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CRETACEOUS RIFTING OF THE GHANA TRANSFORM MARGIN – EVIDENCE FROM ONSHORE APATITE FISSION TRACK DATA AND OPTIMUM THERMAL HISTORY MODELS

E. K. Hayford, F. Lisker and L. Apaalse
(*E.H.K.: Department of Geology, P. O. Box LG58, University of Ghana, Legon; F.L.: Facbberich Geowissenschaften, Uni Bremen, 28334 Bremen, Germany; L.A.: Ghana National Petroleum Company, Private Post Bag, Tema, Ghana*)

Abstract

The rock samples of the granitoid at the marginal ridge of the Ghanaian shelf within La Côte d' Ivoire continental transform margin, have been studied using fission tracks in apatite. The ages of the apatite fission track (AFT), which are mainly metamorphosed igneous rocks, range from 130 to 415 Ma. Apatite fission track measurements demonstrate that the rocks were cooled from temperatures >110 ^{o}C to temperatures below 60 ^{o}C during the early Cretaceous. Quantitative thermal histories, derived from rock data from southern Ghana, indicate two stages of cooling and two stages of denudation during Devonian-Permian times, and in the Cretaceous. The denudation was the result of faults and landslides produced by increases in bathymetric step between the continental margin and the oceanic crust. The latter cooling stage commencing at 130 Ma represents the 2.5–5.5 km of basement denudation which is related to intra-continental transform faulting between West Africa and Brazil. The AFT data of La Cote d' Ivoire-Ghana marginal ridge reveal similar times of cooling, thus, ruling out provenance-related AFT ages of the meta igneous rocks. Instead, cooling of ODP samples from the offshore marginal ridge is the consequence of coeval hydrothermal circulation within intra-continental fault acting between African and Brazilian basements.

Résumé

Hayford, E. K., Lisker, F. & Apaalse, L. : *La scission de crétacé de la marge de transformation ghanéenne – une preuve du sentier de fission d'apatité côtier et les modèles historiques thermiques optimum* . Les prélèvements de roche granitoïde à la crête marginale du banc ghanéen au sein de la marge de transformation continentale de Côte d' Ivoire -Ghana ont été étudiés en utilisant les sentiers de fission d' apatité. Les âges du sentier de fission d' apatité (SFA) qui sont principalement les roches ignées métamorphosés varient de 130 à 415 Ma. Les dimensions de sentier de la fission d'apatité démontrent que les roches étaient refroidies de températures > 110 ^{o}C aux températures au-dessous de 60 ^{o}C pendant les histoires thermiques de crétacés précocés dérivées de données du sud du Ghana indiquent que deux phases de refroidissement et deux phases de dénudation pendant les temps Devonian-Permian, et dans le crétacé. La dénudation était à cause de la faille et le glissement de terrain produit par les augmentations en étape bathymétrique entre la marge continentale et la croûte océanique. La phase de refroidissement de la dernière commençant à 130 Ma représente 2.5-5.5 km de la dénudation du sous-sol qui est lié à la faille de la transformation intra-continentale entre l'Afrique de l' Ouest et le Brésil. Les données de SFA de la crête marginale Côte d'Ivoire - Ghana montrent les temps semblables de refroidissement, écartant ainsi les âges de SFA liés a la provenance de roches méta-ignées. Au lieu de cela le refroidissement du prélèvement du Projet de Développement Côtier (PDC) de la crête marginale est la conséquence de la circulation hydrothermique contemporaine, dans la faille intra-continentale actant entre l'Afrique et le sous-sol Brésilien.

