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Cretaceous crustal thinning in North Africa: Implications for magmatic and thermal events in the Eastern Tunisian margin and the Pelagic Sea

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ABSTRACT

The integrated use of geological, geophysical, and geochemical data from Eastern Tunisia onshore and offshore samples indicate a crustal thinning induced from the Tethyan rifting. This is responsible for the subsequent evolution of the North African passive margin during the Late Cretaceous, and the creation of the fold–thrust belt and associated foreland deformations. This thinned crust was an area of mantle upwelling that favoured the increase of isotherms, the uprise of basalt magma, and the circulation of hydrothermal fluids. The Cretaceous magmatism generated a major hydrothermal event characterised by the circulation of hot fluids along faults and a relatively high heat flow in the basin. Temperature elevation and hydrothermal conditions led to alteration of basalts and generated a new mineral equilibrium around the enclosing sedimentary deposits.

1. Introduction

The current study aims to relate the Cretaceous magmatic and thermal events, known in boreholes from Eastern Tunisia, to the crustal thinning of the North African margin. The Eastern region (Fig. 1) comprises the area between Cap Bon to the North and the Gulf of Gabes to the South. Studies of sub-surface magmatism were mainly based on systematic surveys of data enclosed in oil exploration borehole reports (e.g., SA1, JAR1, MKR3, TEF1, MSL1, MKR5, and EHL1). The aim of this paper is to: (i) describe the main characteristics of the cretaceous magmatism in Eastern Tunisia; (ii) present an example of heat flow measurements using a one-dimensional GENEX basin modelling, and (iii) define the link between the Cretaceous magmatism and the geodynamic evolution of the North African margin.

2. Geological setting

The Eastern part of Tunisia (both offshore and onshore) constitutes the foreland of the Atlas system. It corresponds to a transition zone located between the folded Atlas domain in northern (Rouvier, 1977) and west-central Tunisia towards the Pelagian Sea. It corresponds to a young continental margin mainly formed during the Mesozoic and Cenozoic times (Haller, 1983; Touati, 1985).

During the Cretaceous, the geological structure of the Eastern margin of Tunisia is known to be related to the Tethyan oceanic evolution and the Africa–Eurasia migration:

- in fact, successive N–S and NE–SW riftings along the Triassic, Jurassic and Lower Cretaceous deposits have lead to series of horsts, grabens and semi-grabens structures (Bédir, 1995; Bouaziz, 1995). Previous mapping of the Albian megasequence in the study area allowed the identification of tectonically controlled basins (Bédir, 1995). This megasequence is locally cross-cut by magmatic emissions (Fig. 2);
- during the Cenomanian–Coniacien period, Eastern Tunisia was submitted to a mainly NW–SE to N–S extensional transtensional regime that reactivated some of the previous trends and created new basins and uplifts. The stress field migration and reorientation have led to the formation of echelon folds along wrench faults (Wildi, 1983; Guiraud and Maurin, 1992);
- the sagging Santonian Campanian period is characterised by northwest–southeast wrench-normal faulting, probably responsible for the NW trending grabens and the formation of the folded Atlasic mountain (Dercourt et al., 1986);
- the Africa–Eurasia Convergence is expressed by NE–SW trending folds during the Uppermost Cretaceous and throughout the Palaeocene (Bédir et al., 1992; Patriat et al., 2003; Khomsi et al., 2006).

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3. Analytical methods

Representative cutting samples of the different magmatic rocks from different boreholes were carefully selected, washed in distilled water, and then dried in an oven at 50 °C. The dried basalt samples were sorted using a binocular microscope to remove any contamination by fragments of sedimentary facies. Thin sections prepared from representative samples were prepared to

