
On the depth of oceanic earthquakes : brief comments on « The thermal structure of oceanic and continental lithosphere » by McKenzie, D., Jackson, J. and Priestley, K. Earth Plan. Sci. Let., 233, [2005], 337–349Louis Géli^{a,*}, John Sclater^b^a Marine Geosciences Department, Ifremer, BP 70, 29280 Plouzané, France^b Scripps Institution of Oceanography, UCSD, 9500 Gilman Drive, San Diego, 92093-0220, CA, USA*: Corresponding author : Louis Géli, email address : Louis.Geli@ifremer.fr

The focal depth of earthquakes is a widely-used, critical parameter that provide first-order indications on the mechanical properties of the lithosphere. *McKenzie et al [2005]* have recently pointed out that earthquakes in old continental lithosphere occur almost entirely within the crust. In contrast, earthquakes in oceanic lithosphere commonly occur within the upper mantle, beneath the Moho. In an attempt to explain these observations, the authors have re-examined the thermal models of both oceans and shields. Taking into account the temperature dependence of thermal conductivity and the fact that radiogenic heating in continental shields is not as concentrated at shallow depths as previously believed, they show that most earthquakes in continental regions are confined to crustal regions cooler than 600°C. The temperature dependence of the mantle thermal conductivity results in deepening isotherms within the oceanic lithosphere, in such a way that except beneath the outer rise of trenches, most large, intraplate oceanic earthquakes occur at depths where the temperature does not exceed 600°C. *McKenzie et al [2005]* conclude that « *the mechanical behaviour of oceanic and continental upper mantle depends on temperature alone, while there is as yet no convincing evidence for any compositional effects* ».

In their first plot of earthquake depth versus age of the ocean floor, *McKenzie et al [2005]* used the analytical solution of *Parsons and Sclater [1977]* and a constant thermal conductivity to compute the theoretical temperature contours. They found that 15 earthquakes out of a total of 68 occur at depths where the temperature exceeds 600°C. Three of these earthquakes lie on crust older than 30 Ma and twelve on crust younger than 30 Ma (Fig. 1c). When the temperature dependence of the mantle is taken into account the isotherms deepen. The three earthquakes on crust older than 30 Ma now lie shallower than the depth of the 600°C isotherm (Fig. 7b from *McKenzie et al., [2005]*). However, only five of the earthquakes on crust younger than 30 Ma move to a position shallower than the 600°C isotherm (Fig. 1b). This leaves seven earthquakes (out of an original 68) as exceptions to the model of *McKenzie et al. [2005]* (listed 1 through 7 in Table 1).

There are a number of reasons why the depth of the isotherms under an earthquake epicenter on young ocean floor calculated from a simple thermal cooling model might be in error. First, the depth of the isotherms change most rapidly on young ocean floor. Thus to assign a temperature profile with depth beneath young ocean floor, it is critical that the age of the ocean floor be evaluated correctly. Unfortunately most of the studies determining the depth of epicenters occurred in the 80's when the exact position of the isochrons on the multiple offset seafloor on young ocean crust in both the Indian and Southern oceans was poorly known. In addition, earthquakes in the Southern and Indian oceans have a location error of around 25 kms. This is a large enough distance on the multiple offset transform sections of the Central and Southeast Ridges to place the earthquake on crust that is either significantly younger or older than the crustal age that has been assigned.

Hence, we reexamined the age of the seven earthquakes that lay below the 600°C isotherm after the effect of temperature dependent conductivity was used to compute the depth of the isotherms (Table 1). Two of the seven (events 1 and 2 in Table 1) are located close to the crest of the equatorial East Pacific Rise and five (3 through 7 in Table 1) are found in the Indian Ocean (Fig. 2). We superimposed the epicentral positions and the isochrons [Mueller et al, 1997] on the predicted bathymetry of the equatorial Pacific (figure not shown) and on detailed enlargements of the area around the five events in the Indian Ocean (Fig. 3a-d). We found that all these events in the Indian Ocean lie on crust older than that assigned to them in the original publications (Table 1). We changed the ages and replotted the depth of the earthquakes against age (Fig. 1a). Now only the two near ridge axis from the equatorial Pacific lie significantly below the 600°C isotherm.