Introduction

The conventional method of establishing a long term evolution of continental transform margin is mainly based on geophysical measurements, as well as geological investigation of drill hole samples from i) the marginal ridge, and ii) offshore. The acquired geological data, however, have limited application, due to uncertainties concerning the geological history of the sediment source area and the absence of reliable history of the present marginal ridge during the initial rifting stages (Mascle *et al*., 1998). Particularly controversial are discussions on apatite fission track (AFT) data obtained from Offshore Development Project (ODP) samples, which indicate an Early Cretaceous cooling stage (Table1). Interpretations suggest either erosion of sediment source area or cooling after hydrothermal circulation within intra-continental fault (Clift *et al.*, 1997, 1998; Bouillin *et al.*, 1997, 1998; Basile *et al.*,1998; Wagner & Pletsch, 2001).

It is important to note that predictions of rift related denudation across continental transform margins vary between 350 and 3500 m, depending on the model used. Simple heat conduction models suggest transient uplift of more than 2000 m across a transform margin (Todd & Keen, 1989), and an accumulated denudation of up to 3500 m (Lorenzo & Vera, 1992). Using a 2D numerical thermal model, Gadd & Scrutton (1997) calculated thermal uplift and subsidence profiles across a transform margin similar to that of La Côte d'Ivoire–Ghana. The result of the calculated thermal perturbation of the continental crust

TABLE 1

Apatite fission track results from the PDL- Project 159 (La Côte d'Ivoire and Ghana transform margin; summarized from Mascle et al.*,1998) and that of the present work*

	Hayford et al. *(Present work)*	*Clift* et al. (1997, *1998, 1999)*	*Bouillon* et al. *(1994,1997, 1998)*
Sample sites	*Southern Ghana*	*ODP 959, 960*	*ODP 961,960; Equanaute*
AFT - ages	130- 415 Ma	113 – 88 Ma	118 – 65 Ma
MTL	11.60+0.59-13.50+0.23	12.42+0.16– 13.67+0.11 um	14.2+1.1 – 15.2+13 um
X^2 test	77-100%	0–63%	21–100%
Cooling episodes	Early cretaceous	- Late Jurassic – Early Cretaceous Recently	Late Cretaceous
Max. Paleo-temperature	>110 – 60 °C	60 – 80 °C	-
Interpretation	Hydrothermalism	Rapid erosion of the sediment area	Cooling following heating by —hydrothermalism —rapidlysubsiding basin —increase in geothermal gradient.

showed a thermal uplift between 335-470 m. Similar attempts by Cliff & Lorenzo (1999), using two dimensional flexural seismic reflection predicted an uplift of 1200 -1540 m along La Côte d'Ivoire–Ghana transform margin.

Currently, the most powerful tool to constrain thermal histories between 110 and 60 ^{o}C, and so to unfold the amount and timing of denudation of the uppermost crust, is AFT thermochronology. The AFT has been successfully used in many research centres including the University of Kiel, Germany, where the neutron activator has the required parameters for thermochronology analyses. Unlike the geophysical measurements and geological investigations, AFT provides an additional reliable history of initial rifting stage of the marginal redge.

In the study, AFT data on granitic and volcanic rocks of the southern part of the Ashanti belt in Ghana is presented for the first time, and its significance discussed.

Experimental

Geology

The Birimian rocks form the major part of the Man shield, which occupies the southernmost part of the West African craton. The Man shield comprises a western domain, consisting essentially of Archean rocks of Liberian age (3.0-2.5 Ga) and an eastern domain made up of predominantly Birimian rocks of early Proterozoic age. These have been folded, metamorphosed and intruded by granitoids during the Eburnean event (2.15 Ga). The eastern portion of this terrain is covered by Ghana and Burkina Faso, whose basement comprises supracrustal and intrusive rocks of the Birimian. Within the Birimian is the Tarkwaian becken as subordinate with pockets of Palaeozoic or Cretaceous sediments spread along the coastal belt (Eisenlohr & Hirdes, 1992). During the Pan-African orogeny, northern and eastern Ghana were deformed (Castaing *et al.*,1993).

