The role of pre-break-up heat flow on the thermal history of a transform margin

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Abstract: The paper focuses on the Romanche transform margin on the African side of the Equatorial Atlantic, and draws from thermomechanical numerical modelling and subsequent GIS-based thermal history grid processing.

Our modelling indicates that the early post-break-up thermal history of the transform margin is controlled by the cooling patterns of the adjacent pull-apart terrains, the pre-rift heat-flow regime, laterally passing seafloor spreading centres, and cooling of the newly accreted oceanic crust in two corridors located in front of and behind the spreading centres.

The pre-rift thermal regime controls the background heat flow on top of which the thermal transients develop. If it is cold, the transient anomalies are very distinct on this background. If it is warm, the transient anomalies tend to blend in with background heat flow much better. The most prominent anomalies are related to thinning in the pull-apart terrains located between transforms. They are up to three times wider than anomalies related to the laterally passing spreading centre, the anomaly of which becomes no wider than 20–25 km. Together with oceanic crust accreted in corridors in front of and behind the passing centre, its heat transfer into the transform margin tends to slow down the cooling of the syn-break-up anomalies developed in the pull-apart terrains by rifting.

The thermal history of transform margins (Fig. 1b) is fundamentally different from that of extensional margins (Fig. 1a). It has been described quantitatively only very recently (Rupke et al. 2010; Nemčok et al. 2012), although a discussion of:

- the existence of a laterally migrating heat source represented by a seafloor-spreading centre (Mascler et al. 1988, 1996; Basile et al. 1998; Bouillin et al. 1998; Clift et al. 1998; Clift & Lorenzo 1999; Bigot-Cormier et al. 2005; Antobreh et al. 2009) and
- transform-margin rheology being weakened by adjacent new and warm oceanic crust (Karner & Watts 1982; Holt & Stern 1991; Kooi et al. 1992)

took place for some time.

The aforementioned studies permit understanding of the heating role of the laterally passing spreading centre, using checkpoints located near the ocean–continent transition for quantification of the developing thermal anomaly. They also document the role of the distance of the spreading centre from the transform margin and the dip of the transform fault on the amplitude and life span of this anomaly. What is missing is the three-dimensional (3D) spatial and temporal distribution of the thermal perturbation in the whole transform margin to understand the importance of its role on the maturation history of involved source-rock horizons.

Solving this problem was the motivation for this study, which aims at understanding how the thermal perturbation is controlled by different pre-break-up heat-flow levels. The study draws on 3D finite-element modelling combined with subsequent GIS-based grid processing of the modelled thermal histories at checkpoints organized along three key transects. The results are constrained by thermal

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data from a few wells in the area. Based on a robust sensitivity study, this paper focuses on:

- the development of the thermal perturbation caused by a laterally passing spreading centre;
- the heat transmission mechanisms involved in the thermal perturbation;
- how far this perturbation transmits into the transform margin;
- how this thermal perturbation interacts with pre-existing regional positive thermal anomalies developed by rifting that culminate at the time of continental break-up.

Study area

Before we describe the study area, which was chosen to represent some of the transform-margin features needed for modelling, it is important to emphasize that the model input is not site specific, in an attempt to be generic.

Fig. 1. (a) Sketch of the orthogonal rift evolving into the ocean. The thermal history checkpoint is indicated by the small circle, highlighted by enclosing square in Stage I. Stages: I, orthogonal rifting of continental lithosphere; II, the continental break-up and development of the seafloor spreading centres parallel to the extensional margin; III, early drifting; IV, advanced drifting. (b) Sketch of the strike-slip fault zone with pull-apart terrains evolving into the ocean. The thermal history checkpoint is indicated by the small circle, highlighted by enclosing square in Stage I. Stages: I, rifting of continental lithosphere and the future Ghana Ridge situated at the dextral transform fault; II, the Ghana Ridge adjacent progressively to normal continental crust, then thinned continental crust and then oceanic crust; III, the Ghana Ridge adjacent to the spreading ridge; IV, the Ghana Ridge adjacent to oceanic crust and an inactive transform fault.

Study area showing locations of seafloor spreading ridges in time (Ma) on their relative way out from their contact with the broken-up continent. Rectangle, location of the numerical model, SP, St Paul transform; R, Romanche transform; GR, Ghana Ridge; WPT, Western pull-apart terrain; EPT, Eastern pull-apart terrain.
Models for the tectonic development of the Ghana Ridge (Fig. 2) are summarized in Figure 3a. This ridge has been chosen as the best representation of the knowledge of the ridge described in an extensive amount of literature (e.g. Mascle & Blarez 1987; Basile 1990; Pontoise et al. 1990; de Caprona 1992; Basile et al. 1993, 1998; Mascle et al. 1995, 1996, 1998; Benkhelil et al. 1998a, b; Clift & Lorenzo 1999; Bigot-Cormier et al. 2005). Although the models shown in Figure 3a have some minor differences, they agree in the major points.

These models document the Albian–Cenomanian dextral strike-slip-related deformation along the southern side of the Ghana Ridge, in a zone about 40 km wide (see Basile et al. 1998; Benkhelil et al. 1998b). North of this zone, a series of dextral strike-slip faults were identified. Together, the shear zone and the zone of dextral strike-slip faults represent the damage zone along the transform. These structures lie under a widespread unconformity. Sediments above the unconformity are undeformed by the shear zone and dextral strike-slip faults. They have been dated as Cenomanian–Turonian or younger.

The tectonic development models described in Figure 3a suggest that between the Cenomanian and Turonian, the Ghana Ridge was marked by an active transform margin, during the period between the onset of organized seafloor spreading between South America and Africa, and the passing of the spreading centre (Basile et al. 1998). Magnetic stripe anomaly-based maps of the oceanic crust age (e.g. Müller et al. 1993, 1997) indicate the development of initial spreading centres in two pull-apart terrains: first, one to the SW and, second, one to the NE of the transform bounding the future Ghana Ridge at 108 Ma (see Fig. 2 for location).

