Paleoproterozoic geology of the Toumodi area, Ivory Coast, 1:100,000

J. Mortimer

Department of Geology, University of Portsmouth, Burnaby Road, Portsmouth, UK

ABSTRACT

Field geological mapping of tropical West Africa is hampered by the variable development of deep regolith and tropical rainforest and this has impeded the progress of geological research. Nevertheless, there are areas in which field geological mapping can be effective. A 1:100,000 scale map of the Paleoproterozoic geology of the West African Craton in the Toumodi area of central Ivory Coast was developed on the basis of five months of independent field geological mapping carried out on foot, and with the aid of a motorised vehicle (Main Map). The field mapping was carried out in 1987 and 1988 using traditional field geological techniques and 1950s 1:50,000 and 1:200,000 topographic base maps published by the Institut Géographique National (Paris). Original field observations and the interpreted geological map were recently compiled using a geographic information system software, which was also used to confirm the positional accuracy of the field mapping using satellite imagery. The field geological mapping presented here provided the basis for recognition of discrete lithostratigraphic terranes exposing different crustal levels within the Paleoproterozoic Birimian domain of the West African Craton which are interpreted to have originated as juvenile crustal additions in a Paleoproterozoic accretionary orogen at an obliquely convergent plate boundary.

1. Introduction

The structure and evolution of mountain belts formed at destructive plate boundaries is determined by geological mapping and supporting petrological, geophysical, geochemical and isotopic studies. While continental collisional processes were recognised in the earlier years of plate tectonic theory as a cause of orogenesis, the existence of accretionary orogens (Cawood, 2005; Cawood et al., 2009) has more recently provided a corresponding framework for understanding orogenesis in circum-pacific style orogenic belts in which continental collisions have not been recognised. The understanding of plate tectonic processes in Phanerozoic orogens is aided by the relative youth of these orogens and consequent preservation of topographic expression and geological exposure of different crustal levels. With increasing age, the upper levels of mountain belts are preferentially and progressively eroded thereby removing parts of the geological record and this erosion reduces the scope for comparisons with equivalent crustal levels of more recent orogens. With increasing age, orogens also tend to have progressively reduced topographic expression, often with commensurate reduction in geological exposure. This is particularly evident in tropical and subtropical regions where intense weathering processes have produced thick regolith and residual soils which may significantly cover the underlying bedrock geology.

Geological mapping of Paleoproterozoic orogenic belts in West Africa is hindered by generally poor geological exposure. However, there are exceptions in which field geological mapping can substantially increase the knowledge of their geology. A 1:100,000 scale geological map of some 2700 km² in the Toumodi area of the central Ivory Coast is presented on a Shuttle Radar Topography Mission (SRTM) 1 arc-second topographic base (Main Map), together with an accompanying map of the locations of field observations and field traverses. These provide a measure of map reliability.

Previous geological mapping in the area was conducted by Archambault, Bouige, and Bonnault (1943), Yace (1976) and Morel (1988). The Toumodi area is underlain by part of a deformed Birimian (ca. 2.1 Ga) greenschist facies volcanosedimentary belt in tectonic contact with mostly amphibolite facies tonalite-trondhjemite-granodiorite (TTG) orthogneisses. Syn- and late-kinematic calc-alkaline granites (s.l.) are also present, with both intruding the supracrustals and the late-kinematic granite also intruding the gneisses. A plate tectonic interpretation of the origin and evolution of the Paleoproterozoic crust in the West African Craton was proposed by Mortimer (1990, 1992a, 1992b), compatible with its development in a Paleoproterozoic accretionary orogen. Contemporary isotopic studies provided evidence of Paleoproterozoic crustal growth in the region (Boher, Abouchami, Michard, Albarede, & Arndt, 1992) and although alternative models have
been proposed (Vidal et al., 2009), plate tectonic interpretations of Paleoproterozoic crust in the southern part of the West African Craton (Abity, Dampare, Nude, & Asiedu, in press; De Kock, Armstrong, Siegfried, & Thomas, 2011) and indeed for older Archaean crust in general (Polat, 2012) extending to at least 3.2 Ga (Cawood et al., 2009) have persisted.

