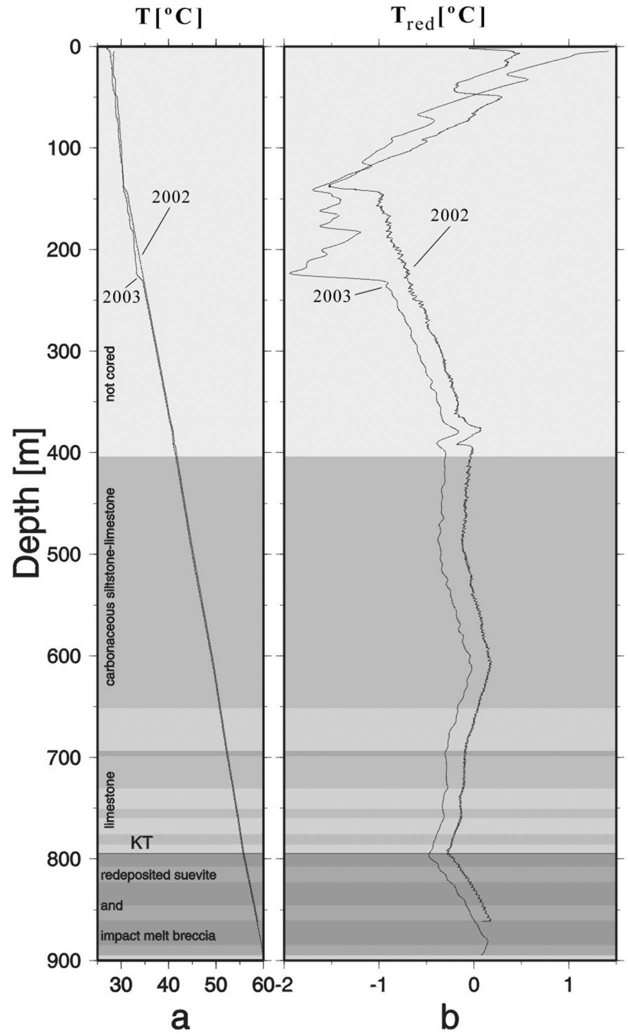

Fig. 4. Temperature profiles measured in Yax-1 borehole in March 2002 (T_7) and May 2003; a) measured profiles; b) temperature profiles reduced by $T^*(z) = 27 + 0.03666\ z$, (°C), z(m).

conductivity (left-hand curve) derived from laboratory investigations (Popov et al. 2004), 5 m averaged values of the thermal gradient (middle curve) calculated from the T_7 profile, and apparent heat flow density (right-hand curve) and 20 meter running means of these values (solid lines) in the 404–666 m. The hatched line shows the mean temperature gradient 36.66 mK/m used for reduction of the temperature profiles (Fig. 2b). The local variation of the temperature gradient is about ±10%, for the thermal conductivity it is about ±20%. The laboratory investigations yield low values of the conductivity ~1.8 W/(m K) from 404 to 576 m depth and higher values of ~2.0 W/(m K) between 576 and 666 m depth. We note that the correlation between the variation of the gradient of the reduced temperature and the thermal conductivity is correct with respect to the sign. However, when the temperature gradient and conductivity are used to calculate the apparent heat flow density, they do not yield a constant value (right hand curve, Fig. 3).

TEMPERATURE LOGGING IN 2003

The borehole Yax-1 was logged again in May 2003, i.e., about 14 months after the first logging campaign, by a joint team of the Geophysical Institute Prague and University of Karlsruhe and in cooperation with the UNAM. The temperature was measured step by step with a depth increment of 2.5 m to 200 m and 5 m from 200 to 895 m using the logging tool ANTARES (ANTARES Datensysteme GmbH). The self-contained temperature data logger with thermistor sensor has a resolution of 1–3 mK in the temperature range 4–60 °C. Its absolute accuracy based on a