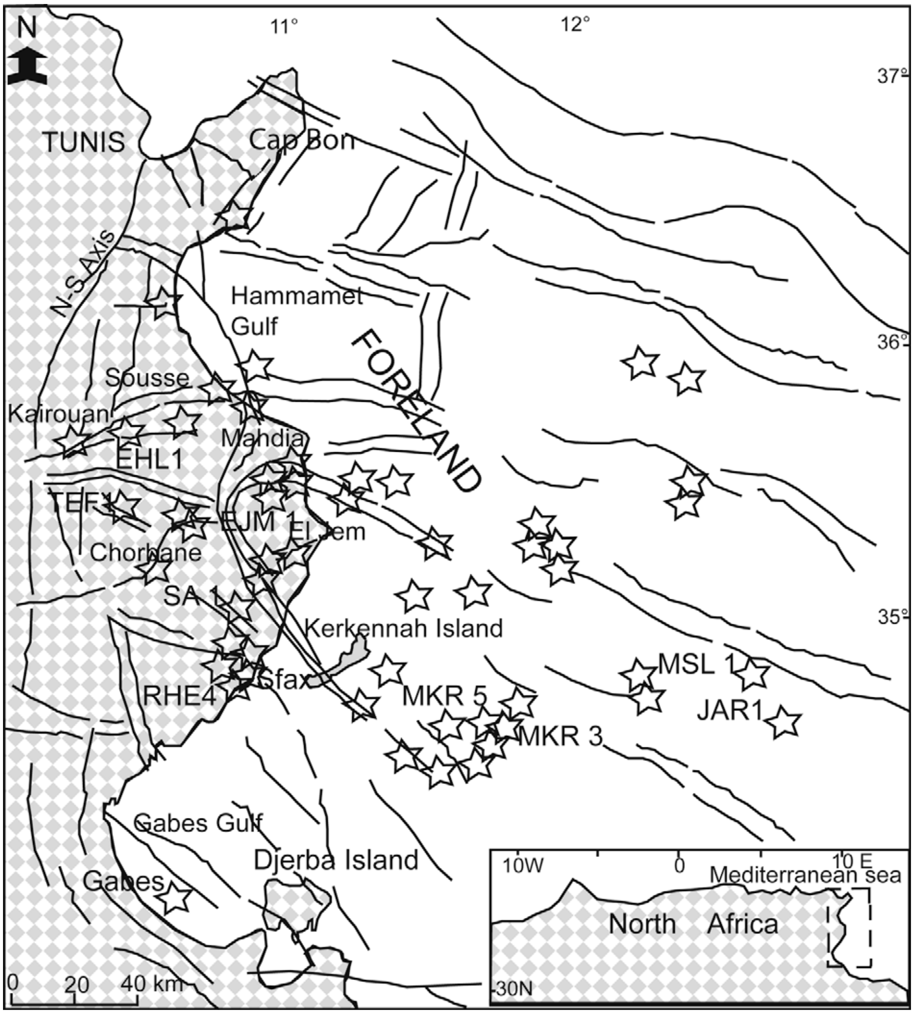

Fig. 1. Structural map of Eastern Tunisia showing the study area. Stars: boreholes that crosscut magmatic rocks.

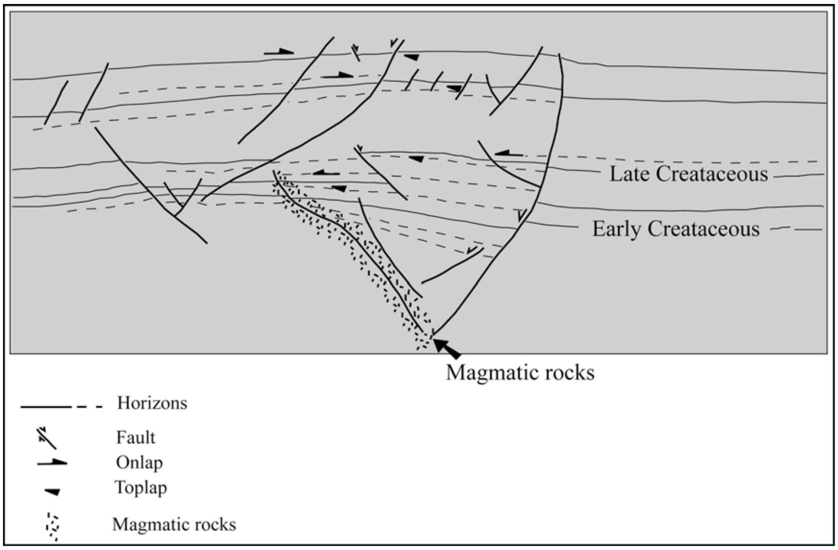

Fig. 2. Seismic profile in the Eastern Tunisia showing synsedimentary normal faults, grabens and horsts structures: witnesses of tethyan rifting (Bédir, 1995).

ensure that the chosen specimens do not contain any calcite vesicles.

Selected samples of the various magmatic rocks and enclosing carbonate were analyzed by Scanning Electronic Microscope (SEM) and X-ray spectrometry analysis at the EDYTEM-CISM Laboratory, University Savoie (France). Analytical procedures, standards and X-ray analysis were as follows: SEM-LEICA, model (Stereoscan 440). Scanning Electronic Microscope with digital tungsten filament, platinum *X*, *Y*, *Z* motorized, rotating 360° (tilt), detectors or secondary electrons backscatter four sectors, resolution: 10 nm, magnification ×100,000.