Another reason why the depth of the isotherm calculated from a simple thermal cooling model might be in error in young ocean floor could simply be due to continuing hydrothermal circulation in the oceanic crust as it moves away from a spreading center. Such circulation could occur through normal ocean floor or in fracture zones at some distance from a spreading center. Lower than expected heat flow in locally sediment-filled fracture zones has been attributed in the past to such hydrothermal activity.

Excessively deep local hydrothermal circulation within the oceanic crust could explain the two deep earthquakes near the crest of the equatorial East Pacific Rise. In addition, it is noticeable that three of the five earthquakes that initially lay below the 600°C isotherm in the Indian Ocean (events 4, 5 and 7 Fig. 3b and 3a) also lie within fracture zones. Also almost all of the earthquakes on the flanks of the mid-ocean ridges in the Indian Ocean lie on or within 25 km of the traces of fracture zones (black dots Fig. 2). These observations provide evidence that fracture zones may have a major influence on the location of earthquakes within the oceanic lithosphere. A combination of deep fracturing whilst the crust is within the transform fault coupled with continued major hydrothermal circulation after the transform fault becomes inactive is a possible explanation.

Additional support for our suggestion is provided by the 7.6 M_w earthquake that occurred on July, 15th, 2003, within the Indian Plate (this event is included as event 8 in Table 1). The hypocenter is located on 1.4 Ma old crust, in a fossil fracture zone, near the crest of the Central Indian Ridge which consists in a series of short spreading segments, offset by closely spaced (by 30 to 80 km), pronounced transform discontinuities, some of which were mapped using swath bathymetry [Drobia et al, 2003]. This event was followed by an important sequence of aftershocks forming a ~ 200 km linear band along the fossil fracture zone (Bohnenstiehl et al, [2004]; Antolik et al, [2006]). The hypocenter, determined by waveform modelling, is located at about 15 km below seafloor, while the CMT analysis using oceanic source structure and all available teleseismic recordings of P and SH wave favors a centroid depth of ~ 20 km [Antolik et al, 2006] (for the difference between hypocenter and centroid depth is clearly explained in Stein and Wysession [2003, page 251]: « Earthquake location bulletins based upon arrival times of body wave phases like P and S give the hypocenter: the point in time and space where the rupture began. CMT solutions, using full waveforms, give the centroid or average location in space and time, of the seismic energy release »). The major portion of moment release could have occurred in two large asperities, located between 100 and 200 km to the northeast of the epicenter, the first at 15 km depth while the second was between 20 and 30 km depth. These depths remain below the 600°C event when $k=k(T)$. A reasonable explanation for this would be the cooling effect of continuous hydrothermal circulation on the fracture zone well after the ocean floor passed beyond the active domain of the transform fault.

Another example is provided by the M_w 7.0 earthquake that occurred in the Atlantic Ocean on the Romanche FZ on March, 14th, 1994. This earthquake has been studied by a number of authors because it was reported to display low frequency signals, several hundreds seconds before the high frequency origin time [Jhmlé and Jordan, 1994]. Because the possibility of anomalously slow rupture preceding the normal speed rupture could be useful for short-term prediction, [Abercrombie and Ekström, 2001] and [Abercrombie and Ekström, 2003] have re-examined the recordings and proposed that the precursory signal could be simply explained as artifacts generated by the modeling procedure. On Figure 4, we show this earthquake on a bathymetric map and in a plan view along the Romanche transform fault plane, together with two other earthquakes (listed in Table 2) that were also relocated using waveform

modelling. In order to account for the age offset at the transform fault, the isotherms represent the average mantle temperature across the fault. When the thermal conductivity does not depend on temperature, all three earthquakes lie below the 600°C isotherms. However, when $k=k(T)$ the two earthquakes located farther away from the spreading centers move to a position shallower than the 600°C. In contrast, the earthquake located near the ridge-transform intersection still lies below the 600°C isotherm. Here again, a reasonable explanation could be the cooling effect of seawater circulation at depth.

