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Thermal history of deep-sea sediments as a record of recent changes in the deep circulation of the eastern Mediterranean

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[1] During three cruises of the MEDRIFF project in 1993 and 1994, 154 geothermal heat flow measurements and seven CTD profiles in the water column have been collected along a 300 km SW-NE oriented transect traversing the Mediterranean Ridge accretionary complex. The original goal of the measurements was to identify areas of anomalous heat flow that could be interpreted as possible sites for fluid outflow. Contrary to expectations, the upper few meters of the temperature profiles in the sediments showed decreasing temperature from the seafloor down to 3 to 6 m depth indicating consistently transient temperature regimes. The only exception (positive heat flow) was found in the Sirte abyssal plain. Measurements collected in the same area at different times indicated that the thermal structure in the bottom water and sediments had changed significantly at weekly, monthly, and interannual timescales. One-dimensional forward modeling of the conductive heat propagation into the sediment explains the observed thermal anomalies, assuming up to 0.5 K warming of the bottom waters that propagated south westward from the Matapan Trench to the crestal area of the Mediterranean Ridge. Analysis of nonsteady state thermal profiles in the upper sediment provided time information on the onset of bottom water warming, by what is now called the Eastern Mediterranean Transient (EMT). The sediment warming started in the Matapan Trench, between spring 1992 and spring 1993, and reached the Mediterranean Ridge crest in spring-summer 1993. The average propagation velocity of the thermal perturbation along the profile is about 0.5–1.6 km d^{-1} (0.6–1.8 cm s^{-1}). *INDEX TERMS:* 3015 Marine Geology and Geophysics: Heat flow (benthic) and hydrothermal processes; 3094 Marine Geology and Geophysics: Instruments and techniques; 1635 Global Change: Oceans (4203); 4211 Oceanography: General: Benthic boundary layers; 4243 Oceanography: General: Marginal and semienclosed seas; *KEYWORDS:* eastern Mediterranean, Aegean waters, sediment warming, heat flow measurements, thermal modeling, thermal history

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1. Introduction

[2] This paper presents the experimental evidence, collected during three cruises within less than one year, of a transient thermal event in the deep bottom water and in the upper 6–8 m of sediments of the eastern Mediterranean. The oceanographic cruises were carried out within the MEDRIFF project (An Integrated Investigation of the Fluid-Flow Regime of the Mediterranean Ridge); they were aimed at the discovery of fluid outflow and inflow through the seafloor of the Mediterranean Ridge accretionary complex, and to the understanding of the mechanisms that drive the flow [*MEDRIFF Consortium*, 1995a, 1995b; *Westbrook and Reston*, 2002]. The MEDRIFF study has been conducted with a diverse range of marine geological and geophysical methods, such as multibeam bathymetric surveys, high resolution single channel seismic profiling, deep-tow side-scan sonar surveys (TOBI and SAR), deep-tow camera observations (SCAMPI), heat flow measurements, in situ pore water pressure gradient measurements (PUPPI) [*Rose and Villinger*, 1998, 1999] and coring.

[3] The first cruise 19/93 of R/V *Urania* (September 1993) collected a regional transect (Figure 1) of closely spaced (1–2 km) heat flow measurements with the purpose, among others, to identify areas of heat flow anomalies that

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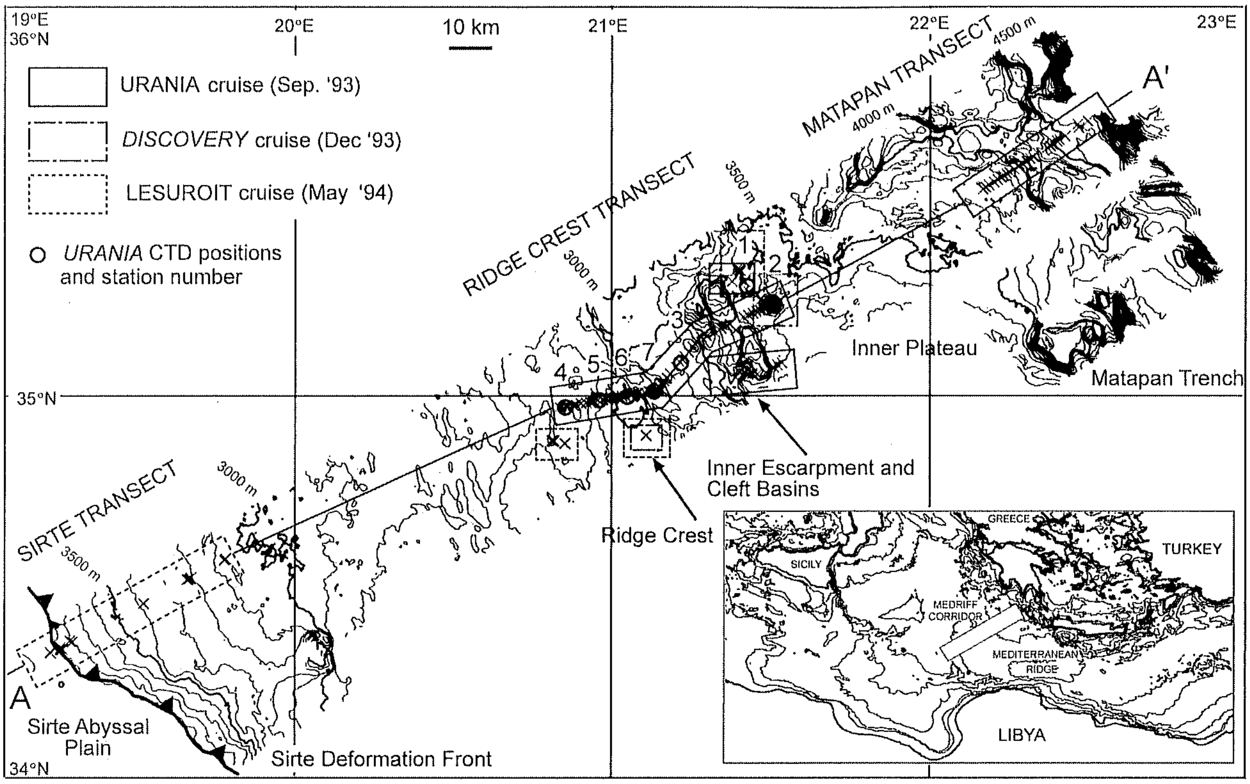

Figure 1. Location of the 154 heat flow measurements (crosses) collected during the three MEDRIFF cruises. Multibeam bathymetry is from *L'Atalante* cruise Heralis, 1992. The bathymetric profile A-A′ is displayed at various scales, in whole or partly, in Figures 2, 5, 7, 8, and 13. Navigation and positioning was GPS controlled.

could be interpreted as possible sites for fluid outflow from the seafloor. Unexpectedly, temperature profiles in the sediments showed a strong negative (concave-down) curvature at a depth ranging between 3 and 6 m below the seafloor; accordingly, the shallow sediments were generally cooler than the bottom water (see section 3). Because it was suspected that the reason for the curvature was the thermal response of the sediments to bottom water temperature changes, several CTD profiles were also collected near the seafloor during the cruise [*Camerlenghi et al.*, 1994; *Della Vedova et al.*, 1998]. Subsequent MEDRIFF cruises 206 of RRS *Discovery* (December 1993 to January 1994) and JASON of R/V *Le Suroit* (May–June 1994) provided additional information on the temperature structure in water and sediments, revealing that both temperature values and shape of the temperature profiles had changed in the few months of time elapsed between the cruises.

[4] One of the basic assumptions in marine heat flow investigations is that the temperature of the deep-sea bottom water remains reasonably stable (ΔT less than a few hundredths of K) over timescales of thousands of years, which is an upper boundary condition for the sediments conducting the geothermal flux from below. Nonsteady state conditions can arise from short term temperature variations, or from thermal transients produced by processes such as sedimentation or erosion [*Hutchison*, 1985], fluid circulation [*Foucher et al.*, 1990], mud volcanism [*Langseth et al.*, 1988], hydrothermal venting [*Thomson et al.*, 1995], or temperature fluctuations in the deep bottom water [*Beck et al.*, 1985; *Lewis et al.*, 1991]. The quasi steady state thermal structure of the deepwater masses that prevails in most oceanic basins has allowed reliable heat flow measurements to be made in the uppermost sediments; but this simple situation does not appear to apply to the area of the eastern Mediterranean investigated during the MEDRIFF cruises.

[5] In this paper we document, at a regional scale, the penetration of dense and warm water masses in the deep eastern Mediterranean [*Roether et al.*, 1996; *Malanotte-Rizzoli et al.*, 1996], also called the Eastern Mediterranean Transient (EMT), from September 1993 to May 1994. Our approach uses an exceptional sediment temperature data set, that reflects the spatial and temporal variability of the thermal structure of the deepwater masses at weekly, monthly and interannual timescales. The one-dimensional (1-D) modeling of heat conduction in the sediments and the best fit with the observed temperature profiles enable us to date the onset of the EMT. This is an important contribution for the understanding of the early history of the transient, which could not been obtained by any other means. To our knowledge analogous studies were carried out in relatively shallow water depths of the Denmark Strait [*Lachenbruch and Marshall*, 1968], and in the Queen Charlotte basin [*Lewis et al.*, 1991].

