Evidence of strong ocean heating during glacial periods.

Causes of ocean heating.

Part 1.

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Abstract

All temperature data collected from deep boreholes drilled throughout the World's Ocean show strong heat flow decreases with depth (a minimum of 40 mW/m^2). Sharp shifts in heat flow are seen within boreholes at depths crossing gas hydrate bottom. This means that during the last glacial bottom water temperature there was on 25-30 degrees of C warmer. Conversely, in isolated and shallow seas, heat flow in the sediments show little change with depth. This means that bottom temperatures were rather stable there. Taking into account all these, average heat flow through ocean crust does not exceed 35 mW/m^2, that is 3 times less existing estimate.

Text

During the last deglaciation period, strongest climate changes occurred across the North Atlantic regions. Analyses of borehole temperatures from the Greenland ice sheet have reported air temperature change estimates of 25°C over the deglaciation (1). Such huge temperature changes cannot currently be explained in the frames of modern knowledge about climate.

We propose that glacial-interglacial cycles are connected with ocean warming (see second manuscript). During glaciation the ocean being dominated by haline circulation. Warm and very high salinity (and therefore dense) waters of the Red Seas slowly filled the ocean interior. Modern day waters flowing out of this sea have temperature 22.5˚C and salinity 41‰ resulting in them being the heaviest waters in the World Ocean (1.029 g/cm^3) (2). This sea acts as strong ocean surface freshener with downwelling waters with salinities of 41‰ replaced by waters of 34.7‰ salinity. Therefore, the open ocean was strongly stratified, making temperature driven circulation not possible in the ocean. Additionally, ocean bottom waters are heated by geothermal heat flux. For example, a geothermal flux of 50 mW/m^2 will heat a 4-km deep water column by 10˚C in 100 thousands of years. Ocean warming will have continued until the water density at depth fell below that of the density of water in the high-latitude seas. Following this, strong convection will start and the ocean will quickly release the accumulated energy cooling it to +2˚C (see second manuscript). The similarity between the isotopic signature of open ocean bottom waters and the Red Sea ($\delta^{18}O$ ~ 4.7 - 5.5‰) during the last glacial maximum (LGM) provides evidence that the Red Sea filled the ocean bottom water reservoir (see second manuscript). However, the most reliable proof of past ocean heating can be determined from temperature profiles of ocean bottom sediments (3). If there was no change in water temperature in the past then heat flux in all boreholes should not change with depth and be equal to geothermal heat flux (heat flux is calculated as multiplication of heat-conductivity coefficient by temperature gradient (3)); and if in the last glaciation ocean was 25-30^0 warmer, then heat flux should decline with depth in bottom sediments as minimum on 40 mW/m^2 (3).

On figure 1A (left side) we show bottom sediment temperature profiles which should be observed on the peak of ocean heating (red line); 11470 years after the ocean cooling (green line) and 14450 years after ocean cooling (blue line). Right side of figure 1A are shown heat flux profiles for each time interval. Calculations are made for 3 different values of geothermal heat flux – 0 mW/m^2, 14 mW/m^2 and 42 mW/m^2; constant with depth heat conductivity coefficient– 1.4 mW/m ^{0}C which the most typical value (see fig. 2), and heat capacity of 3.35 J/cm^3 ^{0}C, which for sediments vary in a narrow range (4). We accepted that over the courses of glaciations, bottom water temperatures slowly (linearly) increased from +2˚C to 32˚C, and then sharply dropped to +2˚C during deglaciations i.e. average bottom water temperatures during the Pleistocene were 16˚C. As initial model parameters, we used 16˚C on the bottom surface, and at a depth of 3 km temperature was set as constant 16, 46 and 106˚C, in compliance with accepted geothermal heat fluxes. In the review we will discuss below (3) the profiles were calculated for a little bit another time intervals, but in whole they are the same.

In many regions, gas clathrates are preserved in the ocean floor sediments (5). If the temperature of bottom sediments has been and is stable, then it should be difficult to detect gas clathrates or methane in the sediments, looking at temperature profile (4). However, if temperatures had increased by over 25˚C during the glaciation, then the most of gas clathrates would have melted, and freezing back after ocean cooling. If the later is true then, we should be able to locate a boundary phase change ("permafrost floor") at a depth of a few hundred meters and this boundary should be slowly moving down. This is a full analogue of real permafrost (4). During gas clathrates crystallization approximately 500 J/g is released (4). Therefore, the build up of gas clathrates releases lots of heat at that horizon resulting in a sharp shift in the heat flow profile and a bend in the temperature profile. In figure 2A, we show profiles with the same conditions as in fig. 1A, but include a third of sediment volume as gas clathrates or oversaturated with methane water. For these scenarios we have accepted 20-21˚C temperatures for that of gas clathrates melting. To ease calculations, we have replaced the conditions of phase change with condition that in the range of temperatures 20-21˚C heat capacity of sediments equal not to 3.35 J/cm^3 ˚C but forty times higher.

If strong ocean heating occurred during glacial periods, then bottom sediment temperature profiles throughout the ocean should mirror those in figure 1. If temperature changes were less than 30˚C, then related heat fluxes were also correspondingly less. If the gas clathrates content in sediments was less, then a leap in heat flux would be observed deeper. If bottom cooling happened slowly - over several thousand years, then heat flux on the surface will increase on 5-15 mW/m^2 as compared with Fig. 1 (3). If the ocean temperature did not change, then the profile must be as at the Fig. 1C. Atlantic, Indian, and Pacific oceans connect by deep straits. Therefore, thermal flow profiles have to be everywhere similar: either as on the Fig. 1A, B or as on the Fig. 1C.