In order to study the thermal evolution, a 1D basin modelling of burial reconstruction, conductive heat flow transfer, and petroleum generation, has been applied to Eastern Tunisia (offshore and onshore areas), using the1D GENEX software (GenTec module). In this study, we used the flow thermal-conductivity method, which unlike the geothermal gradient method, allows an easy and realistic reconstruction of the thermal evolution in the basin. The heat flow and the thermal conductivity were estimated using both, corrected Bottom Hole Temperature (BHT) and the Drill Stem Temperature (DST). $T_{\max}$ and VR parameters of outcropping samples located close to the different wells have been used in order to optimize and control the determination of the "Cretaceous heat flow".

The optimization process involves the comparison of measured temperatures in the wells with those calculated by the software for a given thermal history. In addition, the reliable geological model corresponds to that determining the heat-flow that gives the best fit between the measured and calculated VR. The best calibration was obtained using a constant heat flow (during geological time) ranging between 69 and 71 mW/m^2. Based on the regional geological framework and tectonic interpretation defined in the studied area, different wells were modelled in order to reconstruct the thermal history evolution. This evolution was realized over two stages: (i) study of the wells thermal history using subsurface data, that is to say, heat flow measurements for the actual well, (ii) study of the thermal history using the same well data but replacing the magmatic layer by a lithological composition that is similar to the surrounding rocks, which correspond to the flow measurements in a calculated well (see Table 1).

4. Results

4.1. 1. Petrography and mineralogy of subsurface magmatic rocks

Petrographical and mineralogical data allowed the identification of four events in the Cretaceous sub-surface magmatism of Eastern Tunisia:

1. A minor Neocomian volcanic event represented by altered basalts, mostly composed of albite, carbonates, chlorite, hematite, titanite, interstitial silica, and, chloritised pyroclasts, all cemented by a light-coloured sparite.
2. An Aptian–Albian event, which corresponds to the emplacement of basaltic lavas, mafic intrusions, pyroclastites, tuffs, and volcano–sedimentary rocks (Fig. 3D). The lava flows dispaly vesicular texture, the vesicles being generally filled by chlorite or calcite. Overall, the olivine has been transformed into chlorite. Rare clinopyroxenes are surrounded with rutile (Fig. 4E). Leucoxene forms small, sparsely distributed grains in the matrix. Secondary calcite can be very abundant. The lava flows show a typically spilitic paragenesis (albite, chlorite, prehnite, calcite, rare quartz), the matrix having recrystallized into small laths of albite and chlorite. The intrusions show doleritic and microdoleritic textures, and the same mineralogical compositions as the flows. The pyroclastic rocks consist of millimetre- or centimetre-sized pyroclasts (ashes, lapillis or pumices), often chloritised and transformed into palagonite.
3. A Cenomanian–Turonian event (Fig. 3B), which corresponds to the emplacement of altered intrusions (Fig. 4B and C), lava flows interspersed with breccia, volcanic microbreccia, and pyroclastic rocks. All these rocks have petrographical characteristics (trachytic facies) similar to the previous event. Trachytes consist of alkaline feldspars, rare pyroxenes, and opaque minerals. Epiclastic rocks are present and are formed by the reworking of older volcanic material.
4. A Senonian event (Fig. 3A and C) consisting of altered basalts (Fig. 4A) and pyroclastic (Fig. 4D) products, composed of vesicular pumice fragments (the vesicles are slightly flattened) and volcanic glass.

Electronic microprobe studies of these Cretaceous basalts (Laridhi Ouazaa, 1994) has shown the presence of two groups of basalts with distinct mineral parageneses: 1 – Tholeiitic basalts characterised by two types of clinopyroxene (augite and pigeonite), with TiO_2 contents ranging between 0.59% and 1.08%, plagioclases displaying small variations in composition (An59 to An44), and iron–titanium oxides (Ti–magnetite). 2 – Basalts constituted of olivine (Fo 77–Fo 67), clinopyroxene with high titanium contents (1.52–2.99%), plagioclase (An42–An64), and analcime with sodic, sodi-calcic or even calcic composition. This paragenesis is characteristic of alkaline rocks.

4.2. Thermal history

Basin modelling usually aims to reconstruct the time evolution of a sedimentary basin in order to provide quantitative predictions of the pressure parameter and consequently hydrocarbon genesis. It accounts for porous medium deformation, heat transfer, hydrocarbon formation and migration. First a 1D model such as Genex was used to simulate the temperature evolution during Cretaceous as well as organic matter. The generated "Cretaceous heat flow" model was based on known tectonic history of the basin and calibration to available maturation data. To calculate this palaeo-heat flow, the software takes into consideration the increase and the decrease in heat flow in the basin due to geological events such as subsidence, heat flow refraction (geometric effect), and horizontal fluid circulation along layers. This simulation presents only the effect of magmatic emissions on the thermal history of the enclosing sediment.