2. Field geological mapping methods

In the current era of high-precision satellite positioning systems, high-resolution satellite imagery and SRTM data aiding geological mapping and interpretation, traditional field skills developed when geologists had no alternatives remain essential. Notwithstanding the enormous contribution modern technology can and does make, there are aspects of traditional field mapping which remain central to producing good geological maps as a foundation for geological studies. These include the location on the ground of small outcrops and float (i.e. rock detritus) not visible in imagery, the lithological identification of outcrops and float, the observation and measurement of rock fabrics and the procurement of rock samples suitable for petrographic, geochemical and isotopic studies. Perhaps a less tangible but nonetheless central benefit of field geological mapping on foot is the development of geological ideas in the mind of the geologist, which are continuously informed and tested by the stream of field observations made while walking the ground. Evidence is actively sought to support or to negate these developing ideas and in this search new observations inevitably arise which cumulatively improve the developing geological map and conceptual models.

Geological mapping was carried out in the area shown in Figure 1 in two field seasons during the months of January–April of 1987 and 1988 over a cumulative period of some five months. During these periods, a total of 96 days were spent actively mapping in the field, including a 6-day reconnaissance trip to a northerly extension of the mapped supracrustal belt and its neighbouring lithologies in an area between Katiola and Dabakala and a 4-day reconnaissance trip to the Korhogo area of northern Ivory Coast. These months of the year correspond with a relatively dry period, during which it is easier to work in the field despite higher temperatures than those prevailing during wetter months. Importantly, local savannah grass and shrub burning by farmers during the dry months provides better visibility of, and access to, small rock outcrops amongst new-growth, near-ground vegetation. Given its relatively central location within the area mapped, a single logistical base was used in the town of Toumodi. The mapping team of three consisted of a geologist, a locally hired field assistant and a driver. A routine was followed in which fieldwork was carried out between 06:30 and 14:30, typically during 5–6 days each week, avoiding the hottest period of the day in the mid- to late-afternoon when working conditions are more difficult. Late afternoons and evenings were available for reviewing field notes, drafting preliminary geological maps and planning the next day’s fieldwork.

The mapping team was transported by motorised vehicle between Toumodi and the field area. The vehicle was also used for reconnaissance of minor roads and bush tracks in search of rock outcrops. All field geological mapping was conducted by traversing on foot, always in a team of two people which enabled the geologist to make observations of the lithology and petrofabrics of rock outcrops and record these observations in field notebooks. Rock samples were also taken for subsequent petrographic and geochemical studies. The geologist also determined the geographic location of the observations with reference to 1950s 1:50,000 and 1:200,000 topographic maps produced by the Institut Géographique National (Paris) with sufficient accuracy for map compilation at 1:100,000 scale. The field assistant carried a sampling sledgehammer, rock samples collected, and sufficient water for the day’s work. The driver remained with the vehicle while the mapping team traversed the terrain on foot. Working with a local field assistant also facilitated communication with local people in the Baoulé language regarding the unusual presence and activities of a field geologist, and would also have facilitated the seeking of assistance in the event of injury.

Civilian satellite positioning systems were in their infancy in the late 1980s. The less than complete constellation of Global Positioning System (GPS) satellites then available meant that periods of time were without adequate satellite coverage. Moreover, until 2000 the imposition of Selective Availability degraded positional accuracy to the extent that individual measurements of longitude (or UTM grid-x) and latitude (or UTM grid-y) had typical positional errors of tens to hundreds of metres. Comparable horizontal location precision was achieved in this area during the 1987 and 1988 field geological mapping campaigns using the available topographic maps by a combination of knowledge of approximate location with respect to rivers, small drainage creeks, roads, tracks and villages, and compass bearings of topographic high points visible from the ground and shown on the topographic maps. The area around Toumodi underlain largely by Birimian supracrustals is topographically variable with many hills, and this greatly facilitated positional location using a magnetic compass. Modern GPS positional measurements post-Selective Availability using high-sensitivity receivers enable far superior horizontal positional accuracy of the order of metres in topographically variable terrain and also under dense vegetation, however this technology was not available when the fieldwork was conducted. The positional
accuracy of the 1:100,000 scale geological map has been qualitatively investigated using geographic information system (GIS) software displaying public domain satellite imagery and SRTM topographic data, confirming that the available topographic base maps enabled the location in the field to be determined to within several hundreds of metres. This amounts to several millimetres on a 1:100,000 scale map.