A series of international programs have measured deep sediment temperatures from boreholes drilled throughout the World's ocean basins. These include the Deep Sea Drilling Project (DSDP), legs 1-96 , the Ocean Drilling Project (ODP), legs 100-210 and the Integrated Ocean Drilling Project (IODP), legs 301-340. For each leg results of temperature, heat conductivity measurements in borehole and geological settings were published in the corresponding volumes of "Initial Reports", in chapter dedicated to that borehole (site) and/or in special section dedicated to heat fluxes. All non referenced data below is taken from corresponding Initial Reports.

Measurement of temperature in bottom sediments is a complicated technical task, because during the drilling of boreholes, circulation of cold water (drilling fluid) in the borehole, strongly changes the temperature regime of the sediments. Therefore temperature measurements are conducted with a down hole temperature recorder, which is put down the borehole, and using high pressure a thin probe with temperature sensor is put into the thermally undisturbed sediments. Temperature measurement is usually done every few seconds. On the data file based on temperature registration can be seen as recorder is going down the cold hole's bottom, as temperature of probe quickly rise after probe have penetrated the undisturbed sediments, as temperature of probe after that slowly reaches equilibrium with surrounding sediments (ideally reaches plateau), as then probe is getting removed, and appear in cold water again. Frequently can be seen as probe getting heated penetrating into the dense sediments with friction, and then cool down. If thermo equilibrium wasn't reached over the course of measurements (tens of minutes) then measurement is extrapolated up until equilibrium values (3, 6).

Geothermal measurements made from the Glomar Challenger over the first 5 years of the DSDP to leg 26 have been reviewed by Erickson et al. (1975) (3). At the time of this review, over 3 thousands measurements of bottom's surface heat flux had been conducted. The main goal of the review was to find out if these data corresponds with depth geothermal heat flux, if it wasn't biased with Pleistocene-Holocene bottom water temperature dynamic (3). Erickson et al. reviewed data from 12 boreholes from which 2 or more temperature measurements were collected. We display all these data on Figure 2A (Sites 193 – 254). We excluded from analyses only the most shallow borehole 209 (52 meters) and three shallow boreholes drilled in the rift zone of Red sea. They show very high heat fluxes (115-300 mW/m^2yr (3)) making it impossible to detect bottom temperature dynamics within these shallow boreholes. All black dots on figure 2A are taken from corresponding initial reports and review tables. Erickson et al. included all of this data within the tables, yet much of the data were excluded from the final heat flux graphs. We present the original data from Erikson heat flux graph with orange outline (Figure 2A). The vertical size of the outline represents the extent of the averaging interval and the horizontal size presents probable error estimates made by authors of the review (3).

Basing on the data Erikson et al. concluded: "shallow heat flow values are representative of the earth's heat flux…there is no consistent indication of a significant vertical increase or decrease in heat flux, such as might be caused by long-term changes in bottom water temperature"; (p.2515) "the heat flux usually remains constant within the estimated probable error of the individual heat flow determination with depth" (p. 2527). However, the authors note that: "our error estimates are very subjective" (p.2519). Among all of the data examined in Erickson et al. paper only one site (site 242) had no changes in heat flux with depth (see Fig. 2A). Measurement on the site at the depth 141 m got the highest reliability grade (Fig. 2A).However, here is what we read about the measurement in the Initial report: "On the first run (Site 242), the latching device was attached to the extender with set screws to prevent the DHI (downhole instrument – Z., Z) from being pushed up into the inner core barrel. The latch did not return with the DHI but was recovered as coring continued." And further: "The record for the first run (Figure 1) indicates a relatively constant temperature of 6.25^{0}C after the bottom of the hole was reached. There is no indication of heating due to friction at the pull-out. These observations, coupled with the fact that the release latch on the probe came off, suggest that the probe was pushed up into the inner barrel before it could penetrate the undisturbed sediment. However, heat-flow calcultions indicate that the temperature measured, may be very near the ambient temperature at that depth." (p. 349). From the description follows that temperature of water in the hole's bottom was measured on the depth 141 m, but not temperature of the undisturbed sediment. Nevertheless, the measurement got the lowest error grade. It is unlikely that the waters from the bottom of the borehole are near ambient sediment temperatures as thermo equilibrium requires at least several weeks (6). This suggests that the temperature at this site is significantly higher than 6.25°C resulting in a higher temperature gradient, and a resultant decrease in heat flux with depth (as represented by blue arrows in figure 2A).

In contrast, two deep measurements on site 206 from the Erikson et al. review were given the lowest reliability grade. These data indicate strong decreases in heat flux with depth and were excluded from the final heat flux graphs without clear justification. The quality of these measurements are far from excellent, however as suggested by Von Herzen in the initial report, the fact that two measurements from the same core show low heat flux increase their reliability. This author analyzed all possible reasons that could lead to downward decrease of heat flux: Internal radiogenic or biogenic heating in the upper intervals and upward percolation of interstitial waters could not explain the natural patterns observed. Large changes in bottom water temperatures could result in a downward decrease in heat flux, but Von Herzen could not find an explanation for how such a big ocean water temperature change could occur.

Measurements from sites 184 and 185 also indicate strong decreases in heat flux with depth and therefore were considered as unreliable, and were thus fully excluded from further analyses.

