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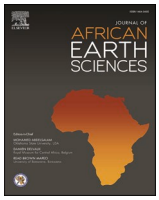
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The Volta basin in Burkina Faso: Lithologic and structural geology constraints along the leading edge of the foreland Dahomeyide fold-thrust belt

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ABSTRACT

The Volta basin in Ghana, Togo and Benin has a narrow NE-striking panhandle extension into Burkina Faso where the Pan-African Dahomeyide fold-thrust belt approaches Paleoproterozoic basement rocks (ca. 2.25–2.10 Ga). We present the results of integrated stratigraphic, structural geology studies of the Volta Basin in Burkina Faso that combines interpretations of high-resolution remote sensing imagery, radiometrics and magnetics to appraise the metasedimentary sequences and stratigraphic setting. We evaluate the degree of deformation and metamorphism across the Volta basin in Burkina Faso and contextualize the tectonic domains with reference to published data for the broader Volta Basin.

The results indicate that felspathic sandstones and greywackes of the Madjoari and Gobnangou massifs were deposited in the Tonian Period (ca. 1000-855 Ma) in a shallow marine environment along the Rodinia continental passive margin. Diamictites, dolomite, chert, phosphorite (576 ± 13 Ma) of the Kodjari Group and siltstone-shale sequences of the Porga Group were deposited in an offshore basin in the middle Ediacaran Period (ca. 635-538 Ma) syn-to post Ediacaran glaciation and possibly during a period of deglaciation.

These metasedimentary rocks were deformed during two deformation events, D1 and D2. D1 ductile-brittle deformation was concomitant to NW-directed fold-thrust formation within the foreland Dahomeyide fold-thrust belt. The intensity of deformation decreases across the panhandle (SE to NW) from isoclinal folding and thrust formation in Atacora Structural Unit, to open style low fold forms near the Madjoari and Gobnangou massifs. In concert, metamorphic grade decreases from greenschist-amphibolite to very low grade (anchimetamorphic).

D2 brittle deformation was progressive, with incremental development of joints, fracture-corridors, fracture-faults and open fold forms during east-west directed shortening.

1. Introduction

The Neoproterozoic Volta basin is situated in the southeast of the West African Craton (WAC) in the countries of Ghana, Benin, and Togo, with a panhandle extension to the northeast into Burkina Faso and Niger (Fig. 1). The basin is composed of metasedimentary sequences that unconformably overlie Palaeoproterozoic basement rocks (ca. 2.25–2.10 Ga) including felsic granulite, orthogneiss, and quartzo-feldspathic paragneiss (Hein et al., 2018). Along its eastern margin, the Volta basin is crosscut and deformed by the Pan-African Dahomeyide fold-thrust belt (ca. 670–540 Ma; Kalsbeek et al., 2008; Affaton, 1990; Kwayisi et al., 2020, 2023).

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The current understanding of the panhandle extension of the Volta Basin in Burkina Faso is derived from (1) studies by Affaton (1975) and Affaton et al. (1980) of the litho-stratigraphy of the basin in northwest Benin and Togo, and southeast Burkina Faso, and (2) localized studies of phosphate occurrences in Burkina Faso and Niger by Leprun and Trompette (1969), Lucas et al. (1980), Ouédraogo (1982), Flicoteaux and Trompette (1998) and Porter et al. (2004). Affaton (1975) used litho-stratigraphic analysis with photogrammetry to correlate lithological units, establish stratigraphic successions, and interpret tectonic domains, namely, (1) a *stable* domain of undeformed geology and (2) a *mobile* zone representing the Dahomeyide foreland fold-thrust belt. The stable zone was divided into an *unfolded zone* and *folded zone*, and the mobile zone was divided into the *Buem* and *Atacora* structural units (Fig. 2). Following on from Vyain (1967), Bozhko (1969b) and Leprun and Trompette (1969), Affaton (1975) established the stratigraphic succession for the basin comprising a lower sequence of greywacke-sandstones (the Boumbouaka Group) and an upper sequence of siltstones-shales (the Pendjari Group) and noted their discordance (unclassified) with respect to the underlying Palaeoproterozoic basement series. The litho-stratigraphy of Affaton (1975) and Affaton et al. (1980) was extended by Affaton (1990) to include the Volta basin in Ghana and the *Internal Domain* of the Dahomeyide belt in Togo. It was adopted by Kabore and Ouédraogo (2006) in their 1/200 000 map compilation of the Volta basin in Burkina Faso for the Geological Survey of Burkina Faso (BUMIGEB) with few additions (Fig. 3).