The approximate locations of the oceanic spreading centres and the oceanic crust just south of the Romanche and St Paul transform faults can be seen in Figure 2, based on the oceanic ages from Müller et al. (1997). The age data show that the first age contour along the margin was at 108 Ma (Albian), probably just after the final rifting between South America and Africa, or at the initiation of the development of the break-up unconformity. The 108 Ma contour is located just west of the transitional crust, south of the two transform faults.

The detailed age of the break-up of the continent cannot be shown based on the magnetic anomalies. This is because the magnetic anomalies that developed during the break-up coincide with the mid-Cretaceous magnetically quiet zone. South of the St Paul transform fault zone (Fig. 2), the continental crusts of Africa and South America ceased to be adjacent some time during 100–104 Ma (late Albian). The spreading centre laterally passed the African continental crust at about 96 Ma (Cenomanian). South of the Romanche transform fault zone, the continental crusts of Africa and South America cleared in about 94 Ma (Cenomanian), and the spreading centre passed the African crust at about 76 Ma (Campanian). These ages for the Romanche transform fault are similar to the ages mentioned in the ODP Leg 159 project-related publications, based on data such as cooling ages derived from the apatite fission tracks and the erosional unconformity penetrated by sites 959 and 960 (see Basile et al. 1998; Bouillin et al. 1998; Clift et al. 1998; Clift & Lorenzo 1999; Bigot-Cormier et al. 2005). The primary transcurrent deformation in the Ghana Ridge was active in the Albian, about the time between the first drifting along the margin and the time when the African and South American crusts were no longer adjacent.

**Methods**

Finite-element techniques were used to gain quantitative insights into the spatial and temporal distribution of lithospheric temperatures, and the surface heat flow of the transform margin during the lateral migration of the seafloor-spreading centre along it. The model geometry is a 3D representation of the transform fault and the adjacent upper lithospheric blocks (Fig. 3b). Different thermophysical properties were assigned to the various lithologies involved. Three different pre-break-up heat-flow scenarios, including cold, medium and hot heat-flow regimes, were studied. The perturbation of the temperature field of the transform margin is implemented by a prescribed temperature anomaly of the travelling spreading centre. The centre changes its position with time according to the migration velocity of the spreading centre. The resulting time – surface heat-flow evolution at selected pseudo-well locations of the transform margin are recorded. They can be used as input for subsequent maturity modelling studies of available well data.

Modelling is based on the finite-element software ANSYS® (Ansys Inc., Houston, TX, USA). It uses a Lagrangian formulation to calculate the 3D temperature field and its changes with time. The governing equation for 3D heat transport by conduction and advection (e.g. Turcotte & Schubert 2002) is:

\[
\rho c \left( \frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} \right) = \kappa \frac{\partial^2 T}{\partial x^2} + \kappa \frac{\partial^2 T}{\partial y^2} + \kappa \frac{\partial^2 T}{\partial z^2} + A
\]
where $x$, $y$, and $z$ are the coordinate directions, $v_x$, $v_y$, and $v_z$ are the displacements in coordinate directions, $T$ is the temperature, $t$ is the time, $\rho$ is the density, $c$ is the specific heat, $\kappa$ is the thermal diffusivity expressed as $\kappa = k/\rho c$, $k$ is the thermal conductivity, and $A$ is the radiogenic heat production.

Model dimensions are $850 \times 200 \times 40$ km, centred on the transform fault. The model uses eight-node isotropic and hexaeder-shaped elements to represent the individual lithological layers. The transform fault separating the two lithospheric domains is described by contact elements. They have a thermal conductivity equivalent to the neighbouring rocks. In total, the model comprises about 92 000 volume and contact elements.

Four different lithologies, including the upper and lower continental crusts, oceanic crust, and mantle lithosphere, were considered. Their specific
Thermophysical properties are temperature-dependent. They include density, thermal conductivity, specific heat and radiogenic heat production, the starting values of which at surface temperatures are summarized in Table 1. Modelling takes into account that density and thermal conductivity are temperature-dependent. The corresponding values, including their temperature-dependent variations, are taken from Clauser & Huenges (1995).

Within the range of crustal temperatures, thermal conductivity of most rocks decreases with temperature. The exact relationship depends mainly on mineral composition, porosity and pore fill (e.g. Clauser & Huenges 1995). Zoth & Hänel (1988) proposed that thermal conductivity, $k(T)$, is a function of temperature, $T$, according to:

$$k(T) = \frac{A + B}{350 + T}$$

where $A$ and $B$ are empirical constants depending on the rock type. Their data for felsic ($A = 0.64$, $B = 807$) and mafic ($A = 1.18$, $B = 474$) rocks are used to represent the temperature-dependent thermal conductivities in the upper and lower crust, respectively. For the mantle lithosphere, the relationship is more complex and shows increasing thermal conductivities at typical upper-mantle temperatures (see also Clauser & Huenges 1995).

A graphical representation of the temperature-dependent thermal conductivities used for the three main lithospheric units is given in Figure 3c.

The temperature-dependence of density, $\rho(T)$, is represented by the following equation:

$$\rho(T) = \frac{\rho(T_0)}{(1 + \alpha(T - T_0))}$$

where $\rho(T_0)$ is the density at the reference temperature $T_0 = 273 \text{ K}$ and $\alpha = 3 \times 10^{-5} \text{ K}^{-1}$ is the volumetric thermal expansion coefficient.

Thermal boundary conditions comprise a constant temperature of $10^8 \text{ C}$ at the Earth’s surface. No lateral heat flow is allowed through the vertical sides of the model. At the base of the model, different basal heat flows were assigned in the cold, medium and hot initial heat-flow scenarios. In combination with radiogenic heat in the continental

Table 1. Thermophysical properties used for modelling

|                     | Density* ($\text{kg m}^{-3}$) | Thermal conductivity* ($\text{W m}^{-1} \text{ K}^{-1}$) | Specific heat ($\text{J g}^{-1} \text{ K}^{-1}$) | Radiogenic heat production ($\mu \text{W m}^{-3}$) |
|---------------------|-------------------------------|------------------------------------------------------|---------------------------------|---------------------------------------------|
| Upper continental crust | 2670                          | 2.95                                                 | 1300                            | 1                                           |
| Lower continental crust  | 3000                          | 2.53                                                 | 1300                            | 0.5                                         |
| Oceanic crust          | 3200                          | 3.14                                                 | 1300                            | –                                           |
| Mantle lithosphere     | 3400                          | 4.76                                                 | 1300                            | –                                           |

*Indicates parameters that vary with temperature.