However, firstly, these boreholes are deep and when estimating errors in gradients, the sum of errors in temperature measurements is divided by difference in depth. Therefore, the greater the distance between the two measurements (the deeper is the borehole) the more reliably the temperature gradient is likely to be calculated. Secondly, both boreholes are drilled in one place on the Umnak plateau in Bering Sea under similar conditions. Measured heat-conductivity and geothermal heat flux at depth is similar in both boreholes (3), increasing the relative reliability of the measurements. Thirdly, the patterns in the data from all four temperature measurements appears of good quality: after the penetration of the probe into the sediments the temperature quickly increased before reaching a plateau in 3-4 minutes. These boreholes show strong heat flux increases at 200 m deep. We see such a profile on figure 1B. An oversaturation of pore water with methane was recorded whilst drilling both boreholes. The bend in the temperature profile in this “combined” borehole is located on the cross point between the temperature profile and profile of temperature of gas clathrates freezing (fig 2A). Most likely today, this site contains gas clathrates – above this bend sits the gas clathrate horizon and below methane in gaseous form.

Borehole 214 showed an increase in heat flux with depth but the authors of the review noted the anomalously high heat-conductivity coefficient in the lower part of the borehole (see Figure 2A). The authors suggest that: “These high conductivity values may have been effected by convection of interstitial water during the conductivity measurement (sediments from the lower interval were noted for their unusually high water content) rather than by an actual increase in the in situ conductivity” (p. 2523). Heat conductivity of sediments as a first approximation is combined from water heat conductivity (0.6 W/m °C) and mineral heat conductivity (1-3 W/m °C) (4, 7). Therefore, the higher the water content the lower the conductivity. If porosity (watering) of sediments increase with depth in the borehole, then most likely heat-conductivity would decrease with depth (7). Temperature gradients were constant in this borehole, therefore heat flux likely decreased with depth (see Fig. 2A).

Borehole 217 results obtained from the original report and Erikson table also showed a decrease in heat flux with depth (Black dots, Figure 2A). By contrast, the heat flux graphs within the Erikson report appear contradictory displaying an incorrect point (orange point on Figure 2A).

Consequently, of 8 investigated boreholes, 7 show decrease of heat flux with depth and the eighth site (214) do probably the same. As can be seen on figure 1a, noticeable bend of temperature profile occur at depths of 400 meters. Accuracy of conductivity measurements are often poor (6) (fig. 2), therefore singular boreholes shallower then 400 meters don’t give reliable estimates. In this review, the most of boreholes are shallow, but there are many of them and it is not correct to conclude from these data that “the heat flux usually remains constant”.

Now let’s analyze the final review based upon all of the boreholes of DSDP, up to leg 96 (6). Authors have made a selection of 80 sites with reliable (by their opinion) measurements of heat flow, and include them into the final table. Authors note “In this data summary we have included only sediment probe heat flow values having … at least three points with interpreted equilibrium temperatures that form a uniform gradient (or a constant heat flow with depth if the conductivity varies significantly). Some potentially good data have thus been excluded, but we feel that these are necessary criteria to establish the validity of a hole bottom temperature probe measurement.” (p.1570). Thus, the authors at the first stage excluded all data which could be indicative of temperature changes of ocean’s bottom. After the selection they made following general conclusions: “there is no conclusive evidence of bottom water temperature changes of a few degrees or more over time scales of tens of thousands of years … this supports the initial hypothesis of Erickson et al. [1975]” (p.1573). If the authors have previously excluded from analyses all data that indicate temperature change on the ocean bottom then in their data summary among 80 sites should be many deep boreholes which approve heat flux stability with depth. But the most of the sites which have gotten into the final table are either shallow or have only one measurement besides surface measurement. We have found there only 3 deep holes (>400 m) drilled in the open ocean in which present two or more temperature measurements and there are thermal conductivity measurements. Of these, only one borehole is classified as having “good” quality (site 533) i.e. the site used by the authors to prove stability of heat flux with depth. However as follows from the measurements data and as it was noted in the initial report these data in fact show a strong decline in heat flux with depth (Figure 2B). The authors of the review have tried to correct these data. They have reduced temperature at the 156 m and 256 m on 0.6^0C. But this small correction does not change situation notably. The thermal flow strongly decreases with depth any way. In addition, as it was noted in the initial report if there is a possibility of a correction, then it might be only correction toward increase of temperature. When temperature probe was removed from the sediments, it hasn’t yet reached equilibrium and temperatures still continued to grow, so authors of the measurement just accepted maximum temperature reached.

Of the remaining 2 sites, graded as “fair”, site 397, was reported in the review as containing 2 temperature measurements, but in fact four measurements were originally made. The lower two measurements were excluded from the review analyses. But these are the most interesting measurements. Measurements on depth of 1438 m gave a downhole temperature of $21\text{-}27^0$C. Precision of this measurements is low, but the fact that this measurement is close to be real value is supported by measurements at depths 448 and 579 meters. They have high quality and show negative heat flow (Fig. 2B). On the Fig. 1A,B we see that this is possible at sharp temperature changes on the ocean’s floor at low geothermal flow. These sediments are rich with methane. The theoretical floor of gas clathrates situates exactly at the bend in the temperature profile (fig. 2B). It is therefore likely that this represents a situation as presented in figure 1B. Because of abundance of methane bubbles in “melted” sediments right under the gas clathrates layer heat-conductivity coefficient can be small, therefore despite the very sharp negative temperature gradient measured at 448-579 meter depths, downward heat flux may be low..

Site 582 also shows very strong decline in heat flux with depth (fig 2B). Maximum of methane concentration there was discovered at depth ~300 meters.

Finally, all three sites that were included into review analyses to prove stable heat flux with depth, in truth do not show this, they show sharp decline of heat flux. We have restricted our analyses (fig 2B,C) only to boreholes with depths >400m, but a similar picture can be seen in data from shallower boreholes. For example, in the final table only 1 borehole (335) exists in the range 300-400 meters. It has “excellent” quality but as seen in initial report it also clearly shows a decline in conductive heat flux with depth.