2. Methods

[6] Two heat flow probes of the Trieste University were alternatively used onboard the *R/V Urania*:

[7] 1. The GTA (Gruppo Tecniche Avanzate S.r.l.-Trieste), a 16-channel digital acquisition system working on a preprogrammed acquisition sequence with no real-time acoustic telemetry. The probe weights 1.2 ton. The lance is 6 m long and bears eight outrigger thermistors (about 65 cm apart), one of which is in the weight stand to measure the temperature near the seafloor. There is a tiltmeter with ±1° accuracy, and a pressure transducer. In situ k measurements are made using a constant heating technique [e.g., *Jemsek and Von Herzen*, 1989]. The accuracy of relative temperature changes is ±0.002 K.

[8] 2. The ARGUS-II probe (Applied Microsystems Ltd., Sydney, B.C.), a second generation instrument with a higher accuracy in relative temperature determination (±0.0005 K) over a broader temperature interval (−2 to +30°C); 16 thermistors arranged in four violin-bow-type outrigger fins, 25 cm spacing between sensors; near-seafloor water thermistor on the pressure case; real-time acoustic telemetry; in situ k measurements using a heat pulse method [*Hyndman et al.*, 1979; *Villinger and Davis*, 1987a]. The violin-bow arrangement used was 5.5 m long with a weight stand of 1 ton.

[9] On the *Discovery* and *Le Suroit* cruises the IFREMER heat flow lance, 4.5 to 9 m long and equipped with seven temperature sensors mounted on outriggers, was used. The upper probe is attached to the upper part of the core-head to measure the near seafloor temperature. The probe is equipped with acoustic telemetry, but it does not allow in situ k measurements. Each heat flow probe deployment provided a single or multiple (up to 12) penetrations. The altitude of the probe over the seafloor was continuously monitored using its own telemetry or a pinger. The uncertainty in penetration depth of the probes is given by the distance between the uppermost thermistor in the sediment and the lowermost thermistor in water. The range of this uncertainty varies from a minimum of ±0.1 m (for a partially penetrated ARGUS II measurement) to about ±1 m (for single overpenetrated ARGUS II, GTA or IFREMER measurements). With all the heat flow probes, sediment temperatures were measured relative to sea-bottom water temperature and extrapolated to infinite time to determine the in situ equilibrium temperature [*Bullard*, 1954].

[10] The thermal conductivity (k) data for the ARGUS pulse-heating probe were reduced using the *Villinger and Davis* [1987a, 1987b] heat flow reduction program, whereas the GTA measurements were processed using the needle probe method [*Von Herzen and Maxwell*, 1959]. Corrections for in situ temperature and pressure were applied according to *Ratcliffe* [1960]. The needle probe method was also used onboard to measure k every 5 cm on thermally equilibrated cores. Because in the investigated area the temperature distribution in the upper few meters of sediment was found to be nonlinear (excluding a few measurements in the Sirte abyssal plain), the thermal gradient varies continuously in this depth interval and therefore cannot be used to compute the heat flow from below.

[11] A Sea-Bird 911 plus CTD system was used on the R/V *Urania* for the in situ measurements of water pressure, temperature, and electrical conductivity, from which density, salinity and sound velocity were calculated according to *Fofonoff and Millard* [1983]. All CTD sensors had been calibrated at the SACLANT Undersea Research Center (La Spezia, Italy) prior to the cruise. In order to correlate temperatures measured in the sediments and in the water masses with different instruments during the cruises, we intercalibrated in situ the CTD profiler with the GTA, ARGUS-II, and IFREMER heat flow probes. For this purpose we chose the stable environment of the upper brine layer of the Urania brine lake [*MEDRIFF Consortium*, 1995a, 1995b; *Corselli et al.*, 1996] as a thermostatic bath; the constant reference depth of the surface of the brine lakes was used to calibrate the pressure sensors of the instruments. The GTA and ARGUS-II probes required uniform corrections of +0.033 and −0.093 K, respectively, with reference to the CTD probe; the temperature correction for the IFREMER probe was only +0.003 K.

Table 1. Number of Attempted and Successful Heat Flow Measurements Carried Out During the Three MEDRIFF Cruises

Cruise	Beginning Date	Ending Date	Attempted HF (n)	Successful HF (n)
R/V *Urania*	12 Sept. 1993	26 Sept. 1993	97	80
RRS *Discovery*	20 Dec. 1993	4 Jan. 1994	31	17
R/V *Le Suroit*	12 May 1994	19 May 1994	26	17

3. MEDRIFF Data Set

[12] The complete data set of equilibrium temperatures and thermal conductivities is available in the form prepared for the European Community MAST-II MEDRIFF project and can be obtained from the senior author.

3.1. Temperature and Thermal Conductivity in the Sediments

[13] The measurements of R/V *Urania* cruise 19/93 are grouped in two main transects (Table 1, Figure 1) from the Matapan Trench (nearly 4600 m water depth) to the Mediterranean Ridge crest (about 2400 m water depth). Spacing of measurements generally varies between 1 and 2 km; the total length of the Ridge Crest Transect is 73 km, whereas the Matapan Transect is 32 km long. Additional measurements were taken sidewise of the Ridge Crest Transect to check the lateral variability of the temperature distribution in the sediments. Closely spaced stations, acquired on the same day, provided a way to reduce the uncertainty range in the depth of penetration to a maximum of ±0.2 m, by adjusting the temperature profiles of overpenetrated measurements (maximum uncertainty) to those partially penetrated (minimum uncertainty). The low gradients on the ridge crest increase the uncertainty to about ±0.5 m. The upper 5–6 m of sediment are cooler than the overlying bottom water (Figure 2). The temperature profiles with depth are mostly upward convex or show highly variable temperature gradients, including zero gradient. A minimum in the temperature profiles can often be observed between 3 and 6 m below seafloor.

[14] Thermal conductivity (k), measured in situ and confirmed by laboratory measurements on 11 cores, shows a general trend of increasing values with depth, that correlates with lithologic and porosity changes down core. Figure 3 shows the distribution with depth of the in situ and laboratory k measurements of the ridge crest area. The spatial variation of the average k in the uppermost sedi-

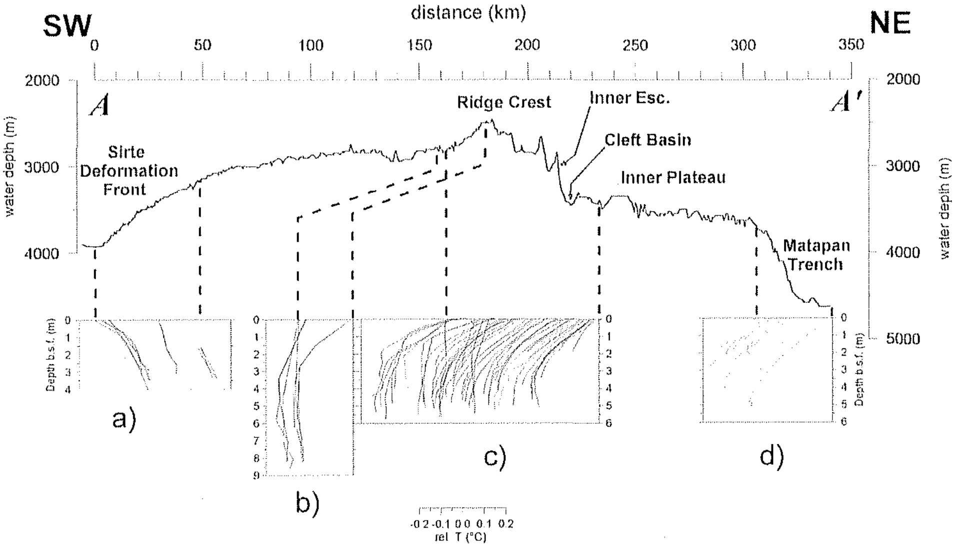

Figure 2. Temperature distribution in the few upper meters of sediment along the MEDRIFF Corridor (see location of profile A-A′ and heat flow stations in Figure 1), represented on common scale plots: (a) Sirte Transect (*Discovery* cruise, 1993); (b) part of Ridge Crest Transect (*Discovery* 1993 and *Le Suroit* 1994 cruises); (c) main part of Ridge Crest Transect (*Urania* cruise 1993 and *Discovery* 1993); and (d) Matapan Transect (*Urania* cruise 1993). The position of each heat flow station is projected along the bathymetric profile A-A′. The temperature scale (x axis) is relative to the seafloor temperature.

ments shows a regional increase from the ridge crest toward the Matapan Trench, with values ranging between about 1.05 and 1.2–1.3 W m^{-1} K^{-1}; this trend is likely associated with the progressive increase of sandy siliciclastic turbidites of Hellenic provenance. The presence of sandy layers limited drastically the penetration of both piston corer and heat flow probes.

[15] The measurements of *Discovery* cruise 206 were concentrated on or within about 10 km of the Ridge Crest Transect (Table 1, Figure 1). Temperature profiles in the few upper meters of sediment show again values lower than in the overlying bottom water, with a temperature minimum at depths ranging between 3 and 6 m (Figure 2). Thermal conductivity measurements were performed on 14 cores, with values ranging from 0.93 to 1.12 W m^{-1} K^{-1}.

[16] The *Le Suroit* cruise JASON explored the outer deformation front of the Mediterranean Ridge (Sirte Transect in Figure 1, Table 1). In this area, temperature profiles in sediments are "normal," with values increasing with depth (linear or slightly upward convex profiles) and with higher positive gradients in the upper 1–2 m (Figure 2). The gradient computed on the deeper and more linear thermal distributions of *Le Suroit* stations HF1, 2 and 4 ranges between 40 and 42 mK m^{-1}. This value is about 20% higher than the thermal gradients measured more than thirty years ago, at stations C9-124 and CH61-29 in the Sirte abyssal plain [*Erickson et al.*, 1977]. This discrepancy likely represents here the influence induced by a present seafloor negative temperature change.

