Deep structure of the southeastern margin of the West African craton from seismic reflection data, offshore Ghana

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Abstract: Seismic reflection data, acquired as part of an oil exploration survey offshore Ghana, have been reprocessed to reveal the deep structure of the Proterozoic continental crust on the continental shelf, off West Africa. The seismic profiles presented are located across the Romanche transform margin, which transects the West African craton (WAC) margin where it is bounded by the Pan-African Dahomeyide orogen. The seismic data reveal highly reflective middle–lower crust of the WAC but a nearly transparent upper crust of *c.* 10 km thickness. Bundles of discontinuous reflections are located at the base of the unreflective upper crust and locally define the trough of a synformal structure interpreted as the keel of a Palaeoproterozoic (Birimian) greenstone belt exposed onshore. The deepest crust imaged is characterized by more continuous, subhorizontal reflections that are very similar to those observed in the lower crust of cratonic areas such as the Superior Province. Near the WAC margin the subhorizontal reflections are truncated by east-dipping reflections in the Pan-African domain, which are correlated with cratonward directed fold-and-thrust structures formed during the *c.* 600 Ma Pan-African orogeny. These seismic observations represent, to date, the first deep seismic reflection images of the West African craton margin and the continental lithosphere in the region.

Seismic reflection surveys have amply demonstrated the capability of the active source technique to reveal the deep structure of Precambrian orogens (Lucas *et al.* 1993; Lewry *et al.* 1994; Calvert *et al.* 1995). Among the significant results of deep seismic reflection experiments are evidence for highly reflective lower crust underlying cratons and well-defined Moho beneath shield areas, and occasional observations of strong reflectors in the continental mantle lithosphere that have been interpreted as relict subduction zones (Green *et al.* 1990; Calvert *et al.* 1995). To date, however, only few deep seismic reflection experiments have been carried out in Africa, although the network of orogenic belts outlining cratons and the cratons themselves are potentially fertile targets for systematic seismic exploration (e.g. De Wit & Tinker 2004). The West African craton (WAC) with its surrounding Pan-African orogens is a prime example of regions yet to be explored. In this paper, we report the results of the reprocessing and interpretation of marine seismic reflection data from an oil exploration survey offshore Ghana, which image the Proterozoic crust across the southeastern margin of the WAC. The data allow correlation of some of the deep reflectors with structures projected from the surface geology and provide, for the first time, seismic images of the deep structure of a critical segment of the WAC boundary. The seismic reflection data presented here also demonstrate the potential for using offshore marine seismic survey data to begin addressing the problem of the paucity of deep seismic data to investigate the continental lithosphere in Africa.

Tectonic setting

The Romanche transform margin offshore Ghana formed as a result of the Mesozoic break-up of Gondwana, and preserves the unmistakable scar of its transform origin (Basile *et al.* 1993; Mascle *et al.* 1996; Attoh *et al.* 2004). This margin is a favourable setting to use marine seismic reflection techniques to investigate the structure of the adjoining continental crust because, unlike rifted margins, a normal thickness of continental crust is predicted to be preserved here. The preservation of minimally extended continental lithosphere in such settings is the result of their formation by wrench shear (Scrutton 1982) and is evident in the satellite-derived bathymetric map (Fig. 1), which suggests that continental crust of significant thickness extends offshore until it abruptly abuts the oceanic crust. This transform margin setting is ideal to image the deep structure of the WAC boundary as well as the bounding Pan-African Dahomeyide orogen using marine seismic reflection data.

Figure 2 displays the relation between the Romanche fracture zone (RFZ) and onshore tectonic elements; it shows that the Ghana transform continental margin, bounded by the RFZ, is

From: Ennih, N. & Liégeois, J.-P. (eds) *The Boundaries of the West African Craton.* Geological Society, London, Special Publications, **297**, 499–508.
DOI: 10.1144/SP297.24 0305-8719/08/$15.00 © The Geological Society of London 2008.

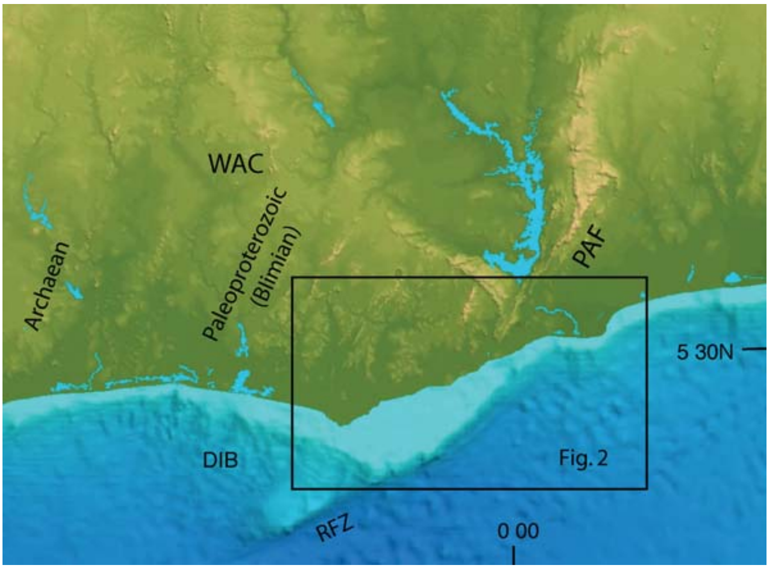


Fig. 1. Satellite-derived topographic–bathymetric map of the southeastern margin of the WAC showing the Palaeoproterozoic and Archaean domains, the bounding Pan-African orogen (Pan-African front; PAF) and the bathymetric expression of the Ghana margin, which suggests that the shelf is underlain by relatively thick continental crust. The Ghana margin is bounded by the Romanche fracture zone (RFZ) and the Deep Ivorian basin (DIB). In the land area, the highest regions (>1000 m) are light brown and the lowest regions are green, and in the ocean basin, areas below 2000 m are deep blue and those above 200 m are light blue, indicating the steep slope along the RFZ.