Example of a heat flow measurement: M'sella-1 borehole (MSL-1) (Table 1)

– Actual borehole (with magmatic layer)

During Late Santonian (79 Ma) and before the emplacement of magmatic rocks, the heat flow value was 53.3 mW/m^2. During the deposition of the Abiod carbonates (Campanian–Maastrichtian, 70 Ma), the heat flow was of the order of 50.8 mW/m^2.

– Simulated borehole (without magmatic layer)

Table 1
Heat flow measurement in borehole MSL-1 (Matoussi Kort, 2003).

Heat flow (mW/m^2) in the actual borehole (with magmatic layer)	Age in Ma	Heat flow (mW/m^2) in the simulated borehole (without magmatic layer)
53.3	79	53.3
52.1	78.7	51.9
51.8	77.2	51
50.8	75	50

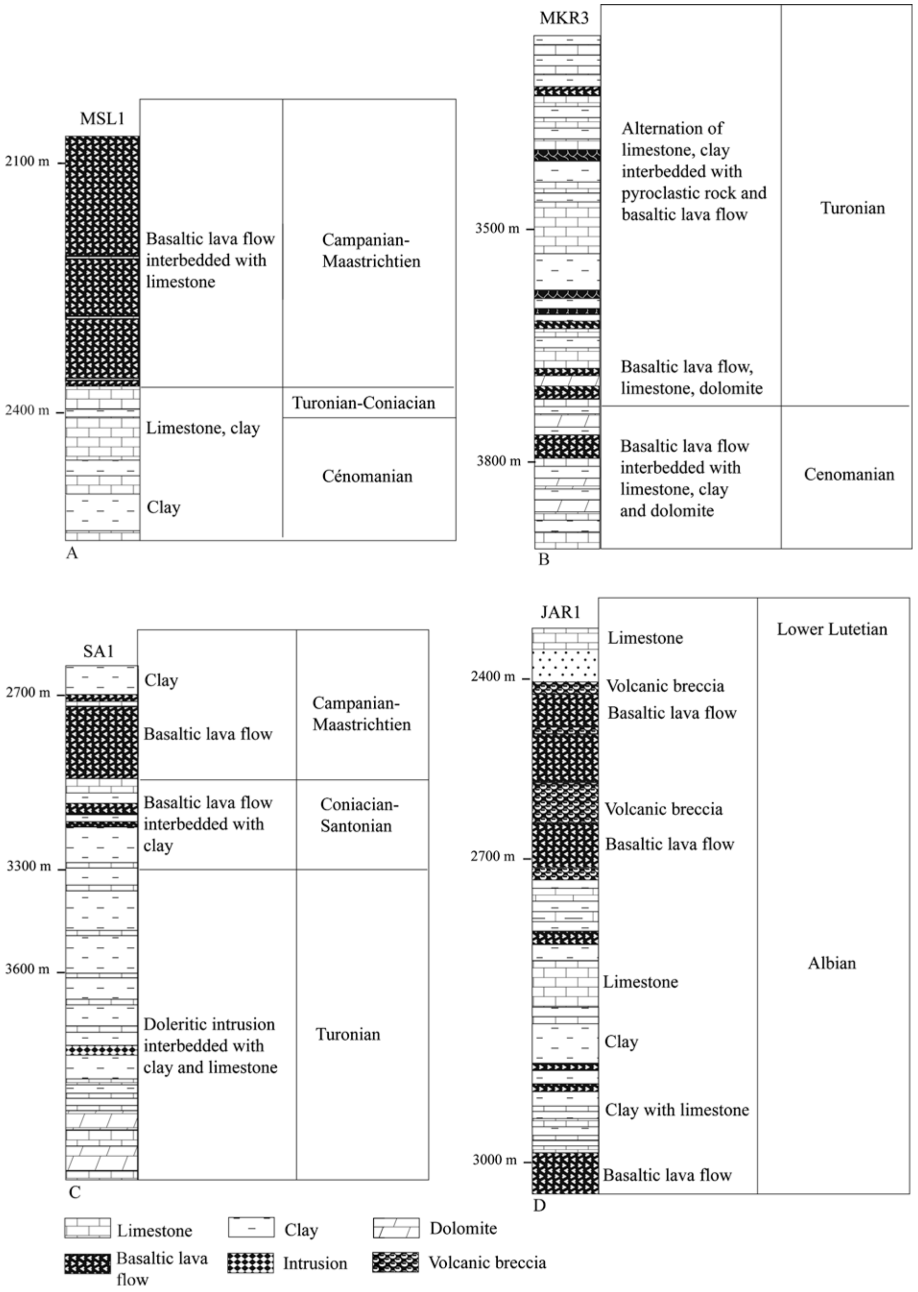

Fig. 3. Selected borehole logs – A: M'sella1 (MSL1); B: Miskar 3 (MKR 3); C: Sidi Abdellah 1 (SA1); D: Jarrafa 1 (JAR 1).

