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Evidence for late Precambrian plate tectonics in West Africa

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In the Gourma and Iforas regions (Mali) rifting occurred around 800–850 Myr ago along the eastern margin of the West African craton with a triple point in Mali, the Gourma being interpreted as an aulacogen. Oceanic closure around 600 Myr led to a collision between the passive continental margin of the West African craton and an active continental margin to the east displaying island arc and marginal trough volcano–clastic assemblages bordering a deformed continental mass intruded by a high-level batholith. The suture is marked by a string of positive gravity anomalies corresponding to the emplacement of ultrabasic and basic rocks including perhaps ophiolites. East–West shortening was accompanied by the translation onto the West African craton foreland of nappes including internal nappes displaying high pressure–low temperature metamorphism assemblages.

A CONTROVERSIAL subject in orogenesis[1,2] is whether plate tectonics had an important role in the Proterozoic[3,4] or whether *in situ* ensialic models fit the facts[5,6] in the best way. To seek an answer, attention has been focused on the Pan-African, the youngest and best preserved of Precambrian orogenic belts. In the past few years a detailed geological and geophysical investigation has been carried out on the critical Iforas–Gourma region in Mali[7–10] (Fig. 1), an area of about 300,000 km^2, crossing the West African craton and the Pan-African mobile belt to the East. The results show convincing evidence of a Wilson cycle ending with collision between a passive continental margin and an active continental margin.

Pre-Pan-African rifting and the Gourma aulacogen

The West African craton, stable since 1,700 Myr, is partly covered by thin flat-lying cratonic sediments younger than 1,000 Myr (refs 11, 12), but along its eastern margin the Gourma basin is characterised by deep subsidence with an accumulation of over 8,000 m of sediments[9] (Fig. 2). The observed sedimentary sequence with an early terrigenous clastic phase at the base (formations I and II), followed by differentiated carbonate deposits indicating lateral passage platform-slope-trough (formation III) and ending with prograde continental clastic sediments (formations IV and V) is typical of a passive margin[13]. Furthermore analysis of palaeocurrents in the overlying Bandiagara Sandstone Group shows a converging drainage pattern centred on the Gourma with transport from the south-west and west. The shape of the basin, as defined by the distribution of slope sedimentary facies (breccias, turbidites) in the carbonate sequence and by the gravity pattern, is that of a trough orientated WSW–ENE representing a gulf of subsidence within the West African craton, which here forms an embayment. It presents all the characteristics of a typical aulacogen[14]. A detailed sedimentological study will be given elsewhere. Gravimetrically it is marked by positive anomalies which can be traced westwards across the West African craton and this suggests a deep crustal heavy source[15]. We conclude that a major change in sedimentation occurred around 850–800 Myr ago with rifting along the eastern margin of the West African craton with a triple point in Mali: the Gourma is thought to be a failed arm which has evolved as an aulacogen, a comparable situation with that of the Benue trough with respect to the Gulf of Guinea in the Cretaceous[4].