Orogenic contraction produced nappe complexes comprising passive margin sedimentary rocks and accreted magmatic rocks in eastern Ghana and Togo between 640 and 580 Ma (Attoh *et al.*, 1997). However, no signatures of Pan-African tectonics are reported from southwest Ghana, indicating that the southern Ashanti belt was widely unaffected by Pan-African amalgamation. During the Palaeozoic–Jurassic pre-rift platform phase between 550-130 Ma, the area of Ghana was a stable, mostly emergent platform with no significant tectonic or magmatic activities (Genik, 1993). In such setting, the deposition of continentally derived sediments continued in the Volta basin and some smaller basins in southern Ghana until late Ordovician to early Cretaceous (Bar *et a*l.,1980).

A major change in the long-term landscape development of southern Ghana commenced after the final break up of western Gondwanaland in the early Cretaceous. During this event, the West African and the Brazilian cratons split apart and the equatorial Atlantic formed as a series of large pull-apart basins, bounded by rifted and transform segments (Ribinowitz & Labrecque, 1979). According to Mascle & Blarez (1987), La Côte d' Ivoire–Ghana transform margin evolution can be divided into three distinct phases: (i) intra-continental transform faulting stage, ii) continental-ocean active transform margin stage and (iii) continent-ocean passive transform margin stage. Apart from this development, the sheared margin of south-western Ghana was characterized by the deposition of 2-5 km of early Cretaceous to Eocene sandstone dominated sediments within the Tano basin (Fig. 1). These sandstone dominated sediments extend towards La Côte d'Ivoire border (Deklasz, 1978; Kesse, 1985). During this process the post-Eocene to recent deposits were restricted to the shoreline and river banks.

AFT methodology

Six meta granitic samples from a 100-km^{2} area of coastal plains between Axim and Sekondi–Takoradi (Fig. 2) were analysed . The AFT data

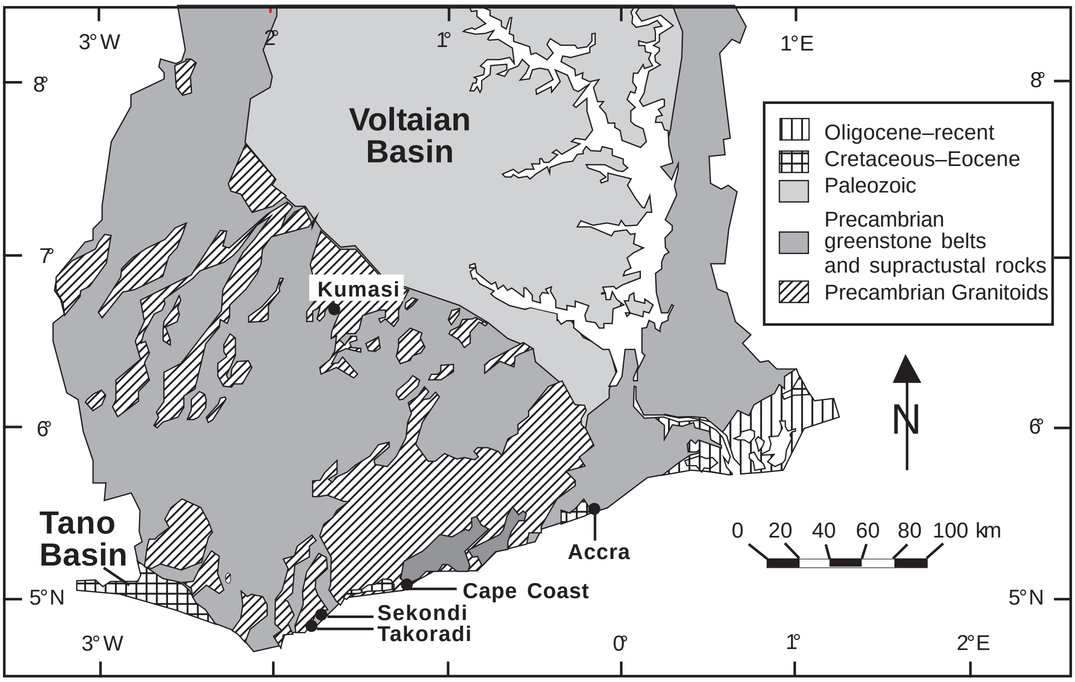

Fig. 1. Simplified geological map of southern Ghana after Kesse (1985), showing the Tano basin, the Sekondi basin and the Volta basin.