By reducing the number of outliers from seven to two (out of sixty eight) we have substantiated the success of McKenzie et al [2005] in arguing that mantle temperature is the governing parameter that controls the depth of oceanic earthquakes. However, the existence of anomalously deep earthquakes (such as the two outliers and the July, 15th, 2007 earthquake) suggest that other physical processes, in addition to the temperature dependence of thermal conductivity – must play a role in lowering the isotherms in very young crust. In addition, the strong tendency for the intra-plate earthquakes in the Indian Ocean to be located on or near fracture zones suggests that these processes are most important at fracture zones. Hydrothermal circulation, for instance, could be one such process. Seawater circulation likely results in lowering isotherms immediately below faults, thus increasing the maximum depth of brittle failure and explaining the unexpectedly deep depths of the earthquakes. This provides indirect evidence that seawater circulates deeply along faults off axis in young lithosphere, a process which so far has been documented only at the crest of spreading centers.

Acknowledgments

This note was initiated while L.G. was on sabbatical at the Institute of Geophysics and Planetary Physics at the University of California at San Diego. The Cecil & Ida Green Foundation is gratefully acknowledged. Dan McKenzie kindly provided the list of earthquakes used in McKenzie et al [2005]. J. S. acknowledges the support of NSFOCEo3-29565 for the work done on this note.

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Tables

LABEL	year	mo	dd	Lat	Long	focal depth (km)	Age (My)	Age Corr. (My)	Mag.	Region	T _{corr} (°C)	Ref.	Focal Mec.
1	1975	10	29	3.9	-103.6	9	3	2.3	5.5	Cocos	> 600	SW	Normal
2	1972	5	2	5.2	-100.3	11	3	3	5.5	Pacific	< 600	BS	Normal
3	1967	1	1	-48.8	112.8	9	3	4.5	6.0	Indian (C)	> 600	BS	Normal
4	1965	12	19	-32.2	78.9	11	4	5	6.0	Indian (B)	> 600	BNS	Normal with SS
5	1966	2	17	-32.2	79.9	12	4	12	6.6	Indian (B)	< 600	BNS	Normal with SS
6	1979	5	22	-43.9	79	17	9	11	5.1	Indian (D)	> 600	BNS	Normal
7	1973	11	17	-1.6	69.9	20	12	17	5.5	Indian (A)	~ 600	BS	Normal to SS
8	2003	07	15	-2.7	68.35	14	1.4	1.4	7.6	Indian (A)	> 600	AAPE	SS

Table 1 : Labels 1 to 7 : List of the 7 intraplate, oceanic earthquakes plotted by *McKenzie et al [2005]* that fall below the theoretical 600°C isotherm after the thermal conductivity is allowed to vary with temperature. Label 8 : hypocenter characteristics of the 2003/07/15 earthquake studied by *Antolik et al [2006]*. Age is age of crust at epicenter, as used in *McKenzie et al [2005]*, based on literature (see « Ref. » Column : BS = *Bergman and Solomon, [1984]*; BNS = *Bergman et al [1984]*; SW = *Stein and Wiens [1986]*; AAPE = *Antolik et al [2006]*). Corrected age (Age_corr) is based on *Müller et al [1997]* global age grid. T_{corr} is the temperature at focal depth computed by *McKenzie et al [2005]* using $k=K(T)$ after age correction. Focal depths and focal mechanisms were all determined using waveform modelling. « Normal with SS » stands for mainly normal focal mechanisms with a slight Strike Slip component.

year	mo	dd	Lat	Long	focal depth (km)
1994	03	14	-1.083	-23.929	17
1995	5	18	-0.95	-21.985	21
1992	12	26	-0.564	-19.318	22.5

Table 2 : List of the three earthquakes from the Romanche Transform Fault displayed on Figure 4. These earthquakes were relocated by *Abercrombie and Ekstrom [2003]* using waveform modelling.