3.2. Temperature and Salinity in Deep Water

[17] Seven CTD profiles from surface to seafloor were collected during the R/V *Urania* cruise. Profiles 1 and 2 were collected on 8 September, the remaining five on 16 and 17 September 1993. The profiles cover a distance of 73 km along the Ridge Crest Transect (see Figure 1). The Matapan Transect is covered only by intercalibrated ARGUS-II temperature profiles in the water column. Potential bottom water temperature (Figures 4 and 5) is ≥13.43°C on the Mediterranean Ridge crest, 13.75°C on the Inner Plateau and >13.77°C in the Matapan trench. The temperature distribution in the bottom water, particularly the cold nucleus at the Ridge Crest, is recorded in the temperature distribution within the sediment (Figure 5). The 2-D distribution of temperature in shallow sediments of the Ridge Crest Transect (Figure 5) and Matapan Transect closely matches the potential temperature distribution in bottom water. The highest lateral variability in the temperature structure is found below 2000 m, where differences of up to 0.4 K can be found at same water depths. The salinity profiles (not shown) also indicate large lateral changes below 2000 m, with highest values (up to 38.85‰) of the entire water column found at the bottom of stations 1 and 2 (Inner Plateau). Clearly, the deep water of the investigated area is characterized by a water mass warmer but denser than the overlying seawater. An additional striking characteristic is the greatly enhanced variability with depth of temperature and salinity of intermediate and deep waters, with respect to the average distribution in the same area known from published studies [*Nittis et al.*, 1993; *Roether et al.*, 1996] (Figure 4).

4. Thermal Anomalies

4.1. Spatial Variability

[18] The temperature profiles (Figure 2) can be grouped in four classes, depending on bottom water temperature range, temperature gradient in sediment (positive/negative, constant/variable with depth), and depth to the minimum temperature (Figure 6). The classes correspond to the main

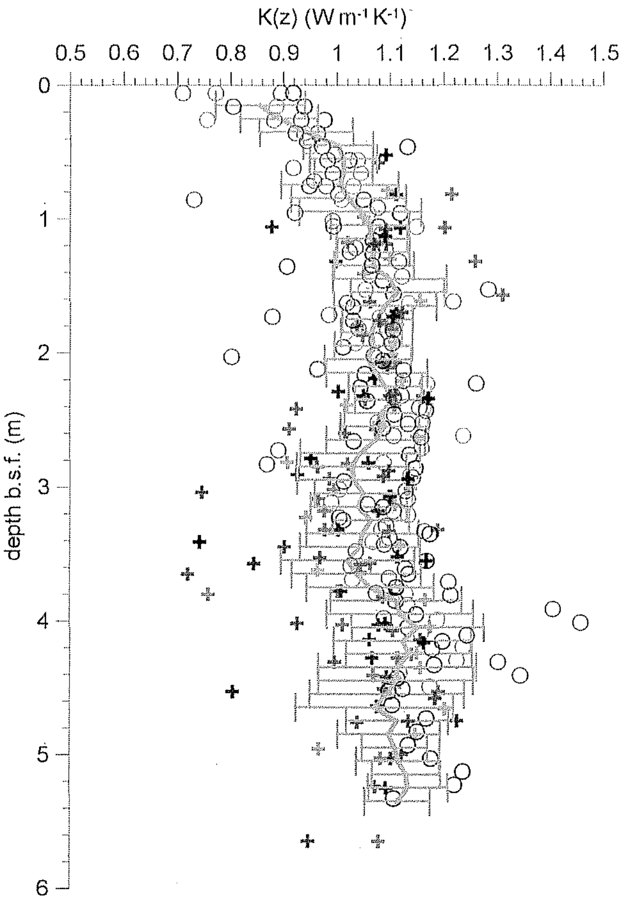

Figure 3. Thermal conductivity (k) measurements on cores GC-03, PC-04, PC-06, and GC-09 (open circles) and in situ (crosses) from the ridge crest area. Average interval k every 10 cm and the corresponding standard deviation were computed using a 30 cm moving window.

physiographic areas along the MEDRIFF Corridor. From east to west, they are: Matapan Trench, Inner Plateau, Ridge Crest, and Sirte deformation front.

[19] In the twelve profiles from the Matapan Trench we found the highest seafloor temperatures of about 14.6°C (potential 13.8°C), and the largest negative thermal gradients. The temperature gradient increases approximately in a linear way with depth, pointing to a null value (minimum temperature) at a depth exceeding 6 m (Figure 6d), the deepest in the study area. The data suggest a homogeneous thermal regime in the sediments of the trench, with no apparent significant lateral variability. However, the amplitude of the bottom water warming may have been strong enough to mask minor local nonhomogeneities in the thermal structure.

[20] In the Inner Plateau area we observed temperatures at the seafloor of about 14.35°C (potential 13.75°C) and negative temperature gradients in the sediments increasing with depth to almost zero values (Figure 6c). The lowest temperature was found at about 4.5 m depth.

[21] The seafloor temperature immediately to the southwest of the Ridge Crest is 13.75°C (potential 13.45°C), the coolest of the entire corridor (Figures 5 and 6b). In an area toward the southwest and northeast from this minimum, 5 to 10 km wide (Figure 7), the temperature increases to values of about 14.15°C (potential 13.70°C). Thermal gradients are null or slightly negative in the upper few meters and become slightly positive below about 3 m. This area displays the highest lateral and vertical variability of the temperature profiles both in the sediments and in the water column. We emphasize that a source of error in depth (as large as ±0.5 m or even larger) is introduced by the difficulty in vertical positioning of the temperature profiles, due to the low temperature gradients (Figure 6c). Generally, the depth of penetration of the thermal disturbance on the crest and its amplitude are the lowest observed for the entire MEDRIFF Corridor. The difference between the lowest temperature at depth and the temperature at the seafloor is about 0.2 K on the Ridge Crest, as compared to 0.3 K on the Inner Plateau and more than 0.4 K in the Matapan Trench. These values give an approximate estimate of the minimum temperature

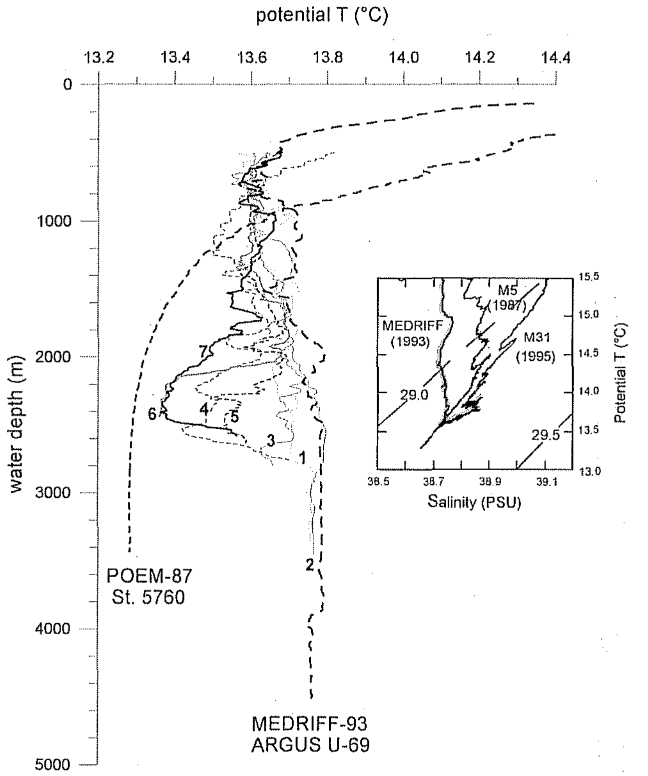

Figure 4. CTD temperature profiles from 1993 *Urania* cruise along the Ridge Crest Transect (numbers 1–7, see location in Figure 1). The thick dashed profiles represent temperature profiles taken 6 years apart in the water column of the Matapan Trench: station 5760 is a CTD profile collected in September 1987 within the POEM-87 program, whereas station ARGUS U-69 is a calibrated temperature profile collected during the *Urania* cruise in 1993. The temperature change with time of the eastern Ionian Seawater masses (about +0.5 K at water depths exceeding 2500 m) is supported by the comparison among temperature-salinity diagrams (inset plot) obtained from measurements collected during *Meteor* cruises in 1987 (station M5-759) and 1995 (station M31-37), after *Roether et al.* [1996], and during the *Urania*-MEDRIFF cruise, in September 1993.