Listed values are given at $0^\circ \text{ C}$. 

Fig. 3. (Continued) (b) Ghana Ridge model set-up. (c) The temperature-dependent thermal conductivities used for modelling.
crust, they result in three different equilibrium surface-heat-flow scenarios studied (Table 2).

The temperature anomaly at the spreading-ridge axis due to the rise of magma is represented by setting the corresponding element nodes to a temperature of 1350°C. The width of the prescribed anomaly is about 10 km. The described temperature constraint remains the same as it moves through the model at an average ridge migration velocity of 21 mm a⁻¹ between 108 and 76 Ma. After 76 Ma, the spreading ridge is outside the model domain and only the thermal equilibration of the anomaly induced by laterally clearing ridge is considered. The temperature field at the beginning of the calculations (i.e. at 108 Ma) already represents a transient temperature field in relation to the previous continental break-up in the western and eastern pull-apart terrains (Fig. 2).

Modelling results along predefined pseudo-wells through the 3D numerical model were exported as spreadsheets recording surface heat-flow values with time and imported into an ArcGIS project. These 25 pseudo-well locations were systematically positioned along and across the transform segment of the continental margin (Fig. 4). Altogether three transects were devised, one longitudinal and two transversal ones, which would help in understanding the thermal history of the transform margin.

The Longitudinal transect is located landwards of the transform fault zone. It extends from the boundary between the transform margin and the pull-apart margin segments in the NE to the boundary between the transform margin and the pull-apart margin segments in the SW (see Fig. 2 for the location of individual segments). The length of section is 421 km, along which nine pseudo-wells are located. Each pseudo-well is separated by approximately 42 km from the next, with the exception of the crossing between the Longitudinal and Western transversal transects.

The Eastern transversal transect is located at the eastern end of the Longitudinal transect. It lies at

| Scenario | Basal heat flow (mW m⁻²) | Equilibrium surface heat flow (mW m⁻²) |
|----------|--------------------------|--------------------------------------|
| Cold     | 30                       | 52.5                                 |
| Medium   | 40                       | 62.5                                 |
| Hot      | 50                       | 72.5                                 |

Fig. 4. Location map of three studied transects with individual pseudo-wells.
the boundary between the transform and the pull-apart margin segments. It is perpendicular to the Longitudinal transect. It contains eight pseudo-wells lined up along it in 5 km intervals with a total distance of 35 km from the transform fault zone that touches both the Eastern and Western transversal transects in the south. In comparison to the Western transversal transect, the well coverage landwards is 5 km less deep than that of the Western transect. This is because the boundary of the oceanic and continental crusts and the Longitudinal transect are not exactly parallel owing to the slight curvature of the strike-slip segment of the break-up trajectory (see Fig. 2).

The Western transversal transect is located as crossing the Longitudinal transect in the place where the spreading ridge was passing at about 88 Ma. It is perpendicular to the Longitudinal transect. Similar to the Eastern transversal transect, eight pseudo-wells are positioned along this transect. The total length of the transect is 35 km.

Heat-flow contour maps were created in an ArcGIS project by filling the space between the two transversal transects with a series of parallel transversal profiles with pseudo-wells. They provided the necessary grid of data for contouring. On top of pseudo-wells of designed transects, this grid includes 60 extra pseudo-wells plotted at equidistant locations from each other. Through linear interpolation based on existing heat-flow values from numerically modelled pseudo-wells, heat-flow values were assigned to each extra pseudo-well for 1 Ma intervals from 108 Ma until Present.

In the case of designed transects, all heat-flow values from the three modelled initial heat-flow scenarios were plotted on line graphs. Two specific ages of 80 and 90 Ma were chosen from them as representative snapshots that are represented as ArcGIS project maps in this paper. Analysis was performed on grid values representing these particular ages in all three scenarios using the Kriging geostatistical interpolation technique. The technique considers both the distance and the degree of variation between known data points when estimating values in unknown areas.

Results

Maps

Surface heat-flow regimes modelled for ages of 90 and 80 Ma are shown in maps. They cover the portion of the Ghana Ridge that experienced the seafloor-spreading centre passage roughly between 108 and 82 Ma (Figs 5–10). Figures 5–7 document that calculated heat-flow regimes vary considerably between cold, medium and hot scenarios at 90 Ma. The colder the initial heat flow, the colder the NE corner of the Ghana Ridge. The warmer the initial heat flow, the warmer the SW corner of the Ghana Ridge. The differences between the hot and medium scenarios, and between the medium and cold scenarios in the NE corner are 3.8 and 4.8 mW m\(^{-2}\), respectively, compared to differences in pre-break-up heat flows of 10 and 10 mW m\(^{-2}\), respectively. The same comparison for the SW corner allows one to compare differences of 2.9 and 5.9 mW m\(^{-2}\) with those of 10 and 10 mW m\(^{-2}\).

The heat-flow regimes calculated for cold, medium and hot scenarios at 80 Ma also show a considerable variation (Figs 8–10). These regimes show an apparently illogical relationship, where the NE corner for medium and hot initial heat flow regimes at 80 Ma is warmer than that at 90 Ma, while the situation is completely the opposite for the cold scenario (Table 3). Conversely, the SW corner for medium and hot initial heat-flow regimes at 80 Ma is colder than that at 90 Ma, while it is exactly the opposite for the cold scenario.

Transects

The thermal history of all pseudo-wells along the Longitudinal transect (see Fig. 4 for the location) can be characterized by the occurrence of two heat-flow maxima (Fig. 11a–c; see also Table 4). The first one, which is warmer, was developed prior to 108 Ma. The ages of the second one, which is not as warm, range from 100 to 64 Ma, depending on the pseudo-well in a NE–SW direction.