Figures

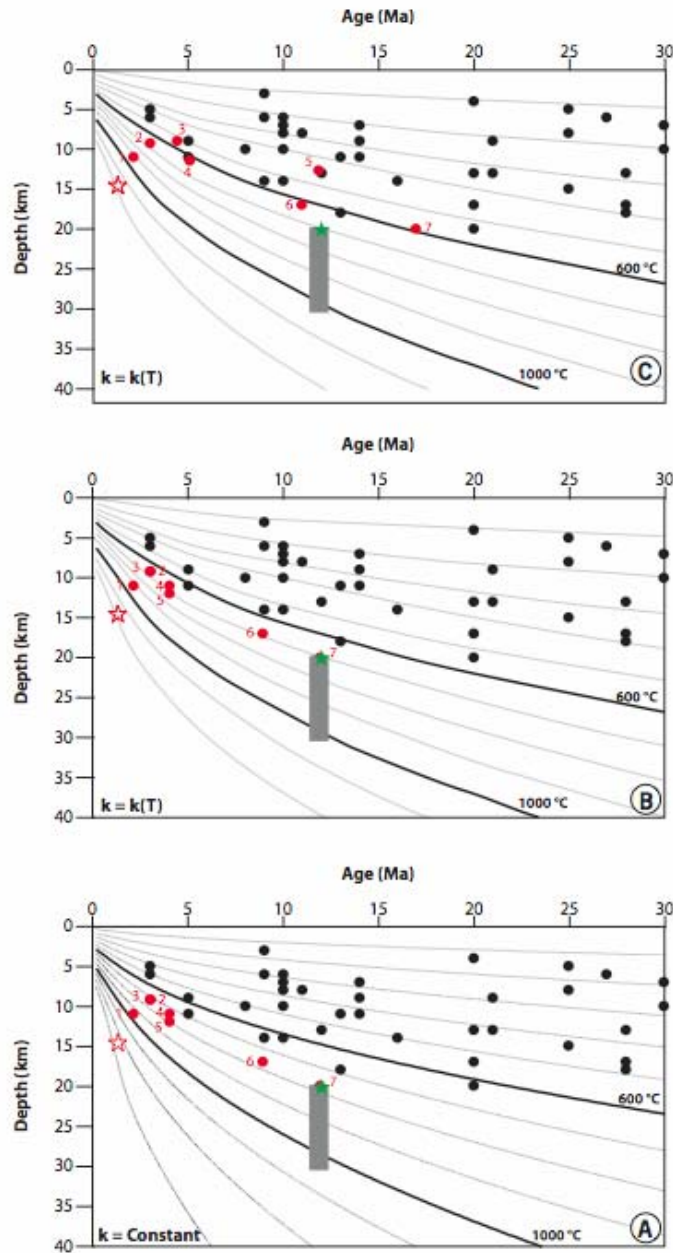


Figure 1 : After McKenzie *et al*, [2005]. Focal depth of non-near trench, intra-plate oceanic earthquakes displayed versus the age (< 30 Ma) of the crust at the epicenter. 1A) When the analytical solution of Parsons & Sclater [1977] is used to compute the theoretical mantle temperature contours ($k=\text{constant}$), a total of 12 intraplate earthquakes appear to occur at depths where the temperature exceeds 600°C. 1B) When the temperature dependence of the mantle thermal conductivity is taken into account ($k=k(T)$), as many as 7 events (red dots, numbered 1 to 7 and listed in Table 1) still lie below the 600°C isotherm. 1C) When the age of crust at the epicenter is corrected (Table 1), only 2 events lie convincingly below the

600°C isotherm. The hypocenter of the July, 15th, 2003 earthquake - listed as event 8 in Table 1 - is indicated by a green star. By inverting all available, good quality, teleseismic data, *Antolik et al [2006]* have shown that the major portion of the moment release occurred in two asperities, located between 100 and 200 km northeast of the hypocenter. The age and depth range of the strongest asperity are indicated by the gray rectangle [*Antolik et al, 2006*]. The 2003 earthquake is located below the 600°C isotherm, even if the temperature dependence of k is accounted for.