The approach of Affaton (1975, 1990) of using litho-stratigraphic analysis and photogrammetry during field mapping relies on the principle that identifiable strata and/or stratigraphic sequences are continuous and can be traced laterally to become mappable units. This approach becomes limiting in structurally complex domains when investigating tectonic architectures and deformation processes. This is particularly true when applied to mobile belts such as the Dahomeyide fold-thrust belt where the lateral continuity of stratigraphic units is complicated by structures such as folds, thrusts, faults and zones of brecciation, various intrusive phases, or regolith. This has been shown by Kwayisi et al. (2020) who combined lithostratigraphy with structural geology, geophysics and remote sensing techniques to revise the crustal architecture and deformation history of a portion of the Volta basin in Ghana and thereby brought focus to the importance of the geodynamic evolution of the Pan-African Dahomeyide belt of West Africa. Kwayisi (op cit.) ultimately concurred with the conclusions of Bozhko (1969b) that the Voltaian terrain is complexly deformed and folded.

In Burkina Faso, the Dahomeyide fold-thrust belt approaches the Palaeoproterozoic basement rocks across a narrow valley (<15–25 km distance; Figs. 1 and 2) and stratigraphic and structural geology complications exist. Unfortunately, prior to this study integrated basin wide litho-stratigraphic and structural geology studies had not been attempted, nor geophysical investigation of the basin to understand its magnetic and radiometric response. This provided the motivation for integrated field studies through the 2015–2018 PADSEM mapping program, which was sponsored by the World Bank.

Accordingly, we present the results of stratigraphic and structural geology field studies of the Volta basin in Burkina Faso that combines interpretations of high-resolution Google Earth imagery, Landsat, radiometrics and magnetics, to (1) appraise the metasedimentary sequences and stratigraphic setting, including important phosphate horizons described by Affaton (1975), Lucas et al. (1980) and Trompette et al. (1980), (2) search for geochronological markers, (3) give definition to tectonic domains, if possible; (4) evaluate the degree of deformation and metamorphism, and (5) contextualize the tectonic domains found in the Volta basin in Burkina Faso within in the broader Dahomeyide fold-thrust belt. Furthermore, we establish a stratigraphic nomenclature for the Volta basin in Burkina Faso to describe the assemblages recognized from outcrop with comparisons to descriptions and stratigraphic columns established for the basin in Ghana by Affaton (1990), Deynoux et al. (2006) and Carney et al. (2010) (Table 1).

2. Background

2.1. Regional geology

The litho-stratigraphy and structure of the Volta basin in West Africa has been discussed by Vyain (1967), Affaton (1975, 1990), Affaton et al. (1980), Deynoux et al. (2006), Carney et al. (2010) and Kwayisi et al. (2020) primarily from studies conducted in Ghana, Benin and Togo, with bio-stratigraphic (Acritarche) and geochronological age constraints

