Journal of the Geological Society, London, Vol. **154,** 1997, pp. 483–489, 6 figs. Printed in Great Britain

Transform tectonics and thermal rejuvenation on the Côte d'Ivoire–Ghana margin, west Africa

P. D. CLIFT[1], J. LORENZO[2], A. CARTER[3], A. J. HURFORD[3] & ODP LEG 159 SCIENTIFIC PARTY

[1]*Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA*
(e-mail: pclift@whoi.edu)
[2]*Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA 70803, USA*
[3]*Department of Geological Sciences, University College, Gower Street, London, UK*

Abstract: Formation of a pronounced basement ridge along many transform continental margins has been attributed to a variety of processes during continental break-up, including transpressional crustal thickening, and thermal rejuvenation and igneous underplating during passage of a spreading ridge. ODP drill holes on the Côte d'Ivoire–Ghana margin now provide the first opportunity to quantify the vertical motions along this type of margin. Apatite fission-track dating of detrital sands suggests that large amounts of erosion occurred on the flanks of an intra-continental wrench zone that predated margin formation. Rapid cooling of >120°C at 120–115 Ma corresponds to erosion of 3.5–5 km along the conjugate Brazilian margin, reflecting *c.* 1 km of tectonically driven uplift, subaerial erosion, and isostatic uplift due to unloading. Following rift initiation at 120 Ma (Aptian), an oceanic spreading axis passed adjacent to this part of the margin at 90 Ma (Cenomanian). Maximum uplift during the ridge–transform intersection was 390 m, considerably less than the 2000+ m predicted by heat conduction models in local isostatic equilibrium. The modern ridge is partially the product of thicker crust (22 km) underlying the ridge than the adjacent Deep Ivorian Basin (19 km), and partially related to flexural unloading of the transform ridge between the end of intra-continental wrenching and ridge–transform intersection. Flexural coupling between the continental and oceanic plates since ridge-transform intersection has caused a progressive depression of the offshore margin, estimated at about 650 m in the study area.

Keywords: West Africa, continental margin, transform faults, fission-track dating, flexure.

Study of the tectonic evolution of transform continental margins has been a relatively neglected field compared to work on the more common passive or active plate boundaries. Ocean Drilling Program (ODP) work on the Côte d'Ivoire–Ghana margin provides for the first time the opportunity to quantify and date the behaviour of a transform margin in an area well constrained by seismic data (Figs 1 and 2; Mascle *et al.* 1996). In particular, the origin of a marked basement ridge along the transform margin at this, and many other such margins, has been a source of much controversy (e.g., Fail *et al.* 1970; Emery *et al.* 1975; Mascle *et al.* 1988). Several processes have been invoked to account for the development of the ridge, many involving the effect of the passage of an oceanic spreading axis along the transform margin following break-up. Thermal rejuvenation of the rifted continental lithosphere has been advanced as a major force driving uplift, with maximum uplift at the time of ridge–transform intersection reaching more than 2 km in some conductive models, which assume local isostatic compensation (e.g., Todd & Keen 1989). Uplift due to frictional heating during the continent–continent transform phase is considered to be very small, <150 m maximum (Todd & Keen 1989). In contrast Lorenzo & Vera (1992) suggested that up to 3.5 km of erosion had occurred as a result of uplift along the transform margin of the Exmouth Plateau mostly due to a transient thermal uplift, but with a component due to thickening of the continental crust by igneous underplating emplaced during passage of the spreading ridge (Lorenzo *et al.* 1991). Crustal thickening along the continent–ocean transition could also be caused by transpressional deformation during the intra-continental wrench phase, although differences in the original degree of extension of the ridge compared to the adjacent rifted passive margin basin could also account for the present morphology. Studies of multichannel seismic lines crossing the ridge have been interpreted as showing a progressive vertical growth of the ridge since break-up, favouring an origin related to ridge-transform intersection (Basile *et al.* 1993).

Regional geology

The Côte d'Ivoire-Ghana margin lies in the equatorial Atlantic at the eastern end of the Romanche Fracture Zone (Fig. 1). The age of formation of the margin is not well constrained, due to the lack of marine magnetic anomalies on the adjacent seafloor (Rabinowitz & LaBrecque 1979). However regional plate reconstructions using anomalies in the southern and central Atlantic have provided constraints suggesting break-up began in the Early Cretaceous (post 140 Ma; LePichon & Hayes 1971; Rabinowitz & LaBrecque 1979). More recently Klitgord & Schouten (1986) suggested an age of around 120 Ma (early Aptian) for break-up in this region, which agrees relatively well with biostratigraphic data from the onshore Benue Trough of Nigeria and Mayo Oulo Lere Basin of Cameroon, indicating break-up-related sedimentation starting in the Barremian (Brunet *et al.* 1988). For the purpose of this paper we choose an age of 120 Ma (Early Aptian) for the start of rifting.