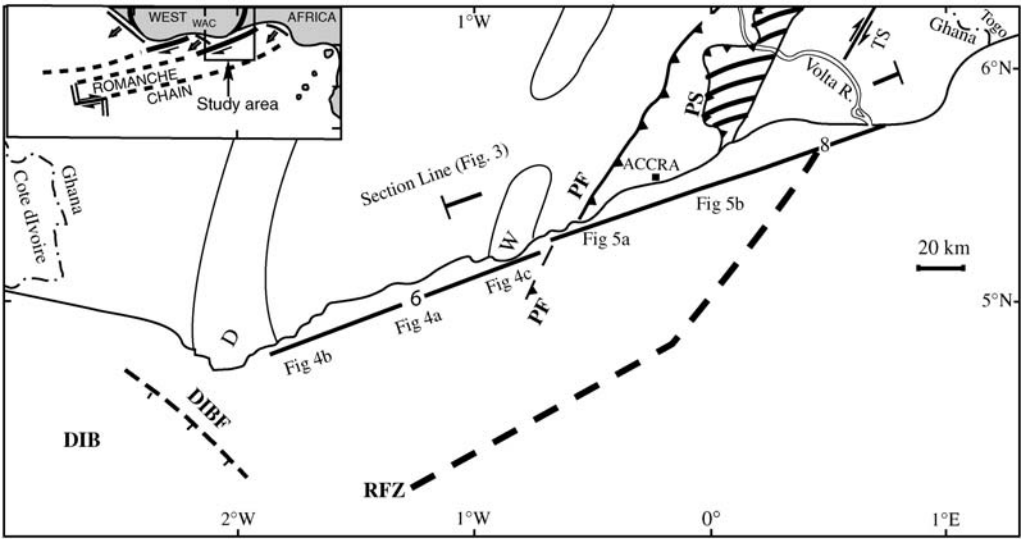


Fig. 2. Principal tectonic elements of onshore geology in relation to the deep seismic sections: PF, Pan-African Front; PS, Pan-African Suture (HP mafic suture zone unit shown by striped pattern); TS, Trans-Saharan Shear Zone; DIB, Deep Ivorian basin; DIBF, Deep Ivorian basin fault. Palaeoproterozoic greenstone belts are shown (W, Winneba; D, Dixcove). Inset shows the RFZ in relation to other Atlantic fracture zones.

an oblique transect of the boundary between the WAC underlain by Palaeoproterozoic (Birimian) rocks and the Pan-African Dahomeyide orogenic belt (Attoh & Ekwueme 1997). Along this transect, the principal tectonic units of the onshore geology include prominent structures of the Pan-African orogen that are favourably oriented to be imaged by offshore seismic reflection lines. The major tectonic elements of the Dahomeyide orogen include the Pan-African front (PF), which represents the western limit of deformation in the external zone, and the Pan-African suture (PS), represented by a ductile shear zone at the base of high-pressure mafic granulites that define the eastern edge of the WAC (Castaing *et al.* 1993; Attoh *et al.* 1997; Attoh & Morgan 2004). Offshore seismic reflection profiles reveal the projections of the Pan-African structures beneath the shelf strata (Attoh *et al.* 2004) and indicate that the projection of the RFZ coincides with the Trans-Saharan shear zone (TS), a dextral shear zone, rather than the PS or PF as was previously assumed (Edwards *et al.* 1997; Attoh *et al.* 2005). The southwestern limit of the Ghana shelf is defined by the Deep Ivorian basin (DIB), which is bounded by a normal fault, the Deep Ivorian basin fault (DIBF) (Fig. 2). This fault formed as part of the lithospheric-scale rift system, which was kinematically coupled to the Romanche transform during the opening of the Atlantic (Attoh *et al.* 2004).

To the west of the Pan-African front (PF, Fig. 2) is the Palaeoproterozoic (Birimian) granite–greenstone terrane of the WAC. It is composed of NNE–SSW-striking greenstone belts (D and W, Fig. 2) as well as intervening metasedimentary belts intruded by granitoids. These lithologies underlie the southeastern terrane of the extensive *c*. 2.1 Ga juvenile crust (Attoh & Ekwueme 1997). The Birimian granite–greenstone terrane of the WAC displays many similarities to Late Archaean greenstone belt terranes such as those of the Superior Province of Canada (Sylvester & Attoh 1992, and references therein). Because granite–greenstone belts are significant components of many cratons, the deep structure of such terranes and the nature of their boundaries are important to understanding the origin of the cratonic lithosphere worldwide.

Figure 3 is schematic geological cross-section of the southeastern margin of the WAC and its bounding Pan-African Dahomeyide orogen. It shows the current interpretation of the structures within the Dahomeyide orogen such as the westward verging folds represented by Ataccora nappes and panels of thrust-bounded units. Granitoid rocks to the east of the suture zone are inferred to represent terrane accreted to the WAC margin. The Winneba greenstone belt (W) is schematically shown as a synformal structure west of the Pan-African front.