During Late Santonian, the heat flow was 53.3 mW/m^2. During the Campanian–Maastrichtian (70 Ma), the heat flow was averaging 50 mW/m^2. In the simulated borehole, the heat flow decrease was greater than in the actual borehole.

	79 Ma		70 Ma
Borehole without magmatic rocks	53.3 mW/m^2	→	50 mW/m^2
Borehole with magmatic rocks	53.3 mW/m^2	→	50.8 mW/m^2

From the Santonian to the Campanian–Maastrichtian, the heat flow ranged from 53.3 to 50.8 mW/m^2 in the observed borehole, whereas in the simulated borehole, the heat flow ranged from 53.3 to 50 mW/m^2. This difference between wells during this period is considered to be related to the magmatic events. The estimated value of the heat flow of the magmatic rocks in borehole MSL-1 is 0.8 mW/m^2 (Fig. 5A–C).

5. Discussion

During the Jurassic and the Cretaceous, the geodynamic evolution of Tunisia was marked by a complex rifting compared to the rest of the Maghreb. In Eastern Tunisian basins, the reported Tethyan rifting of the Jurassic–Lower Cretaceous was controlled by major faults, presumably linked to basement unconformities (Khomsi et al., 2004; Abbes, 2004). They have been interpreted as Jurassic faults, with a strong strike-slip component, within a transform margin (Bédir, 1995), allowing the development of an unstable carbonate platform (Turki, 1985; Soussi, 2000). Most of the Jurassic