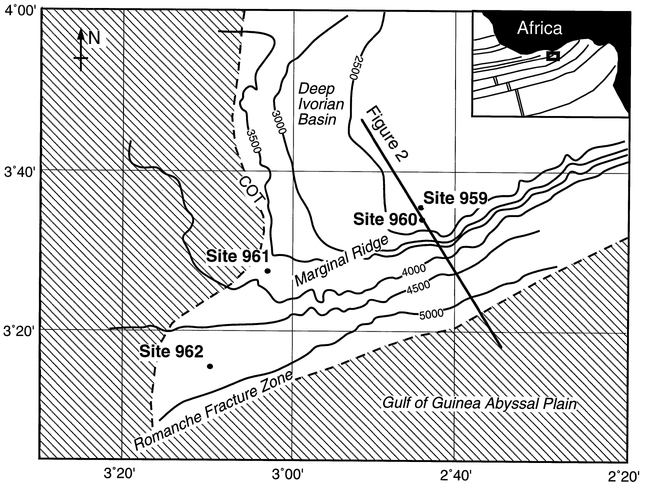

Fig. 1. Bathymetric map of the Côte d'Ivoire–Ghana margin showing the location of ODP Sites 959–962 on the marginal ridge that is continuous with the Romanche Fracture Zone. Insert shows the location of the region on the equatorial west Africa coast.

Dating ridge–transform intersection is difficult due to the lack of magnetic anomalies in the adjacent oceanic crust, although estimates can be made from average spreading rates. Structural data from core at ODP Site 959 show that deformation was active until at least 99 Ma (late Albian; Mascle *et al.* 1996). Bouillin *et al.* (1994) employed apatite fission-track (AFT) techniques to date the thermal rejuvenation of the marginal ridge caused by ridge-transform intersection, using samples of tectonized Lower Cretaceous sandstones recovered by submersible from the steep southern slope of the marginal ridge. Bouillin *et al.* (1994) inferred that the heat transferred to the continental margin during ridge-transform intersection, probably through the means of hot fluids at shallow crustal levels, would be sufficient to cause total resetting of the tracks in the apatites so close to the continent–ocean transition. Cooling ages ranged from the Late Cretaceous to Eocene on first analysis (44–68 Ma), although re-examination of the same samples confirmed only older ages, ranging from 68 to 92 Ma (Bouillin *et al.* in press). An age for ridge–transform intersection of about 90 Ma would thus appear to be consistent with AFT data and also large scale plate reconstructions (Klitgord & Schouten 1986). Assuming a constant rate of plate separation it is possible to estimate the time at which the intra-continental transform regime was replaced by an active ocean–continent system, being half way between the start of rifting and ridge–transform intersection. We thus estimate intra-continental wrenching ceased at about 105 Ma.

Drill Sites

Four sites on the Côte d'Ivoire–Ghana margin were drilled during Leg 159 (Mascle *et al.* 1996); Sites 959 and 960 are located on the crest of the ridge, while Sites 961 and 962 are situated close to the ridge but further west towards the continent–ocean transition on the west side of the Deep Ivorian Basin (Fig. 1). Sites 961 and 962 show long stratigraphic gaps in their sedimentary record between tectonized clastic sediments of Early Cretaceous age and a Neogene pelagic drape. This hiatus is probably related to long term mass wasting along the steep slope of the transform ridge. As such these sites provide little information on the behaviour of the margin after the end of intra-continental wrenching (105 Ma). Sites 959 and 960 however provide almost continuous sedimentation throughout the Cretaceous and form the basis of this study (Fig. 3). At each site an Aptian–Albian (99–121 Ma) clastic deltaic–lacustrine sequence, showing intense deformation, is unconformably overlain by a mixed clastic/carbonate sequence of shallow water facies, dated as Turonian to Santonian (93–83 Ma), passing up into deeper water hemipelagic shales (Upper Cretaceous to Palaeocene), Lower Tertiary siliceous sediments, and finally pelagic Neogene chalks and carbonate oozes. No obvious shallowing of the sediment facies is visible, although the Cenomanian (93–99 Ma) is missing at Site 960 and was presumably eroded before the deposition of the shallow marine Turonian (93–89 Ma). At Site 959 the Cenomanian–early Turonian is present as a condensed shallow-water deposit of peloidal limestone and high-energy carbonate sands. Water depths remain shallow until the Late Cretaceous when they show a long term deepening to the present. Sedimentary evidence is compatible with the interpretation indicating ridge–transform intersection in the late Cenomanian–Turonian (89–99 Ma).

Apatite fission-track analyses

Apatite fission-track analysis is ideally suited to obtain information relating to low temperature (<130°C) thermal histories, specifically the magnitude and timing of maximum palaeotemperature. For geologically relevant timescales fission tracks are stable at temperatures <*c.* 50°C; above this temperature

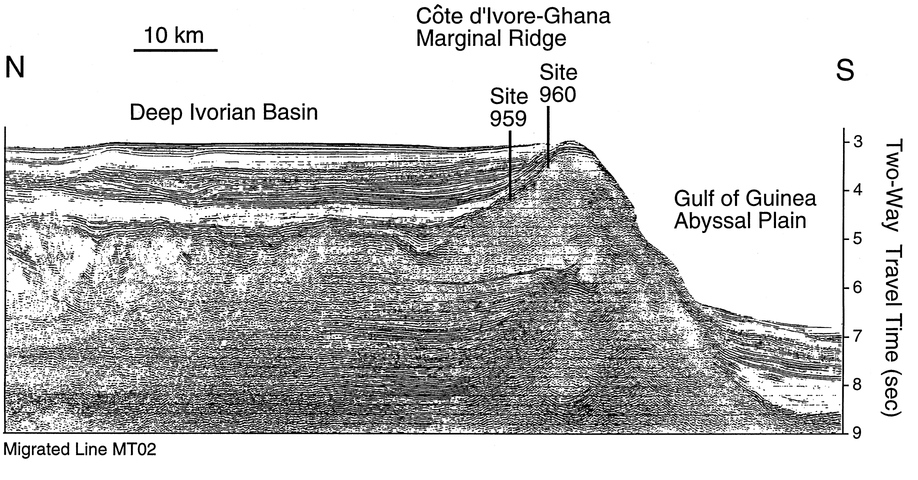

Fig. 2. Multichannel seismic line running across the Côte d'Ivoire–Ghana margin, showing the prominent acoustic basement of the marginal ridge and its steep southern margin (from Basile *et al.* 1993)