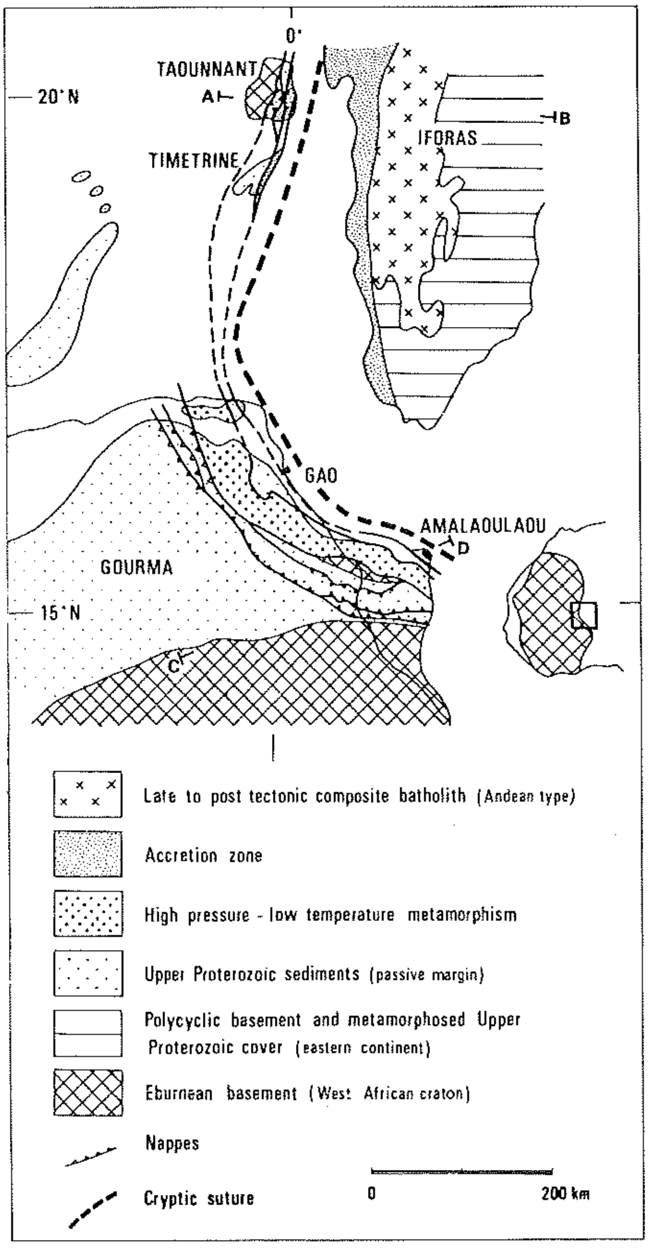

Fig. 1 Major structural units of the Iforas–Gourma region (Mali).

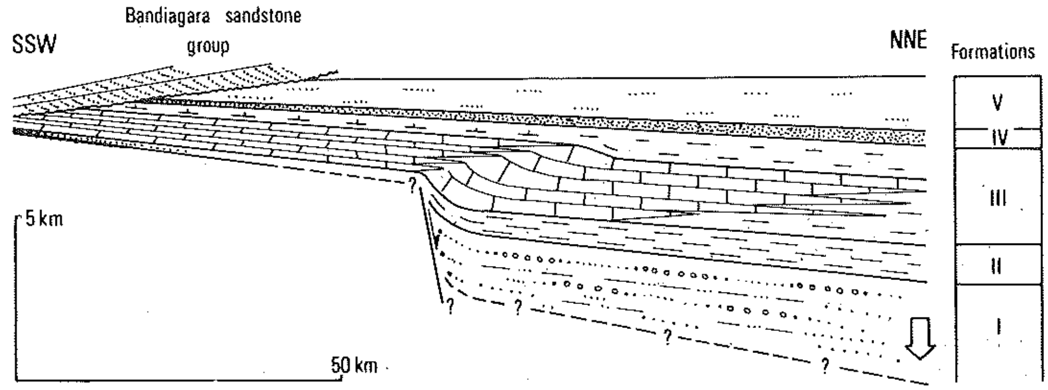

Fig. 2 Schematic SSW–NNE section showing variations in facies and thickness of the Gourma formations I–V.

The associated magmatism would be represented to the North in northwestern Hoggar by the intrusion at around 800 Myr of gabbros and ultrabasic rocks into Upper Proterozoic quartzites and dolomites of shelf type[12,16], and by the presence of deformed north–south dyke swarms of alkaline and peralkaline metarhyolites, undersaturated soda-trachytes and metaphonolites superimposed on basic dyke swarms which may represent the roots of a pre-Pan-African palaeorift[16]. In northeastern Gourma at Amalaoulaou gabbros and ultrabasic rocks are believed to have intruded the base of the crust at ~850 Myr before high pressure–high temperature granulite conditions and to have been tectonically emplaced around 600 Myr at a high level in the suture zone (Lancelot and de la Boisse, personal communication).