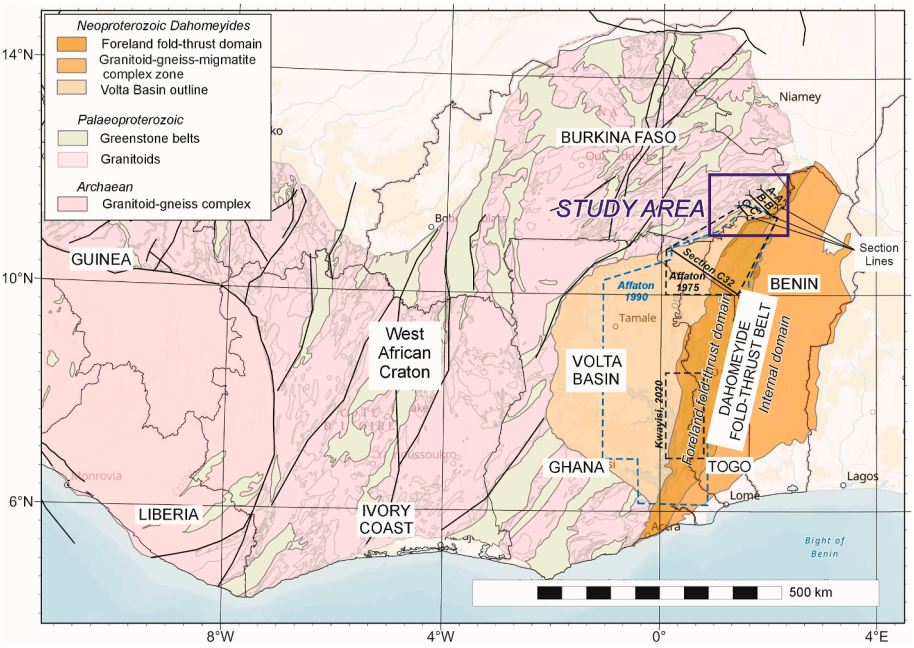


Fig. 1. Location map of the Volta Basin in the West African craton (modified after Markwitz et al., 2016). Studies areas of Affaton (1975, 1990), and Kwayisi et al. (2020) are shown in dashed lines. The study area and location of three NW-SE section lines (A-A'. B-B′, C-C′) are given for this study. The NW-SE section line C32 of Affaton (1975) extends for 190 km from the village of Dapango in Togo to Perma in Benin.

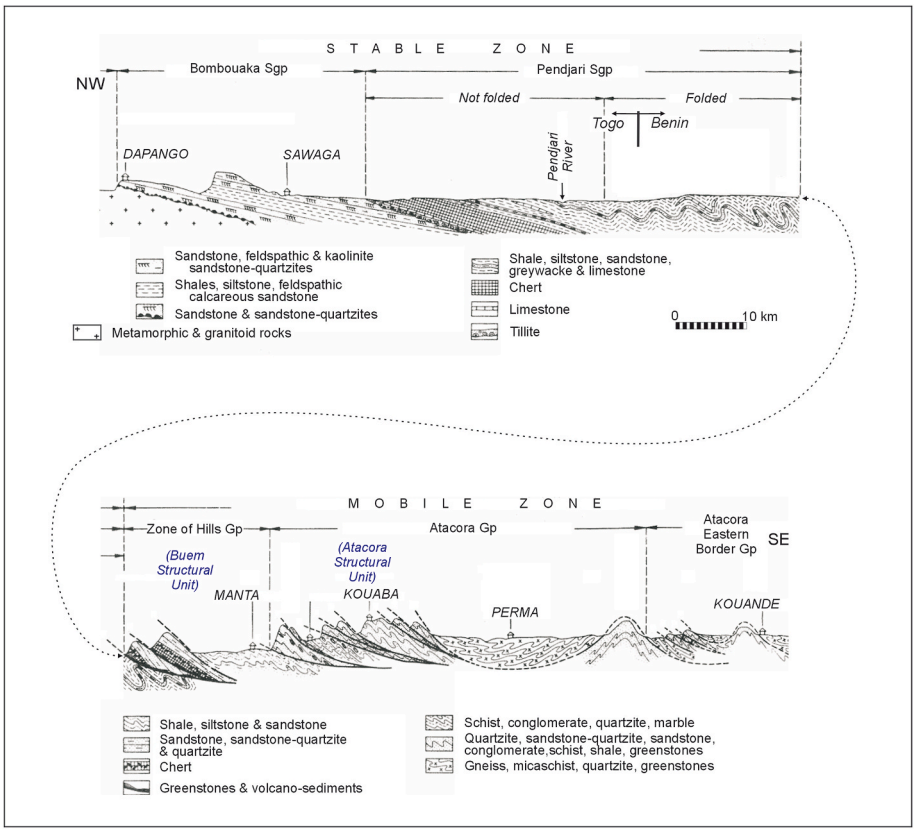


Fig. 2. A modified version of the schematic NW-SE section C32 from Affaton (1975) with a *stable domain* of undeformed geology and *mobile zone* representing the Dahomeyide foreland fold-thrust belt, with Buem and Atacora structural units. The distance between the town of Perma in Benin at Lat/Long 10.123052° and 1.439382° and Dapango in Togo at Lat/Long 10.873542° and 0.200808° is approximately 160 km.