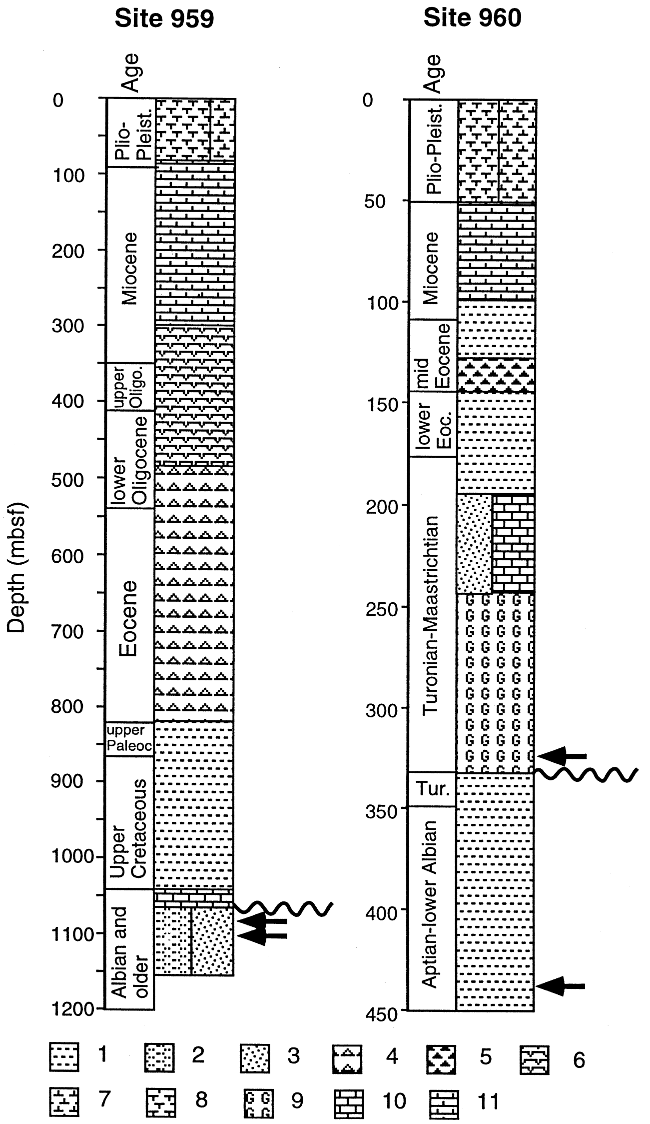

Fig. 3. Schematic stratigraphic log of Sites 959 and 960, where the most complete sections, recording the vertical motions of the margins were documented. 1, claystone; 2, siltstone; 3, sandstone; 4, porcellanite; 5, chert; 6, diatomite; 7, nannofossil ooze; 8, foraminiferal ooze; 9, grainstone; 10, limestone; 11, nannofossil chalk. Arrows mark the location of AFT analyses.

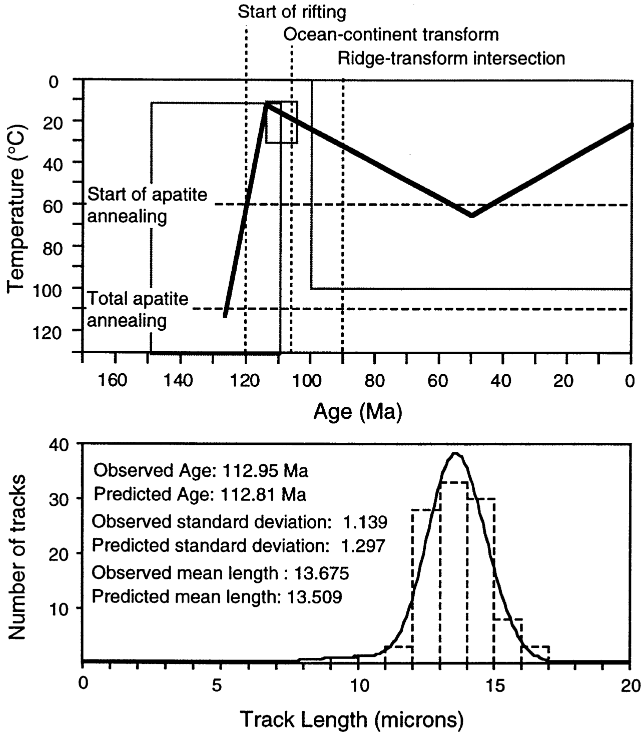

Fig. 4. (**a**) Modeled AFT thermal histories for detrital apatite taken from sample 960A-37R showing rapid cooling at around 115 Ma, during the presumed intra-continental transform phase. Boxes represent the constraints to modeling imposed by the FT age, age of sedimentation, and present day borehole temperatures. (**b**) Model parameters predict a track length distribution very similar to that actually measured from the sediments.

partial annealing (track shortening) occurs until at temperatures of 110–125°C (for most apatite compositions), fission tracks are completely annealed. Because fission tracks form continuously, each track can experience a different maximum temperature, resulting in an integrated length distribution diagnostic of the sample's cooling history. The range of observed track lengths can thus be used to model the cooling of a given sample through this temperature range (see Green *et al.* 1989 for a full discussion of this technique).