In addition to SRTM 1 arc-second topographic data and interpreted linear topographic features, Figure 2 shows the locations of field observations and the network of traverses undertaken on foot and in a vehicle during the course of field mapping, with a 1-km buffer around each traverse. The geology of areas lying within the traverse buffers are known with a higher degree of confidence than those lying outside the traverse buffers. Those areas lying outside of the traverse buffers are generally interpolated and in some cases extrapolated from observations made within the traverse buffers. That is not to say that those areas lying outside of the traverse buffers are poorly known because the geological structure provides an adequate framework for interpolation, and to a lesser extent for extrapolation, and can therefore be used with some confidence within the mapped area. In addition, the availability of topographic maps in the field and the observed correlation between some topographic features and underlying geology further aided the geological mapping between traverses. Despite the relatively subdued topography ranging from 73 to 320 m in elevation, the mapped geology shown in Figure 2(d) (and more completely in the main 1:100,000 geological map) shows good correspondence with elements of the topographic data. This provides assurance of the stated positional accuracy of the geological map.

In addition to the accurate topographic base maps with magnetic declination information, essential field equipment used in the collection of data that went into the production of the 1:100,000 geological map included a 10× hand lens to aid mineral identification, a mirror-sighting compass-clinometer with a transparent plastic base for measuring the bearing of topographic features to assist with the determination of geographic location, making dip and strike measurements of rock fabrics and for plotting those measurements on draft maps, a ∼0.6 kg geological hammer for removing weathered surfaces from rock outcrops where advantageous, a ∼5 kg sledgehammer for collecting rock samples from outcrops suitable for the preparation of thin sections and for geochemical analysis, and a sturdy canvas rucksack for carrying rock samples, water and food. Rock samples for petrographic and geochemical studies were shipped from Abidjan to the UK at the end of each field season.
Challenging working conditions prevailed in the field. Relatively high temperatures increased the risk of dehydration and together with high humidity resulted in permanently, uncomfortably wet clothes. Abundant and persistent small flies required the development of a certain mental strength to remain focussed on the geological mapping task, while the presence of venomous insects and snakes required constant vigilance. Malaria was, and remains, endemic in Ivory Coast. In addition to geological field skills, the collection of field data for the geological map presented here therefore required a certain stoicism and persistence probably typical of tropical lowlands worldwide.

Figure 2. SRTM 1-arc-second topographic data shown without and with interpreted linear topographic features. Summary geological map shown with and without field observation locations and field foot and vehicle traverses.
3. Geology

The West African Craton comprises Archaean and Paleoproterozoic domains (Cahen, Snelling, Delhal, & Vail, 1984). The area mapped in this study lies within the Paleoproterozoic domain, in which predominantly linear volcanosedimentary greenstone belts are separated by granitoids, including banded orthogneisses, foliated and unfoliated intrusive. A theme in geological studies of the craton has been the nature of the basement to Birimian volcanosedimentary greenstone belts, and specifically whether orthogneisses which have a higher metamorphic grade than the greenstone belts and which originated at deeper crustal levels are reworked Archaean crust or Paleoproterozoic juvenile crustal additions. Boher et al. (1992) presented the reworked Archaean crust or Paleoproterozoic juvenile belts and which originated at deeper crustal levels have a higher metamorphic grade than the greenstone belts, and specifically whether orthogneisses which

ment to Birimian volcanosedimentary greenstone belts, and specifically whether orthogneisses which have a higher metamorphic grade than the greenstone belts and which originated at deeper crustal levels are reworked Archaean crust or Paleoproterozoic juvenile crustal additions. Boher et al. (1992) presented the first isotopic evidence supporting a Paleoproterozoic (ca. 2.1 Ga) origin. Notwithstanding the need for additional geochronological data throughout the craton to continue to address this question, field geological observations can provide a lithostratigraphic framework for chronostratigraphic studies.