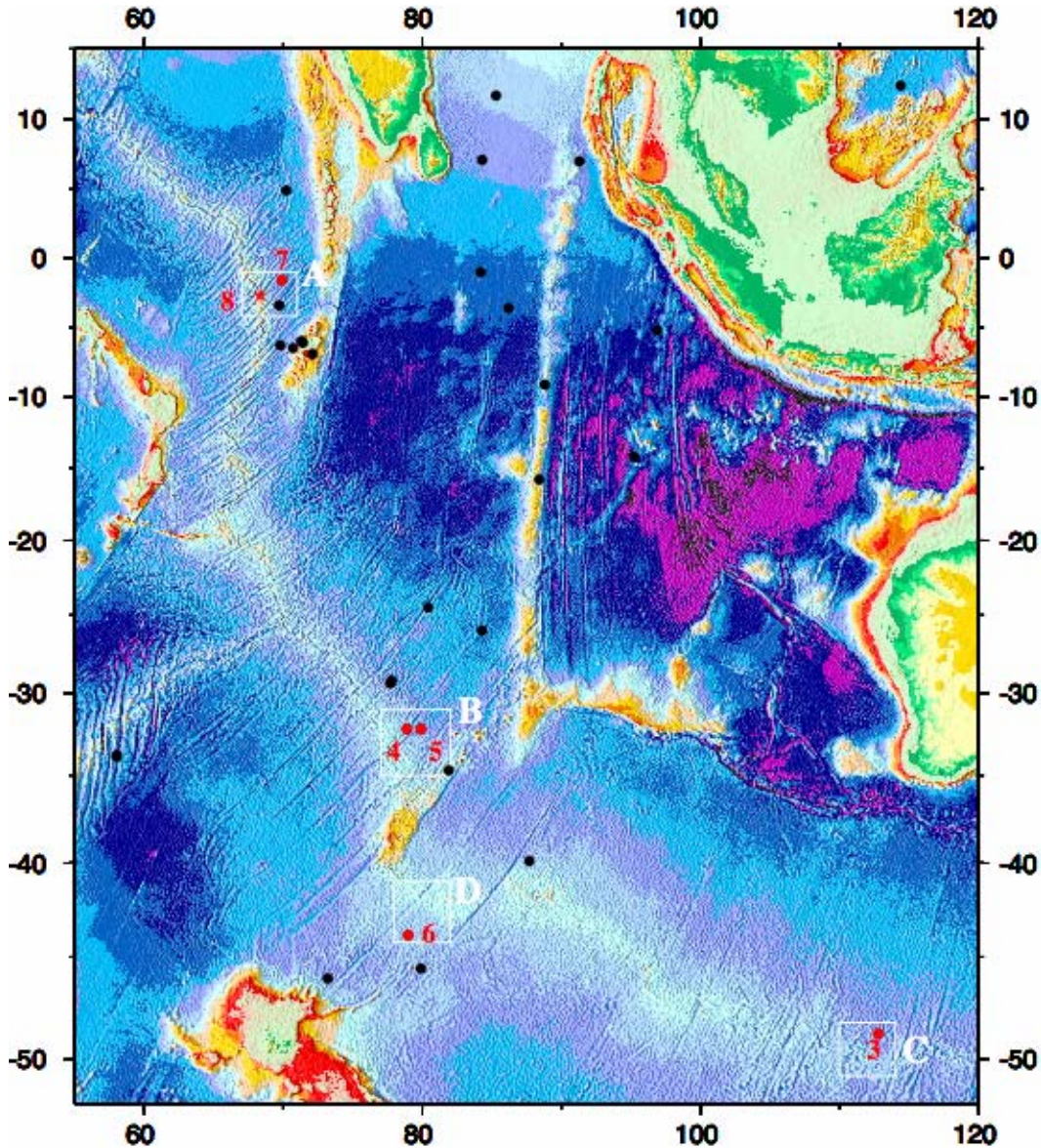


Figure 2 : Satellite derived topographic map of the Indian Ocean, after [*Smith and Sandwell, 1997*] with location of intraplate earthquakes listed in table 1. Black lines indicate ocean seafloor isochrons, after *Müller et al, [1997 and submitted]*. Labelled numbers indicate crustal age in Ma. Red dots indicate earthquakes whose focal depth fall below the 600°C isotherm after the temperature dependence of thermal conductivity has been taken into account. The remaining earthquakes used in *McKenzie et al [2005]* are represented by black dots. When crustal age at the epicenter is corrected, only earthquake number 4 and 6 fall below the 600°C