In an attempt to provide a better age constraint to ridge–transform intersection AFT analysis was performed on sandstones taken from the tectonized sediments at each of Sites 959 and 960. The samples were analysed at University College, London, following irradiation at the Risø Reactor at the National Research Center, Rosklide, Denmark. Four samples gave good quality age data, all of which were similar to the stratigraphic age, indicating that these samples have not been totally reset (>120°C) since deposition. All quoted ages are central ages, with the full analytical data being published separately (Clift *et al.* in press). At Site 959 sample 959D-71R gave an age of 105 ± 5 Ma, while sample 959D-73R gave an age of 88 ± 4 Ma. At Site 960 sample 960A-37R gave an age of 113 ± 4 Ma and sample 960A-59R gave an age of 108 ± 4 Ma. Modeling of fission track length and age data using the approach adopted in Gallagher (1995) allows a 'best' thermal history for each sample to be derived. The technique is based on a form of stochastic search over a broad range of thermal histories using a genetic algorithm. Figure 4 shows the results of modeling the FT data for sample 960A-37R. In this example the data require a component of pre-depositional cooling from >120°C between 120 and 115 Ma followed by minor post-depositional annealing in the Eocene with temperatures of ≤70°C, which are insufficient to significantly modify the earlier, provenance-related thermal history. The remaining three samples, irrespective of their measured ages, all yielded similar thermal histories that require a component of pre-depositional rapid cooling at 120–115 Ma.

The age of rapid cooling predates the end of sedimentation of the tectonized sequences. As the deformed nature of the sediments indicates that the margin must have been active up to this time it is not possible for ridge-transform intersection to have caused this heating and cooling. The cooling history recorded by the apatites is one reflecting a process operative during intra-continental wrenching. Diagenetic clay minerals within these sediments (Holmes in press) show that *in situ* heating of the sediment above 90°C has not taken place, constraining the cooling to being pre-depositional. We thus interpret the rapid cooling to reflect rapid erosion of the basement adjacent to what has been interpreted as a pull-apart basin, based on the presence of large thicknesses of syn-transform sediment close to the margin. As there is no appropriate source immediately north of the ridge, it is presumed that the sediment was derived either from the relatively unrifted basement to the south, i.e., NE Brazil, or along strike from African basement to the east. The need for an initial tectonically driven uplift limits the source to being relatively close to the transform boundary. Assuming normal geothermal gradients of approximately 30° km^{-1}, 120°C of cooling would correspond to 3.5–5 km of denudation from the combined effects of *c.* 1 km of tectonically driven uplift and isostatic rebound associated with subaerial erosion.

The fission track data show that the apatites from the drill samples were not reset by a passing ridge crest after deposition (cf., Bouillin *et al.* 1994, in press). The apatites may have experienced some very minor annealing during the Eocene, although exactly what is causing this is not clear. There is no evidence to suggest that this is burial related, yet this period is one of passive thermal subsidence when enhanced heatflow would not be expected. Interestingly, Pickett (in press) notes the presence of a structural break at 759 mbsf, within the Eocene section suggesting tectonic activity at this time. Nonetheless, the samples are dominated by an earlier provenance-related thermal history reflecting cooling of the source terrain from which they were eroded. The effect of ridge-transform intersection on these samples is insignificant.

Flexure

Topographic and gravity studies on the northern edge of the Falkland Plateau (Lorenzo & Wessel 1995) have shown that flexural coupling between the oceanic and continental plates is occurring at this transform margin. If this process is manifest at other passive transform margins it might be expected to significantly affect their subsidence histories, as the present day depth to continental basement close to the continent–ocean transition will be greater than if the margin subsidence was compensated by Airy isostasy. In effect, coupling between the two plates causes a downbending of the continental plate adjacent to the continent–ocean transition, whereas the oceanic plate is dragged up by a similar amount. Such coupling might be expected to begin following the end of active motion along the plate boundary. That this is occurring on the Côte d'Ivoire–Ghana margin is shown by the fact that the sediment-unloaded depth to basement of the adjacent oceanic crust is 500 m shallower than would be predicted for its age (cf. Stein & Stein 1993). In this study we model the progressive, increasing flexural deformation of the Côte d'Ivoire–Ghana margin using a cooling halfspace model (Sandwell & Schubert 1982), rifted at 120 Ma and undergoing coupling since ridge–transform intersection (90 Ma). In effect continental crust with a 30 Ma age is juxtaposed at the time of ridge–transform intersection against 0 Ma old oceanic crust. Since the new oceanic crust will cool and subside more quickly than the rifted continental plate, flexural coupling will cause the continental crust to subside more rapidly than it would otherwise. The program of Lorenzo & Wessel (in press) is used to calculate the increasing flexural deflection, which reaches 650 m today and is shown in Fig. 5. In order to interpret the subsidence history of the margin in terms of thermal rejuvenation by the passing spreading ridge crest it is first necessary to subtract the flexural effect from the total subsidence to estimate what the depth to basement would have been if local isostasy had been operating throughout the margin's evolution.