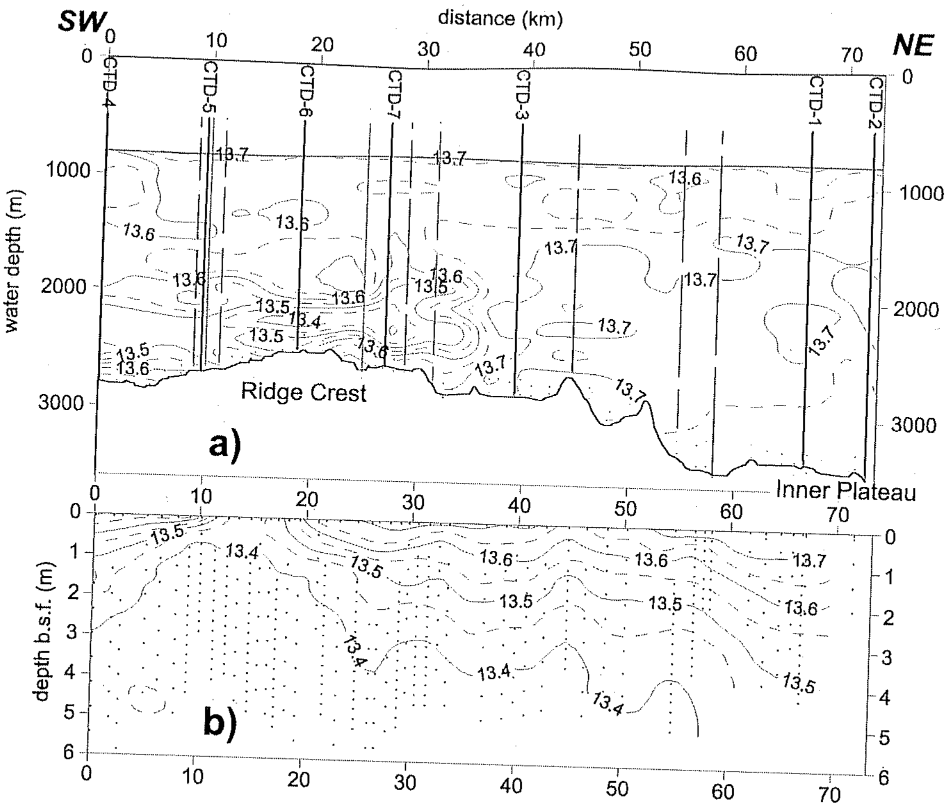

Figure 5. Composite vertical section showing the contoured potential temperature distribution with (a) depth in the water column as compared to (b) temperature in the upper few meters of sediment, along the Ridge Crest Transect (see location in Figure 1). CTD profiles (bold vertical lines) and intercalibrated heat flow probe profiles (thin vertical lines) were used in the seawater. Heat flow probe data were used in the sediment (dots).

increase at the seafloor, indicating that the warming is larger in the Matapan Trench.

[22] The observed seafloor temperature along the Sirte Transect (Figure 2) is in the range of 13.85° to 13.90°C (potential 13.35°C). The temperature gradients in the sediment are positive and decreasing with depth (Figure 6d), indicating most likely a recent temperature decrease of about 0.1 K. The measurements collected near the Sirte abyssal plain show a larger temperature disturbance near the seafloor than those up slope, thus indicating that colder deep ocean currents must have been active recently at the base of the Mediterranean ridge, at least in the lowest 100–200 m above the Sirte abyssal plain.

4.2. Time Variability in Sediments and Water Masses

[23] The temperature profiles both in the water column and in the sediments were dramatically different from what we expected from the few scattered heat flow measurements

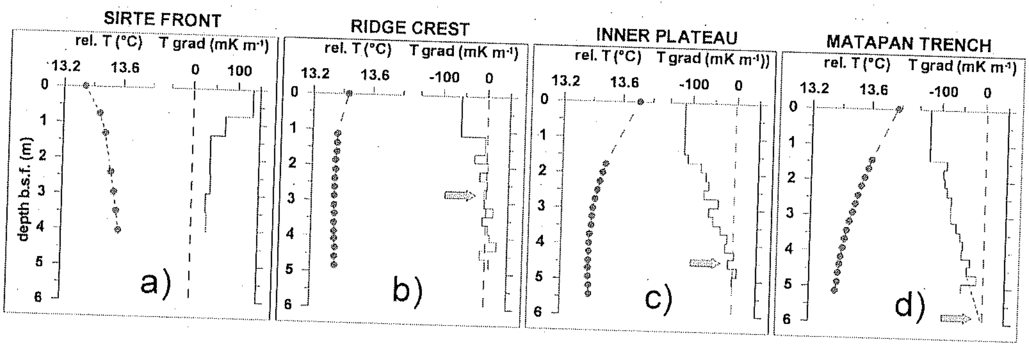

Figure 6. Sediment temperature distribution in typical individual stations from four characteristic areas along the MEDRIFF corridor (see Figure 1 for location). The arrows point out the depth to null temperature gradient (minimum temperature). (d) In the Matapan Trench the depth to the minimum temperature is linearly extrapolated. The null gradient depth shallows progressively from the Matapan Trench (6 m) toward the Inner Plateau (4.5 m) and the Ridge Crest (2.5–3.5 m). (a) In the Sirte Front area the thermal gradient is positive.

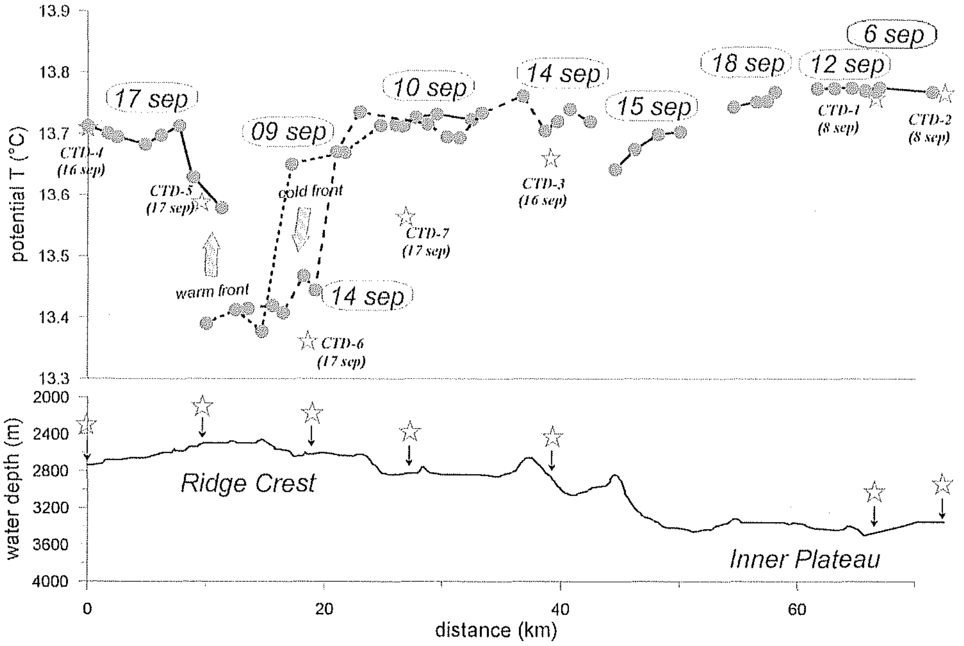

Figure 7. Potential temperature at the seafloor (solid dots) along the Ridge Crest Transect (see location in Figure 1), at different dates during *Urania* 1993 cruise, superimposed on the bathymetric profile. Measurements collected in the same day are plotted in clusters. The seafloor temperature on the crestal area is affected by a variability at a week timescale: from 9 to 14 September a decrease of about 0.25 K has occurred between km 15 and 21 ("cold front"), whereas from 9 to 17 September an increase of about 0.3 K has occurred between km 8 and 13 ("warm front"). Stars indicate the position of the CTD stations.

[*Erickson*, 1970; *Erickson et al.*, 1977; *Haenel*, 1972; *Erickson and von Herzen*, 1978; *Della Vedova and Pellis*, 1986, 1992; *Camerlenghi et al.*, 1995] and regional oceanographic data available in the Jonian Sea [*Nittis et al.*, 1993]. Changes in the observed profiles, although scattered in space and unevenly sampled in time, can be evaluated at weekly, monthly, and interannual timescales.

[24] Three sets of heat flow measurements, collected on the Ridge crest within a time window of 10 days during the *Urania* cruise, indicate a high seafloor temperature variability at ~1 week timescale (Figure 7, between km 8 and 23 of the transect). A decrease of about 0.2 K occurred in the period from 9 to 14 September, between km 15 and 21, whereas an increase of about +0.2–0.3 K occurred from 9 to 17 September at km 11 (Figure 7). CTD-6 showed a further decrease of 0.1 K at about km 20, from 14 to 17 September. The +0.3 K sea bottom water warming at station U-04 (9 September) has not yet affected the seafloor at station U-01 taken on the same day (Figure 8a). On 15 September, temperature at station U-40 shows that, although the bottom water has cooled by about 0.25 K, the upper meter of sediment still records the warming event. On 17 September, station U-47 shows a return of the sea-bottom water to the temperature of the warming event, although excess penetration of the probe does not allow measurement of the thermal structure in the upper meter. Moreover, several profiles show small-scale curvature changes below 1 m, which probably represent the propagation at depth of previous temperature fluctuations at the sea-bottom. The comparison between overpenetrated measurements and incomplete penetrations (Figure 8a) reduces the uncertainty in penetration depth to 20–30 cm, at best. In summary, temperature changes in the sea-bottom water, as high as 0.2–0.3 K in amplitude, occur over a timescale of the order of one week. They further suggest that a cold front propagated at the seafloor from SW to NE with an apparent velocity of 1 km d^{-1}.

[25] Temperature changes at monthly timescales have been inferred from a comparison of the temperature profiles measured in the same areas during different cruises. The bottom water regional thermal anomaly persisted through the three cruises, with a general warming trend of 0.01 K $month^{-1}$; in addition, on the Ridge Crest, a cooling event probably occurred between December 1993 and May 1994. This means that, similar to that observed for the weekly timescale variations, the crestal area of the Mediterranean ridge is an area of deepwater instability also at a monthly timescales. On the Ridge Crest, the increasing temperature of the sediment at the same depth, from September 1993 to December 1993 to May 1994 (Figure 8b), is associated to a downward propagation of the minimum temperature, and strongly suggests a gradual warming of the sediment over a timescale of several months, in response to a persistently warmer seafloor water temperature. In the Matapan Trench, on the other hand, the seafloor has undergone a substantial warming throughout, leaving no significant trace of initial thermal fluctuations in the deepest part of the temperature profiles (Figure 2d).