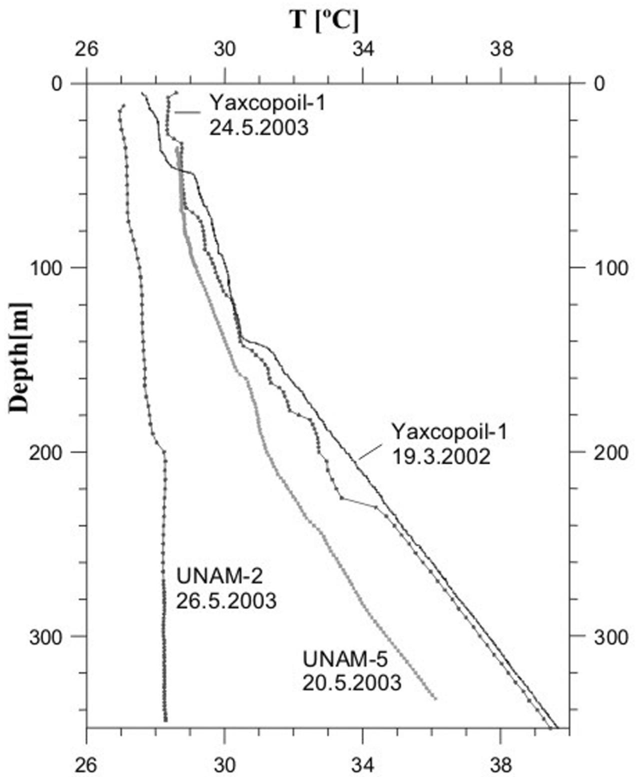

Fig. 5. Temperature profiles for the uppermost 350 m measured in the Yax-1 borehole in March 2002 and May 2003, and temperature profiles recorded in the boreholes UNAM-2 and -5 in May 2003.

calibration by metal block calibrator B140 and thermometer F150 (both Automatic Systems Laboratories) is a few hundredths °C. To ensure the maximal resolution of the probe, which decreases with increasing temperature range, the upper limit of the range was chosen at 60 °C. This temperature was reached at 895 m during the 2003 measurement.

Fig. 4a shows the last temperature profile T_7 of the 2002 logging campaign together with the 2003 profile. Below 230 m, the two curves are practically parallel with the 2002 profile being higher by 0.15–0.25 °C. The mean temperature gradient in May 2003 is 37.3 mK/m, which is about 2 percent higher than observed in March 2002. The increase can be explained by the disappearance of the effects of drilling, which typically warm up the upper part of the hole and cool the lower part, and, thus, reduce the temperature gradient. The offset between the 2002 and 2003 profiles is made more clear in the reduced temperature plot in Fig. 4b. One of the most conspicuous features in the parallel section of the profiles is the gradient oscillation between 370 and 400 m. This is just above the bottom of the non-cored upper part of the hole, where a correlation with lithology is not possible. A nearly 50 percent increase of difference between the two profiles below this zone is worth noticing. It is slowly diminishing downward. The temporal changes observed in the logs from the 2002 campaign are rather small in this section (see Fig. 2c).

The largest difference between the 2002 and 2003 profiles appears in the uppermost 230 m (Fig. 4b). Whereas the 2002 profile indicates groundwater convection limited to the uppermost 150 m, the 2003 profile shows a finer structure of convective features down to the depth of 230 m, see also Fig. 5, where in addition, for the upper 350 m depth range temperature measurements performed in 2003 in the UNAM-2 and -5 boreholes that were drilled before 1995 are displayed for comparison. The curved structural elements suggest that a system of nine convective cells exists, separated approximately at the levels of 30, 70, 90, 115, 145, 165, 180, and 235 m, which may indicate the position of major fractures. This pattern is similar to that of the temporal temperature changes observed in 2002 (Fig. 2c). It is worth mentioning, however, that the zone of the high gradient between 45–50 m in the 2002 profile, which exhibited one of the highest rates of temporal changes at that time, is marked by a near zero gradient and a local temperature minimum at 40 m in the 2003 profile. Presumably, this effect is caused by the reestablishment of the fresh–saline water circulation system, which also appears in temperature profiles measured in cenotes (Beddows et al. 2002; Stoessel et al. 2002; Stoessel, personal communication).