The suture

Oceanic closure 200 Myr later during the Pan-African is marked by a suture outlined by a string of positive gravity anomalies with amplitudes of over 30 mgls locally attaining 80 mgls which may be followed over a distance of 2,000 km and which correspond in the Iforas–Gourma region to the position of basic and ultrabasic complexes (mainly layered metagabbros and quartz gabbros) and may include ophiolites (Fig. 3). Interpretation of profiles across the anomalies[15] using the inverse approach[18] and linear programmation[19] shows that the structures, considered as homogeneous bodies with densities >2.8 g cm^{-3} and generally >2.9 g cm^{-3} continue to depths varying from 6 to 20 km. Geometry shows that bodies with a density of 3 g cm^{-3} must be unrooted. In shape they generally show an easterly dip which is in accord with the general movement pattern with thrusting towards the West African craton and with direct field observations made along the banks of the Niger.

South-west and west of the suture

In the Gourma (Figs 1, 4) nappes outcrop over a zone 300 km by 50–80 km wide[20]. The internal nappes (mainly micaschists and quartzites) characterised by high pressure–low temperature metamorphism display flat-lying foliation. Foliation planes bearing phengite cut earlier sharp folds and the grade of metamorphism increases to the south-west where it attains eclogite conditions with a very pure jadeitic pyroxene (de la Boisse, personal communication). Stretch lineation association with NE–SW minor folds perpendicular to the general strike, are well developed within the nappes and along the lower grade mylonitic quartzite soles of the nappes. In northern Gourma the internal nappes come into direct contact with the para-autochtonous folded greenschist facies Gourma formations by underthrusting towards the south-west; to the south they are faulted against the Bourré Massif. The Bourré Massif[21] is a sub-vertical horst of Eburnean granite dated at 2,080± 20 Myr[22] intrusive into subsequently retrograded amphibolite facies Birrimian sediments, overlain in unconformity by upper Proterozoic sericite quartzites and basal polygenic conglomerate. The horst was extruded after the passage of the external nappes, a situation comparable to that of the Mont

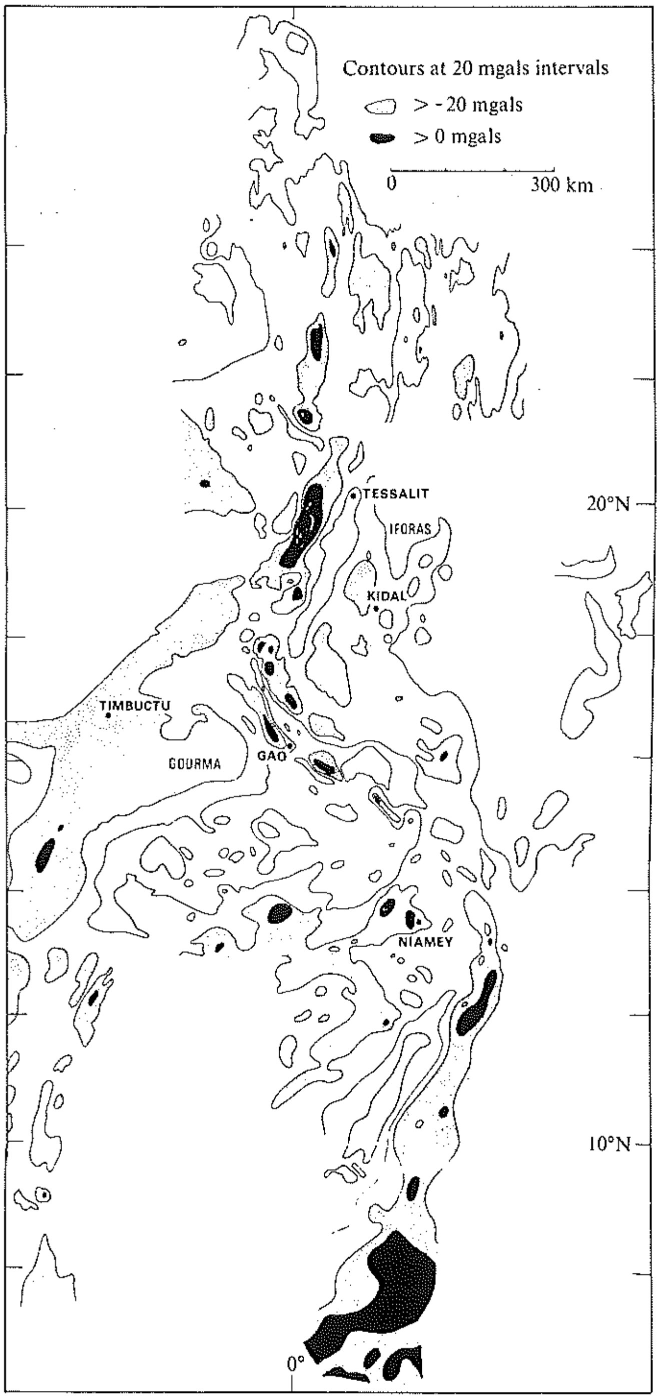

Fig. 3 Simplified Bouguer anomaly map of the eastern margin of the West African craton.