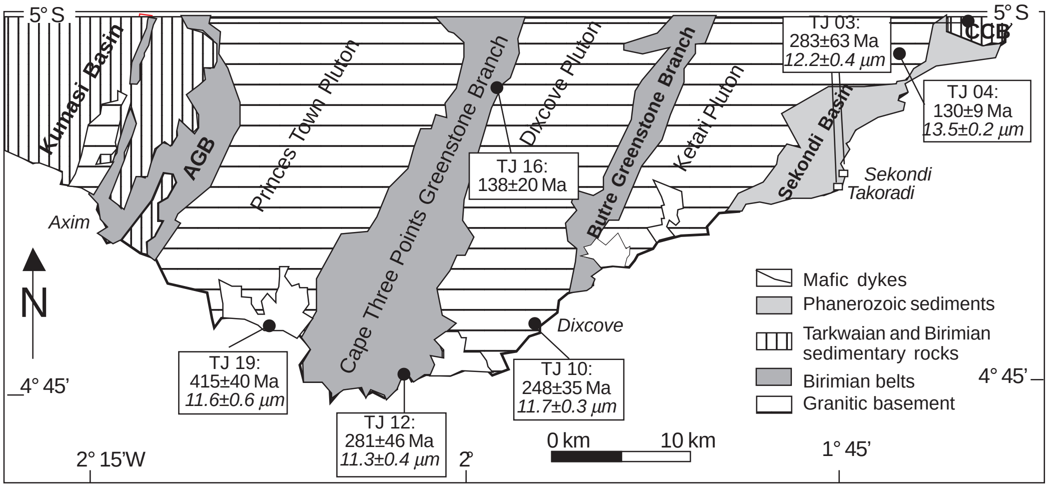

Fig. 2. Simplified geological map of the southernmost part of the Ashanti belt after Loh & Hirdes (2000) showing sample locations, apatite fission track ages, and mean track lengths. AGB denotes Axim Greenstone Belt, and CCB denotes Cape Coast Batholith.

TABLE 2
Apatite fission track data of the southern Ashanti belt (Ghana)

Sample	*Lithologic unit*	*Lat. N Long. W*	*Alt. [m]*	r_D $[10^6 cm^{-2}]$ (N_d)	R_S $[10^6 cm^{-2}]$ (N_s)	r_I $[10^6 cm^{-2}]$ (N_i)	*CC (U) [p.p.m.]*	*P* $(.\alpha)^2$ *[%]*	*FTA [Ma]*	*MTL [µm]*	*S.D. [µm]*
TJ 03	Granite CCB	4° 59.1	10	1.011	0.538	0.366	0.46	100	282±63	12.15+.35	2.31
TJ 04	Granite KP	4⁰ 57.0	20	1.204	1.279	2.281	0.46	77	130+9	13.50+.23	1.25
TJ 10	Granite	4° 47.5	10	1.207	0.528	0.489	0.63	84	248+35	11.67+.32	1.97
TJ 12	Amph. DP	4° 45.2	10	1.025	0.714	0.494	0.43	100	281+46	11.67+.32	1.97
TJ 16	Granite CTPGB	4° 46.5	60	1.0181	0.725	1.024	0.75	100	138+20		
TJ 19	Metab. PTP	4° 47.7	10	1.225	0.862	0.478	0.60	100	415+40	11.60+0.59	2.04