Seismic reflection profiles

Seismic data and processing

The multi-channel seismic reflection data used in this study were acquired for oil exploration by Geophysical Services Incorporated (GSI) in the 1980s. Digital tapes containing stacked seismic sections for selected lines, including the two lines discussed in this paper, were made available to us by Western Geophysical Incorporation. Although the survey was designed to image the sedimentary section of the Ghana shelf and slope, the record lengths are long enough to image basement structures on the lines near the coast. The two lines discussed here were selected because they are located close to the shoreline and contain significant record lengths beneath the Phanerozoic sedimentary section. Our efforts focused on post-stack reprocessing, carried out using ProMax (TM, Landmark Corporation) software. Most of the post-stack improvement in the sections shown were the result of coherency enhancement and time variant scaling (e.g. Kong *et al.* 1985), which revealed some of the deep structures better than migrated sections (Attoh *et al.* 2004).

Interpretation of seismic sections

Attoh *et al.* (2004) used available chronostratigraphic data from oil exploration wells located across the Ghana shelf to calibrate the seismic stratigraphy and this led to the identification of three principal stratigraphic sequences representing pre-, syn- and post-rift strata. The pre-rift sequence consists largely of Palaeozoic strata ranging in age from Devonian to Carboniferous deposited on Palaeoproterozoic basement. The synrift sequence consists of Aptian to Albian siliciclastic strata, which have a distinct continental facies. These strata are inferred to have been deposited in pull-apart basins that formed during early stages of continental break-up along intracontinental strike-slip fault zones (Mascle *et al.* 1996). Seismic images of folding and faulting of the pre-rift and synrift strata were also presented and interpreted by Attoh *et al.* (2004) as the products of transpressional deformation related to transform tectonics.

The seismic sections shown in Figure 4 are along line 6, which is located primarily in the offshore projection of the WAC. They reveal strong reflections in the Palaeoproterozoic continental crust beneath the reflectors of the overlying

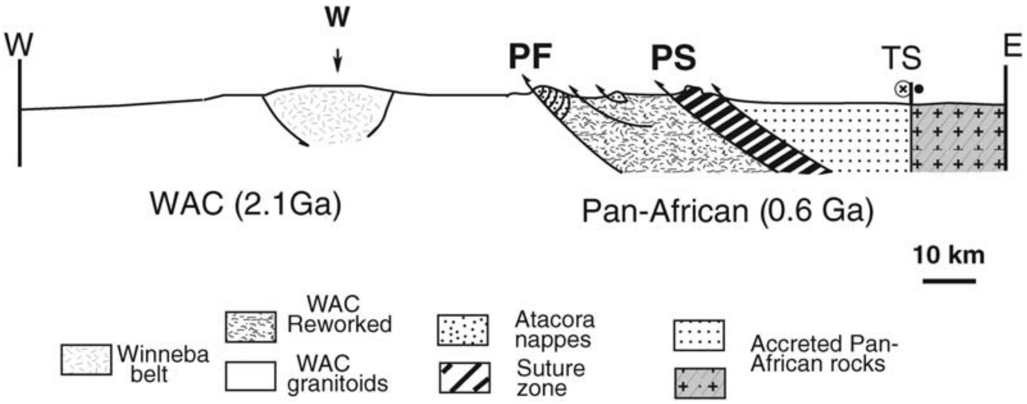


Fig. 3. Schematic geological cross-section of southeastern margin of the WAC and its bounding Pan-African Dahomeyide orogen.

sedimentary strata consisting of Palaeozoic (pre-rift) and Mezozoic (synrift) sequences. Near the centre of this profile (Fig. 4a), the sedimentary strata are offset by up to 3.5 s along a steep, east-dipping normal fault; on the downthrown side of this fault Devonian–Carboniferous strata show evidence of thickening from east to west and are interpreted as growth strata deposited during a Palaeozoic rifting event. The overall structure is interpreted as a half-graben. In the western, upthrown block of the half-graben, the stratified rocks thin rapidly (to less than 0.5 s) allowing access to a significant thickness (*c*. 6.0 s) of Palaeoproterozoic WAC basement. The Proterozoic crust underlying the downthrown block, and especially east of it (Fig. 4a), also reveals prominent reflectors that provide important information on the structure of the WAC.

Figure 4b is the detailed seismic section of the western end of line 6; it displays a non-reflective upper crust down to a depth of 3 s. This non-reflective upper crust (*c*. 10 km thick) contrasts sharply with highly reflective crust below 3.5 s. Discontinuous reflection bundles (B1, B2 and B3) with typical vertical extents of *c*. 0.3 s occur at 3 s (5900 CDP (common depth point)) and 3.4 s (5500 CDP) and 3.6 s (5300 CDP). The reflection bundle at B1 apparently dips shallowly eastward and projects to the B2 reflections, suggesting that B1–B3 reflections, with minor offsets, may represent reflectors that define the base of the upper crust, which is inferred to be composed of the metasediments and paragneisses exposed onshore. This non-reflective upper crust may represent Palaeoproterozoic intrusions. In contrast, the bundles of strong, subhorizontal reflections between 4 s and 7 s (B4–B5) are characteristically more continuous and define a crustal zone of strong reflections that is similar to middle and lower crustal reflections just above the Moho in the Superior Province (Calvert *et al.* 2004) and other cratons. Assuming a velocity of 6–7 km s^{-1}, the maximum depth estimate for these reflections is, however, only 20–25 km, which would correspond to depths in the middle crust rather than the lower continental crust. The longest of these deep reflections (B5) extends for *c*. 15 km (6000–5400 CDP) between 6.5 and 7 s (Fig. 4b, at the bottom of section) and is subhorizontal.