[26] The comparison between our ARGUS-II temperature profile carried out in the water column in the Matapan Trench area and the closest CTD profile (at a distance of about 100 km) obtained in September 1987 within the POEM program [*Malanotte-Rizzoli and Robinson*, 1988; OGS Preliminary Data Report Cruise POEM-05-87, unpublished

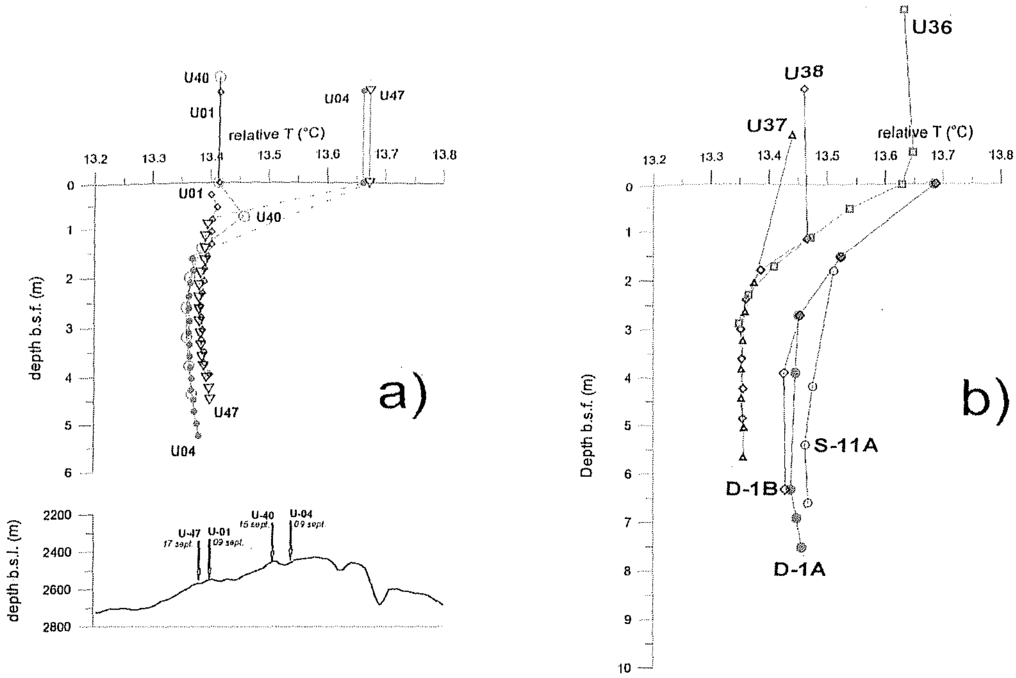

Figure 8. Thermal record of a rapid temperature change of the near bottom water and in the sediment on the ridge crest. (a) Weekly timescale: the temperature fluctuation (0.25 K) at the seafloor induces a disturbance in the first meter of sediment. Stations U-01 and U-04 are 8 km apart and were collected on 9 September; they were repeated, as U-47 and U-40, respectively, about 1 week later. The plot suggests that a cell of warm water, present over station U-04, but not over station U-01 on 9 September, could have moved over station U-47 on 17 September (see location on the inset profile and also Figure 7). (b) Monthly timescales: the temperature change (0.25 K) persists over several months, associated with sediment warming to progressively increasing depths. Temperature profiles collected in December 1993 (*RRS Discovery* D-1A and D-1B) intersect at about 2 m below seafloor the profile collected in the same location in May 1994 (R/V *Le Suroit* S-11A), suggesting short-term fluctuations at the seafloor as well (see Figure 12).

report, 1987] shows that drastic modification of the surface, intermediate, and deepwater thermal structure occurred over a time span of 6 years (inset of Figure 4). The average temperature below 2000 m has increased by about 0.5 K. The 1993 ARGUS profile shows numerous high-spatial-frequency changes in the water column that were not present in 1987. However, part of this difference may be related to different resolution between CTD and ARGUS II probes.

[27] A regional study on the deep circulation of the entire Mediterranean, carried out on the base of 600 stations [*Wüst*, 1961], shows potential seafloor temperatures of about 13.2°C in the eastern Ionian basin and a remarkable vertical homogeneity within the bottom water layer (>1500 m). Moreover, on the base of the distribution of oxygen in the deep waters, *Wüst* [1961, p. 3268] states that "... it seems probable that some smaller influences come from the Aegean Sea by occasional overflow through the channels ..., but because of the small number of observations, the conditions of this overflow cannot yet be sufficiently examined." Thus the deep waters of this region, being relatively close to potential sources, appear to have more variability than other Mediterranean regions. The detailed temporal and spatial measurements presented here indicate significant deepwater temperature variability that might have previously gone undetected from sparser conventional heat flow measurements [*Erickson*, 1970; *Erickson et al.*, 1977; *Haenel*, 1972; *Della Vedova and Pellis*, 1986; 1992; *Camerlenghi et al.*, 1995].

5. Modeling of the Thermal Transient in Sediments

[28] In order to reconstruct in space and time the evolution of the thermal disturbance induced by warming of bottom waters, and to evaluate the undisturbed temperature gradient, we used the 1-D equation describing the propagation of a thermal disturbance through a conductive media. The solution of the one dimensional heat transfer equation [*Carslaw and Jaeger*, 1959] for a linear variation over time of temperature (T) at the upper boundary of an homogeneous and isotropic half-space is given by *Jessop* [1990]:

$$T(t,z) = T_0 + Gz + \Delta T(t)\left[\left(1 + 2x^2\right)\mathrm{erfc}(x) - \left(\frac{2}{\sqrt{\pi}}\right) x e^{-x^2} \right], \quad (1)$$

where

T_0 undisturbed T at z = 0, before the onset of the T change (°C);

G undisturbed T gradient in the sediments (mK m^{-1});

z depth below seafloor (m);

erfc complementary error function;

$\Delta T(t)$ const · t = linear T increase with time at z = 0;
$x = \frac{z}{2\sqrt{\kappa t}}$.
t is the time since the onset of the T change (s) and κ is the thermal diffusivity of the sediments obtained as

$$\kappa = \frac{k}{\rho c} \quad (2)$$

where k is the thermal conductivity (W m^{-1} K^{-1}), ρ is the bulk density of the sediment (kg m^{-3}), and c is the specific heat (J K^{-1} m^{-3}).

[35] If ΔT occurs instantaneously and then remains constant, i.e., the temperature change is reached in one step, then T(t, z) is described by

$$T(t,z) = T_0 + Gz + \Delta T \quad \mathrm{erfc}\left(\frac{z}{2\sqrt{\kappa t}}\right) \quad (3)$$

where

$$T(t, z = 0) = T_0 + \Delta T, \qquad t \geq 0.$$

[36] The assumptions for these models are (1) heat propagates by conduction only; (2) thermal properties are constant with depth; (3) the initial thermal conditions were steady state, with constant undisturbed temperature gradient. Coring has shown a mainly homogeneous hemipelagic sediment with occasional centimeter-scale layering, produced by ash layers and organic rich intervals (Figure 3).

[37] To estimate the thermal diffusivity of the upper 6 m of sediment in each area we used the k data from cores and in situ measurements, computing first the mean equivalent thermal conductivity ($\overline{k_{eq.}}$) for increasing sediment thickness and then the corresponding mean equivalent diffusivity. The $\overline{k_{eq.}}$ was computed using the thermal resistance method [*Bullard*, 1939] and the average $k_{av.}(z)$, estimated from the experimental data, with a 30 cm moving window:

$$\frac{z_n}{\overline{k_{eq}}(0, z_n)} = \int_0^{z_n} \frac{dz}{k_{av}(z)}. \quad (4)$$

[38] Figure 9 shows the mean equivalent thermal diffusivity for the ridge crest area, obtained from the thermal conductivity measurements of Figure 3. The range of the mean equivalent thermal diffusivities for the various areas is

Ridge Crest	$\kappa = 2.65 - 3.50 \times 10^{-7} m^2 s^{-1}$
Inner Plateau	$\kappa = 2.65 - 3.50 \times 10^{-7} m^2 s^{-1}$
Matapan Trench	$\kappa = 3.25 - 4.00 \times 10^{-7} m^2 s^{-1}$

[39] For the Sirte abyssal plain area, we use the *Erickson et al.* [1977] average k of 1.0 W m^{-1} K^{-1}, which means an average κ of 3.2×10^{-7} m^2 s^{-1}.

[40] Two models were computed for each key area (Table 2), using the analytical solutions (1) and (3), respectively. All models were prepared using the appropriate mean equivalent thermal diffusivities. The ΔT values, representing the seafloor warming, were estimated by comparison between MEDRIFF data and the potential bottom temperatures of *Wüst* [1961] and POEM 1987 data [*Malanotte-Rizzoli et al.*, 1996] (see, e.g., Figure 4). Once the ΔT is estimated, we let G to vary in a predefined range and compute a sequence of thermal decay curves, with a one month time interval. The model results are then compared with the temperature profiles measured at typical stations of every key area; the best fit between one of the computed curves and the experimental data indicate the final result, expressed in terms of G and t. It should be stated that all model solutions are nonunique.