isotherm but then only just (see Fig. 1a and Table 1). Earthquakes in insets A, B, C and D are detailed in Fig. 4. Red star indicates the epicenter location of the July, 15th, 2003, M_w 7.6 earthquake (listed as event 8 in Table 1 ; also see Fig. 5), after *Antolik et al. [2006]*.

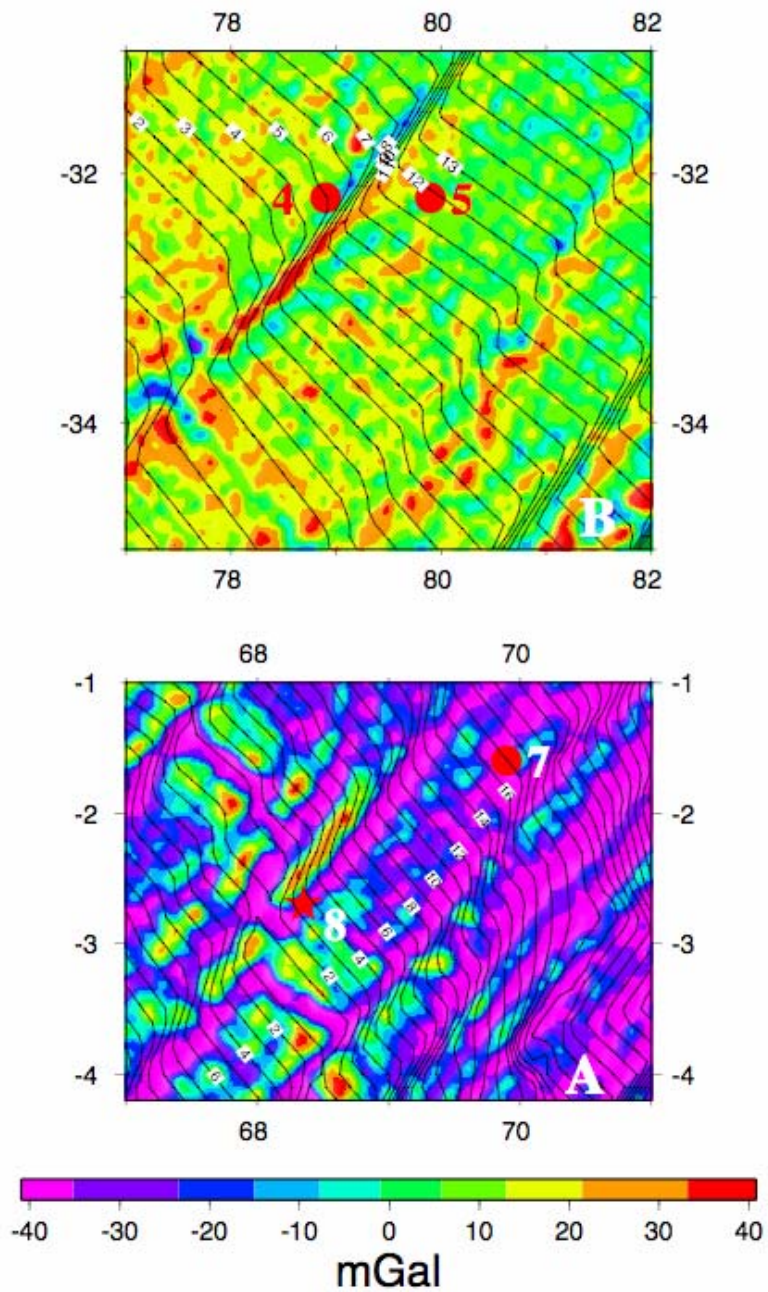


FIGURE 3 (A & B)

Figure 3 : Satellite derived gravity, after [Sandwell and Smith, 1994] for areas corresponding to insets A, B, C and D shown in Fig. 3. The red star in A indicates the epicenter location of the July, 15th, 2003, M_w 7.6 earthquake (see Fig. 5), after Antolik et al. [2006]. See caption of Figure 1 for the signification of the other symbols.