In Figure 4c, between 1700 and 1300 CDP, the 'bow-tie effect' characteristic of opposite-dipping bands of reflectors is evident at 4.5 s (C1). It indicates a synformal structure, which is here interpreted as the trough of the Winneba greenstone belt (W, Fig. 3). This synformal trough correlates with the eastern projection of the inferred base of supracrustal rocks to the west (B1–B3, Fig. 4b) and represents the first ever seismic image of the deep structure of a Palaeoproterozoic greenstone belt in the WAC. Assuming typical continental crust velocities of 6–7 km s^{-1}, the estimated preserved thickness of greenstone belt supracrustal succession is *c*. 12 km, a thickness that is close to the stratigraphic thickness of typical greenstone belt sequences of the WAC (e.g. Attoh & Ekwueme 1997, tables 5.4.1 and 5.4.2), in contrast to the thickness of 4–5 km estimated from gravity anomaly models. For example, Attoh (1982) presented gravity models to show that the maximum thickness of the Palaeoproterozoic Nongodi greenstone belt is less than 5 km whereas the estimated stratigraphic thickness is greater than 9 km. Similarly, in the Archaean Sula greenstone belt of Sierra Leone the total stratigraphic thickness is about 8 km (see Attoh & Ekwueme 1997, and references therein), which is greater than typical estimates from gravity anomalies.

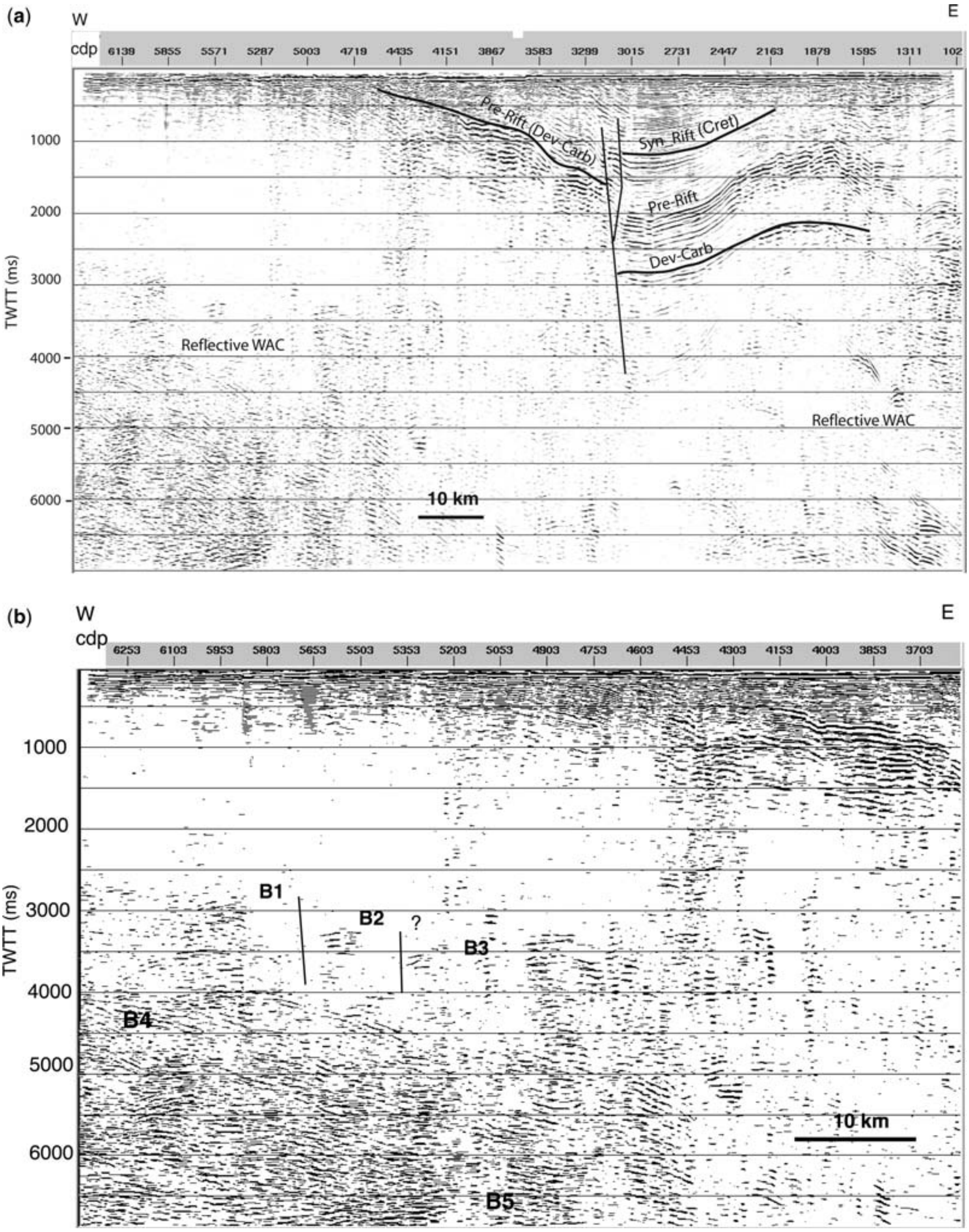


Fig. 4. Seismic profiles along line 6. TWTT, two-way travel time. (**a**) Reflective Palaeoproterozoic crust in the upthrown block and beneath the half-graben filled with thick Palaeozoic growth-strata. (**b**) Reflections at the western end of line 6, showing nearly transparent upper crust beneath thin Palaeozoic strata underlain by highly reflective middle crust (below 4.0 s). (**c**) 'Bow-tie' pattern of opposite-dipping reflections (C1) indicating a synformal structure correlated with the Palaeoproterozoic Winneba greenstone belt and prominent, east-dipping, deep reflections (C2) near the WAC margin.