Now let’s investigate data of deep boreholes which were not included in the final table in the review. Besides the already mentioned site 185 this is also the site 406. It is presented in the table but only as a shallow borehole with 3 measurements. In truth, it was a deep borehole with 5 temperature measurements showing a decline of heat flux with depth (fig. 2b). At site 549 was not only one measurement, as noted in the table, but 2 and heat flux declines there with depth as well. Site 568 was excluded from the table, but noted in the appendix. There heat fluxes declined also. The temperature profile of this borehole reached a bottom of gas clathrates (fig. 2b). This is validated by the drilling results. Gas clathrates were detected from this borehole at 190-315 m and 391-410 m depths (these gas clathrates were taken up on board). Below 410 meters, as drilling showed, gas is in a nonhydrated state. If one more temperature measurement below this depth had been conducted in this borehole then a sharp shift in the heat flux would likely have been obtained.

We checked all of the deep boreholes from the open ocean DSDP drilling program and found that all of them show strong heat flow decreases with depth. Now let’s investigate boreholes drilled in isolated basins –Mediterranean and Black seas. There are 3 such deep boreholes contained in the table of the review. All of them have “excellent” quality. Their high quality is especially noted in the review (6). They differ from boreholes in the open ocean by displaying stable heat flux. These measurements indicate that water temperatures in the bottom of these seas during the late Pleistocene differ not much from modern (12.5˚C and 9˚C).

In review based on DSDP results deep temperature measurements were excluded from analyses. In following drilling projects such measurements became very rare. Among initial reports of ODP and IODP we found only 4 deep boreholes in open ocean that have temperature measurements in undisturbed sediments deeper then 400 m. In a united 671 - 948 borehole, measurements were conducted during legs 110 and 156. Combined results are presented on figure 2c. (We have corrected one obvious mistake made at temperature calculations at depth 247m). The temperature gradient below 100 m stays almost stable and a decline in heat flux with depth occurs due to the reduction in heat conductivity. On the same site in parallel borehole 948D temperature loggers were installed. In 18 months when borehole temperatures stabilized, they indicated approximately the same result – a stable temperature gradient (72˚C/km) below 100 meters.

At site 704 a decline in heat flux with depth was recorded (fig. 2c). Additionally, temperature measurements based on porosity and resistivity of sediments at this site also showed a strong decrease in thermal flux with depth (7).

On site 801 during leg 144, 2.5 years after drilling, the temperature profile was measured in detail. Data on heat flux from this borehole is likely to be the most reliable of all. The decline in heat flux with depth found (fig 2c) strongly correlates with model results (fig 1a).

In borehole 1093 heat flux also declined. Numerous measurements in the upper interval were conducted with limited distance between them, increasing errors in heat flux. If to average these data, then decline of heat flux with depth become obvious. Importantly, although the measurement quality at the site was low the most important measurement in this borehole (depth of 482 m) was made with “excellent” quality.

Borehole 1226 has crossed the line of stable gas clathrates at 305 m depth, and exactly at this point there is a sharp bend in temperature profile (fig. 2c). This may indicate the borehole piercing a low-power gas clathrates horizon. This is evidenced by high methane concentrations and a clear peak in the velocity of p-waves at this depth.

Now we investigate boreholes of isolated seas and shallow water. Borehole 1352 drilled on the continental border 60 km east of New Zealand to a depth of 344 meters is the only deep borehole which indicated heat flux increase with depth. This means that in this region during the peak of glaciation, when New Zealand was covered with glaciers, water surface temperatures were close to zero (today ~9˚C).

The Japan Sea freezes in the winter; it is connected to the ocean by only shallow straights. During legs 127/128, 5 boreholes were drilled to depths of 130 to 300 meters. All of them showed precisely uniform profiles of temperatures and stable heat flow. This means that bottom temperatures were stable (~0˚C) both in glacial periods and today.

Borehole 1324 was drilled on the north of Mexican gulf at the depth of 1057 m. This site displays complicated bottom water temperature dynamics. In the upper part of this borehole a temperature gradient of ~100˚C/km was measured, which then declined to 18.6-21.3˚C/km. Deeper than 300 m, it declined further to 16.2-16.7˚C/km and below 530 m it will likely rise again. Today at a depth of 1 km in the North Atlantic water temperatures are 6-10˚C, in large part from Mediterranean Sea waters (2). But the temperature at the ocean's bottom of site 1324 is +2˚C meaning that there is an influence of water from Arctic seas. Possibly, initial Holocene bottom waters at this site were cold, then they were penetrated by Mediterranean waters before Arctic waters penetrated once again.

We have analyzed all of the temperature measurements from sediments of deep oceanic boreholes. However, boreholes drilled in young ocean floor basalts also exist. Unfortunately, the top layer of young basalts is highly permeable and when they are pierced with borehole, flow of cold heavy water inside the borehole takes place (6). Even weak flow changes temperature profile, it became concave and smooth; it does not have bends which have to exist in places of sharp thermal conductivity changes (for example site 1309D).