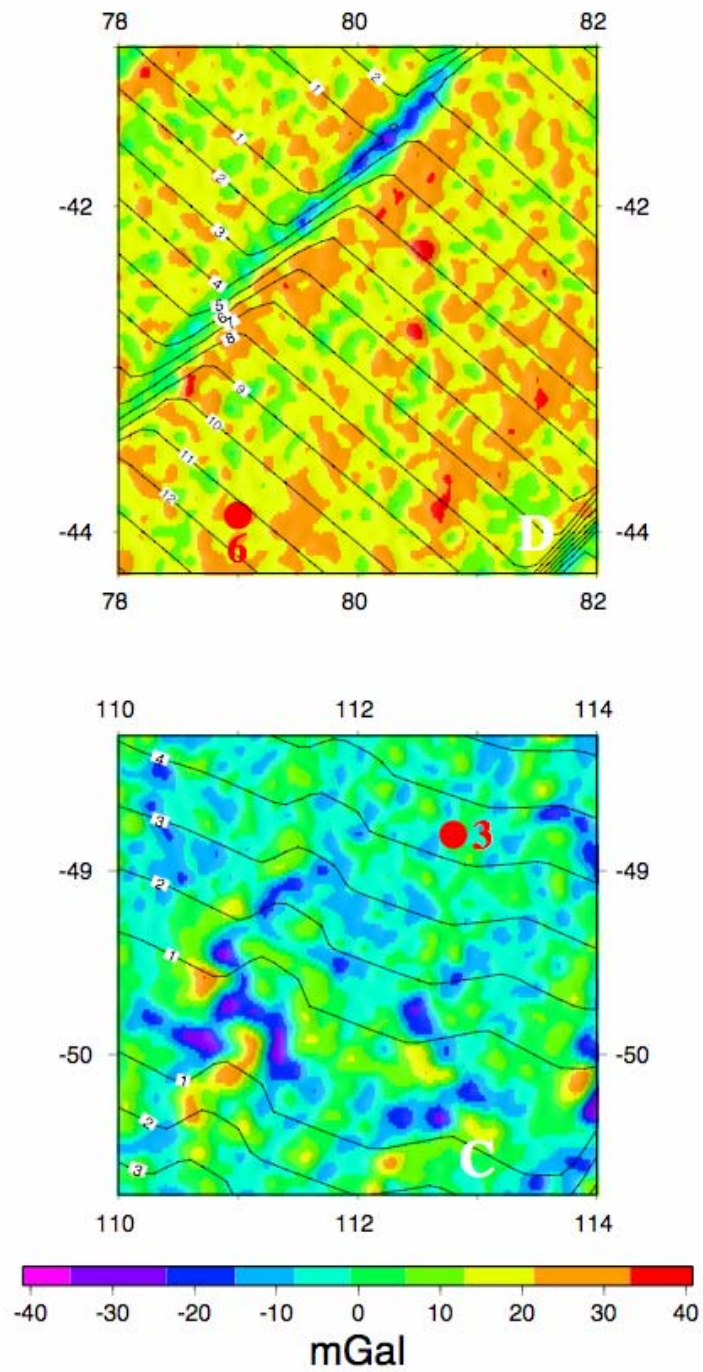


FIGURE 3 (C & D)