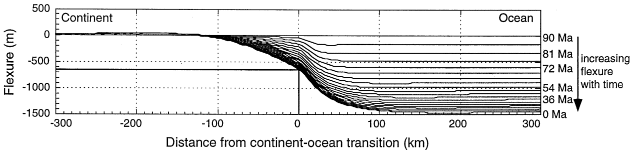

Fig. 5. Flexural model of the Côte d'Ivoire–Ghana margin, using a 22 km thick continental crust, with rifting starting at 120 Ma. Incremental flexure is shown as a function of distance from the continent–ocean transition in 20 time steps starting at the time of ridge-transform intersection (90 Ma) and continuing until the present. Thick, dark lines show how flexural deformation close to the continent–ocean transition today is responsible for around 650 m of vertical displacement.

Subsidence analysis

The stratigraphy at each of the ODP drill sites can be used to reconstruct the vertical motions of the margin since break-up through performing a backstripping subsidence calculation (Sclater & Christie 1980). Although this method assumes local isostatic equilibrium this can be corrected for by using the flexural model shown in Fig. 5. The tectonic subsidence of the pre-rift basement can be calculated using the sediment thicknesses, ages and lithologies, as well as water depth estimates derived from the cored material, to remove the effects of sediment and water loading. The result is a vertical motion history that can be linked to tectonic processes. By estimating a minimum and maximum water depth for each biostratigraphic tie point two subsidence curves are generated, between which the actual basement subsidence is believed to lie. The two subsidence curves show the effective uncertainties in the subsidence analysis, as water depths represent by far the largest variable. One problem encountered in this area was that drilling at both Sites 959 and 960 terminated in syn-transform deposits, and so an estimate for the thickness of underlying material had to be made in order to correct for the compaction and loading of this material. On the basis of seismic and submersible observations it appears that syn-transform clastic sediments overlie Pan-African basement at the base of the marginal ridge (Mascle *et al.* 1994), giving a total of about 2 km of syn-transform sediments. Water depth estimates were taken from micropalaeontological constraints both from the shipboard work (Mascle *et al.* 1996), and later work on agglutinated foraminifers indicating mid-bathyal depths (500–1500 m) during the Late Cretaceous–Palaeocene (M. Kaminski pers. comm. 1995).

Figure 6 shows the results of the backstripping operation after correction for the incremental flexure. The reconstructed curves are compared with the extensional subsidence curves of McKenzie (1978) for a variety of stretching factors (β). Active extension, directed principally parallel to the transform margin, is considered to have ended with intra-continental wrenching (Mascle *et al.* 1996). Two cross-cutting model curves are shown for the period prior to ridge–transform intersection. The steepest curve (maximum β) runs from the minimum water depth point at the start of rifting to the maximum water depth point at the end of rifting (resulting in the greatest possible relative uplift at the time of ridge–transform intersection). The

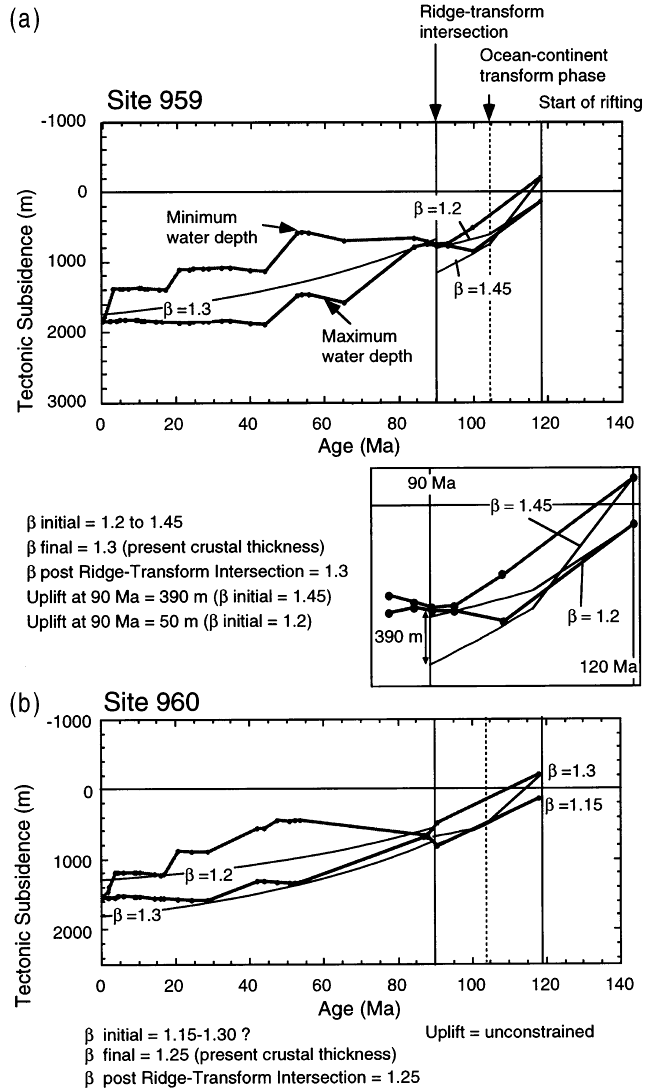

Fig. 6. Backstripped subsidence curves for Sites 959 and 960, also corrected for the progressive flexural depression of the margin, so as to reconstruct what the subsidence would have been if the margin had remained in a state of local isostatic equilibrium. Insert below (a) is a close-up of the early subsidence history at Site 959, showing how the relative uplift is measured by the difference between the minimum and maximum β models and the reconstructed histories.