Note: Sample localities are indicated in Fig. 3. Standards used for the analyses of apatite were taken from rocks from Durango, Fish Canyon and Mount Dromedary. Abbreviations are as follows: Lat : Latitude; Long: Longitude; Alt: Altitude above sea level; r_D, r_S, r_I: are the number of spontaneous and induced track densities that were counted; N_d, N_s, N_i: are the number of counted dosimeter, spontaneous and induced tracks; CC: Correlation coefficient; P(C^2): Chi square probability; FTA: Fission track age (all samples pass C^2 test at > 5%); MTL: Mean track length; S.D.: Standard deviation; CTPG: Cape Three Points Greenstone; PTP: Prince Town Pluton; Amph.: Amphibole; DP: Dixcove Pluton; KT: Ketan Pluton; CCB: Cape Coast Batholith.

obtained from the samples are listed in Table 2. Apatite mineral concentrates from the samples were separated, mounted and etched following procedures in Gleadow (1984), and were irradiated at the well-thermalised DR3 graphite reflector facilities in RISO, Roskilde (Denmark). Fission track ages were determined by external detector method (Gleadow, 1981), applying the zeta calibration technique, z = 388.1+7.4, for dosimeter glass CN5 as described by Hurford & Green (1983). Errors are quoted as + IS (conventional method) (Green, 1981). For dating, the FT-Stage program of Dumitru (1993) has been used. Apatite fission-tracks were counted and measured with a Zeiss Axiotron microscope at a magnification of 1600 ¥ and 2000 ¥, respectively, under dry objectives. If possible, at least 20 grains were counted, and 100 confined tracks were measured for each sample. Confined fission tracks were measured following the recommendations of Laslett *et al*. (1982).

Improved estimates of the magnitude and timing of cooling can be obtained by quantitative modelling. Optimum thermal history models were determined for each sample using the program Monte Tax (Gallagher, 1995). This modelling procedure uses a genetic algorithm (Gallagher & Sambridge, 1994) to optimise the stochastic production of successive generations of thermal history models which are tested against the observed data. For this study, the Durango fission track annealing model of Laslett *et al*. (1987) was adopted. This model makes it possible for the microprobe to detect an apatite composition with F and Cl contents of 0.7 and 0.1 per cent, respectively.

Results

The AFT ages (Table 2) of the samples range from 130 ±9 to 415±40 Ma. This age range ironically is considerably younger than the inferred Palaeoproterozoic ages of the host rocks, and that of the last potential metamorphic overprint during the Pan-African orogeny. All samples have high C^2 probabilities between 77 and 100 per cent, indicating similarity in age. The mean track lengths (MTL) vary from 11.3 to 13.5 µm. In general, the fission track characteristics allow the distinction of two groups of samples with different cooling behaviour; a first group of samples with average AFT ages of 134±15 Ma (TJ04, TJ16), and a second group of samples with average AFT ages of 306 ± 40 Ma (TJ03, TJ10,TJ12, TJ19). The first group is characterised by AFT ages of 130 Ma, C^2 probabilities of 100 per cent, and the longest MTL (13.50 µm) with the smallest standard deviation (1.25µm) of all samples. The group samples spent only a short time in the apatite partial annealing zone (PAZ: 110 ±10– 60 °C), and cooled rapidly from temperatures of 110 – 60 °C in the early Cretaceous.

Irrespective of the wide range in ages (250-400 Ma), all samples of the second group have similar fission track signatures. Their single grain ages vary, and they have shortened MTL <12.2 µm with large standard deviations of 2 µm. Such AFT pattern indicates that the samples of the second group cooled very slowly through the higher temperatures of the PAZ in Palaeozoic times. Because of the slow cooling, minor temperature difference in the order of some 10 °C led to varying crustal level or geothermal gradient.