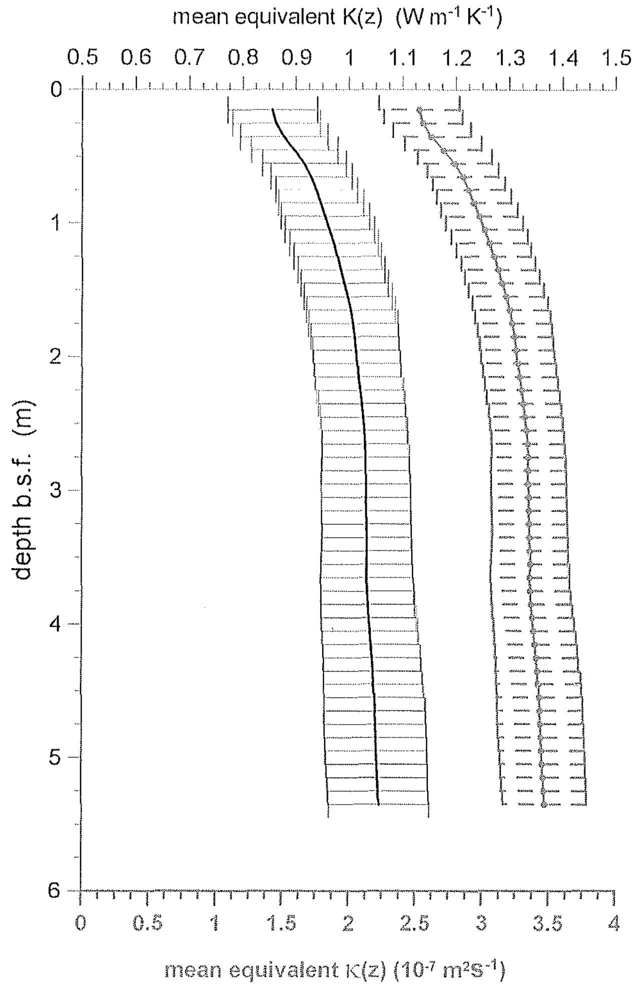

Figure 9. (left) mean equivalent thermal conductivity ($\overline{k_{eq.}}$) versus depth ± S.D., computed using the thermal resistance method [*Bullard*, 1939] for increasing sediment thickness on the data shown in Figure 3 and (right) corresponding mean equivalent thermal diffusivity.

5.1. Sudden Warming Model

[41] The results of the models (equation (3)) depend on the input parameters ΔT and κ(z), and on the measured T(z) profiles. To assess the model sensitivity, we run a test changing the input parameters for the Matapan Trench

Table 2. Summary of the One-Dimensional Modeling Results, Such as the Undisturbed Thermal Gradients (G) and the Onset Times of the Warming, for the Sudden and Gradual Warming Models (11 and 12)[a]

	Sudden Warming Model			Gradual Warming Model		
Area	ΔT, K	G, mK m^{-1}	Onset of the Warming	ΔT, K	G, mK m^{-1}	Onset of the Warming
Matapan Trench	+0.5[b]	12	March 1993	0.5	1	March 1992
Inner Plateau	+0.5[b]	40	April 1993	0.5	30	October 1992
Ridge Crest	+0.4[b]	15	July 1993	0.4	15	April 1993
Sirte Front	−0.12[c]	30	Aug–Sept 1993	0.12	30	August 1993
SW Ridge Crest	+0.10[b]		computed timing is			
	+0.27[b,d]		consistent with observation			
	−0.17[c]	18	dates (Figure 12)			
	+0.04[c]					

[a]Assuming the experimental ΔT values for the seafloor warming from the *Urania* cruise and from the other cruises as indicated.
[b]*Urania* cruise (Sept. 1993).
[c]*Le Suroit* cruise (May 1994).
[d]*Discovery* cruise (Dec. 1993 to Jan. 1994).

(Figure 10). The results show that the estimate of the onset time is quite sensitive to z misplacements of the measured T(z) profiles (±25% in time for ±25 cm in z) and to ΔT values (±10% in time for ±0.05 K in ΔT), whereas changing the thermal diffusivity by ±S.D. (not in figure) induces a slight change in the estimate of the onset time of ±0.2 months. We used time steps of 1 month and compared predicted temperature profiles with experimental data for four areas along the MEDRIFF Corridor (Figure 11, Table 2).

[42] In the Matapan Trench (Figure 11d), the temperature profile is consistent with a thermal transient caused by an instantaneous increase ΔT of 0.5 K in the sea-bottom water temperature about 6 months earlier (March 1993). Toward the SW, ΔT stays the same on the Inner Plateau (Figure 11c) and decreases to 0.4 K on the Ridge Crest (Figure 11b), while the age of the warming gradually decreases to a minimum of about 2 months (July 1993). Modeling the Sirte front temperature data in the sediments (Figures 6d and 11a) shows a

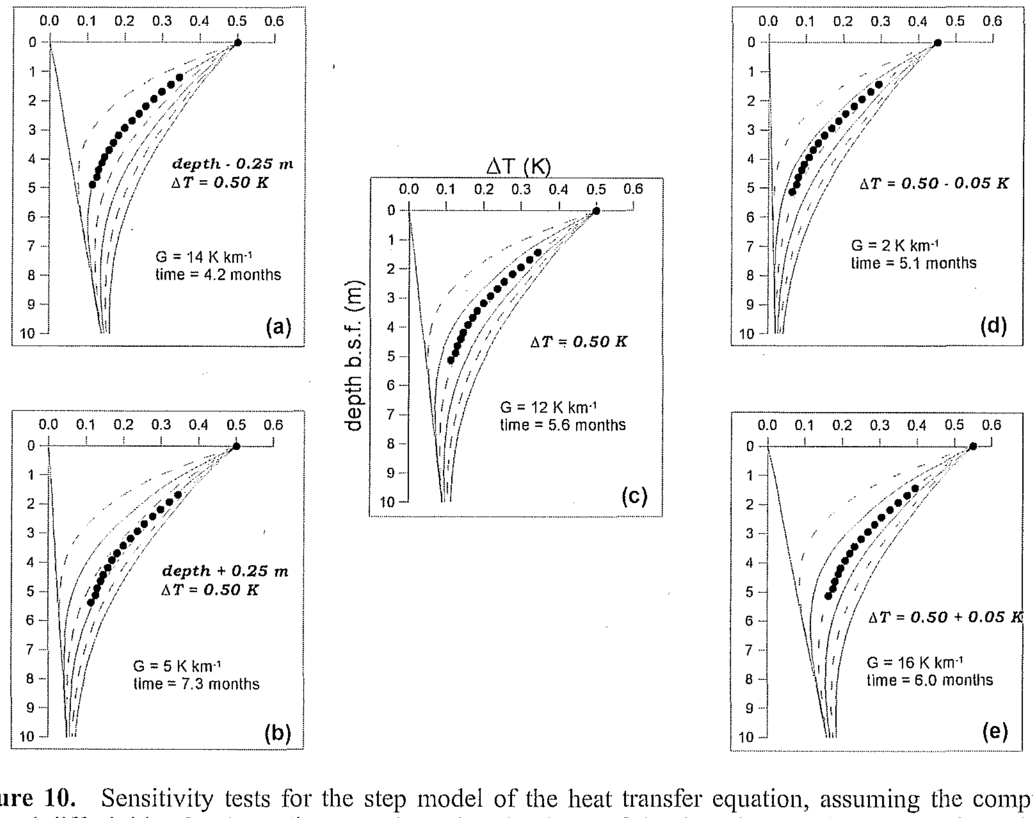

Figure 10. Sensitivity tests for the step model of the heat transfer equation, assuming the computed thermal diffusivities for the sediment and varying the depth of the thermistor probes and the intensity of the warming. The test has been performed comparing model results with data from the Matapan Trench, station U-69 (solid dots). The undisturbed temperature distribution is indicated by the straight line; the evolution of the thermal structure in the sediment, following the sudden temperature change of ΔT, is represented by selected curves (time step: 2 months). (c) The best fit solution provides an undisturbed temperature gradient of 12 mK m^{-1} and an onset time for the warming of approximately 6 months, assuming a ΔT = +0.50 K. By changing (a) and (b) the probes depth or (d) and (e) the ΔT by the indicated amounts, we can estimate the sensitivity of the model.