Blanc in the western Alps. The external nappes are sub-horizontal and probably pellicular. They consist essentially of schistose formations belonging to the passive margin displaying greenschist facies metamorphism devoid of high pressure conditions. Over large areas one observes an upright succession and flat schistosity and a-type lineations within the nappes. The Gourma formations I–V described above[13] as forming a pre-Pan-African aulacogen have been strongly deformed to form the para-autochtonous foreland. Major folds are overturned to the south-west and are superimposed on early pre-nappe east–west folds[9]. Between the front of the nappes and Hombori (100 km) several tens of kilometres of shortening implies a 'décollement' with respect to the underlying basement. The non-metamorphic Bandiagara Sandstone Group overlies in unconformity the Gourma Formations I–V and has been affected by a later phase of folding.

Four-hundred kilometres further north, in the Taounnant region two flat-lying superimposed nappes have been mapped directly overlying eroded Eburnean (2,000 Myr old) basement. The lower one consists of a mylonitised unit of quartzites–dolomites presumably belonging to the passive continental margin whereas the overlying one is composed of strongly epidotised metabasalts and diabases containing a blue amphibole, which are thought to come from an oceanic domain to the east. Similarly to the South in the Timetrine, the quartzites, meta-arkoses, phyllites, large serpentine bodies and metabasalts with blue amphibole, are also interpreted as nappes, but here the relationships with the Eburnean basement are obscured by the Cretaceous.

A characteristic feature west of the suture is the total absence of autochtonous Pan-African magmatism. To the east of the suture a strongly deformed zone ~100 km wide is composed of a late Upper Proterozoic volcano–clastic assemblage. It consists of flysch-like metagreywackes with turbidites, conglomerates composed exclusively of volcanic and plutonic pebbles, dacitic breccias and meta-basalts and later meta-andesites volcanic greywackes and a terrigenous flysch unit, suggesting island arc and marginal sea environments, still active during the earlier deformation of the more internal continental domain of the Iforas, a situation similar to that of the upper Cretaceous to Mid-Tertiary flyschs of Western Alps. This assemblage is comparable to that of the 'Série verte' described 300 km further north in North-west Hoggar[16] where geochemical studies have shown the immature nature of the greywackes[23] and the probable derivation of andesites in liaison with a subduction zone by partial melting of the mantle followed by low pressure fractionation[24]. This zone is injected by a considerable volume of predominant pre-tectonic ultrabasic rocks, gabbros and diorites the volume of more acid terms, tonalites and adamellites increasing eastwards. This accretion zone, apparently devoid of an ancient sialic substratum, follows the sheared western margin of the Iforas. It is significant that greywacke formations with associated calk-alkaline magmatism which are widely developed in western Hoggar and the Iforas are totally absent west of the suture. Such an absence would be explained by the former existence of an ocean separating two continents.