Later, the samples must have been exposed again to temperatures not much lower than 110 °C before they finally cooled to surface temperatures (Gleadow *et al.*, 1986; Green *et al.*, 1989). The style of the thermal histories obtained using this strategy are very similar for all samples. According to these models, the samples from the southern Ashanti belt cooled through the PAZ during the mid-Palaeozoic. Only sample TJ19 shows cooling commencing during early Palaeozoic. Subsequently, the samples were reheated to temperatures between 85 and 95 °C. Final cooling of the rocks of the second group occurred simultaneously with the rocks of the first group, beginning during the early Cretaceous.

Discussion

In discussing the evolution of the Ashanti belt, it is important to note the absence of igneous intrusions during the Phanerozoic age and the absence of significant thermal instability during this period. Invariably, these are conditions under which denudation is likely to have played a role in the evolution. Besides, the West African craton between 550 —130 Ma is described as a stable pre-rift platform phase (Genik, 1993). This presupposes a long-lasting stability of thick cratonic crust, and so implies a low geothermal gradient of 15-25 °C km^{-1} (Rao *et al.*, 1982).

Therefore, the geothermal gradient prevailing during the West African craton times should be commensurate with the recent one for which values between 15 °C km^{-1} (Gunnell, 2003) and 23 °C km^{-1} (Roussel & Lesquer, 1991) are reported. Such cooling pattern (of 15 °C and 23 °C km^{-1}) suggests (i) mid-Palaeozoic episode of slow and homogeneous denudation along the south-eastern margin of the Leo shield, and (ii) variable denudation of the newly created La Côte d' Ivoire–Ghana transform margin since the early Cretaceous break up of western Gondwanaland.

Modelling results as well as the occurrence of late Ordovician to early Cretaceous sedimentary rocks unconformably overlaying the Birimian basement, clearly speaks for basement denudation. Minimum cooling during the mid-Palaeozoic period was approximately 30 °C. This minimum estimate is based on the timing of sedimentation in the nearby Sekondi basin, on the style of cooling implied by the AFT data (Table 2), and on the temperature difference between the upper and lower limits of PAZ.

If a geothermal gradient between 15° and 23° km^{-1} is applied to these estimates of cooling, then Devonian to Permian denudation would be between 1.3 and 6.7 km, indicating a long-term denudation rate of 9-45 m my^{-1}. The trend of decreasing AFT ages towards the preserved remnant of the Sekondi basin (Fig. 2) from E and W, suggests increasing denudation from the distal basement towards the basin. This pattern indicates that basement denudation and related deposition of the erosional products were locally restricted, and that the Sekondi basin probably did not exceed its recent extent during Devonian to Permian times.

Although the immediate cause of basement denudation is not constrained and the nature of Sekondi basin is still unclear (Kesse, 1985; Loh & Hides, 2000), there seems to be a general relation to the late Palaeozoic W-E compressional regime built up by the collision of Gondwanaland (Dallmeryer & Lecorche, 1990). The Sekondi basin could have been formed as one of the basins in the foreland and parallel to the NNW-SSE trending Rokelides orogen in Sierra Leone. Such origin would be supported by the trend of the distinctive gravitative low immediately below the Sekondi basin (Barrit & Kuma, 1998).

The beginning of sudden cooling in the early Cretaceous is indicated by AFT ages of the two youngest samples, TJ 04 and TJ 16, and detected in the modelled cooling paths of all samples. Given a recent annual surface temperature of 27 °C (Von Gnielinski, 1986), the amount of post-Jurassic cooling varies between 60° and 85°. Using a stable geothermal gradient of 15°-23° km^{-1} (Gunnell, 2003; Roussel & Lesquer, 1991), the accumulated denudation of La Côte d'Ivoire-Ghana margin since the beginning of the continental rifting stage is estimated to have been between 2.5 and 5.5 km. Considering a Cenozoic long-term denudation rate of 11-16 m Ma^{-1}, as postulated for the topographically and climatically comparable kimberlite diatreme system in Sierra Leone (Thomas, 1995), denudation range between 1.5 and 5 km can be envisaged for early Cretaceous rifting.