Geological studies of the Toumodi area of Ivory Coast have included preliminary reconnaissance (Archambault et al., 1943) and a focus on petrography and geochemistry of Birimian volcanics (Morel, 1988; Yace, 1976), in what was called the Fétékro belt. Mortimer (1990, 1992a, 1992b) adopted an integrated lithostratigraphic, structural and geochemical approach to the study of the geodynamic evolution of the orthogneisses, volcanosedimentary and intrusive granite (s.l.) components of the Paleoproterozoic domain exposed in the Toumodi area, based on the independent field geological mapping presented here. This work provided a new framework for a plate tectonic interpretation of the origin of the supracrustal and plutonic intrusives (including orthogneisses) at a Paleoproterozoic convergent margin which may now be considered to have been an accretionary orogen.

An overview of the geology of the Toumodi area is presented here to complement the presented 1:100,000 scale geological map. The reader is referred to Mortimer (1999, 1992a, 1992b) for a more comprehensive description of the lithostratigraphy, structural evolution, geochemistry and plate tectonic interpretation of the geodynamic evolution of this part of the West African Craton. The Paleoproterozoic lithostratigraphy of the Toumodi area is shown schematically in Figure 3.

The Birimian volcanosedimentary rocks in the Toumodi area comprise a succession of proximal, and predominantly volcanioclastic lithologies which were called the Toumodi Volcanic Group (TVG) by Mortimer (1990, 1992a). The exposed volcanics are geochemically bimodal, and this provided a basis for the determination of four mappable formations within the preserved volcanic pile. At the base of the TVG, the Zaakro Formation is predominantly mafic with intercalated felsic lithologies. The overlying Bomba River Formation comprises felsic lavas and pyroclastics. An erosional hiatus at the top of the Bomba River Formation marked by the development of a polymict basal conglomerate defines the base of the Akaoka Formation, which comprises otherwise almost entirely mafic lithologies. At the top of the TVG the Bofia Formation comprises predominantly felsic lithologies with minor intercalated mafic material.

Mafic lithologies are clinopyroxene-phryic high-Mg basalts and proximal volcanioclastics of komatiitic to tholeiitic affinities, whereas felsic lithologies include proximal facies calc-alkaline pyroclastics and lavas. Epiclastic lithologies comprising eroded and re-sedimented detritus from the evolving volcanic pile are present throughout the volcanic succession. The TVG is variably deformed and metamorphosed, comprising rocks with well-preserved volcanic and volcanioclastic textures as well as schists in which metamorphic textures predominate. Greenschist facies metamorphic conditions typically produced albite-chlorite-epidote assemblages in mafic lithologies. Clinopyroxene phenocrysts were replaced by chlorite-actinolite-tremolite-epidote. A low temperature blue-green variety is the only hornblende encountered.

The geological structure within the TVG is dominated by NE- to NNE-striking upright, isoclinal folds and associated metamorphic foliation and cleavage, although four deformation phases with associated structures were recognised by Mortimer (1990). At its western limit, the TVG is intruded by foliated calc-alkaline intrusive granites which by virtue of their predominantly vertically dipping, NE- to NNE-striking foliation are considered syn-kinematic.

At its eastern limit, the TVG is thrust over amphibolite facies orthogneisses which have a N-S structural grain, called the Kan River Gneisses (KRG) by Mortimer (1990, 1992b). This contact is a profound structural and metamorphic discontinuity across which the NE- to NNE-striking greenschist facies Birimian supracrustal volcanic pile is in thrust contact with the N-S striking predominantly amphibolite facies mid- to lower crustal KRG. Given the structural nature of this tectonic contact, it follows that the Zaakro Formation, which lies at the base of the preserved TVG stratigraphy, may not be the original base of the TVG. The main deformation effects of this tectonic contact are seen in the KRG, where the tectonic transport of the TVG over the KRG is demonstrated by kinematic indicators within the westerly dipping N-S striking shear fabric in the Boni Andokro Shear Zone (BASZ) within the KRG. BASZ deformation effects within the TVG include westwards-dipping low-angle discontinuities marked by metre-scale quartz veins within hundreds of metres of the contact with the KRG and minor mylonitised zones near the contact. The structural and metamorphic
discontinuity between the TVG and KRG was interpreted by Mortimer (1990, 1992a, 1992b) to be a convergent margin terrane boundary in the sense of Coney, Jones, and Monger (1980).