Pseudo-wells LT-9 and LT-8 have the highest values of the first maximum. Remaining pseudo-wells LT-1–LT-7 recorded the same first thermal maximum, but it is much less pronounced. A comparison of the scenarios shown in Figure 11a–c indicates that the amplitude of the first thermal maximum is similar in all cases of initial heat-flow scenarios.

With respect to the second thermal maximum, Figure 11a–c shows that the more distant the pseudo-well is from the NE end of the transect, the younger the age of the second thermal peak. Furthermore, Figure 11a–c also documents that the further the pseudo-well lies from the NE end of the transect, the warmer the second maximum. This phenomenon can be observed in all three modelled scenarios, although the peak values of the second maximum become larger with warmer initial heat flow. If we use the peak values recorded by pseudo-well LT-9 as an example, the cold scenario reaches a peak value of 92 mW m\(^{-2}\), while the medium and hot scenarios reach 97 and 103 mW m\(^{-2}\), respectively.

The Eastern transversal transect is located in the NE part of the studied transform-margin segment.
Fig. 5. Heat-flow regime of the Ghana Ridge at 90 Ma calculated for the cold pre-break-up heat-flow scenario.

Fig. 6. Heat-flow regime of the Ghana Ridge at 90 Ma calculated for the medium pre-break-up heat-flow scenario.
Fig. 7. Heat-flow regime of the Ghana Ridge at 90 Ma calculated for the hot pre-break-up heat-flow scenario.

Fig. 8. Heat-flow regime of the Ghana Ridge at 80 Ma calculated for the cold pre-break-up heat-flow scenario.
Fig. 9. Heat-flow regime of the Ghana Ridge at 80 Ma calculated for the medium pre-break-up heat-flow scenario.

Fig. 10. Heat-flow regime of the Ghana Ridge at 80 Ma calculated for the hot pre-break-up heat-flow scenario.
(Fig. 4). It contains eight pseudo-wells arranged in a linear fashion. They are spaced at 5 km intervals up to a total distance of 35 km landwards from the transform fault (Fig. 4).

Thermal histories recorded by most of the Eastern transversal transect contain a single heat-flow maximum (Fig. 12a–c). Only the northernmost pseudo-wells also contain a subtle remnant of an earlier thermal maximum.

An interesting comparison of the Eastern and Western transversal transects is provided by Table 5. It shows that the maximum value of the second thermal peak is more-or-less the same in the most oceanwards located pseudo-wells of both the Eastern and Western transects. This value oscillates between 210 and 216 mW m$^{-2}$. Conversely, the remnant heat flow, represented by the base of the second thermal peak in Figure 12a–c, changes from a range of 62–71 mW m$^{-2}$, representing the Eastern transect, to 76–87 mW m$^{-2}$, representing the Western transect (Table 5).

The Western tranversal transect is located in the SW part of the studied transform-margin segment (Fig. 4). It contains eight pseudo-wells. Their locations are set at 5 km intervals, up to a total distance of 35 km from the transform fault into the continent. The southern end of the transect met the laterally clearing spreading centre at 88 Ma.

Thermal histories of the pseudo-wells (Fig. 13a–c) indicate that the heat flow started to increase prior to the spreading centre passing the southern end of the Western transect. Furthermore, the general trend here is a relatively fast decline in heat flow from 108 Ma until around 100 Ma, at which time the spreading centre began migrating towards the SW.

**Interpretation**

**Maps**

Figures 5–7, which are described in the Results section, indicate that, because of the heating effect of the spreading centre and heating effect of the oceanic crust surrounding it, the differences between heat-flow values in the NE and SW corners of the Ghana Ridge for 90 Ma are not a linear function of initial heat-flow values. While the differences between initial heat flows representing cold, medium and hot scenarios are set to be 10 mW m$^{-2}$, the differences between calculated corner values between neighbouring scenarios increase towards colder scenarios. This indicates that understanding the role of various heat-transfer mechanisms on the thermal history of the Ghana Ridge would require detailed analysis of thermal histories recorded by pseudo-wells belonging to the three studied transects (see Fig. 4).

While the 90 Ma snapshot maps (Figs 5–7) represent the heat-flow regime of the Ghana Ridge segment, which is still in contact with spreading centre in its western portion, the 80 Ma snapshot maps (Figs 8–10) document the regime of the Ghana Ridge segment that is no longer in contact with the spreading centre.

The thermal consequence of this difference can be observed when one compares all three scenario-related thermal regimes calculated for 90 Ma (Figs 5–7) with those calculated for 80 Ma (Figs 8–10). The correlation is shown in Table 3. One can observe fast cooling of the portion of the Ghana Ridge close to the passing-by spreading centre in the case of warmer initial heat flows and slow cooling of the portion of the Ghana Ridge distant from the passing-by spreading centre in the case of warmer initial heat flows. This apparently indicates that there are probably two different mechanisms transferring heat from the passing-by spreading centre into the transform margin. On top of these, there are both the transfer of heat from the accreted oceanic crust and the dissipation of the rift-related thermal anomalies. Differentiating all four mechanisms would require a detailed interpretation of thermal histories along the transects, which are recorded by their pseudo-wells.

**Transects**

The Longitudinal transect was designed to record the spreading-ridge-driven heat-flow perturbation
Fig. 11. (a) Surface heat flow with time from 108 Ma to 0 Ma recorded by pseudo-wells of the Longitudinal transect, calculated for the cold initial heat-flow scenario. Pseudo-wells LT-1–LT-9 are arranged from NE to SW in the direction of the passing spreading centre. (b) Surface heat flow with time from 108 Ma to 0 Ma recorded by pseudo-wells of the Longitudinal transect, calculated for the medium initial heat-flow scenario. See (a) for explanations.
migrating from the NE to the SW. The migrating perturbation was recorded in the thermal history of nine pseudo-wells (LT-1–LT-9), arranged from NE to SW. Each pseudo-well record contains two heat-flow maxima described in the Results section (Fig. 11a–c). The first one, which is warmer, was developed prior to 108 Ma. The ages of the second one, which is not as warm, range from 100 to 64 Ma, depending on the pseudo-well location in a NE–SW direction.