shallower curve runs from the maximum water depth at the start of rifting to the minimum water depth point at ridge–transform intersection, resulting in very little relative uplift. Both of these models are consistent with the given water depth constraints.

Since thermal rejuvenation of the lithosphere, and/or igneous underplating and crustal thickening, might be expected at ridge–transform intersection, the model curves are truncated at this time. The model curve for the period following ridge–transform intersection has been shifted vertically to match the slopes of the reconstructed subsidence history. Slope, and not depth, is the sole determining criteria in placing the model curve for this later time period, as any igneous underplating along the margin would shift the depth of the basement vertically, making the absolute depth an unreliable measure of lithospheric β. The slope of the model curve after 90 Ma therefore reflects only the total lithospheric β following ridge–transform intersection.

Effect of ridge–transform intersection

One aspect of the curves that is apparent on first inspection is the lack of a major uplift event at around 90 Ma. To determine the amount of uplift it is necessary to compare the reconstructed depth to basement with that predicted if there had been no thermal rejuvenation. We use the extension model of McKenzie (1978) to calculate the expected depth to basement at ridge–transform intersection for the β derived from the syn-rift section. The lack of subsidence data at Site 960 predating ridge–transform intersection makes the determination of uplift difficult, as there is no base level with which to compare the reconstructed depth at 90 Ma, although the 2 km estimate for the syn-transform deposits would indicate an initial β of about 1.15–1.3. At Site 959 the apparent uplift of the basement relative to the McKenzie subsidence profile is modest. An estimate of the maximum uplift can be achieved by following the steepest tectonic subsidence curve (β=1.45). The subsidence model shows a 390 m discrepancy with the reconstructed history (Fig. 6). Conversely, the minimum extension estimate (β=1.2) shows a 50 m discrepancy, interpreted as transient thermally driven uplift.

Following ridge–transform intersection, subsidence at both Sites 959 and 960 was relatively slow, corresponding to a total β of 1.3 at Site 959 and 1.25 at Site 960. At Site 959 this is only slightly more than the initial β, suggesting that the degree of thermal rejuvenation (i.e. thinning) of the lithosphere during ridge–transform intersection is small. This interpretation is in accord with the minor relative uplift observed at Site 959. Since thermal rejuvenation is modest and has dissipated in the 90 Ma since ridge–transform intersection, it is possible to infer the total effective β from the present day depth to basement, after correcting for flexural depression of the margin. The depths correspond to a total β of 1.3 at Site 959 and 1.25 at Site 960, reflecting the fact that Site 959 is positioned slightly off the ridge crest, on the edge of the Deep Ivorian Basin. Furthermore, the present depth to basement at Site 959 is the same as that which would be expected from the inferred crustal extension from the syn-rift period (β=1.2–1.45). There is no evidence to indicate either continued extension or rethickening of the crust by igneous underplating since the end of intra-continental wrenching.

Discussion and summary

The degree of thermally driven uplift at ridge–transform intersection recorded in the sediments of the Côte d'Ivoire–Ghana margin is very much less than that estimated from seismic studies of transform margins such as the Exmouth Plateau (Lorenzo & Vera 1992) and the Newfoundland margin (Todd *et al.* 1988), as well as from simple heat conduction models such as Todd & Keen (1989). This implies that the degree of heat transfer across the continent–ocean transition, at least along the Côte d'Ivoire–Ghana margin, is very much less than assumed in these models. Subsidence reconstructions show that any uplift generated at ridge–transform intersection is dissipated shortly afterwards and cannot be responsible for the modern shape of the ridge. Instead the small increase in β going north from Site 960 to Site 959, as well as bathymetry and seismic surveys (Sage 1994), suggest that the initial stretching of the continental crust may have been lower on the crest of the ridge compared to the adjacent Deep Ivorian Basin. In effect the transition from rifted crust in the Deep Ivorian Basin to unrifted crust on the Brazilian side of the margin would be gradational across the width of the marginal ridge. It is noteworthy that wide angle seismic surveys across the ridge in the vicinity of the drill sites also show thicker crust under the ridge compared to the Deep Ivorian Basin (Sage 1994), an interpretation supported by modeling of marine gravity anomalies (Pontoise *et al.* 1990). However, evidence from tectonized Aptian–Albian sediments, which form the acoustic basement of the ridge, suggests that the present ridge was the site of a pull-apart basin during intra-continental wrenching (Mascle *et al.* 1996), implying thinner crust than on either side. This basin is known to have suffered transpressional deformation and inversion, on the basis of positive flower structures observed in seismic lines (Basile *et al.* 1996), and this would permit the once thinned crust to have been rethickened to the degree now observed (i.e., 22 km). The subsidence analysis does not allow the two alternative explanations or the presence of thicker crust under the marginal ridge than under the Deep Ivorian Basin to be distinguished.