The Iforas is a highly deformed sheared continental domain of 2,000 Myr old granulite basement with remnants of supracrustal platform deposits (quartzites and dolomites) overlain by late Upper Proterozoic marginal sea volcano–clastic sediments including a possible tillite intruded by abundant pre-, syn- and post-tectonic granitoids. A zone of late high temperature-low pressure metamorphism with the local occurrence of granulite facies rocks, charnockites and norites (Aguelhoc, Iforas, Egatalis, North-west Hoggar) coincides with the westernmost known area of sialic rock and its Upper Proterozoic cover[20]. A vast composite late to post-tectonic calk-alkaline batholith capped by flat-lying rhyolitic lavas (Nigritian)[10] and cut by sub-alkaline and alkaline ring-complexes occupies the external zone of the continental domain. It coincides with a regional positive gravity anomaly. Emplacement occurred in a zone subjected to pronounced vertical uplift leading to unroofing during the Pan-African. Existing U–Pb data on Zircons (Lancelot, personal communication) suggest this late batholith to have been emplaced in a relatively short interval between 615 and 590 Myr, the dates 616±11 Myr and 613±3 Myr corresponding respectively to a diorite and quartz monzonite, and 586±13 Myr to a hedenbergite–hastingsite–perthite granite belonging to the Kidal ring-complex. Magmatic activity in this zone, however, must have taken place over a long period of time, as the late batholith cuts foliated diorites corresponding to a deeply eroded pre-tectonic palaeobatholith about 700 Myr old. A striking feature of the batholith is the presence of spectacular dyke swarms. Early east–west striking swarms consist essentially of subordinate basic dykes, quartz-microdiorites micro-adamellites and felsites which locally were truncated by high-level adamellite and perthite granite. They are cut by important north–south swarms composed of subordinate basic dykes and

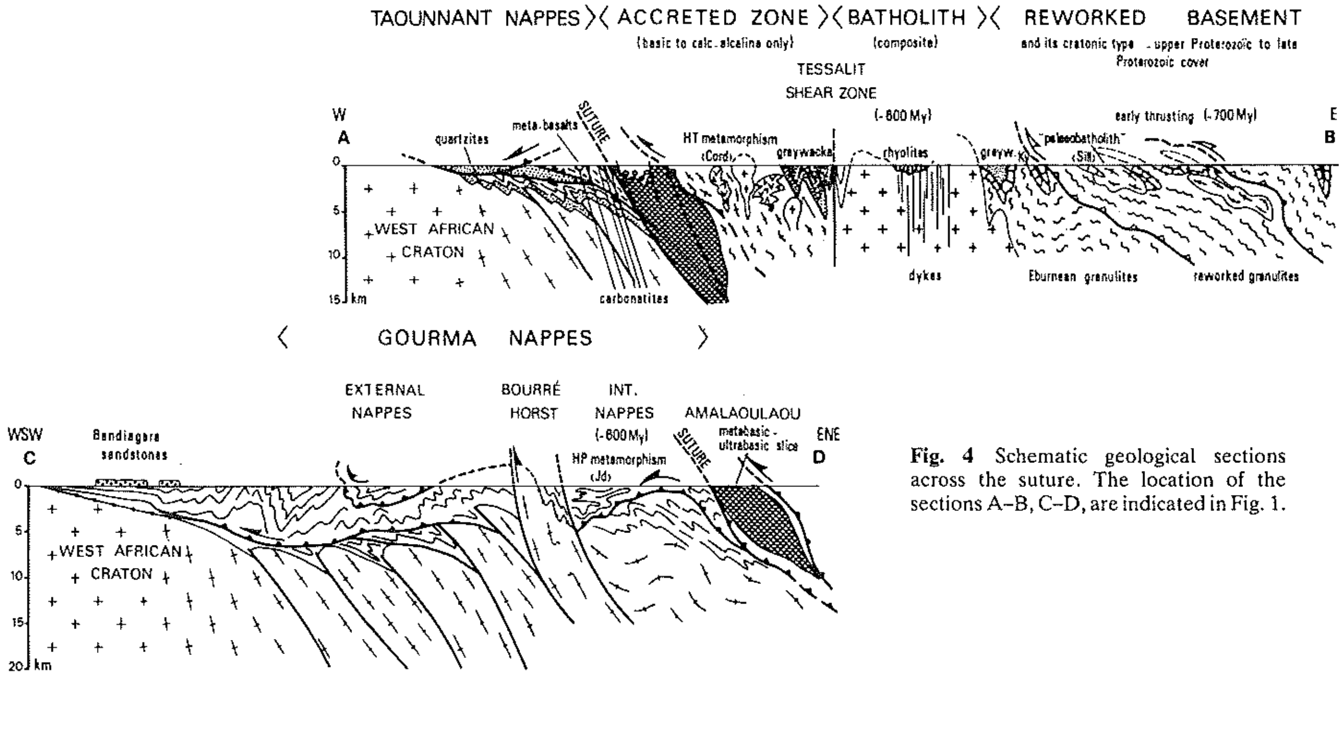

Fig. 4 Schematic geological sections across the suture. The location of the sections A–B, C–D, are indicated in Fig. 1.