A development of the first, warmer, thermal maximum is attributed to the Barremian–early/middle

![Fig. 11. (Continued) (c) Surface heat flow with time from 108 Ma to 0 Ma recorded by pseudo-wells of the Longitudinal transect, calculated for the hot initial heat-flow scenario. See (a) for explanations.](image)

#### Table 4. Characteristics of heat-flow peaks in each thermal scenario per pseudo-well along the Longitudinal transect

| Pseudo-well | Difference between remnant and peak heat flow* (mW m⁻²) | Duration of peak heat flow† (Ma) | Time of the spreading-centre passage (Ma) |
|-------------|----------------------------------------------------------|---------------------------------|----------------------------------------|
|             | Cold | Medium | Hot     | Cold | Medium | Hot     |                          |                          |
| LT-1        | 3.46 | 3.65   | 3.86    | 8    | 7      | 8       | c. 105                  |
| LT-2        | 3.67 | 4.12   | 4.53    | 9    | 9      | 10      | c. 104                  |
| LT-3        | 3.57 | 4.20   | 4.81    | 9    | 10     | 10      | 101.5                   |
| LT-4        | 3.36 | 4.04   | 4.82    | 9    | 10     | 11      | c. 99                   |
| LT-5        | 3.10 | 3.80   | 4.64    | 8    | 11     | 12      | c. 96                   |
| LT-6        | 2.75 | 3.38   | 4.18    | 8    | 9      | 12      | 93.5                    |
| LT-7        | 2.20 | 2.71   | 3.33    | 7    | 8      | 10      | 91                      |
| LT-8        | 1.16 | 1.42   | 1.77    | 5    | 6      | 7       | 85.5                    |
| LT-9        | 1.57 | 1.79   | 2.09    | 5    | 6      | 7       | 83                      |

*The difference between the background heat flow and the peak heat flow is the heat-flow increase measured from the lowest value before the anomaly and the peak value.

†The duration of the peak heat was measured as the time difference between the lowest value before the anomaly and the peak value of the anomaly.
Fig. 12. (a) Surface heat flow with time from 108 Ma to 0 Ma recorded by pseudo-wells of the Eastern transversal transect, calculated for the cold initial heat-flow scenario. Pseudo-wells ET-1–ET-8 are arranged from south to north in a direction landwards from the transform fault. (b) Surface heat flow with time from 108 Ma to 0 Ma recorded by pseudo-wells of the Eastern transversal transect, calculated for the medium initial heat-flow scenario. See (a) for explanations.
Albian rifting in the two pull-apart terrains in the study area (see Fig. 2 for the location) that reached the late Albian break-up (Nemčok et al. 2012). This is indicated by the fact that pseudo-wells LT-9 and LT-8, which are located very close to the Western pull-apart terrain, have the highest values of the first maximum (compare Fig. 11a–c). These two pseudo-wells are located on the thinnest continental crust of all pseudo-wells of the Longitudinal transect. Unlike the other pseudo-wells, they are not neighbours to the relatively thick continental crust. Indeed, on the contrary, they are neighbours to the considerably thinned crust of the Western pull-apart terrain. A comparison of Figure 11a–c indicates that the first thermal maximum here is not considerably modified by the pre-break-up thermal regime.

With regard to the second thermal maximum, Figure 11a–c shows that the further the pseudo-wells are from the continental break-up in the Eastern pull-apart terrain, where the lateral travel of the passing-by spreading centre started, the younger the age of the second thermal peak. This indicates that the control of the second thermal perturbation is the heat transfer from the passing-by spreading centre into the transform margin.

The second maximum becomes warmer in the pseudo-wells in a NE–SW direction. If the local thermal maximum is ignored for the moment, this indicates that the remnant heat-flow regime for the

Table 5. Comparison of the characteristics of the second thermal peak calculated for all three pre-break-up heat-flow regimes between the Eastern and Western transversal transects

| Scenario | Eastern, second peak – top | Eastern, second peak – base | Eastern, first peak, maximum | Western, second peak – top | Western, second peak – base | Western, first peak, maximum |
|----------|----------------------------|----------------------------|----------------------------|---------------------------|---------------------------|-----------------------------|
| Cold     | 212                        | 62                         | 210                        | 210                       | 76                        | 132                         |
| Medium   | 214                        | 67                         | 211                        | 211                       | 82                        | 133                         |
| Hot      | 216                        | 71                         | 213                        | 213                       | 87                        | 135                         |

*Surface heat-flow values are in mW m$^{-2}$, and compared characteristics are the values at the top and base of the thermal perturbation. Also compared are the highest values of the first thermal peak recorded by the pseudo-well located most landwards of the transform fault.
Fig. 13. (a) Surface heat flow with time from 108 Ma to 0 Ma recorded by pseudo-wells of the Western transversal transect, calculated for the cold initial heat-flow scenario. Pseudo-wells WT-1–WT-8 are arranged from south to north in a direction landwards from the transform fault. (b) Surface heat flow with time from 108 Ma to 0 Ma recorded by pseudo-wells of the Western transversal transect, calculated for the medium initial heat-flow scenario. See (a) for explanations.
last pseudo-wells affected by the SW-travelling spreading centre is the warmest. This suggests that the pseudo-wells of the Longitudinal transect must have experienced the heat transfer from the corridor with newly accreted oceanic crust prior to the passage of the spreading centre. They also must have experienced the heating from the migrating spreading centre prior to its passing the respective pseudo-well, in a way similar to an iron plate warming up all over when touched by a hot subject at only one of its ends. This situation does not seem to change between the three initial heat-flow scenarios, only the peak values of the second maximum become larger with warmer initial heat flow. However, the differences between these peak values do not exactly match the differences between initial heat-flow regimes of the three modelled scenarios. This indicates a complex heat transfer in their control.

Figure 11a–c also indicates that there is a distinct time lag between the passage of the spreading centre past the respective pseudo-well and the development of the second thermal maximum. For example, in the case of pseudo-well LT-6, the spreading centre passed at around 91 Ma. The time lag between this passage and the development of the heat-flow peak is 14 Ma. This lag is the time it takes to transfer the heat from the passing spreading centre to the pseudo-well, which lies landwards of the continent–oceanic crust boundary, via horizontal heat transfer. For pseudo-well LT-9, the spreading centre passage takes place at approximately 83 Ma, whilst the anomaly peak occurs at 73 Ma (Table 4).