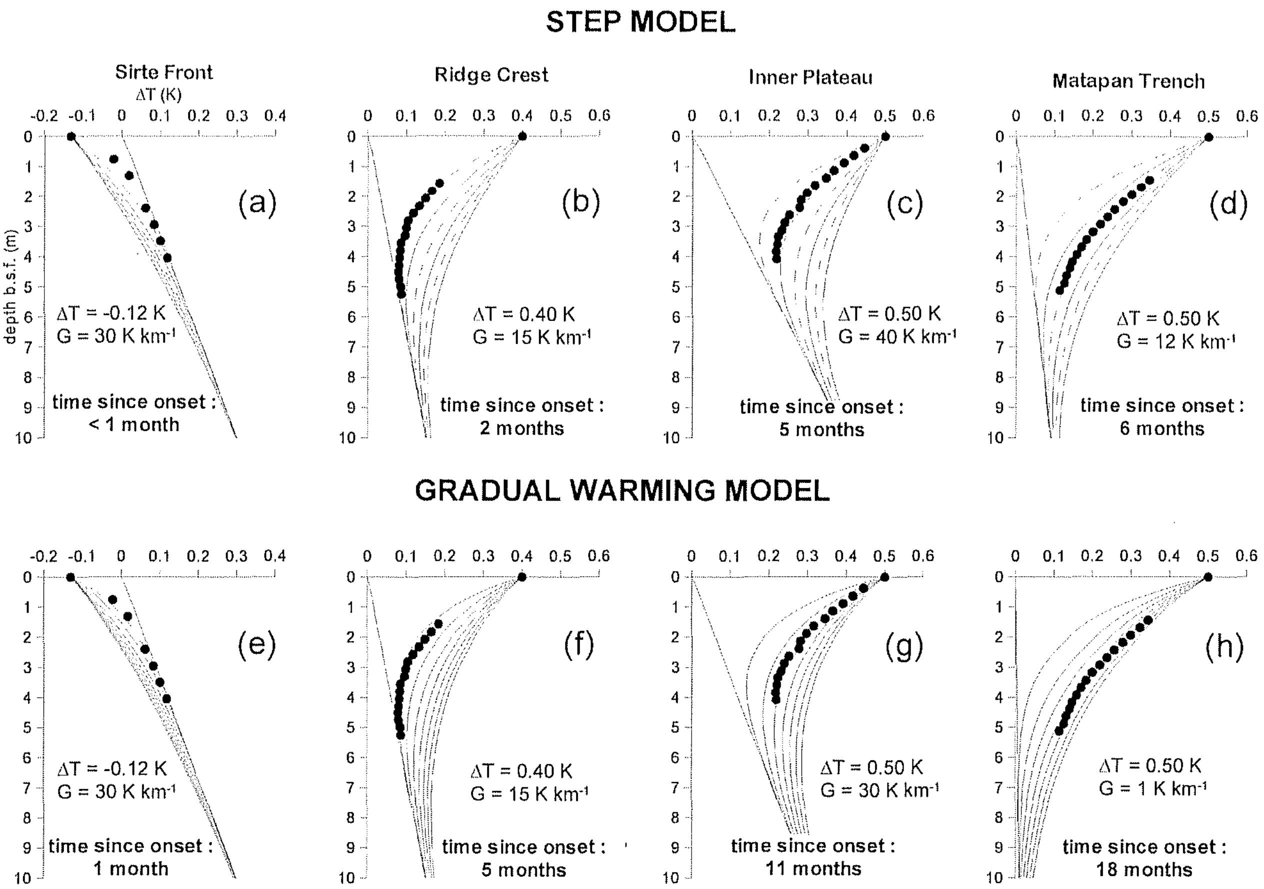

Figure 11. (a)–(d) Step-warming models and (e)–(h) gradual warming models, applied to four characteristic areas of the MEDRIFF corridor (see location in Figure 1). The sediment gradual warming models were computed assuming a linear increase of bottom water temperature from undisturbed conditions to the maximum warming. The curves show modeled temperature distributions with depth obtained using the ΔT and G parameters indicated: two-month spacing for models from Figures 11a to 11e and 4-month spacing for models from Figures 11f to 11h. Solid dots are the experimental temperature data. The solutions are obtained from the best fit between data and models. The ages of the step-warming model are considerably younger than those of the gradual warming model.

very recent (<1 month) cooling of the seafloor by −0.12 K. The undisturbed temperature gradient is variable according to the various geological domains. According to the sudden warming model, the onset of the warming episode at the seafloor started in the Matapan Trench during the spring 1993 and propagated toward the SW with decreasing intensity.

5.2. Gradual Warming Model

[43] Because the instantaneous temperature change assumed by the sudden warming model is an oversimplified description of the propagation of the seafloor warming, we also carried out simulations of the thermal transient in the sediments assuming that the temperature at the seafloor increases linearly with time from the undisturbed conditions to the maximum estimated warming. Calculations are as in the sudden warming model (Figure 11, Table 2): each T(z, t) curve was computed at the end of the time interval assumed for temperature linear increase. The slope of the linear temperature change is thus dependent on the length of the time interval considered. In comparison with the sudden warming model, this model implies longer times of warming at the seafloor to produce thermal disturbances of comparable amplitudes.

[44] G and ΔT values obtained are in some way comparable with those inferred from the sudden warming model, with a larger spreading of possible solutions, but thermal disturbances would have begun earlier (Table 2). However, it should be noticed that the G values estimated for the Matapan Trench are likely unreliable, because the temperature measurements in the sediment are too shallow with respect to the depth of minimum temperature (Figure 6). The dates of the warming onset are: March 1992 in the Matapan Trench, October 1992 in the Inner Plateau area, January 1993 in the Cleft basin and April 1993 on the Ridge Crest. The onset times computed for the representative areas along the Ridge Crest and Matapan transects have the same trend as those computed with the sudden warming model, but with about twice the magnitude.

5.3. Sediment Warming at the Western Front (SW Ridge Crest Area)

[45] The temperature profiles acquired in the same area (southwest of the Ridge Crest) during the three cruises and

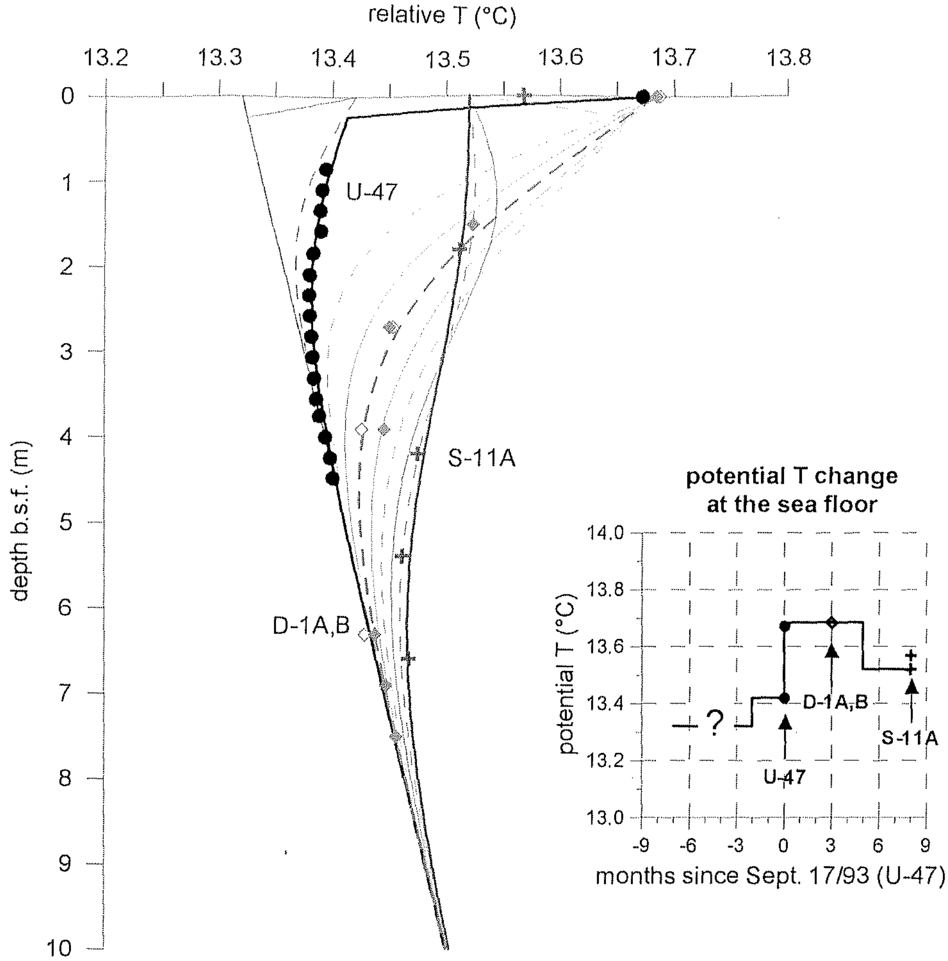

Figure 12. Reconstruction of the "waning and waxing" of the western front of the EMT (SW of the ridge crest), from intercalibrated temperature data collected in the sediments during the three cruises. Model curves every month, dashed every two. The inset diagram illustrates the temperature change at the seafloor.

the differences in their T(z) distribution allowed both a more accurate modeling, useful to reconstruct the evolution of the thermal transient in the bottom waters, and an indirect validation of the thermal modeling itself. The temperature profiles measured in the sediment locate this area at the front of the warming Aegean waters (Figure 5) and record the waxing and waning of the front as it continuously changes the thermal boundary condition at the seafloor. The temperature change at the seafloor was schematized using the step warming function, as shown in the inset plot of Figure 12. The solutions are consistent with an evolution of the warming in various phases: (1) a seafloor warming of +0.10 K (from 13.32° to 13.42°C) occurred at station U-47 in mid July 1993 (2 months before mid September); (2) a further warming of about +0.27 K (from 13.42° to 13.69°C) affected station U-47, likely 1 week or so before the measurement (approximately 10 September 1993); (3) D-1A and D-1B temperature data, measured 20 December, are consistent with a model that follows by 3 months the September warming (+0.27 K); (4) a relative seafloor cooling of −0.17 K (from 13.69° to 13.52°C) occurred at station S-11A in February 1994 (about 3 months before mid May) and the S-11A temperature data in the sediment (four points only) are consistent with this model; and (5) the seafloor temperature at station S-11A was slightly increasing in May, from 13.52° to 13.56°C.

6. Discussion

[46] A regional transient process in the intermediate and deep eastern Mediterranean water masses was described on purely oceanographic bases by *Roether et al.* [1996], *Malanotte-Rizzoli et al.* [1996], and *Roether and Klein* [1998] using data collected until 1995. According to *Roether et al.* [1996], dense Aegean waters outflowed the sills of the Cretan arc and sank into the Hellenic trenches, filling them from the bottom and causing upward displacement and mixing with preexisting bottom waters. Our observations indicate that the new bottom waters have slowly spread onto the Mediterranean Ridge, propagating the thermal pulse in the sediments toward the SW. The sediment record provides constraints on the onset time of the warm and dense waters at the seafloor, but it does not bear information on the spreading dynamics from the Aegean Sea source to the Mediterranean seafloor.