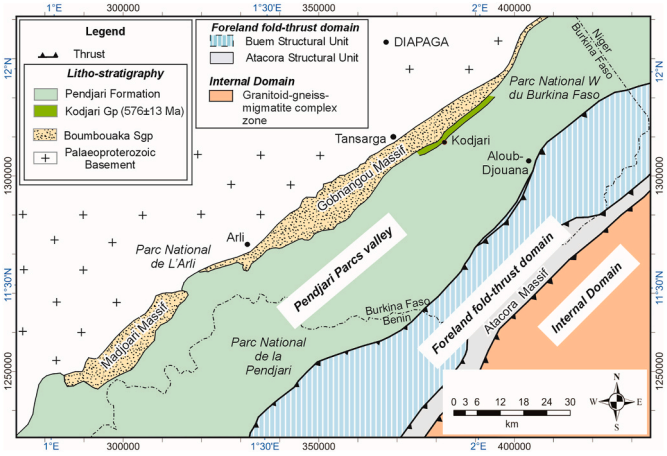


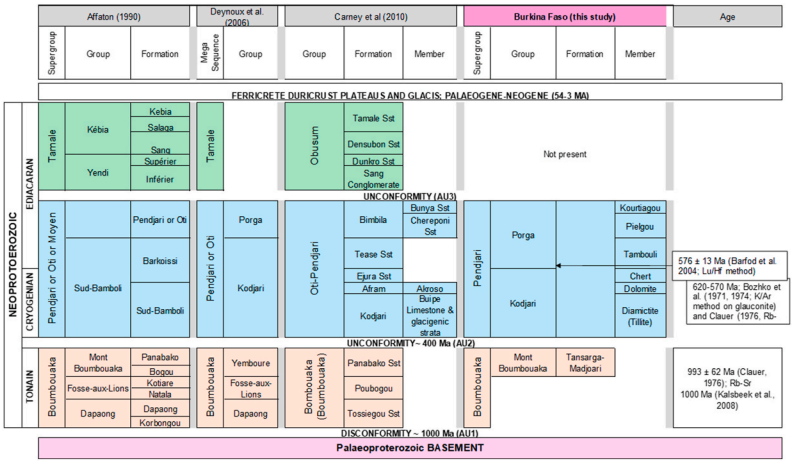
Fig. 3. Schematic structural geology map presented by Affaton (1975 & 1990, Fig. 31) and Kabore and Ouedraogo (2006) of the Volta Basin in Burkina Faso, gridded for WGS84 UTM31N and latitude/longitude. The map broadly locates the position of the *Dahomeyide foreland fold thrust domain* and *Internal Domain* in Benin and Burkina Faso. The *fold thrust domain* was broadly divided into the Buem and Atacora structural units as interpreted by Affaton (1975) from photogrammetry.

by Bozhko et al. (1971, 1974), Clauer (1976), Clauer and Deynoux (1987), Barfod et al. (2004), Kalsbeek et al. (2008), Ganade et al. (2016), and Antonio et al. (2021) from across the Volta basin. Although stratigraphic subdivisions and names have varied between authors over time (e.g., *Group* versus *Supergroup* versus *Megasequences*), most researchers now agree that the basin stratigraphy is divided into three supergroups, namely (from bottom to top), the Boumbouaka, Pendjari and Tamale supergroups (Table 1); the Tamale Supergroup is absent from Burkina Faso.

Historic studies of the structural character of the Volta basin are limited to litho-stratigraphic correlation and observations of fold forms along field traverses in Benin (e.g., section C32 of Affaton, 1975, Fig. 3), photogrammetry to extract lineaments and fold attributes, and general observations of litho-stratigraphic relationships from outcrops in Togo and Ghana. These include: (1) summaries of field investigations in Ghana by the joint Ghana-Russian Geological Study (1969–1972), (2) petrographic and field studies of phosphate deposits by Barthelet (1975) and Trompette et al. (1980), and (3) regional field studies by Bozhko (1969a, b), Affaton (1975), Simpara (1978), Simpara et al. (1985), and Affaton (1990). In these studies, the Buem and Atacora structural units are described in terms of their lithological character, stratigraphic facies, bedding geometry and stratigraphic correlatives (c.f., Koert, 1906 cited in Affaton, 1990) rather than their structural or metamorphic character (i.e., fault geometry, shear foliations, lineations, joint systems, metamorphic grade). Affaton (1990) after Bozhko (1969a, b) stated that the Buem Structural Unit is generally composed of formations that are equivalent to those found in the Pendjari Supergroup, while Kwayisi et al. (2020) correlated the Buem Structural Unit (in Ghana) with the Boumbouaka Supergroup. Anonymous (1989) reported quartzites and metagraywackes, dolerite-basalt for the Buem Structural Unit in Benin.