At this point, it would be useful to differentiate the background heat flow from the rifting-related transient heat flow. The background heat flow can be viewed as the thermal floor across the area, which is thermally equilibrated and served as a basis for the respective finite-element model scenario. The rifting-related transient heat flow is the heat flow produced by the first, rift-related, thermal anomaly associated with pull-apart terrains developing towards the continental break-up. Other transients are added due to the warming of the transform margin by the accreted oceanic crust and the long-range and long-lasting heat-transfer effects of the passing spreading centre. All of these transient heat flows mixed together control the magnitude of the second thermal maximum. Its occurrence time period is controlled by the passage of the spreading centre.

Both transversal transects record the landwards propagation history of the thermal perturbation driven by the passing spreading centre, from south to north, in a thermal history of eight pseudo-wells labelled from south to north.
Apart from the local and short-term heating effect of the passing spreading centre, the transversal transects help in the understanding of:

- the long-term heating effect of the laterally clearing spreading centre on the entire transform margin;
- the heating provided by oceanic crust juxtaposed against the continental crust of the transform margin along the transform fault zone;
- the effect of the initial heat-flow regime on the history of transform-margin cooling from the syn-break-up thermal perturbation.

In comparison to the Western transversal transect, the Eastern transversal transect is more distant from its closest pull-apart terrain, the Eastern pull-apart terrain, which made it to break-up by thinning (compare Figs 1b, 2 & 4). The portion of the transform margin, which the Eastern transversal transect represents, was juxtaposed against oceanic crust for a longer time than that represented by the Western transversal transect. The laterally clearing spreading centre passed the southern end of the Eastern transversal transect around 106 Ma, which is about 18 Ma prior to the spreading-centre passage of the southern end of the Western transversal transect.

Pseudo-wells of the Eastern transversal transect contain single important heat-flow maximum. It is represented by the second thermal peak described in the text on the Longitudinal transect as caused by the heat transfer from the passing-by spreading centre (Fig. 12a–c). For the moment, we can focus our attention on pseudo-wells, which are located in most landward locations. Their thermal history is not overwhelmed by the local-scale and short-term heating effect of the passing-by spreading centre, and in these cases we can recognize a subtle remnant of the first, rifting-related, thermal peak, which was also described earlier in the case of the Longitudinal transect as a separate heat-flow maximum.

The Eastern and Western transversal transects (Table 5) show that the maximum value of the second thermal peak is roughly the same in the more oceanwards-located pseudo-wells (also compare Figs 12 & 13). They also show that the remnant heat flow, represented by the base of the second thermal peak (compare Figs 12a–c & 13a–c), is about 14–16 mW m\(^{-2}\) higher in the Western transect (Table 5).

The tops and bases of the second thermal peak indicate that the local and short-term effect of the passing spreading-centre thermal anomaly is very prominent in a relatively narrow zone near the transform fault. This local and extreme heating greatly exceeds any other heating mechanisms in this zone. This explains the absence of observable effects from other heating mechanisms on the peak value of this perturbation in this narrow zone. It is the base of the second thermal peak, representing the remnant heat flow, which indicates the effects of:

- the pre-break-up background heat flow, which represents the equilibrium heat-flow regime before the development of any thermal perturbations described in the text;
- the transient heat flow associated with crustal thinning in the Western and Eastern pull-apart terrains;
- the length of time of heating provided by the juxtaposed oceanic crust;
- the length of time during which the transform margin was being heated via its contact with the laterally clearing spreading centre.

The effect of the passing spreading centre, during the time when it is either not yet or already not in contact with the southern end of the Eastern transversal profile, can be observed using the following analysis. The thermal history recorded by pseudo-well ET-1 shows a rapid heat-flow increase for about 1 Ma after the passage of the spreading ridge (Fig. 12a–c). This indicates that the lateral heat transfer from the passing spreading centre takes some time to penetrate into the transform margin. However, this penetration right at the boundary with the transform fault takes place from the first contact of the spreading centre with the transform margin up until the time when the spreading centre clears the transform margin completely. This time interval represents the period of overall heating of the transform margin by the migrating spreading centre regardless of its location at a specific time. Furthermore, while the local heating by the migrating centre stops when the centre leaves a certain location, the dissipation of the thermal anomaly towards the continental interior lasts for some time after the spreading ridge has cleared.

Figure 12a–c also indicates that the distance of the pseudo-well from the transform fault affects the lateral heat transfer into this pseudo-well. For example, pseudo-well ET-1 registers the highest heat-flow peak of all the transect pseudo-wells, which is very similar to the heat-flow peak of WT-1 in the Western transversal transect. This highest peak developed earlier than that of the less prominent peaks in more landwards-located pseudo-wells of the Eastern transversal transect. The travel time needed for the thermal perturbation to reach pseudo-wells further away from the transform fault is called the time lag. Table 6 shows such thermal anomaly time lags for several pseudo-wells. They are calculated as the difference between the time of the passage of the spreading centre and
the development of the peak thermal perturbation in a particular pseudo-well.

When compared with the Western transversal transect, the time lag experienced by the first four pseudo-wells of the Eastern transect from the transform fault, representing a 20 km-wide zone, is shorter. Pseudo-well ET-1 records a time lag of 5 Ma (Table 6). This lag then progressively increases by 1 Ma landwards for the other following pseudo-wells between ET-1 and ET-4. With respect to the time lag experienced by those first four pseudo-wells, it does not seem to have been influenced by the initial heat-flow regime. However, from pseudo-well ET-4 further landwards, the time lag does start to become considerably influenced by the initial heat-flow regime. While pseudo-well ET-5 shows a time lag of 11 Ma for the cold scenario, it has a time lag of 29 Ma for the hot scenario. As discussed later, the more distant pseudo-wells of the Western transversal transect do not record such an influence, and their time-lag distribution continues for more distant wells in a fashion exhibited by the pseudo-wells proximal to the transform fault. Thus, between the cold and hot scenarios, the time lag increases enormously in pseudo-well ET-5. The lateral heat transfer in the cold scenario appears to be creeping slowly over a long period of time; however, with a background heat-flow increase of 10 mW m\(^2\), the duration is doubled.