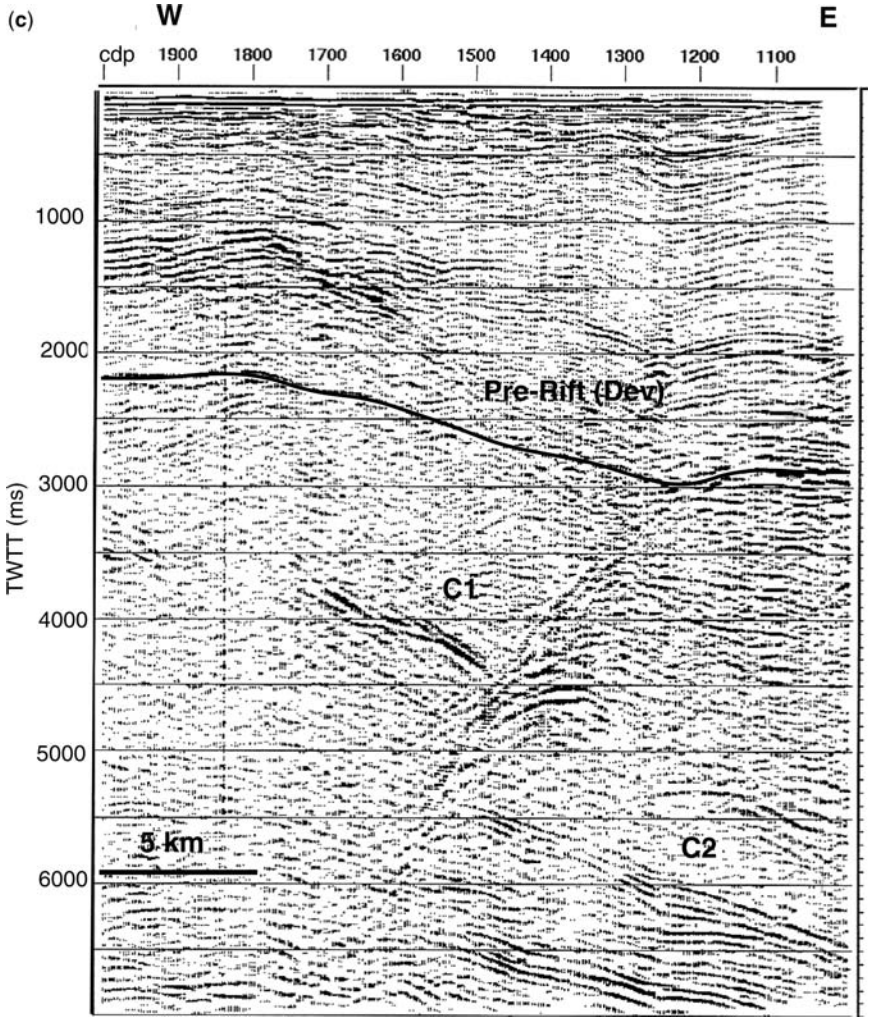


Fig. 4. (*Continued*).

The deep reflections near the eastern end of line 6 (Fig. 4c; C2) dip to the east from 5.5 s to 7 s. This feature is consistent with the apparent easterly dip of the mid-crustal reflections in the WAC (Fig. 4a), which may indicate overall tilt of the crust underlying the Ghana shelf as a result of uplift along the lithospheric-scale normal fault (DIBF, Fig. 2) located to the west of the seismic sections. This uplift was probably in response to the formation of the DIB by rifting, a deformation that was kinematically linked to wrench displacements along the Romanche transform during the opening of the equatorial Atlantic (Basile *et al.* 1993; Attoh *et al.* 2004). Thus the western segment of the Ghana margin represents an uplifted block formed by flexural rebound as a result of displacement along the DIBF where relatively deep, east-tilting Proterozoic crust is preserved by the tectonic processes linked to transform margin formation. The strong, east-dipping, deep reflections near the WAC margin (e.g. C2 in Fig. 4c) may, however, also be relict of the thinning of the continental margin during Neoproterozoic rifting leading to the formation of the eastern margin of the WAC. This earlier rifting was responsible for the creation of the WAC margin, which was subsequently sutured along the Pan-African Dahomeyide orogen.

Line 8 is located mainly in the Pan-African domain (Fig. 2) and, as such, provides the setting to image the deformed rocks of the WAC margin. Near the western end of line 8, reflections below

3.5 s (Fig. 5a) are interpreted as structures related to the Pan-African front (PF). The east-dipping deep reflections contrast with the coherent reflections of the Palaeozoic (pre-rift) and Mesozoic (synrift) strata overlying them. The deep reflections (D1–D2) between 4 and 7 s project to the structures with similar dip in the PF zone of the onshore surface geology (Attoh *et al.* 1997). These deep reflections are characterized by bundles of strong reflections (<0.3 s thick), separated by broader zones (up to 1.0 s thick), and are especially well developed from 7300 to 7700 CDP. The apparent flattening of these structures (E1–E2, Fig. 5a) between 3.5 and 4.5 s (at 8000–7800 CDP) is also consistent with the nappe structures of the Pan-African Dahomeyide external zone. The apparent changes in the amplitude of deep reflections are ascribed to the variable intensity of deformations in the Pan-African zone, especially in the deformed margin of WAC represented onshore by protomylonitic granitoid gneisses.