Integrated litho-stratigraphic, structural geology and geophysical studies by Kwayisi et al. (2020) in Ghana characterized the Buem and Atacora structural units as thrust-bounded blocks and placed them in the Dahomeyide foreland fold-thrust domain based on key strato-structural attributes, as well as radiometric and magnetic character. They recognized three deformations (D1-D3) from study of the Buem Structural Unit, namely, (1) D1 bedding-parallel fabrics; (2) D2 thrust faults and

Table 1
Stratigraphic columns established for the Volta Basin in Ghana by Affaton (1990), Deynoux et al. (2006) and Carney et al. (2010). The stratigraphic section for the study area in the Volta Basin in Burkina Faso is shown on the right. The Tamale Supergroup does not occur in Burkina Faso. AU1 = nonconformity of (Xiao and Tang, 2018); AU2 = angular unconformity; AU3 = angular unconformity related to erosion of the Pan-African and deposition of the Tamale molasse; AU4 = Palaeogene-Neogene unconformity. Geochronological ages are given for metasedimentary sequences deposited in the Volta basin in the Tonian and Cryogenian periods by Clauer (1976; Rb-Sr clay), Kalsbeek et al. (2008; Pb-Pb detrital zircon) and by Bozhko et al. (1971, 1974; K/Ar method on glauconite), but a marker horizon and constraint is given by the Lu–Hf dating of the phosphorite by Barfod et al. (2004) that yielded an age of 576 ± 13 Ma.



steep ENE-striking foliations that are axial planar to upright isoclinal folds; and (3) D3 open folds and kinks. D2 dominates the deformational history in the Buem Structural Unit in Ghana and corresponds to WNW-vergent fold-thrust tectonics. The Buem Structural Unit lies west of the Atacora domain, as well as a broad internal domain (Fig. 1) that is made up of the Pharusian suture zone (in central Benin) and granitoid-gneiss-migmatite complex zone (Attoh, 1998; Attoh et al., 1997; Nude et al., 2009; Kwayisi et al., 2023).

2.2. Local geology

In the Volta Basin panhandle in Burkina Faso, greywacke-sandstone beds of the Boumbouaka Supergroup dominant the landscape. The beds are exposed over 140 km of strike length along the Madjoari and Gobnangou massifs (Fig. 3), where they present as 120–140 m high cliffs. They are also exposed in the Atacora Massif along the Burkina-Benin border where they are folded, schistosed and brecciated.

In contrast, the overlying metasedimentary sequences of the Pendjari Supergroup crop out sporadically across the Pendjari Parcs valley (Fig. 3), which lies between the Madjoari-Gobnangou and Atacora massifs. The base of the Pendjari Supergroup is composed of diamictite, dolomite and chert beds in the Kodjari Group, and is phosphatic, with zeolite facies low-temperature conditions (<250C) reported by Flicoteaux and Trompette (1998) at the Aloub-Djoana phosphate deposit (Fig. 3).

The Diamictite Member of the Kodjari Group has been described and detailed by Leprun and Trompette (1969), Affaton (1990) and Porter et al. (2004), with comparisons to outcrops in northern Togo. Those authors classified the Member as a glacial tillite after Koert (1906, cited in Affaton, 1990) and his studies and observations in the Buem Structural Unit in Ghana. Leprun and Trompette (1969) measured apparent striations on a pavement near the village of Kodjari with an azimuth of 100–120 and concluded an ESE direction of glacial transport. They noted the presence of rare, striated clasts and a polished pavement veneer.