The most intensively studied basalt borehole is 504. It is the deepest borehole (2111 m), and contains detailed heat conductivity measurements as well as permeability measurements. In the upper part of basalts, permeability is 10^{-13} m^2, water is flowing into the borehole there. By 536 m depth, permeability decreases to 10^{-17} m^2 and water filtration is impossible below this point. Age of these basalts are 5.9 million years. On top they are covered with 275 m thick layer of sediments. Heat flux measured in these sediments is equal to 196 mW/m^2. This corresponds with measurements made on bottom surface conducted in the area around this borehole. High precision temperature measurements were conducted in this borehole during legs 92, 111, 137, 140, 148. All measurements indicated that conductive heat flux in basalts calculated through temperature curve declined from 180-200 mW/m^2 at 550 m to 120-125 mW/m^2 at 1000 meters depth, and remained the same down to the bottom of the borehole. All possible reasons for such a strong decline in heat flux (excepting changes of bottom’s temperatures) were considered in detail (Initial Report, Leg 111). But a convincing reason was not provided. One potential explanation suggested that heat conductivity in basalts can increase with increasing pressure and temperature, and for values measured on board of the ship should be made a correction for in situ conditions (leg 92). However special investigations showed that pressure influence is minor, and with temperature increase heat conductivity within temperature range 28-170°C in opposite decline by 0.0054-0.01 W/m °C on each degree of temperature rise (8). This is more likely a general rule for crystal geological material; exclusion from this rule is only glassy (amorphic) basalts (8, 9). Experiments on sedimentary samples from Hole 549 (calcareous silty mudstone, calcareous sandy mudstone, sandy limestone, and sandy siltstone) indicate a decrease in conductivity by between 0.007 and 0.011 W/m°C per degree over the temperature range zero to 80°C (10). For deep and hot boreholes it is a very strong correction, because of it heat-conductivity coefficient and calculated heat flux can be reduced twice.

For deep boreholes in unconsolidated sediments this correction is also valuable, since sediments compress with depth. Analyzing data from borehole 504 (and all other boreholes) this correction was never applied, since it just strengthens the heat flux decline with depth, which is broadly considered cannot happen. In contrast to mineral carcass thermal conductivity of water increases with temperature rise (3). The correction has been always done in full strength (3,6) even when sediments' porosity and temperature gradient strongly decreases with depth.

To sum up: it is supposed that heat flow on the bottom of all oceans does not change with depth; but we have checked all deep boreholes of open ocean and did not find evidence to that. In contrast, a sharp decline was observed (fig. 2). It is assumed that this is due to sediments below 300 m being dense making it impossible to measure probe temperatures from them without errors (6). But we can see the decrease of heat flow in the shallow boreholes and in the upper parts of the deep boreholes, too (Fig. 2). In isolated seas, where deep drilled boreholes sediments are also dense these measurements give uniform and reliable results and in shallow waters heat flow even grows with depth. In boreholes 504, 801 and 948 temperatures were measured inside the borehole after they have reached heat equilibrium, and in all of these boreholes a strong decline of heat flux with depth was observed. This cannot be just a random effect. All deep boreholes of the open ocean have indicated similar declines in heat flux with depth. We see that heat fluxes on the ocean floor are at least 40mW/m^2 higher than geothermal flux. If there is a bend on a temperature profile, then it corresponds with the boundary of stable gas clathrates (184, 397, and 1226) (fig 2). Such results could not be a result of just a chance. This means that most of temperature measurements were in truth done reliably and reflect actual situation. These data give much interesting information.

We reached our conclusion of a heat flux decline with depth not using statistical methods or averaging data sets, but from analyzing each borehole. The conclusion of a 25°C temperature change in Greenland was based upon evidence from one core, yet we base our conclusion on numerous.

At the moment it is not possible to reconstruct the last ocean cooling in great detail. Was cold water penetrating Atlantic and Pacific interiors simultaneously? When was the strongest overturning occurring, in Bolling-Allerod or after Younger Dryas? Yet, by comparing measured temperature profiles (and especially profile of site 801) (fig 2) with modeled ones (fig 1) we see that ocean floor heating was strong, 25- 30˚C. Only such a heating would cause gas clathrates to melt, and at their second freezing sharp bends would occur in temperature profiles.

Today on average heat fluxes measured on the bottom surface through ocean floor of Miocene age (range 5.3-23.7 Myr) are equal to 81.9 mW/m^2, of Oligocene age (23.7-36.6 Myr) to 62.3 mW/m^2 (11). In theory, as the lithosphere cools (moving away from rift zones) heat flux must decline proportionally to the square root of crust age (11, 12). As age increases by four heat fluxes decrease by twice, but in reality the decrease is very small. On the oldest ocean floor (Late Jurassic, 144-163 Myr) the mean heat flux is relatively high, 51.3 mW/m^2 (11).

In the first approximation, heat flux through old lithosphere is equal to heat-conductivity coefficient of lithosphere multiplied by temperature gradient in the lithosphere, which in turn is equal to the change in temperature between top and floor of lithosphere, divided by its thickness (12). Consequently to explain such high heat fluxes from the old ocean floor it is necessary to suppose very high solidus upper mantle temperatures -1450˚C, and a very high coefficient of heat conductivity – 3.14 W/m ˚C (12). Even at these so high values, and with a lithosphere thickness of 95 km (12) heat flux will be only 48 mW/m^2 (12). However using such parameters, heat fluxes calculated for young oceanic lithosphere strongly exceed heat fluxes measured on the ocean bottom (11, 12) - for Miocene crust by 40 mW/m^2 and for Oligocene crust by 31 mW/m^2 (11)– parameters of the model are significantly overstated. But if we subtract 40mW/m^2 from these heat fluxes related to warmer oceans in the LGM, then deep heat flux declines with motion from rift zone would be much higher: Miocene crust would emit 41.9 mW/m^2, and late Jurassic crust would emit 11.3 mW/m^2 – in four times. If we take more realistic value of solidus hydrous peridothites – 950˚C (11) and coefficient of heat conductivity of 1.5 W/m °C (reminding that heat conductivity tends to strongly decline as temperatures increase (8, 9), then for same thickness of lithosphere we would obtain heat flux of 15 mW/m^2, that is in 3 times less. If we add 40 mW/m^2 to it then we would obtain heat flux through ocean floor of 55 mW/m^2 This is the most typical heat flux for ocean bottom (11).