Flexural unloading of the major faults that form the transform boundary may also play a significant part in the formation of the marginal ridge. After accounting for the greater sediment loading experienced by the crust of the Deep Ivorian Basin compared to the ridge (i.e., about 1600 m of post-rift sediment) the difference in elevation between the basin and ridge is about 550 m. However, as the marginal ridge is more seriously affected by the flexural coupling across the margin than the Deep Ivorian Basin we would predict that the difference would actually be 650 m greater if the margin was in local isostatic equilibrium. Simple isostatic calculations suggest that the crustal thickness differences between basin and ridge (22 km versus 19 km; Pontoise *et al.* 1990) would account for 300 m of this total, assuming standard crustal densities. The average slope of the transform margin is around 12°, which even supposing some slope degradation through time suggests that the major bounding faults dip oceanward. As intra-continental wrenching ceased the margin would thus have been unloaded with the removal of the Brazilian crust to the south, allowing flexural rebound, much as footwall uplift represents rebound in extensional settings (Barr 1987). Such rebound would have taken place soon after the start of active continent–ocean transform motion, and we suggest that this process may account for the other 900 m of relative uplift, a hypothesis supported by the 20 km wavelength of the ridge uplift, characteristic of flexural unloading on this scale (Barr 1987). Coupling of the two plates following ridge–transform intersection would prevent this process being an important factor from this time onwards.

Apatite fission-track data from sediments from the ridge at Sites 959 and 960 indicate a rapid cooling at 120–115 Ma, which is too early to be related to ridge–transform intersection. They indicate rapid erosion of 3.5–5 km close to the transform margin and redeposition as lacustrine or deltaic deposits within a pull-apart basin. This figure is similar to the estimate of 2–5 km of denudation since 1.2 Ma documented by AFT dating from the northern San Andreas fault (Dumitru 1991). Along the Dead Sea transform about 3000 m of recent tectonic uplift is noted along the southeastern side of the Dead Sea, although this has yet to be deeply eroded (M. Eyal pers. comm. 1996). The Côte d'Ivoire–Ghana margin appears to have behaved as a typical intra-continental transform zone before final separation of Africa and Brazil.

P.D.C. would like to thank G. Karner, J. Mascle, M. A. Holmes, D. Watkins, K. C. Lohmann and S. Allerton for stimulating discussions, and K. Gallagher and A. Roberts for informative reviews. E. Uchupi provided comments on an earlier version of this manuscript. JOI/USSAC provided support for AFT analysis and salary support for P.D.C. This is WHOI contribution number 9372.

References

Barr, D. 1987. Lithospheric stretching, detached normal faulting and footwall uplift. *In*: Coward, M.P., Dewey, J.F. & Hancock, P.L. (eds) *Continental Extensional Tectonics*. Geological Society, London, Special Publications, **28**, 75–94.

Basile, C., Mascle, J., Sage, F., Lamarche, G. & Pontoise, B. 1996. Pre-cruise and site surveys: a synthesis of marine geological and geophysical data on the Côte d'Ivoire–Ghana transform margin. *Proceedings of the Ocean Drilling Program, Initial Results*, **159**, College Station, TX (Ocean Drilling Program), 47–60.

——, ——, Popoff, M., Bouillin, J.-P. & Mascle, G. 1993. The Côte d'Ivoire–Ghana transform margin: a marginal ridge structure deduced from seismic data. *Tectonophysics* **222,** 1–19.

Bouillin, J.-P., Poupeau, G., Riou, L., Sabil, N, Basile, C., Mascle, J., Mascle, G & Equanaute Scientific Party 1994. La marge transformante de Côte d'Ivoire–Ghana: premières donneés thermo-chronologiques (campagne Equanaute, 1992). *Comptes Rendus de l'Acadamie des Sciences, Paris* **318,** 1365–1370.

——, ——, Labrin, E., Basile, C., Sabil, N., Mascle, J., Mascle, G., Gillot, F. & Riou, L. Fission track study of the marginal ridge of the Ivory Coast–Ghana transform margin. *Geo-Marine Letters*, in press.

Brunet, M, Dejax, J., Brillanceau, A., Congleton, J., Downs, W., Duperon Landoueneix, M., Eisenmann, V., Flanagan, K., Flyn, L., Heintz, E., Hell, J., Jacobs, L., Jehenne, Y., Ndjeng, E., Mouchelin, G. & Pilbeam, D. 1988. Mise en évidence d'une sédimentation précoce d'âge Barrémien dans le fossé de la Bénoue en Afrique Occidentale (bassin du Mayo Oulo Léré, Cameroun), en relation avec l'ouverture de l'Atlantique sud. *Comptes Rendus de l'Acadamie des Sciences, Paris* **306,** 1125–1130.

Clift, P.D., Carter, A. & Hurford, A.J. Apatite fission track dating of ODP Sites 959 and 960 on the transform continental margin of Ghana, west Africa. *Proceedings of the Ocean Drilling Program, Scientific Results,* **159**, College Station, TX (Ocean Drilling Program), in press.

Dumitru, T.A. 1991. Major Quaternary uplift along the northernmost San Andreas Fault, King Range, northwestern California. *Geology* **19,** 526–529.