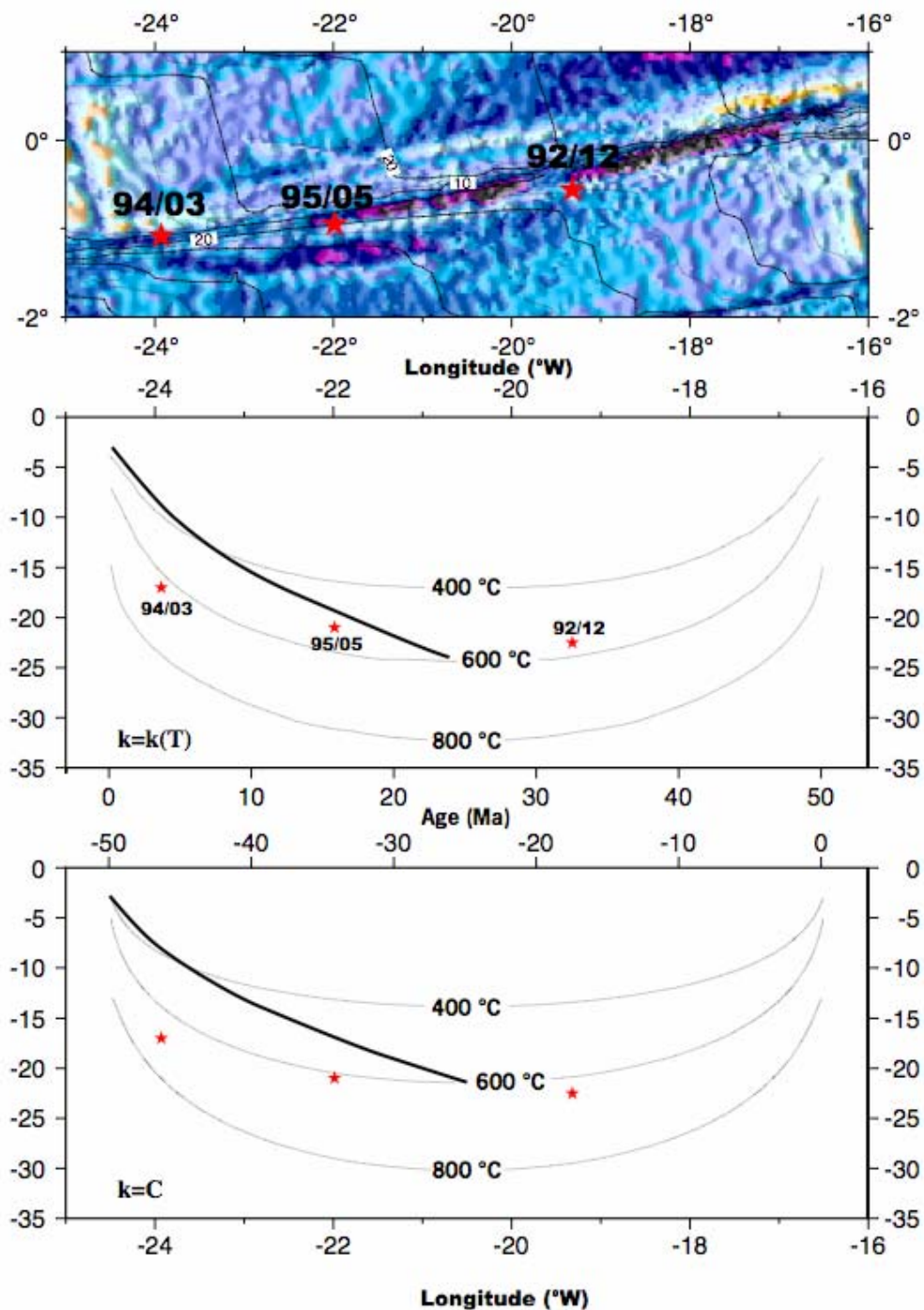


Figure 4 : The upper map represents the satellite derived bathymetric map of the Romanche FZ with the position (red stars) of the three earthquakes listed in Table 2. Earthquakes are identified by date (Year/Month). Isochrons are from Müller *et al* [2007, submitted]. The thin lines in the two lower figures

represent the theoretical mantle isotherms below the transform fault. Because of the age offset at the transform, the mantle temperature is averaged across the fault. Note the double scale for the x-axis : for longitude W (between -25° and -16°) and for age (between 0 and 50 Ma and between -50 Ma and 0). The thick line represents the 600°C isotherm between 0 and 25 Ma on adjacent crust undisturbed by the transform fault effect.