Estimating average heat flux through the ocean floor it was obtained value of 101 mW/m^2 (11). At this heat flux calculations, fluxes through the young ocean crust (younger 66 million years) were calculated by a model (12). This model as we showed overestimate heat flux by ~ 3 times. On the rest of the territory flux is overestimated by 40 mW/m^2 and possibly more, i.e by 3-4 times. As a result, average heat flux through ocean crust does not exceed 35 mW/m^2.

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Figure captions

Figure 1. Profile of bottom sediments temperatures and profile of conductive heat flows for scenarios of cycling changes of ocean bottom temperatures from +2^{0}C to +32^{0}C during glacial-interglacial dynamic. Red lines is temperature profile for various deep heat flows at the time of maximum heating of the ocean floor. Green and blue lines are temperature and heat flow profiles for the time periods of 11470 years and 14450 years after sharp ocean cooling. A- is scenario for sediments not saturated with methane; B – is scenario showed gas hydrate formation. Curve bends on the temperature profiles and leaps on heat flow profiles show gas hydrate bottom. C – temperatures and heat flows at stable temperature on the bottom (+2^{0}C) and at the same deep heat flows.

Figure 2. Profiles of temperatures, thermal conductivity, temperature gradients, and heat flow in the bottom sediments in the open ocean.

A – boreholes measured during legs 1-26 and available in the review (3). Data marked orange columns were taken from the resultant graph (3). Blue arrows are our data corrections. **B** – all deep boreholes measured during DSDP and used in review (6). **C** - deep boreholes measured during ODP and IODP. Thermal conductivity data: large dots – are average values for depth intervals as it showed in the initial reports; small dots are initial values; circles are average values of thermal conductivity per depth intervals we calculated from initial data. Numerals on the figures are number of leg, number of borehole and ocean deep. Blue dotted lines are the depth where gas hydrates freeze or thaw (5). Among all these boreholes the only borehole 1352 (depth 344 m) shows an increase of heat flow with depth.