The heat-flow evolution from 108 Ma until Present in the hot scenario (Fig. 12c) includes a slow warming for the pseudo-wells located at a distance of 20–35 km from the transform fault, once the spreading centre has passed. The increase in the local heat-flow regime is minor, expressed only in decimal values of mW m\(^{-2}\). This is the reason why they should be considered to lie outside the influence zone of the transform-margin heating controlled by the laterally passing spreading centre. In the cold scenario (Fig. 12a), a constant decrease in heat-flow regime is observed in the thermal histories of pseudo-wells located more than 25–35 km from the transform fault. This decrease is caused by thermal equilibration following the passage of the spreading centre.

The Western transversal transect was designed to help observe the effect of the corridor of the accreted oceanic crust in front of the laterally passing spreading centre. This is because this effect at this transect took place for much longer than that at the Eastern transversal transect; that is, its effect should be enhanced. Indeed, the thermal histories of the pseudo-wells of the Western transversal transect (Fig. 13a–c) indicate that the heat flow started to increase prior to the spreading centre passing by. Therefore, Figure 13a–c documents that both the warming by the adjacent oceanic crust and the lateral heat-flow migration in front of the migrating spreading centre pre-heated the crust of the transform margin. The increase is most pronounced in the thermal history of pseudo-well WT-1, which is closest to the transform fault.

Figure 13a–c also shows that there is a distinct time lag in the thermal anomaly build-up after the passage of the spreading centre. Pseudo-wells further landwards from the transform fault experience a heat-flow increase, which is minimal. When comparing pseudo-wells WT-1 and WT-2 (Table 7), the heat-flow increase is much larger for pseudo-well WT-1 located closest to the margin; whereas, for

| Table 6. Time lag between the spreading centre passage and the heat-flow peak development in all three initial heat-flow scenarios for selected pseudo-wells of the Eastern transversal transect |
|-----------------------------------------------|
| Pseudo-well | Thermal anomaly peak time lag (Ma) |
| Cold | Medium | Hot |
| ET-1 | 5 | 5 | 5 |
| ET-2 | 6 | 6 | 6 |
| ET-3 | 7 | 7 | 7 |
| ET-4 | 9 | 9 | 10 |
| ET-5 | 11 | 14 | 29 |
| WT-1 | 11 | 11 | 11 |
| WT-2 | 12 | 12 | 12 |
| WT-3 | 13 | 13 | 13 |
| WT-4 | 14 | 14 | 14 |
| WT-5 | – | 14 | 15 |

| Table 7. Comparison of spreading-centre pre-heating and the effect of thermal perturbation over a distance of 5 km for all three initial heat-flow scenarios |
|-----------------------------------------------|
| Pseudo-well | Heat-flow increase until point of passage (mW m\(^{-2}\)) | Duration of pre-heating (Ma) |
| Cold | Medium | Hot | Cold | Medium | Hot |
| WT-1 | 9.04 | 8.83 | 8.57 | 11 | 11 | 12 |
| WT-2 | 0.49 | 0.66 | 0.86 | 3 | 4 | 5 |
pseudo-well WT-2, located 5 km landwards, the heat-flow increase is relatively small.

Thus, only the first two pseudo-wells from the transform fault react to the local heating effect of the spreading centre in a distinct fashion. In other pseudo-wells, which are located more than 5 km landwards, almost no local short-term heating effect is seen, although some thermal anomaly peak could be recognized in the first six wells from the transform fault. The lag time of the peak thermal anomaly development is 11 Ma for pseudo-well WT-1, 12 Ma for pseudo-well WT-2, 13 Ma for pseudo-well WT-3, and 14 Ma for pseudo-wells WT-4 and WT-5 (Table 8). These observations indicate that the lateral heat transport advances landwards at a rate of 5 mm a\(^{-1}\) from the transform fault. The maximum distance of such developed thermal perturbation from the transform fault is about 20–25 km.

As it can be seen in Table 7, the hot initial heat-flow scenario understandably produces the highest heat-flow regime. The associated thermal anomaly lasts for the longest period of time and the heat-flow increase is noticeable, especially in pseudo-well WT-2.

### Discussion

An earlier numerical simulation of the Ghana Ridge (Nemčok et al. 2012) provided no clear indication of flexural uplift. A lack of any distinct flexural uplift or isostatic rebound in this study was explained by high temperatures, such temperatures can weaken the lithosphere of the transform margin to the point of having a very low flexural rigidity. The interpreted low flexural rigidity was in accordance with observations made by Karner & Watts (1982), Holt & Stern (1991) and Kooi et al. (1992) for the situation shortly after rifting.

The checkpoints of the Nemčok et al. (2012) simulation were located in the narrow zone of the transform margin next to the transform fault. However, the results of this study indicate that this narrow zone provides the thermal record dominated by the extreme effect of the laterally passing spreading centre, which makes the effects of other warming mechanisms difficult to decipher.

It is the design of the two transversal transects that permits the heat transfer from the laterally passing spreading centre into the transform margin to be observed in detail. Only this approach can demonstrate that just a 5–10 km-wide zone undergoes development of an extreme thermal peak, which then dissipates landwards in much a less extreme manner. The influence zone is no wider than 20–25 km.

The location of the Longitudinal transect within the aforementioned extreme heating zone does not improve the understanding much beyond that provided by Nemčok et al. (2012), apart from the better visualization of the thermal peak in time in association with the laterally passing spreading centre. However, it is the comparison of the two transversal transects that allows the effect of the newly accreted oceanic crust in two corridors in front of and behind the migrating spreading centre to be seen. A much warmer ‘base’ heat flow, from which the spreading-centre-related thermal peak rises, in the Western transversal transect in comparison with that in the Eastern transect indicates the ‘pre-heating’ effect of the oceanic crust corridor in front of the advancing spreading centre.