As stated previously, the Dahomeyide fold-thrust belt in Burkina Faso is represented by the Buem and Atacora structural units as described by Affaton (1975) and Affaton et al. (1980). These trend northeastwards along the border region of Burkina Faso and Benin. The contact of the Buem Structural Unit with 'undeformed' rocks in Burkina Faso is interpreted to be a mylonitic thrust plane (Barthelet, 1975) based on rock exposures in a shallow valley near the village of Aloub-Djouana (Fig. 3); however, for the most part, the contact has not been mapped in Burkina Faso.

Ferricrete duricrust plateaus and scree slopes unconformably overlie all stratigraphic units and blanket the geology along the border region with Niger. The ferricrete duricrust plateaus formed in several stages during the Palaeogene. The scree slopes effectively comprise diamictite horizons that are derived from remobilized duricrust, screes of Volta basin units and basement rocks, and formed during the Neogene (Brown et al., 1994; Gunnell, 2003; Beauvais et al., 2008; Chardon et al., 2018).

3. Methodology

Field work across the Volta Basin in Burkina Faso was conducted in the November to April dry seasons of 2016–2017 by EFFIGIS Geosolutions Inc® for the World Bank funded Projet d'Appui au Développement du Secteur Minier (the 2015–2018 PADSEM project), in collaboration with the Ministère de l'Énergie, des Mines, et des Carrières (MEMC) of Burkina Faso and through the Bureau des Mines et de la Géologie du Burkina Faso (BUMIGEB). Field work was conducted from a basecamp in the town of Diapaga, 23 km north of the Gobnangou Massif (Fig. 3), with remote sensing work completed in 2015, 2017–2018 and 2023–2024. Field work was conducted by 4 W drive and/or on foot along NW-SE traverse lines (as much as possible), and along strike of lithological contacts (mostly NE-SW). Electronic field notebooks (tablets) were used during the second phase of the survey in 2017. Observation points were positioned using GPS (UTM coordinates, WGS 84, Zone 31 N); bedding and structural measurements were reported using right hand rule (000/00) for planar surfaces and plunge and azimuth (00 -> 000) for linear features. Structural analysis, calculated mean values, and rose plots were produced using GEOrient 10.00® software

(Holcombe, 2023). Three schematic cross-sections were constructed (A-A′, B-B′ and C-C′) to interpret the combined datasets. Samples were collected for petrography and litho-geochemistry but are not reported herein. Access to some parts of the field area was restricted by the Gendarme Nationale and/or not possible due to security risk (e.g., the far west of the Madjoari Massif). It was therefore essential to complement field studies with remotely sensed data, and airborne magnetic and radiometric imagery. The study area locates several important trans-national parks and wildlife reserves with limited vehicular access.

Remote Sensing used the Landsat 8 and Aster VNIR multispectral satellite data, which were acquired by EFFIGIS Geosolutions Inc® from the United States Geological Survey (USGS) in the form of orthorectified images. The definition of these images (15 m resolution instead of 30 m) was improved by Pan-Sharpening. Historic view Google Earth mapping