Emery, K.O., Uchupi, E., Phillips, J., Brown, C. & Mascle, J. 1975. Continental margin off Western Africa: Angola to Sierra Leone. *American Association of Petroleum Geologists Bulletin* **59,** 2209–2265.

Fail, J.P., Montadert, L., Delteil, J.R., Valery, P., Patriat, P. & Schlich, R. 1970. Prolongation des zones de fractures de l'océan Atlantique dans le golfe de Guinée. *Earth and Planetary Science Letters* **7,** 413–419.

Gallagher, K. 1995. Evolving temperatures histories from apatite fission-track data. *Earth and Planetary Science Letters* **136,** 421–435.

Green, P.F., Duddy, I.R., Laslett, G.M., Hegarty, K.A., Gleadow, A.J.W. & Lovering, J.F. 1989. Thermal annealing of fission tracks in apatite 4: quantitative modeling techniques and extension to geological timescales. *Chemical Geology* **79,** 155–182.

Holmes, M.A. Thermal diagenesis of Cretaceous sediment recovered during ODP Leg 159 to the Côte d'Ivoire–Ghana margin. *Proceedings of the Ocean Drilling Program, Scientific Results*, **159**, College Station, TX (Ocean Drilling Program), in press.

Klitgord, K.D. & Schouten, H. 1986. Plate kinematics of the Central Atlantic. *In*: Vogt, P.R. & Tucholke, B.E. (eds) *The western North Atlantic regions*. The Geology of North America, **M**. Geological Society of America, 351–377

LePichon, X. & Hayes, D.E. 1971. Marginal offsets, fracture zones and the early opening of the South Atlantic. *Journal of Geophysical Research* **76,** 6283–6293.

Lorenzo, J.M. & Vera, E.E. 1992. Thermal uplift and erosion across the continent–ocean transform boundary of the southern Exmouth Plateau. *Earth and Planetary Science Letters* **108,** 79–92.

—— & Wessel, P. 1995. Tectonic and stratigraphic response to flexure across a continent–ocean transform boundary: Falkland/Malvinas Plateau, South Atlantic. *EOS* **76,** 580.

—— & —— Flexure across a continent–ocean fracture zone: The northern Falkland/Malvinas Plateau, South Atlantic. *Geo-Marine Letters*, in press.

——, Mutter, J.C., Larson, R.L. & Northwest Australia Study Group 1991. Development of the continent–ocean transform boundary of the southern Exmouth Plateau. *Geology* **19,** 843–846.

Mascle, J., Blarez, E. & Marinho, M. 1988. The shallow structure of the Guinea and Côte d'Ivoire–Ghana transform margins: their bearing on the equatorial Atlantic Mesozoic evolution. *Tectonophysics* **155,** 193–209.

—— & Equanaute Scientific Party 1994. *Les marges continentales transformantes Ouest-Africaines–Côte d'Ivoire, Ghana, Guinée*. IFREMER, Série Repères Océan, **5**.

——, Lohmann, G.P., Clift, P.D., et al. 1996. *Proceedings of the Ocean Drilling Program, Initial Results*, **159**, College Station, TX (Ocean Drilling Program).

McKenzie, D.P. 1978. Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters* **40,** 25–32.

Pickett, E.A. Structural observations from the Côte d'Ivoire–Ghana Transform Margin. *Proceedings of the Ocean Drilling Program, Initial Results*, **159**, College Station, TX (Ocean Drilling Program) in press.

Pontoise, B, Bonvalot, S., Mascle, J. & Basile, C. 1990. Structure crustale de la marge transformante de Côte d'Ivoire–Ghana deduite des observations de gravimétrie en mer. *Comptes Rendus de l'Acadamie des Sciences, Paris* **310,** 527–534.

Rabinowitz, P.D. LaBrecque, J.L. 1979. The Mesozoic Atlantic ocean and evolution of its continental margins. *Journal of Geophysical Research* **84,** 5973–6002.

Sage, F. 1994. *Structure Crustale d'une Marge Transformante et du Domaine Océanique Adjacent: exemple de la marge de Côte d'Ivoire–Ghana*. Ph.D. Thesis, Univ. Paris VI.

Sclater, J.G. & Christie, P.A.F. 1980. Continental stretching: an explanation of the post Mid-Cretaceous subsidence of the central North Sea basin. *Journal of Geophysical Research* **85,** 3711–3739.

Sandwell, D. & Schubert, G. 1982. Lithospheric flexure at fracture zones. *Journal of Geophysical Research* **87,** 3949–3958.

Stein, C.A. & Stein, S. 1993. Constraints on Pacific midplate swells from global depth-age and heat flow-age models. *In*: Pringle, M. et al. (eds) *The Mesozoic Pacific; Geology, Tectonics and Volcanism*. American Geophysical Union Monographs, **77**, 53–76.

Todd, B.J. & Keen, C.E. 1989. Temperature effects and their geological consequences at transform margins. *Canadian Journal of Earth Sciences* **26,** 2591–2603.

——, Reid, I. & Keen, C.E. 1988. Crustal structure across the southwest Newfoundland transform margin. *Canadian Journal of Earth Sciences* **25,** 744–759.

Received 22 April 1996; revised typescript accepted 22 October 1996.
Scientific editing by Alan Roberts and Nick Kusznir.