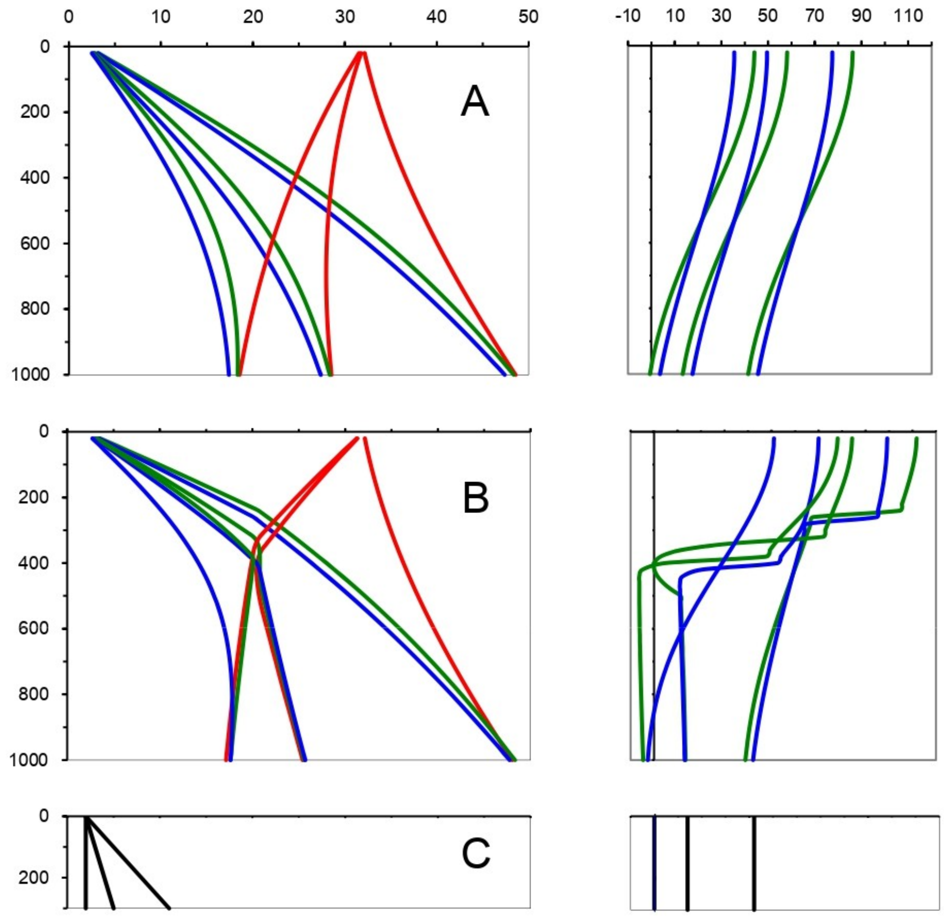
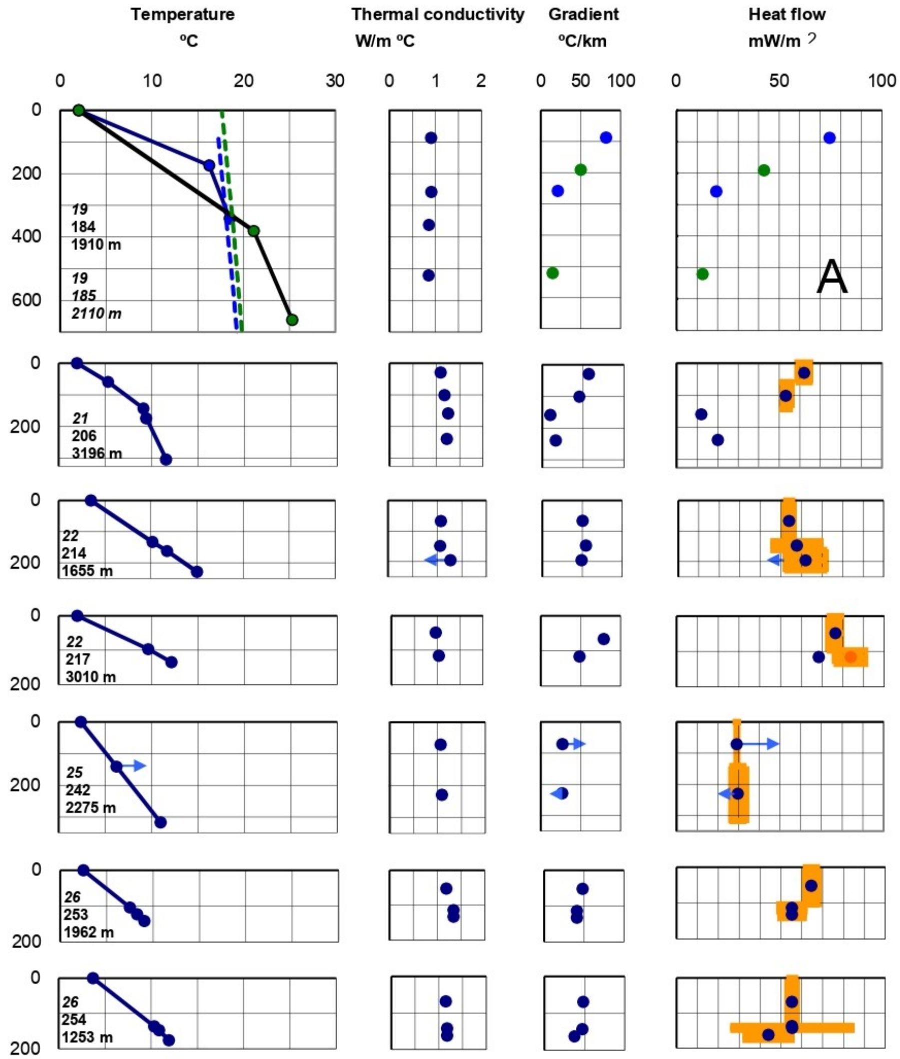
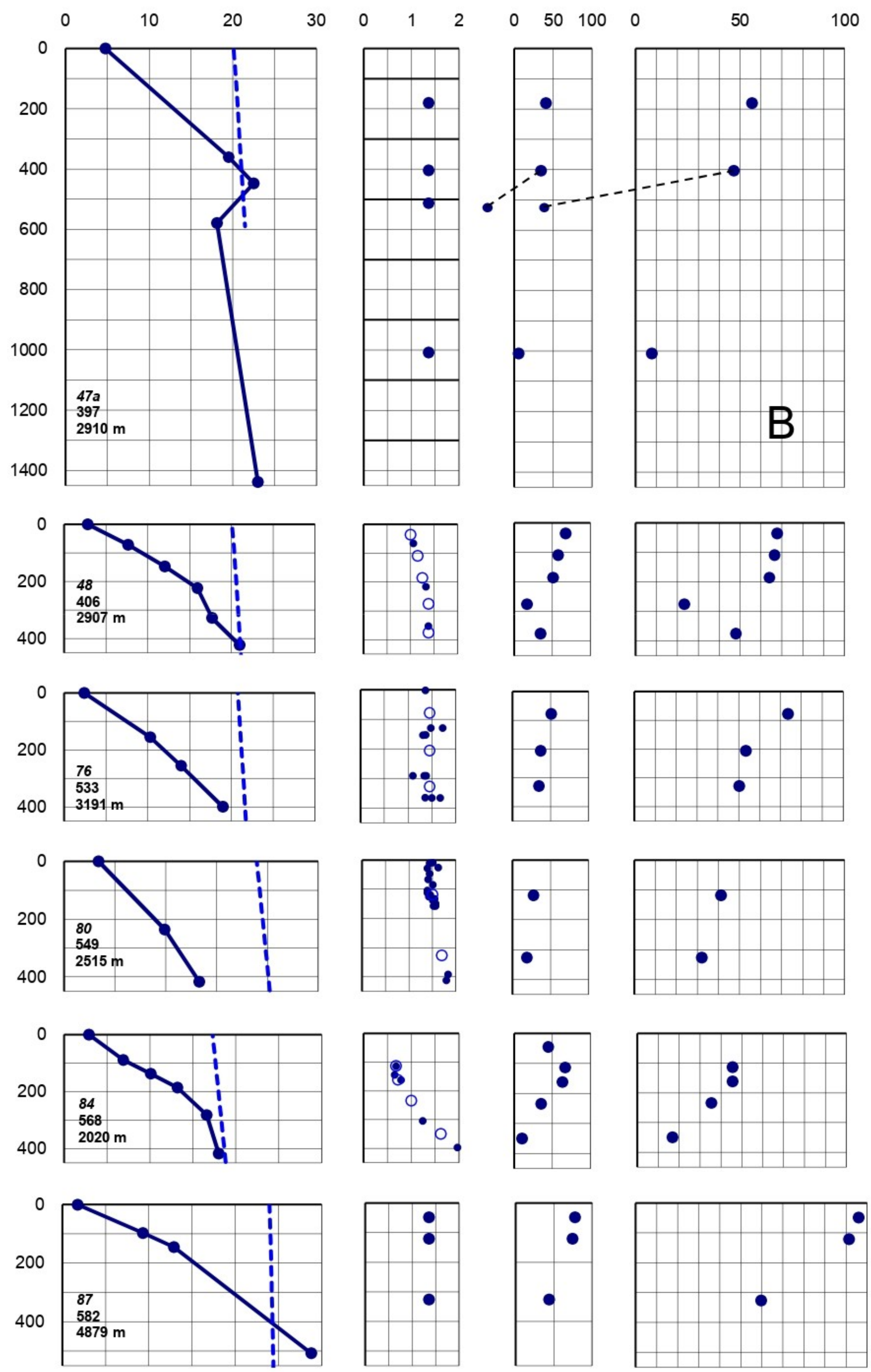