All present models of transform margin evolution emphasize the importance of flexural uplift along the transform border (Clift *et al.*, 1997). When transform faults connect divergent plate boundaries, a narrow and elongated valley develops that is bounded on at least one side by an uplifted shoulder. Such deep trough evolved along La Côte d'Ivoire-Ghana margin because of the Gondwanaland break up between Brazil and West Africa. La Côte d'Ivoire (Tano) basin is divided lengthwise by a fault (with a throw) of some kilometres (Deklasz, 1978). North of the fault, only 300 m of Pliocene and Quaternary sediments are deposited, whereas south of it more than 5 km of post-Jurassic sediments are preserved. As in essentially all West African coastal basins, the basal beds (Aptian) are continental, with a thickness increasing eastward from 470 m in eastern La Côte d'Ivoire to more than 2 km in the vicinity of Axim (Deklasz, 1978).

The late Jurassic/early Cretaceous begin of basin subsidence suggested by Deklasz (1978), as well as the thickness of the Cretaceous-Recent sedimentary sequence, are in very close agreement with the timing and the amount of denudation detected by our AFT data. Although the AFT data do not allow the determination of the mode of denudation in detail, they show evidence of significant denudational unloading and flexural response of the southern Ashanti belt during the Cretaceous period. The eroded material was first deposited in the troughs as the transform faulting continued. It was not until the onset of continental separation and the opening of the central Atlantic at Aptian times (Klitgord & Schouten, 1986) that the offshore marginal ridge (Fig. 3) developed as the most prominent feature of the current sheared margin.

An early Cretaceous episode of rapid cooling has also been suggested in AFT studies on rock samples from the ODP sites 959, 960 and 961 (Fig. 3) on the marginal ridge, and from *Equanuatte*

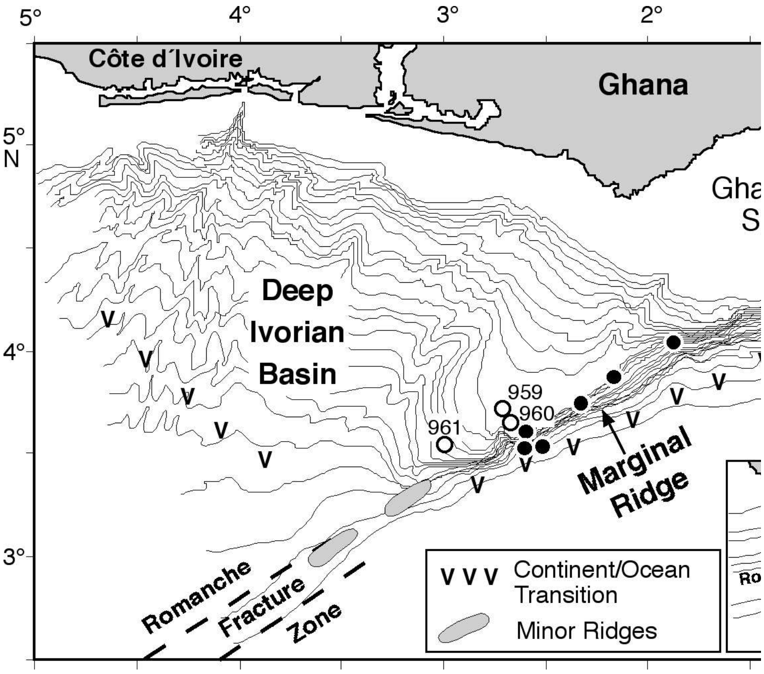

Fig. 3. Schematic transversal section of the onshore La Côte d'Ivoire (Tano) basin (after De Spengler & Delteil 1966) and the offshore marginal ridge of La Côte d'Ivoire – Ghana transform margin (simplified after Basile *et al*., 1998).

samples offshore La Côte d'Ivoire-Ghana transform margin (Clift *et al.*, 1997, 1998; Bouillin *et al.*, 1998; Hayford *et al.*, 2006). There, AFT ages of tectonized early Cretaceous sedimentary rocks are very similar to the stratigraphic ages of the samples. They are interpreted to reflect either erosion of the sediment source area (Clift *et al.*, 1997, 1998; Wagner & Pletsch, 2001) or cooling following hydrothermal overprint (Bouillin *et al*., 1998; Basile *et al*., 1998).