The true 3D visualization of the interacting five thermal regime-influencing factors, which are listed in the ‘Conclusions’, needs to be taken with caution concerning details. It is only the thermal histories of the pseudo-wells of the three studied transects that were modelled by the coupled thermomechanical, finite-element simulation. The GIS approach of inserting extra pseudo-wells into the region bounded by three studied transects and implementing linear interpolation to calculate their thermal histories introduced a simplification to the spatial and temporal distribution of heat flow. Although it does not rule out the main observed trends, the distribution is somewhat simplified. Therefore, this paper concentrates on results, which can be determined from study of the pseudo-wells that were modelled by finite-element simulation.

It is also important to emphasize that the finite-element modelling did not attempt to simulate the thermal history of the Ghana Ridge exactly. For a site-specific study, the model would require the area-specific information from xenoliths and deep refractivities surveys to be honoured in order to set up rheologies and thicknesses of the modelled lithospheric layers. The thicknesses of the lower and the upper crust in the model were chosen to be 15 km. While various sensitivity studies with respect to different crustal geometries and their

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**Table 8. Time lag between the passage of the spreading centre and heat-flow peak development in all three initial heat-flow scenarios for selected pseudo-wells of the Western transversal transect**

| Pseudo-well | Thermal anomaly peak time lag (Ma) |
|-------------|-----------------------------------|
|             | Cold | Medium | Hot   |
| WT-1        | 11   | 11     | 11    |
| WT-2        | 12   | 12     | 12    |
| WT-3        | 13   | 13     | 13    |
| WT-4        | 14   | 14     | 14    |
| WT-5        | –    | 14     | 15    |
thermal parameters can be carried out, this study focused its sensitivity studies on the recognition of:

- the role of different syn-rift thermal regimes on the post-break-up thermal anomaly;
- the geometry of the thermal perturbation caused by the laterally passing spreading centre;
- the heat-transmission mechanisms involved in the thermal perturbation.

Any site-specific quantitative prognosis would have to take into account the conditions at specific margins.

**Conclusions**

The Ghana Ridge transform-margin segment underwent progressive heating due to a laterally passing oceanic spreading centre from 108 Ma until 76 Ma, by which time the spreading centre cleared the African continental crust (Nemcık *et al.* 2012). The average spreading centre migration rate was 21 mm $\text{a}^{-1}$. It controlled a laterally migrating thermal perturbation, which becomes younger from NE to SW. The total width of the zone influenced by this perturbation, which is parallel to transform fault, is about 20–35 km.

The thermal history of the Ghana Ridge was affected by the following factors:

1. Regional cooling of the elevated thermal regime developed by rifting in the pull-apart terrains that culminated at break-up;
2. Short-term local extreme heating driven by the laterally passing spreading centre;
3. Long-term regional heating by the laterally passing spreading centre;
4. Long-term heating by the newly accreted oceanic crust located in corridors in front of and behind the passing spreading centre;
5. The effect of background initial heat flow on the cooling rate of the above-mentioned transient thermal events (1)-(4).

(1) Unlike the transform margin *sensu stricto*, where the continental break-up was controlled by strike-slip-dominated separation, the pull-apart terrains reached break-up by crustal thinning. The elevated temperature field at the beginning of calculation, at 108 Ma, represents a transient temperature field related to the Barremian–early/middle Albian rifting and the late Albian continental break-up in pull-apart terrains at both ends of the modelled transform-margin segment. This is indicated by the fact that pseudo-wells LT-9 and LT-8, closest to the Western pull-apart terrain, are characterized by the largest maxima related to the syn-break-up thermal peak.

(2) The short-term extreme heating provided by the thermal anomaly of the spreading centre moving along the transform margin propagates landwards relatively slowly in comparison with the centre migration rate of 21 mm $\text{a}^{-1}$. This heating first develops a distinct thermal maximum in the 5–10 km-wide zone of the continental crust next to the transform fault. Here it greatly exceeds any other heating mechanisms. Then the heating propagates landwards, while the previously mentioned local thermal maximum dissipates at a rate of about 5 mm $\text{a}^{-1}$. This occurs because the maximum is no longer fed by the spreading centre that has already cleared. The thermal peak that developed beyond the 5–10 km-wide zone is minimal, and is beyond recognition after the first 20–25 km of heat transfer.

(3) The long-term regional heating by the laterally passing spreading centre cannot be distinguished from the heating effect of the adjacent warm new oceanic crust because they work in combination. Both effects combined manage to warm up the remnant heat-flow regime progressively more in subsequent locations as one goes from NE to SW. The long-term regional heating is indicated by the observation that the background heat flow, which forms the base of the spreading-centre-related local peak, becomes warmer for transform-margin segments undergoing this long-term heating for longer.

(4) The role of newly accreted oceanic crust adjacent to the transform margin in its heating is controlled by the age of this accretion, which varies along the margin. Along the transform margin, the base of the heat-flow regime, from which the spreading-centre-related thermal peak rises, becomes warmer with increasing time difference between the oceanic crust accretion and the development of the spreading-centre-related thermal peak. Because the horizontal heat transport from the migrating spreading centre into the transform margin is four times slower than the migration rate of the centre, it must be the accreted oceanic crust that plays an important role in margin heating. It preheats most the transform-margin regions not yet reached by the spreading centre. A much less important factor in the ‘preheating’ of transform margins prior to the arrival of the spreading centre is the long-term regional heating by the passing spreading centre. Neither of them increases the spreading-centre-related thermal anomaly with the duration of their effect.

(5) Our modelling indicates that the pre-rift equilibrium heat-flow regime exerts only minor modification on the syn-break-up thermal peak. The warmer initial heat flow causes a slight warming of the thermal peak related to the lateral passage of the spreading centre. The pre-rift heat-flow regime combined with cooling of the rift-related
thermal anomaly, the effects of the laterally passing spreading centre and the cooling oceanic crust adja-
cent to the transform margin control the magnitude of the thermal peak driven by the spreading centre
passing by. It is the passage of the spreading centre itself that controls the occurrence time period of the
thermal peak driven by the passing spreading centre. Analysis of the time lags in lateral heat transport
for varying distances at different initial heat-flow regimes indicates that the anomaly driven by the
passing spreading centre in the case of the cold initial heat-flow regime dissipates faster than for
warmer regimes.

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