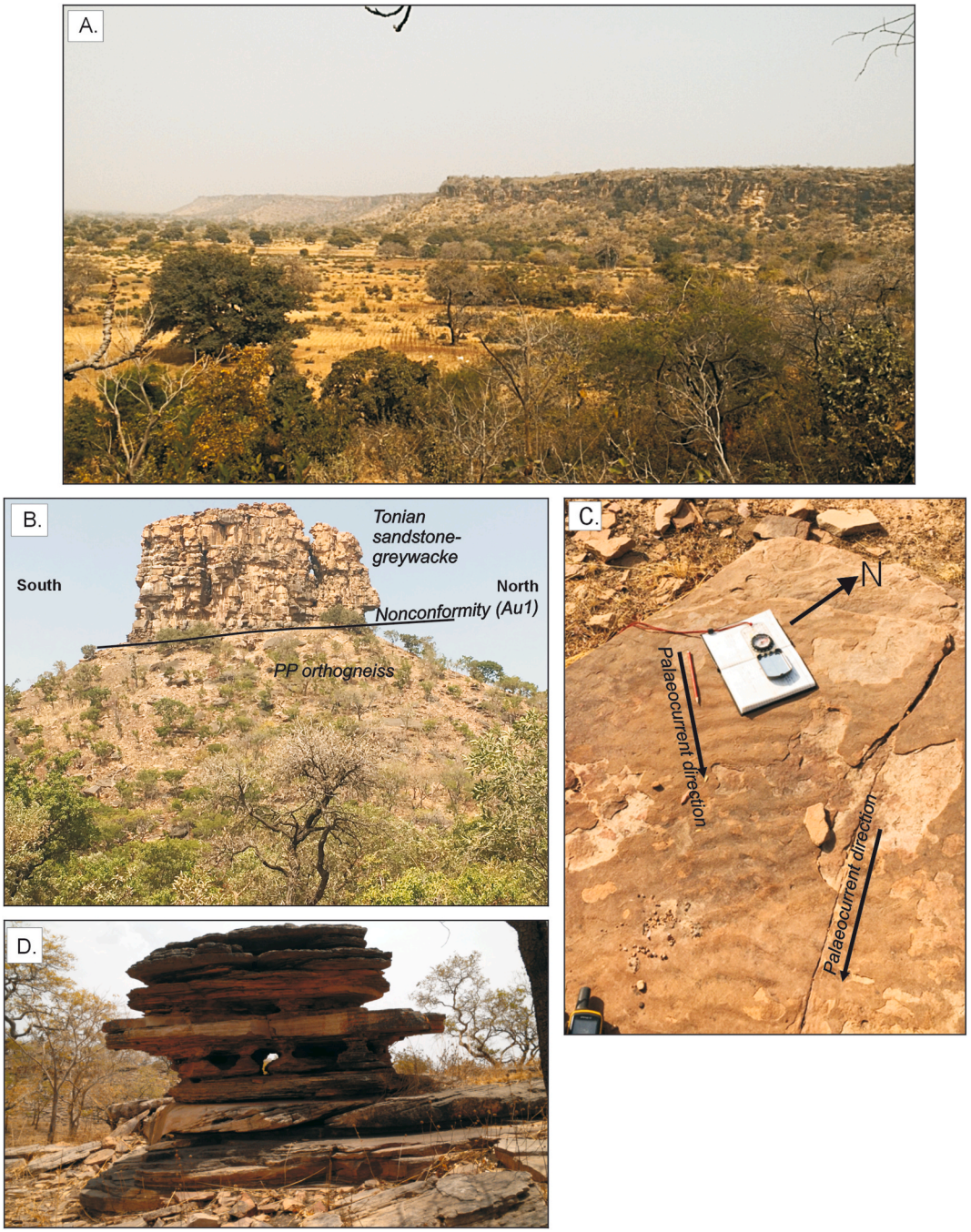


Fig. 4. a. View of the sandstone-greywacke and quartzite beds of the Tansarga-Madjoari Formation along the northwest cliff face (120–140 m) of the Madjoari Massif. The view is to the east from the Pagou Mesa.
b. The 1.5 × 1.3 km Pagou Mesa is located 8 km north of the Madjoari Massif near the village of Arli. It exposes the sandstone-greywacke and quartzite beds of the Tansarga-Madjoari Formation above a nonconformity angular unconformity (AU1) that dips approximately 10°S. It is evidence that the Volta Basin had a greater footprint than is currently known.
c. The Tansarga-Madjoari Formation is characterized by asymmetric ripples (WGS84 UTM 31 N 386 843 1 318 597). In this image the bedding orientation is 301/04, with palaeocurrent direction to 107° and 138°.
d. Characteristic cross-stratification of fine to medium grained sandstone-greywacke and quartzite beds of the Tansarga-Madjoari Formation along the 140 km length of the Madjoari and Gobnangou massifs (WGS84 UTM 31 N 380 927 1 315 229).

was particularly useful in photogeological interpretation along the border region of Burkina Faso and Benin.

Remote Sensing satellite imagery was used to identify outcrops and linear attributes. The technique has limitations in this region of West Africa because of (1) low topographic relief in the Pendjari Parcs valley, (2) vast plains of clay soil, and (3) regions of forest, parks or partial reserves. Additionally, attribute extraction was made difficult by human features such as seasonal tracks, livestock and wildlife tracks, scars from seasonal burning of grasses, and the rapid seasonal growth of vegetation. Crop and plough marks also cause considerable soil disturbance, limiting the effectiveness of image interpretation year-on-year. In Burkina Faso and northwest Benin, additional limitations include biases between outcrop-dominant regions over the Gobnangou, Madjoari and Atacora massifs, and subcrop and cover regions in the Pendjari Parcs valley. In part, these limitations were overcome using the historic view option in image warehouses, such as is available through Google Earth; these give the interpreter the opportunity to compare historic and current image views. Nonetheless, a judicious approach and development of confidence criteria was standard practice. Interpretations were validated against field evidence, whenever possible.