However, the theory of tectonically driven uplift, sub aerial erosion, and isostatic uplift because of unloading is not sustainable anymore since even the youngest of the onshore basement samples representing the source area of the Ghana transform margin (Wozazek & Krawinkel, 2002) shows older AFT age than any of the ODP/ Equanuate samples (Table 1). If such an amount of crust has been striped away in a very short time (i.e. 5 Ma), then, source material of much older cooling age would have been found at the base of the Cretaceous strata from the ODP sites. Besides, the AFT age from late Cretaceous samples from Bouillin *et al.* (1997, 1998) vary between 65 and 118 Ma.

Considering the short time intervals between AFT and stratigraphic ages, and the rather continuous sedimentation in a regional scale, a cooling/denudation rate similar to the Aptian one could be applied. By this application, the geothermal gradient used above alone would reflect up to some tens of kilometres of continental denudation of the late Cretaceous deposits of La Côte d'Ivoire-Ghana margin. Even if this is a maximum constraints, such an amount of denudation during the late Cretaceous is a magnitude higher than the estimate of 2.5-5.5 km. Besides, the pile of continental sediments deposited in the narrow onshore basins is much thicker than the one in the deep Ivorian basin, therefore, a rapid transport of eroded material from the continental sediment source towards the marginal ridge and its rapid deposition there does not seem very likely. Discussing further, the Gurapore and Sao Francisco cratons on the conjugate Brazilian margin have older AFT ages (80-300 Ma) (Harman *et al.,* 1998) than the ODP samples, which further indicate that the present coast of northern Brazil could not possibly have been the potential source area of the eroded material for La Cote d'Ivoire-Ghana transform margin as indicated by Cliff *et al.* (1998).

Neither La Côte d'Ivoire-Ghana nor the Brazilian margins display any relevant morphological feature which could be related to very rapid coastal uplift in the early Cretaceous, nor is there any plausible mechanism that can explain such rapid short-term uplift without isostatic crustal response.

Conclusion

The application of AFT analysis to samples from the southern Ashanti belt indicates that the present land surface comprises exposed rocks that cooled below 110 ^{o}C between Devonian and Permian times, and from temperatures of >110 ^{o}C to temperatures below 60 ^{o}C during the early Cretaceous. Cretaceous cooling of the upper crust because of denudation in the order of 2–5.5 km is the result of intracontinental rifting associated with the evolution of La Côte d'Ivoire-Ghana transform margin. The timing and magnitude of this denudational episode correlates closely with the sedimentation pattern of the narrow coastal basins (Tano and Sekondi basins).

The spatial and temporal patterns of long-term erosion reported in this paper are incompatible with the view of source-related AFT ages of 88-113 Ma from Aptian to Cenomanian ODP samples put forward by Cliff *et al*. (1998). Consequently, the authors strongly support the hypothesis proposed by Bouillin *et al*. (1998) that the apatite crystals were heated *in situ* by hydrothermal circulation within an intracontinental fault acting between African and Brazilian basements. This interpretation is also consistent with clay transformation and fluid inclusion data, indicating palaeotemperatures between 120 and 180 ^{o}C below a pre-late Albian erosional unconformity in the sedimentary sequence of the marginal ridge (Holmes, 1998; Lespinasse *et al*., 1998), and with other geological observations summarized by Basile *et al*. (1998).

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