Fig. 1.



Temperature
ºC
Thermal conductivity
W/m ºC
Gradient
ºC/km
Heat flow
mW/m 2
A
19
184
1910 m
19
185
2110 m
21
206
3196 m
22
214
1655 m
22
217
3010 m
25
242
2275 m
26
253
1962 m
26
254
1253 m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0 50 100
0 50 100
0
200
400
600
800
1000
1200
1400
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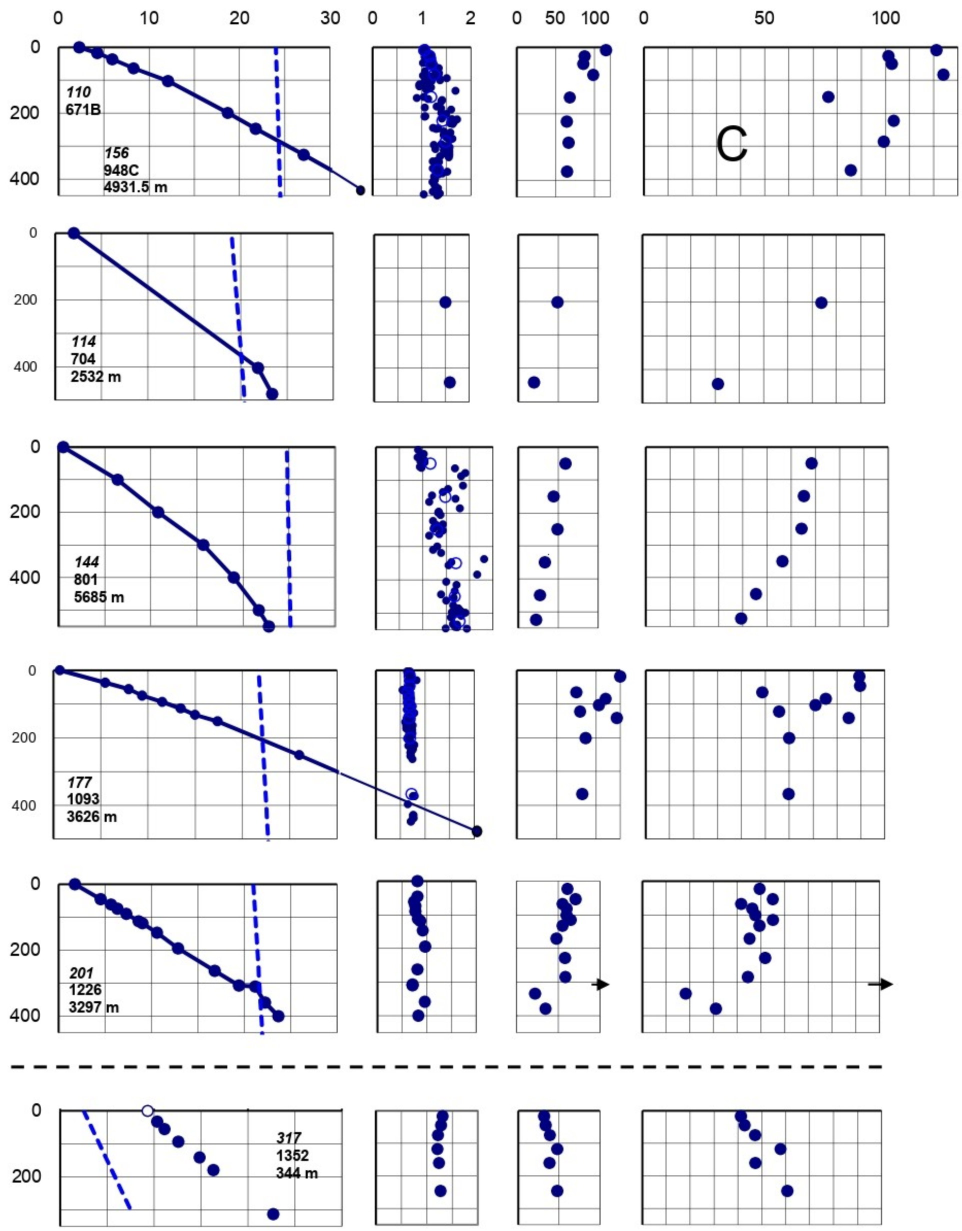
397
2910 m
B
48
406
2907 m
76
533
3191 m
80
549
2515 m
84
568
2020 m
87
582
4879 m


0
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20
30
0
1
2
0
50
100
0
50
100
0
200
400
110
671B
156
948C
4931.5 m
C
114
704
2532 m
144
801
5685 m
177
1093
3626 m
201
1226
3297 m
317
1352
344 m

Fig. 2.