Figure 5b displays the reflections in the Pan-African domain near the central part of line 8; they consist of deep, east-dipping reflection bundles (F1–F2) which contrast with the subhorizontal reflections of the overlying pre-rift Palaeozoic strata. The western end of the prominent deep reflections (F1) coincides with the projection of the Pan-African suture zone (PS) mapped on the surface whereas a broad zone to the west of it is relatively unreflective. This broad, unreflective crust extends to the zone of deep reflections near the west end of line 8 (Fig. 5a); it is here interpreted as consisting of weakly foliated granitoids, as evident in the variable intensity of deformation in the surface rocks. The coincidence of the strong reflections (F1) with the projection of PS (Fig. 5b) is considered significant, as it may represent the elusive deep seismic image of the Pan-African Dahomeyide suture. Assuming average crustal rock velocities of 6–7 km s^{-1} and noting that the thickness of the Phanerezoic sedimentary section is over 2 s, the estimated thickness of Palaeo- and Neoproterozoic crustal sections imaged in Figure 5 is <12 km. Thus the section of the WAC margin imaged here probably represents upper crustal levels, especially considering that the orogenic belt is assumed to be underlain by over-thickened crust.

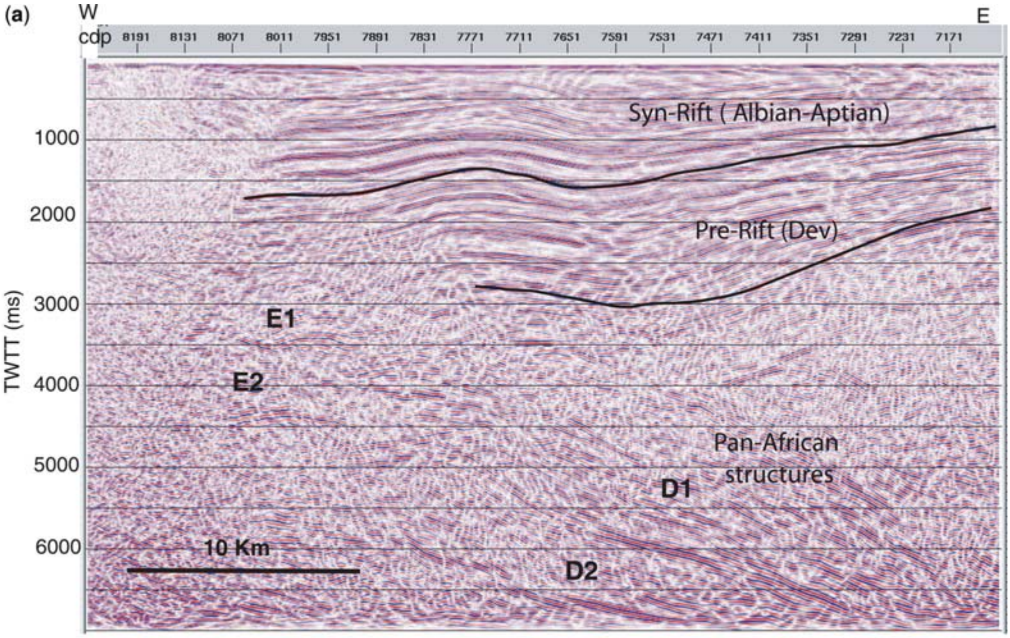
In comparing the reflections along line 6 with those along line 8 (Fig. 5) the transition from the WAC domain to the Pan-African domain becomes evident. For example, the reflections in the WAC domain (Fig. 4) are largely subhorizontal to gently dipping and apparently represent deeper crustal levels, whereas those from the Pan-African belt are characterized by significant dip and apparently represent higher crustal levels.

Discussion

The southeastern margin of the WAC provides the setting to address several critical problems in this region, using deep seismic reflection data. These problems include (1) determining the deep structure of the Pan-African domain, which preserves the record of West Gondwana assembly from the WAC and adjoining cratons (Amazonian and São Francisco–Congo), and (2) evaluating the inference from seismic tomography of the WAC margin (Ritsema & van Heijst 2000), which showed that a shear-wave velocity anomaly corresponds to this boundary. The anomaly has been interpreted as evidence for a cool, thick, cratonic lithosphere (>200 km) beneath the WAC in contrast to the thinner, warm lithosphere beneath the surrounding Pan-African domain. Thus this region is clearly a key transect to investigate lithospheric aggregations during Gondwana assembly (using controlled source seismic imaging techniques). The data presented in this paper, although limited, confirm the potential of using deep seismic reflection data to map the cratonic boundary and contribute to the understanding of some of these problems.