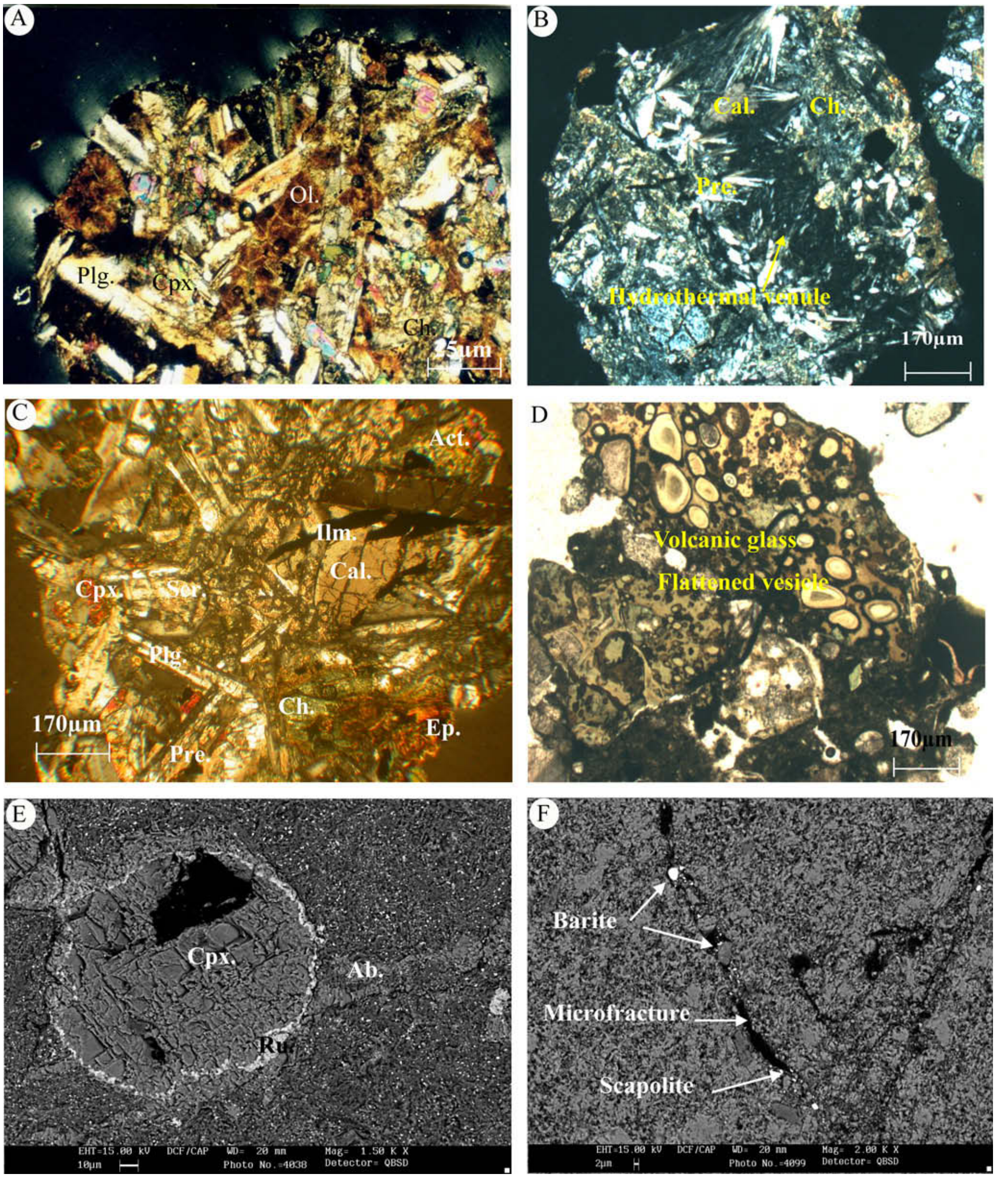

Fig. 4. (1) Microphotographies of selected rocks (cross-polarized light): A – MSL1 (2210 m) doleritic basalt with transformed olivine (Ol.) remplaced with phyllitic products and Chlorite (Ch.), albitised Plagioclase (Plg.) and clinopyroxène (Cpx.). B – TEF1 (2370 m) doleritic intrusion showing hydrothermal venule rimmed with radiannig Prehnite (Pre.), Chlorite (Ch.) and Calcite (Cal.). C – TEF1 (2220 m) doleritic intrusion with albitised Plagioclases (Plg.) partially replaced by Prehnite (Pre.) and Sericite (Ser.). Calcite (Cal.), Chlorite (Ch.) and phyllitic substitute Olivine (Ol.), Clinopyroxenes turned into Actinote (Act.) and Epidote (Ep.). D – SA1 (2775 m) Pyroclastic products with flattened vesicle and volcanic glass (witness of explosive volcanism. (2) Scanning electron microscopy (SEM) pictures of E – albitised Plagioclase, Clinopyroxene rimmed by rutile (Ru.). F – Void (microfracture) infilling by Barite (Ba.) and Scapolite (Sc.).

fault zones are believed to have been inherited from Triassic as indicated by interstratified basaltic lavas within Triassic deposits. This syn-sedimentary extensional regime lasted up to the Cenomanian. By the early Late Cretaceous, the Africa–Eurasia relative movement changed drastically as a consequence of the opening of the South-Atlantic Ocean (Rosenbaum et al., 2002).

The movement of Africa relatively to Europe, which was an eastward left–lateral displacement since 175 Ma, changed progressively into a N–S convergence between 92 Ma and 46 Ma, leading to the development of a set of structures of different scales (Frizon de Lamotte et al., 2008). The Santonian event resulted from the collision between the African–Arabian and Eurasian plates. New stress-fields favoured NE–SW extension along the African plate margin, generating or rejuvenating some rifts [e.g., in the Euphrates trough and in the Libya–Tunisia area as in the northwestern Sirt basin and the Pelagian Sea, (Guiraud, 1998)]. During the Late Cretaceous, the Sirt rifting developed NW–SE trending faults, which are at right angle to the convergence direction between the African and European plates and which are well depicted on seismic profiles of the Sahel area and Gulf Hammamet of Eastern Tunisia (Bédir et al., 1992; Patriat et al., 2003). The authors demonstrated that this phase, already known in Algeria (Laffitte, 1939), covers in reality all the Maghreb. This complexity of the geodynamic evolution of Tunisian sedimentary basins is due to the fact that this area lies next to a transform fault and on the western edge of an active margin. This is especially true of the Eastern Domain, where crustal thinning is manifested by extensional tectonics and the emplacement of major magmatic bodies (Ellouz, 1984; Laridhi Ouazaa, 1994; Laridhi Ouazaa and Bédir, 2004; Laridhi Ouazaa et al., 2005; Mattoussi Kort et al., 2008).

The geophysical data of Tunisia provided by the Geotraverse Program, show the existence of crustal thinning in Eastern Tunisia