It is not yet clear, if the convective system between 150 and 230 m existed prior to drilling and represents the heat transfer conditions typical for the broader vicinity of the drill site, or if it is a result of water circulation restricted within the column between the casing and formation. If the convection existed prior to the drilling, then its poor expression in signature in the 2002 record means that the time necessary for its full restoration was longer than the time elapsed from the shut in and the 2002 logging. On the other hand, the advance of the convective pattern downward between March 2002 and May 2003 could be explained by convection behind the casing and then would have a technical origin.

CONCLUSIONS

Our observations show that groundwater circulation is prominent in the upper part of the hole above the depth of 400 m. On the basis of this finding, we conclude that temperature measurements in cenotes and shallow boreholes can generally not be used to provide a reliable determination of heat flow density. No large-scale temporal variations in the temperature profiles have been observed below 400 m during the logging period indicating that, in this region, the thermal state has already returned to almost undisturbed conditions after the first 10 days following shut in. This rapid recovery presumably indicates a considerable convective contribution to the heat transport during this period or even before while drilling. Small scale changes are interpreted as a signal of local fluid effects associated with fractured rocks.

At the depth of 404–666 m, from which core samples were available during this investigation, local variations of the temperature gradient and the thermal conductivity determined from averaging over 5 meter intervals are about ±10% of the mean value for the gradient and about ±20% for the conductivity (Fig. 3). From this point of view the temporal change of the mean temperature gradient from 36.7 to 37.3 mK/m derived from the 2002 and 2003 temperature logs is negligible regarding the determination of the heat flow value. It may, however, indicate a long term restoration effect of the temperature field in the surrounding of the borehole which can be related either to the reestablishment of the natural convective system which existed before drilling started and which could not yet be detected in the 2002 temperature logs or to a slow conductive thermal recovery process.

According to the laboratory measurements by Popov et al. (2004), a value of 2.0 ± 0.2 W/(m K) is typical for the thermal conductivity of saturated core samples between 404–666 m depth. Therefore, the thermal conductivities of the rock types encountered in this depth range, when combined with a mean temperature gradient of 36.7 mK/m, yield an apparent heat flow density of between 65 and 80 mW/m^2. This range is higher than values proposed by Matsui et al. (1998) and Flores-Marquez et al. (1999) for a well at this location in the Chicxulub crater. Our heat flow value does not indicate a systematic decrease in heat flow density with distance from the crater center as suggested by Matsui et al. (1998). To improve the reliability of our heat flow density determination and its possible variation with depth in the Yax-1 borehole, the temperature measurements should be extended down to the bottom of the hole.

The temperature profiles recorded in 2002 and 2003 in the Yax-1 borehole cross the lithological boundary associated with the Chicxulub event at a depth of 794.63. Thermally, this boundary is represented by a step from 32.6 to 43.3 mK/m in the thermal gradient that, we believe, is caused by the lithological change from Tertiary limestone/siltstone to impact suevites.

Reduced temperatures plots have been shown to be informative as they emphasize changes in the temperature gradient and allow better comparison between logs. The plots were particularly useful in the carbonaceous siltstone/ limestone layer between 404 and 666 m where a dense petrophysical profile with strongly varying properties has been determined (Popov et al. 2004), but the reduced temperature profile shows only two small systematic changes in the slope of the temperature profile. At present it is not clear why the 404–666 m interval appears to be divided into three layers—each with different thickness when considering the petrophysical and the thermal data, respectively. This effect may be a consequence of the different scales involved in determining thermal conductivity compared to the temperature and needs further investigation.

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