several generations of quartz microsyenite, granophyres and rhyolites which can be followed over a distance of over 250 km in the axis of the batholith and which coincide with the Nigritian rhyolite fields and the alignment of ring-complexes. In a different context the batholith displays features reminiscent of an Andean-type batholith[25]. The general disposition of calk-alkaline magmatism east of the suture suggests an easterly dipping palaeo-subduction zone and the high pressure–low temperature metamorphism of the internal nappes of the Gourma would fit with this picture. The late alkaline rocks in the ring-complexes may be related to verticalisation of the Benioff plane accompanied by a diapiric rise of mantle material east of the suture[26].

General movement pattern

The Eburnean basement and supracrustal Upper Proterozoic formations of the Iforas have a complex structural and metamorphic history. Early Pan-African intracontinental deformation dated by the earliest syntectonic granites at 693 ± 0.3 Myr (Renaud Andreopoulos, personal communication) and which took place in barrowian metamorphic conditions generated large northwesterly moving crystalline nappes which were subsequently refolded, leading to considerable tectonic thickening and locally pronounced NW–SE metamorphic gradients[27]. This early phase of deformation produced ENE–WSW structures which have also been observed in the accretion zone and suggest an early collision still not well defined. Late Pan-African deformation directly related to collision with the West African craton resulted in considerable east–west shortening in western Iforas and in the translation of nappes onto the foreland west and south-west of the suture. A characteristic feature east of the suture is the spectacular development of shear belts with a complex history. There is evidence for early sinistral movement along N° 20 trending shear belts and in the closing stages of collision for dextral movement on north–south belts leading to the northwards displacement of western and central Iforas with respect to eastern Iforas. Molassic sediments similar to the 'Série Pourprée' of western Hoggar dated at around 530 Myr (ref. 7) occur in grabens and fill a north–south palaeo-rift on the West-African craton between the suture and Timetrine–Taounnant where it is associated with undersaturated syenites and carbonatites. Late movements as young as the Upper Cambrian produced open north–south folds in the molassic sediments and a system of conjugated NNW sinistral and ENE dextral wrench faults, a system largely developed throughout the Pan-African mobile zone of West Africa[28].

Conclusions

All the evidence points to a modern-type orogenic belt involving a collision during the closing stages of the Pan-African, between the passive continental margin of the West African craton and the active continental margin of an eastern continent. This conclusion fits the recognition of obducted ophiolites at Bou Azzer (Morocco) along the northern margin of the West African craton[29] and supports the collision hypothesis advanced for the Togo–Benin segment[3]. Looking at the Touareg shield (Hoggar, Aïr, Iforas) as a whole, the general pattern of shear belts and late Pan-African deformation seen at an eroded level, shows striking analogies with the tectonic pattern of Asia produced by the collision of India[30]. Palaeomagnetic evidence suggests important horizontal displacement during the Pan-African[31], and proposed reconstructions for 800 Myr and 675 Myr indicate open situations between North America and Gondwanaland and oceanic closure at 600 Myr (refs 32, 33). As no measurements exist for the West African craton, these results are not incompatible with the former presence of a pre-Pan-African ocean situated east of the West African craton.

This article presents the results obtained by a team composed of E. Ball, R. Bayer, J. M. Bertrand, R. Black, H. de la Boisse, A. M. Boullier, R. Caby, J. Ducrot, J. Fabre, J. R. Lancelot, M. Leblanc, A. Lesquer, A. Moussine-Pouchkine, P. Morel-à-l'huissier, U. Renaud-Andreopoulos, J. Sarfati of the Centre Géologique et Géophysique de Montpellier, I. Davison and L. I. Wright of Leeds University and H. Ba and S. Ly of the Direction Nationale de la Géologie et des Mines of Mali. The project was carried out in collaboration with the Direction Nationale de la Géologie et des Mines of Mali and with ORSTOM for the gravity survey. We acknowledge the financial support of the CNRS, the INAG and the BRGM.

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