The contrasting deep reflections of the WAC crust compared with the Pan-African domain are similar to those of other Proterozoic continental margins (e.g. Lucas *et al.* 1993; Hall *et al.* 1995) but these data represent the first such observations in West Africa. Deeper seismic reflection data are needed across this and other segments of the WAC boundary to further document lithospheric interactions during Gondwana assembly. In the WAC itself, a significant result of the interpretation of the available data is the estimate of the thickness of Palaeoproterozoic greenstone belts that is consistent with those from stratigraphic measurements. In contrast, the estimated thickness of greenstone belts based on gravity anomaly models tends to be significantly low (e.g. Attoh 1982), and this has been a perplexing problem of greenstone belt geology. In the Pan-African Dahomeyide domain, the east-dipping, deep reflections beneath the weakly deformed, subhorizontal, Phanerozoic reflectors are those predicted from onshore geological observations. The dipping structures in the transition zone between the WAC and the Pan-African domain may represent relict structures of the thinning of WAC lithosphere during rifting but could also be the result of Pan-African deformation extending deep into the craton.

The strong reflectivity of the WAC deep crust is typical of cratonic areas, suggesting a common origin of the reflections (Klemperer 1987; Green *et al.* 1990; Calvert *et al.* 1995). The subhorizontal attitude and the amplitude of reflectors in the deep crust are, however, unexpected from surface



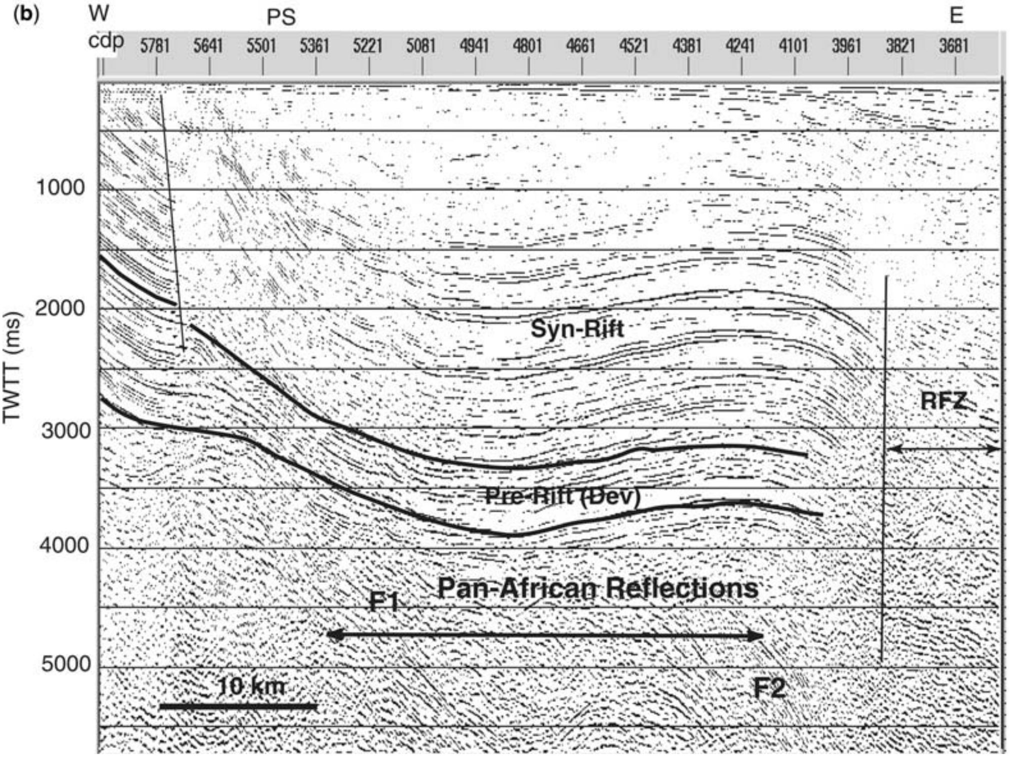


Fig. 5. Seismic profiles along line 8 showing deep reflections: (**a**) correlated with Pan-African structures onshore (D1–D2, E1–E2) along the deformed margin of the WAC; (**b**) (F1–F2) underlying the projection of the Pan-African suture zone (PS).

geological considerations or predictions of physical properties of the deep crust. For example, whereas the surface geology displayed on maps and evident in the field relations on which they are based presents complex dipping structures, the deep reflections, in contrast, suggest simple, near-horizontal structures. In that sense, there appears to be a disconnection between the surface geology projections and deep reflections, but such complex structures, including the presence of subhorizontal sills, are beyond the resolution of the seismic reflection technique. The occurrence of strong reflections in the lower crust below the brittle–ductile transition is also unexpected, although it has been suggested that the acoustic discontinuities may be related to the presence of fluids in the deep crust (e.g. Ross *et al.* 2004). Connolly & Podladchikov (2004) have shown that, in appropriate tectonic settings, fluid flow in the deep crust can be restricted to a zone of neutral buoyancy that can preserve optimally oriented porosity domains to account for lower crustal reflectors. Their model predicts an inverted pressure gradient, which acts as a barrier to upward fluid flow, resulting in the stagnation of deep-crust generated fluids that can account for mid-crustal seismic reflectivity.

This project was supported by a grant from Petroleum Research Fund of the American Chemical Society (PRF 34908-AC8). Thanks go to Western Geophysical Incorporation for providing the offshore Ghana seismic data and to the Ghana National Petroleum Corporation for information on and permission to access the data. A. Calvert, C. M. Doucouré and M. De Wit provided helpful reviews of the paper.

References

ATTOH, K. 1982. Structure, gravity models and stratigraphy of an Early Proterozoic volcanic–sedimentary belt in northeastern Ghana. *Precambrian Research*, **18**, 275–290.