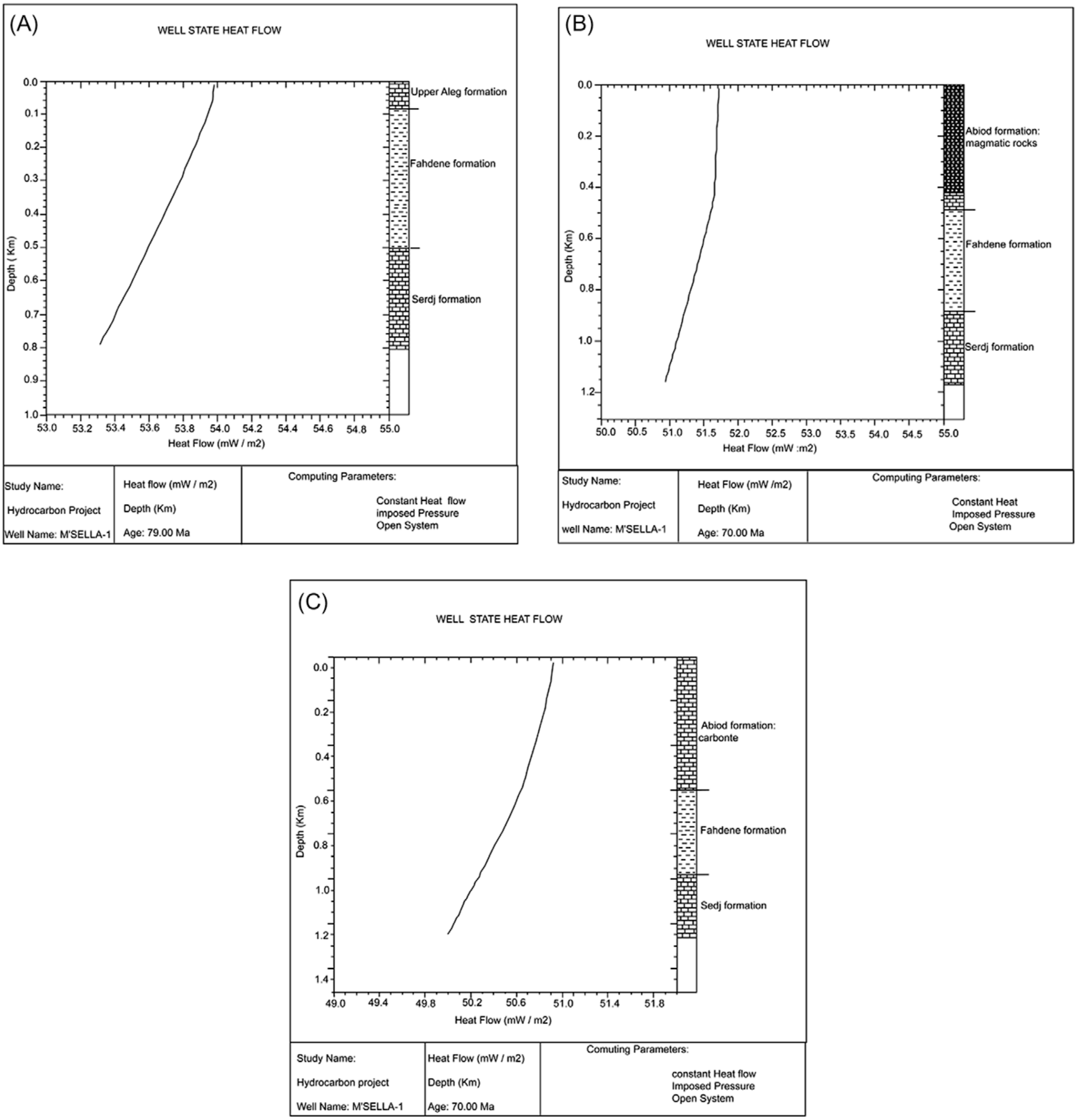

Fig. 5. Diagram showing the evolution of the heat flow measured in the M'sella-1 borehole. A: Before the emplacement of magmatic rocks. B: During the emplacement of magmatic rocks. C: In the simulated borehole (created by the software) (Matoussi Kort, 2003).

resulting into Moho rise (25–30 km) (Fig. 6). This thin crust is a mantle rising zone that favours magmatic and thermal events, elevation of isotherms, rise of basalt, magmatism, and hydrothermal mobilisation. The Aptian–Albian magmatic event that occurred in Eastern Tunisia is contemporaneous with the rifting and the extensional tectonic event that affected this area. The alkaline and tholeiitic magmatism underlines the extensional structure of Eastern Tunisia during the Aptian–Albian and the Cenomanian–Turonian. The emplacement of the tholeiitic basalts is linked to the formation of a highly fractured zone (rift) within a zone of crustal fragility. Many authors (Makris et al., 1985; Fernàndez et al., 1989; Seber et al., 1996; Teixell et al., 2005; Zeyen et al., 2005; Fullea et al., 2006) have described a similar observation. However, the system evolved rapidly and alkaline basalts and their differentiated products replaced the tholeiitic basalts. During the Maastrichtian, the explosive volcanism represented by pyroclastic rocks is contemporaneous to compressive events.