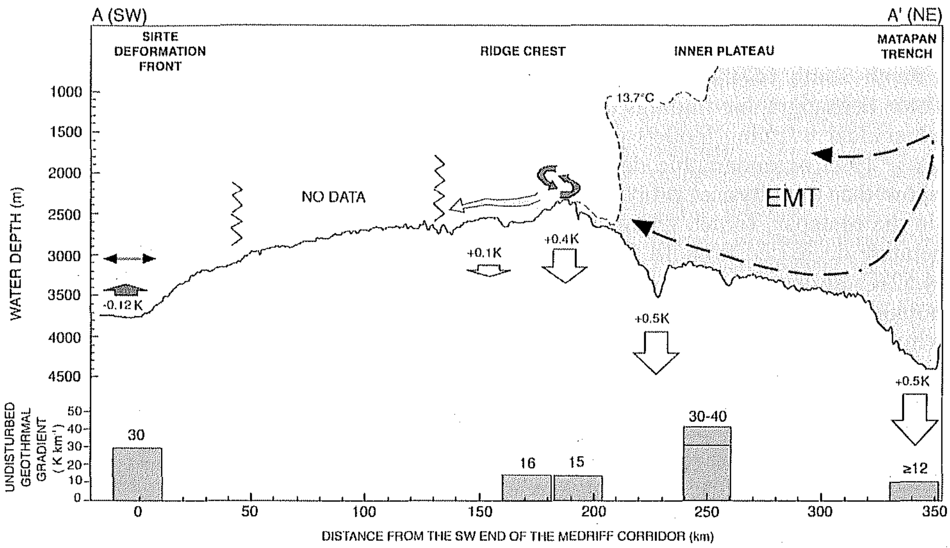

Figure 13. Cartoon summarizing the main results of this study, including the advance of the EMT onto the Mediterranean Ridge, the related thermal disturbance induced in the sediment, and the undisturbed thermal gradient at several locations along the corridor. Ranges of undisturbed G values reflect results from sudden and gradual warming models (see Table 2).

[47] According to our simplified description of the process, it is likely that, during the intrusion of warm and highly saline water into the Matapan Trench, a rapid increase in temperature occurred and thereafter the rate of increase declined toward no change of temperature with time. Therefore we believe that the results of the sudden warming and gradual warming models represent the lower and upper temporal boundaries of the early history of the EMT, respectively (Table 2). The sediment warming has been observed up to the crest of the Mediterranean Ridge over a total distance of 190 km from the Matapan Trench, covering a range of water depth from 4500 to 2600 m. There is a 100 km gap in the heat flow data between the south westernmost measurements on the ridge crest and those made at the Sirte deformation front. Therefore we have no data to document a possible extension of the sediment warming to the SW of the Ridge Crest. However, heat flow data collected at the Sirte deformation front, in the water depth range between 3000 and 3900 m, exclude sediment warming and demonstrate that the propagation of the warm and saline near-bottom water body has not reached this area. Instead, a small recent cooling event (Figure 11e) is likely due to back and forth movement of old Adriatic and more recent Aegean waters. Modeling of this event indicates that it could be seasonal, as suggested by the predicted age of about 1 month before May 1994, or produced by a recent episode of outflow of Adriatic deep waters, as suggested also by *Malanotte-Rizzoli et al.* [1996], on the basis of high chlorofluorocarbon (CFC-112) concentrations in the western Ionian abyssal plain. In this respect, however, *Klein et al.* [2000] suggest that it is likely that the Adriatic Sea did not produce bottom water over much of the 1990s. Our interpretation of the thermal transient at the Sirte deformation front remains speculative.

[48] The time variability of the temperature structure in the sediments is present only beyond the Ridge Crest (to the SW) and indicates dynamic instability of the thermal structure at monthly (Figure 12) and weekly timescales. These observations may indicate that the propagation front of the warm bottom water intrusion had not extended far to the SW of the Ridge Crest, at least from September 1993 to May 1994. The regional warming reached first the bottom of the Matapan Trench between March 1992 (gradual warming) and March 1993 (sudden warming). The onset of the Aegean outflow through the straits of the Cretan arc must have occurred some time earlier. The propagation front had reached the Ridge Crest and possibly beyond, about 2000 m higher in elevation and 190 km to the SW, in spring or summer 1993. A rough estimate of the average propagation velocity of the thermal transient at the seafloor ranges thus between 0.5 and 1.6 km d^{-1} (gradual and step change models, respectively). The significant topographic changes along the path of propagation of the water mass may contribute additional variability to this estimate.

[49] The largest amplitude of the warming at the seafloor is estimated at +0.5 K in the Matapan Trench. It is likely that a seasonal modulation affected the production and outflow of Aegean warm and saline water, causing a seasonal modulation of the temperature increase at the seafloor. The weekly and monthly timescale temperature instabilities observed during the three cruises to the SW of the ridge crest has a magnitude of about 0.2–0.3 K and is confined to the most elevated area of the Ridge, where water masses of different temperature and salinity meet and may mix (Figures 12 and 13).

[50] We postulate that in September 1993 the Aegean water mass was confined deeper than the 13.65°C potential temperature isotherm (Figure 5a), which reached approximately 1400 m water depth on the Inner Plateau. Starting from about 20 km to the NE of the Ridge Crest, the Aegean waters was in contact with a colder water mass, which produced an area characterized by short-term temperature fluctuations at the seafloor. *Roether et al.* [1996] estimated that the deep penetration of Aegean waters started in 1988

or later, with an outflow rate of about 1×10^6 m^3 s^{-1}; *Theocharis et al.* [1998] showed evidence of Aegean waters at about 1600 m depth south of the Cretan Straits in September 1989. These oceanographic findings do not rule out either sudden or gradual warming models proposed in this paper. The *Meteor* 1995 oceanographic data [*Roether and Klein*, 1998] show that the physical properties of the deepwater masses in the Matapan Trench remained almost unvaried (the temperature decreased from 14.55°C in September 1993 to 14.52°C in January 1995). This finding suggests that the cooling rate is very small (0.015 K year^{-1}) and that the maximum warming could have slightly exceeded 14.55°C sometimes before September 1993. Because the onset of the warming event, as estimated from our gradual and sudden warming models, ranges from March 1992 to March 1993, respectively, we conclude that the seafloor warming phase of the EMT reached its maximum within about one year and thereafter started to decline.

7. Conclusions

[51] We have collected an exceptional data set of anomalous temperature profiles in deep-sea sediments across the Mediterranean Ridge and Matapan Trench, that documents the thermal forcing of the EMT on the undisturbed sediment temperature distribution.

[52] The temperature of the few upper meters of sediments is generally colder than the bottom water. A temperature inversion occurs at systematically variable depths in the range of 3 to 6 m from the NE to the SW along the MEDRIFF corridor. The profiles were found strongly related to the temperature structure of the deep bottom waters. The space and time variability of the temperature, both in the sediment and in the water masses, indicates that they are all related to a single regional process, identified as the progressive spreading of warm and dense saline Aegean waters, filling the Matapan Trench and rising onto the Mediterranean Ridge (Figure 13). The temperature profiles in the Sirte abyssal plain are not affected by this regional disturbance, but show rather a very recent cooling (spring 1994), likely induced by back and forth movement of cold bottom water of Adriatic origin, most likely advected before the onset of the EMT.

[53] The modeling of propagation of the temperature disturbance in the sediment has provided parameters for the onset time (t) of the thermal transient, as well as for the undisturbed thermal gradient (G). These parameters, combined with the oceanographic data in the area, make it possible to reconstruct the early history of the EMT: the sea bottom warming started in the Matapan Trench, between spring 1992 and spring 1993. This postdates earlier estimates of the onset of the EMT [e.g., *Roether et al.*, 1996]. The transient reached the Mediterranean Ridge Crest in spring-summer 1993. Thus the average propagation velocity of the thermal transient at the seafloor ranges between 0.5 and 1.6 km d^{-1}.

[54] The analysis of the spatial variability of the temperature structure in water masses and in the sediments allowed us to localize the warming event in relation with seabed topography, stressing the importance of the ridge crest acting as a barrier to the spreading of the newly formed dense waters.

[55] The sediment in deep seas can be therefore an accurate recorder of recent large-scale oceanographic changes. The transient thermal record in the sediment, caused by past changes in the deepwater mass, allows, when detected, the determination of timing, intensity and extent of oceanographic events not usually revealed because of lack of measurements in the near-bottom water column. During the MEDRIFF cruises, we were fortunate to observe in real time a major progressive oceanographic change, before the decay of the thermal transient in the sediment. The results presented cannot normally be obtained by conventional hydrological studies, and complement the previous work conducted by oceanographers in the same area.

[56] **Acknowledgments.** Captains and crews of the R/V *Urania*, *RRS Discovery*, and R/V *Le Suroit* are acknowledged for their effort in conducting the sea operations. During the *Urania* cruise, Guido Meton and Keith Najmulski contributed with valuable technical development and assistance to the two heat flow probes of the Trieste University, and the shipboard party actively contributed to the successful acquisition of the data. Vedrana Kovacevic and Beniamino Manca, from OGS Trieste contributed with some processing of the CTD data and made OGS oceanographic data in the same area available. The manuscript greatly benefited from comments and suggestions by Jean-Pierre Betoux, Wolfgang Roether, Heiner Villinger, Graham Westbrook, Trevor Lewis, and two anonymous reviewers. Funding for the cruises was provided by CNR-Italy, NERC-UK, and IFREMER-France, postcruise work was supported by the European Union contract MAST2-CT92-0037 (MEDRIFF) and by the Italian program SINAPSI - Marine Ecosystems. Giulio Pellis passed away in September 2002, just before the submission of the last revision. This paper could not have been completed without Giulio's enthusiastic contribution.

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