The KRG comprises four main mappable orthogneiss units (Mortimer, 1990, 1992b) (Figure 3). These are the Loukouyakro Suite (LS) which consists of migmatitic and banded gneisses, the Dieri Kouassikro Trondhjemite (DKT) which is a homogeneous intrusive contained wholly within the deformation envelope of the BASZ, Augen gneiss of the Brobo Shear Zone (BSZ) and the Orumboboka Group Amphibolites which are discrete bodies of banded and massive, structurally discordant amphibolites. The LS, DKT and Augen gneiss of the BSZ comprise a TTG-suite intrusive complex.

Figure 3. Schematic Paleoproterozoic lithostratigraphy of the Toumodi area.
The LS was metamorphosed to amphibolite facies. In places where shearing is weak or absent, it is characterised by plagioclase-green hornblende, biotite-epidote and biotite-green hornblende-epidote (+/- muscovite) mineral assemblages and widespread development of a plagioclase-green hornblende-biotite-epidote-muscovite-sphene mineral assemblage in mafic xenoliths. The poikilitic texture of hornblende in the LS demonstrates its metamorphic origin. Localised retrogression of the amphibolite facies assemblages is confined to shear zones.

The DKT is a homogeneous biotite-bearing intrusive which lacks the amphibolite facies metamorphic mineral assemblages of the LS and therefore its emplacement post-dates the amphibolite facies event. Igneous plagioclase-quartz-biotite-epidote-muscovite is locally preserved, and accompanied by idiomorphic sphene of probable igneous origin. The DKT is contained wholly within the BASZ envelope where exposed and metamorphic biotite-epidote assemblages are confined to discrete blastomylonitic shear zones.

The KRG contains the ductile, crustal-scale, approximately 2 km wide BSZ, which was first recognised by Lemoine (1982) some hundreds of kilometres further north. In its central part it comprises a homogeneous augen gneiss with vertically dipping S-C mylonite fabrics indicating sinistral movement. Amphibolite facies assemblages are retrogressed to muscovite-bearing greenschist facies within discrete shear-controlled domains within the central part of the BSZ demonstrating a protracted shearing history probably occurring during progressive uplift of the KRG. S-C fabrics overprint both the LS and the DKT along the margins of the BSZ demonstrating that they predate at least the most recent shearing. Mortimer (1990, 1992a) proposed some 40 km of sinistral displacement across the BSZ based on a comparison of the Birimian volcanosedimentary stratigraphy in the central and northern parts of the Fétékro greenstone belt and the emerging understanding of the structural evolution of the Birimian volcanosedimentary belts and adjacent orthogneisses.

The eastern boundary of the KRG is marked by another major structural and metamorphic discontinuity called the Dimbokro Shear Zone (DSZ) by Mortimer (1990, 1992a, 1992b). Low-grade siliciclastic sediments of the Comoé basin are exposed to the east of the DSZ. The zone of shearing is defined by the structural interleaving of LS and siliciclastic sediments over a width of at least hundreds of metres. Discrete shear bands in the LS within the envelope of the DSZ are marked by sub-vertical centimetre-scale deformation-related quartz ribbons, which are locally kinked with a sinistral sense of rotation. Like the BASZ, the DSZ was interpreted by Mortimer (1990, 1992a, 1992b) to be a convergent margin terrane boundary.

Both the TVG and the KRG were intruded by calc-alkaline granodiorite-granite plutons with a fundamentally different petrology to the KRG orthogneisses. These I- and S-type intrusives include foliated to weakly and non-foliated types which have consequently been mapped as syn-kinematic and late-kinematic types, respectively. The petrogenesis of these calc-alkaline intrusives and calc-alkaline felsic volcanics within the TVG by partial melting of TTG-suite plutonic rocks was proposed by Mortimer (1990) based on their trace element geochemistry.