ATTOH, K. & EKWUEME, B. N. 1997. The West African shield. *In*: DE WIT, M. J. & ASHWAL, L. (eds) *Greenstone Belts*. Oxford University Press, Oxford, 517–528.

ATTOH, K. & MORGAN, J. 2004. Geochemistry of high-pressure granulites from the Pan-African Dahomeyide orogen, West Africa: constraints on the origin and composition of the lower crust. *Journal of African Earth Sciences*, **39**, 1201–1208.

ATTOH, K., DALLMEYER, R. D. & AFFATON, P. 1997. Chonology of nappe assembly in the Pan-African Dahomeyide orogen, West Africa: evidence from ^{40}Ar/^{39}Ar mineral ages. *Precambrian Research*, **82**, 153–171.

ATTOH, K., BROWN, L., GUO, J. & HAENLEIN, J. 2004. Seismic stratigraphic record of transpression and uplift on the Romanche transform margin, offshore Ghana. *Tectonophysics*, **378**, 1–16.

ATTOH, K., BROWN, L. & HAENLEIN, J. 2005. The role of Pan-African structures in intraplate seismicity near the termination of the Romanche Fracture Zone, West Africa. *Journal of African Earth Sciences*, **43**, 549–555.

BASILE, C., MASCLE, J., POPOFF, M., BOULLIN, J. P. & MASCLE, G. 1993. The Ivory Coast–Ghana transform margin: a marginal ridge structure deduced from seismic data. *Tectonophysics*, **222**, 1–19.

CALVERT, A. J., SAWYER, E. W., DAVIS, W. J. & LUDDEN, J. N. 1995. Archaean subduction inferred from seismic images of a mantle suture in the Superior Province. *Nature*, **375**, 670–674.

CALVERT, A. J., CRUDEN, A. R. & HYNES, A. J. 2004. Seismic evidence for preservation of the Archaean Uchi granite–greenstone belt by crustal extension. *Tectonophysics*, **388**, 135–143.

CASTAING, C., TRIBOULET, C., FEYBESSE, J.-L. & CHEVREMENT, P. 1993. Tectonometamorphic evolution of Ghana, Togo, and Benin in the light of the PanAfrican/Brasiliano orogeny. *Tectonophysics*, **18**, 323–342.

CONNOLLY, J. A. D. & PODLADCHIKOV, Y. Y. 2004. Fluid flow in compressive tectonic settings: Implications for midcrustal seismic reflectors and downward fluid migration. *Journal of Geophysical Research*, **109**, B04201, doi:10.1029/2003JB002822.

DE WIT, M. J. & TINKER, J. 2004. Crustal structures across the central Kaapvaal craton from deep-seismic reflection data. *South African Journal of Geology*, **107**, 185–206.

EDWARDS, R. A., WHITMARSH, R. B. & SCRUTTON, R. A. 1997. The crustal structure across the transform continental margin off Ghana, eastern equatorial Atlantic. *Journal of Geophysical Research*, **102**, 747–772.

GREEN, A. G., MILKEREIT, B., MAYRAND, L. J. ET AL. 1990. Deep structure of an Archaean greenstone terrane. *Nature*, **344**, 327–330.

HALL, J., WARDIE, R. J., GOWER, C. F., KERR, A., COFLIN, K., KEEN, C. E. & CAROLL, P. 1995. Proterozoic orogens of the northeastern Canadian shield: new information from the Lithoprobe ECSOOT crustal reflection seismic survey. *Canadian Journal of Earth Sciences*, **32**, 1119–1131.

KLEMPERER, S. L. 1987. Reflectivity of the crystalline crust—Hypothesis and tests. *Geophysical Journal of the Royal Astronomical Society*, **89**, 217–222.

KONG, S. M., PHINNEY, R. A. & CHOUDHURY, K. R. 1985. A nonlinear signal detector for enhancement of noisy seismic records. *Geophysics*, **50**, 539–550.

LEWRY, J. F., HAJNAL, Z., GREEN, A. ET AL. 1994. Structure of a Palaeoproterozoic continent–continent collision zone: a Lithoprobe seismic reflection profile across the Trans-Hudson orogen, Canada. *Tectonophysics*, **232**, 143–160.

LUCAS, S. B., GREEN, A., HAJNAL, Z. ET AL. 1993. Deep seismic profile across a Proterozoic collision zone: surprises at depth. *Nature*, **363**, 339–342.

MASCLE, J., LOHMANN, G. P., CLIFT, P. D. ET AL. (eds) 1996. *Proceedings of the Ocean Drilling Program, Initial Report, 159*. Ocean Drilling Program, College Station, TX.

Ritsema, J. & van Heijst, H. 2000. New seismic model of the upper mantle beneath Africa. *Geology*, **28**, 63–66.

Ross, A. R., Brown, L. D., Pananont, P. *et al*. 2004. Deep reflection surveying in central Tibet: Lower crustal layering and crustal flow. *Geophysical Journal International*, **156**, 115–128.

Scrutton, R. A. 1982. Passive continental margins: a review of observations and mechanisms. *In*: Scrutton, R. A. (ed.) *Dynamics of Passive Margins*. American Geophysical Union, Geodynamics Series, **6**, 5–15.

Sylvester, P. J. & Attoh, K. 1992. Lithostratigraphy and composition of 2.1 Ga greenstone belts of the West African craton and their bearing on crustal evolution and the Archaean–Proterozoic boundary. *Journal of Geology*, **100**, 377–393.