The emplacement of this magmatism generated a local geothermal gradient anomaly and circulation of hydrothermal fluids. The sedimentary series of the Cretaceous were locally affected by temperature increase. Income of heat and chemical elements, particularly magnesium, in relation with the emplacement of magmatic pulses engendered new clay mineral equilibrium (Mattoussi Kort et al., 2008). In addition, dissolution and precipitation by metasomatic mechanisms of new minerals such as barite, scapolite (Fig. 4F) and pyrite in the microfractures of enclosing

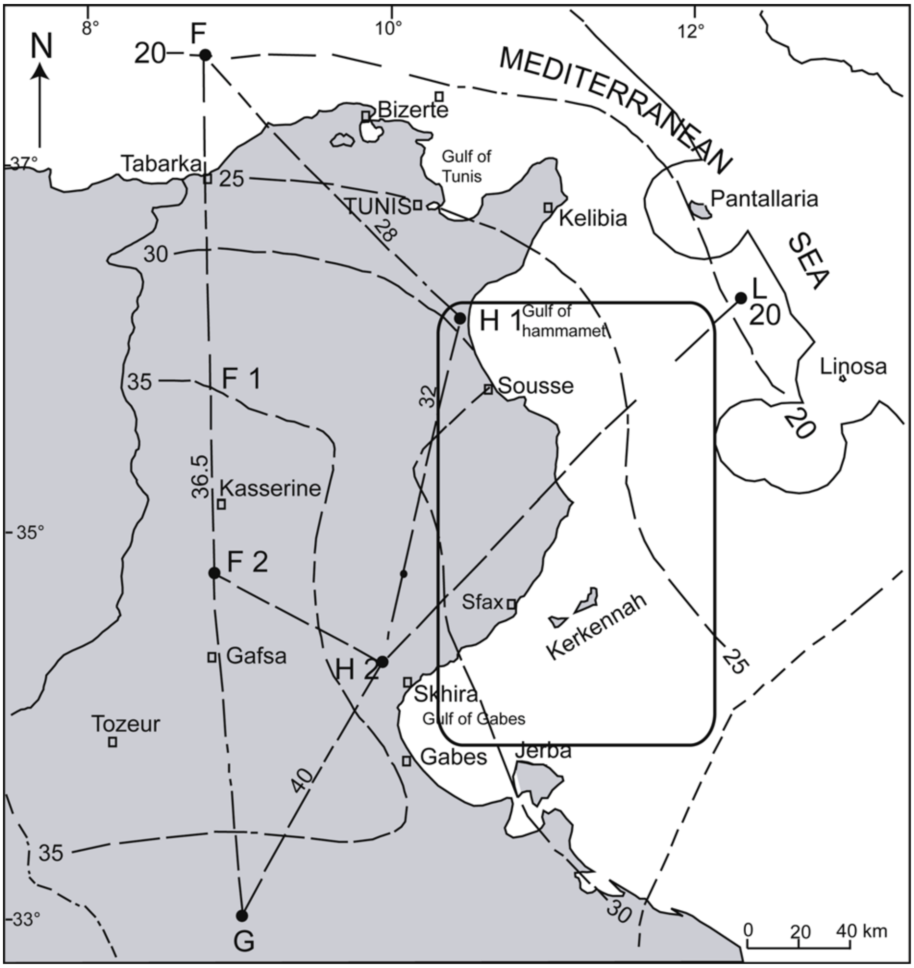

Fig. 6. Map showing the depth of the Moho (25 km) in Eastern Tunisia (European Geotraverse Programme, 1990) (F, F1, F2, L, L, L20, H1, H2 and G are geodetic points) (Buness, 1992).

carbonate rocks. This is an introduction of metals by exhalations of hydrothermal events and heated seawater–basaltic interaction. A similar observation is known in tholeittic flows of the North Atlantic (LeHuray, 1989), in the California (Canet et al., 2005) and in Canada (Cabral and Beaudoin, 2007). The use of basin modelling to calculate palaeo-heat flows following the emplacement of the magmatism allowed us to build up a picture of the thermal events that affected this region. As temperature is an important factor for the organic matter maturation, the emplacement of magmatic rocks is accompanied by a thermal effect and an increase in the geothermal gradient which may lead to a more rapid our maturation. Consequently, identifying the areas in which the magmatism has the greatest effect is of great economic interest for petroleum exploration.

6. Conclusion

Petrological and mineralogical studies of Cretaceous magmatism and geophysical subsurface data on the Eastern Tunisian margin and Pelagic Sea allowed us to reconstruct and highlight the relationships between the geodynamic evolution of the North African margin and the magmatic occurrences in the region. In fact, crustal thinning concord with the rifting and the extensional tectonic event that affected this area. The magmatic occurrences and repartition are directly linked to deep rooted faults that enabled basaltic magma ascent. The emplacement of this magmatism generated the circulation of hydrothermal fluids and localised heat flows. Altered basalts and mineral transformations on the enclosing sediments are the result of hydrothermal activities in this region. In order to evaluate the increase in heat flow, we have used a 1D modelling basin calibrated with organic matter parameters. This simulation shows the probable effect of magmatism on hydrocarbon maturation.

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