Late W–E to NW–SE brittle faulting occurs in all lithostratigraphic units on a wide range of scales. Field observations show that these brittle structures are strike-slip faults, and the transition from early ductile shearing (BASZ, BSZ, DSZ) to late brittle faulting is likely to be the result of a protracted deformation history during progressive exhumation of these terranes during orogenesis.

The structural histories of the TVG and KRG are compatible with their having a shared deformation path following the assembly of the TVG and KRG terranes (Mortimer 1990, 1992b).

In addition to some felsic dykes, a small unfoliated granite stock within the TVG (first mapped by Yace, 1976) attests to the presence of late-kinematic felsic intrusives within the supracrustal belt. The geological section presented together with the 1:100,000 geological map provides an interpretation of the possible emplacement of felsic magma along thrust fault conduits.

4. Discussion

The characterisation of the KRG as a magmatic arc comprising a suite of plutonic igneous rocks which have been deformed by ductile crustal-scale sinistral strike-slip shearing and ductile orthogonal thrusting in an evolving Paleoproterozoic accretionary orogen is consistent with its geodynamic evolution in the Paleoproterozoic domain of the West African Craton along an oblique convergent margin. Under this model, the KRG terrane is interpreted to be the mid-to lower crustal remnant of an island arc which was metamorphosed to amphibolite facies before being progressively uplifted and unroofed during the assembly of Birimian terranes. The overlying volcanic component of the arc was eroded. The TVG is an upper crustal remnant of a similar arc complex, or arc-related basin of which the underlying plutonic intrusive component has not been exposed, but which might be expected to resemble the TTG-suite gneisses of the KRG. The petrogenesis of felsic volcanic lithologies in the evolving TVG stratigraphy can be understood to have arisen by the partial melting of such TTG-suite lithologies (Mortimer, 1990), probably by heat transfer from crustal ponds of juvenile mafic magma erupted in the TVG.
Given the complex nature of deformation along an obliquely convergent plate boundary in which uplift may be episodic and geographically focussed, it does not follow that fragments of deeper crust (e.g. the KRG) are necessarily older than fragments of shallower crust (e.g. the TVG). However, such an age relationship would seem to provide the simplest explanation of the observed field geology, that is, the KRG is an older Paleoproterozoic arc complex than the TVG. A resolution of their absolute ages will require geochronological investigations of both the KRG and TVG.

5. Conclusions

Field geological mapping of tropical West Africa is hindered by the variable, but generalised development of deep regolith and localised tropical rainforest and this has impeded the progress of geological research. Nevertheless, there are areas in which field geological mapping can provide essential geological data for the investigation of crustal development of the West African Craton. A 1:100,000 geological map of the Paleoproterozoic geology of part of central Ivory Coast has been produced by independent fieldwork conducted in 1987 and 1988 together with the application of GIS software. The geological map has been overlain on a SRTM 1 arc-second topographic base. In addition the locations of field observations and field traverses are presented, which provide a measure of the reliability of the geological map, clearly showing where it has been interpolated between and extrapolated beyond field observation locations. At the scale at which mapping was conducted, areas beyond 1 km of a field traverse are significantly less well-known.

The field geological mapping presented here provided the basis for recognition of discrete lithostratigraphic terranes exposing different crustal levels within the Paleoproterozoic Birimian domain of the West African Craton which are interpreted to have had their origins as juvenile crustal additions in discrete island arc complexes in an accretionary orogen at an obliquely convergent plate boundary.

The 1:100,000 geological map contributes to the geological framework of studies of the geodynamics of the West African Craton and also provides a new baseline for future geological map improvements in the area.

Software

The geological map and elements of the manuscript figures were constructed using the freely available QGIS 2.14.0. A vector PDF file of the geological map was produced by the additional use of Inkscape 0.91. The geological section was constructed using Inkscape 0.91, as were elements of the manuscript figures.

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