The airborne magnetic and radiometric datasets were purchased and reprocessed by EFFIGIS Geosolutions Inc® and SAGAX Afrique SA®. The original geophysical survey was flown in 1976 as part of a project to remap eastern Burkina Faso and funded by the Canadian International Development Agency (CIDA). Flight lines were oriented NW-SE and spaced 500–1000 m apart. However, although useful for interpretation of the Palaeoproterozoic basement to the north, the magnetic data resolution across the Volta basin was limited and only helpful in identifying weak lineaments (magnetic low) in magnetic images.

In contrast, total count radiometric data (K, U and Th) complimented the Remote Sensing datasets and defined broad domains and lineaments in the near surface environment. The radiometric data identified the extent of key litho-structural features, particularly the unconformity at the contact of the Boumbouaka and Pendjari supergroups. Uranium mapping proved useful for mapping of phosphate horizons and the regional extent of sandstone units.

4. Results

4.1. Stratigraphy

4.1.1. Boumbouaka Supergroup

In Burkina Faso, the Boumbouaka Supergroup is represented by the Mont Boumbouaka Group (Table 1), which is dominated by metamorphosed felspathic sandstone and greywacke beds of the Tansarga-Madjoari Formation as exposed along the Madjoari and Gobnangou massifs (plateaus) and Pagou Mesa (Fig. 4a–b). The metasandstone/greywacke beds form cliffs (120–140 m) on the northwestern flank of the Madjoari and Gobnangou massifs (Fig. 4a). Although, the Mont Boumbouaka Group is estimated to be 500–700 m thick in Ghana (c.f., Affaton, 1990), it does not exceed 100–120 m thick in Burkina Faso.

The metasandstone/greywacke beds are monotonous in composition and sedimentary textures are well-preserved. They are fine to medium grained, cross-bedded, ripple-marked and massively cross stratified (Fig. 4c–d). Gritstone and polymictic conglomerate beds are rare. Bed gradation is millimetric to decametric in scale, but also rare. Massive cross-stratified beds that are intercalated with ripple-marked beds suggest an interplay between wind-blown sand accumulation and shallow marine deposition in a coastal marine environment. Rare soft-sedimentary deformation features such as load casts, centimeter-scale sand dykes, and syn-sedimentary micro-faults are indicative of minor reworking of unconsolidated sediment during deposition. Desiccation features such as mud cracks are sometimes found in fine-grained greywacke beds.

Ripple marks occur throughout the sequence. They are generally asymmetric (Fig. 4c). However, straight, sinuous or lingoidal ripple forms are common and indicate laminar flow of water across unconsolidated sediment. Symmetric ripples indicate there may have been reversals in palaeocurrent directions, as noted by Affaton (1990). However, the general palaeocurrent direction is northeast or southeast, with mean calculated palaeo-flow directions towards 032 and 110.

The metasandstone/greywacke beds are sometimes feldspathic and/or kaolinic, but rarely micaceous. Quartz grains are rounded to subrounded indicating maturity of form, and well-sorted. Iron oxides and hydroxides are present as coatings on bedding planes and fracture surfaces.

Petrographically, the metasandstone/greywacke beds are subarkosic, isogranular to heterogranular. Their matrix is composed of subrounded quartz (up to 80 %), orthoclase (up to 15 %) and rare plagioclase, set in a siliceous, microcrystalline or cryptocrystalline cement. The occasional lithic clasts (up to 5 %) consist of quartzite and composite quartz microgranules. Rare tourmaline and zircon crystals are present as inclusions in the quartz clasts. Based on these characteristics, the environment of deposition and provenance of the clast fraction of the metasandstone/greywacke beds is best assigned to shallow marine tidal to marine lagoonal, with sediment provenance from a granitoid hinterland (continental).

The metasandstone/greywacke beds dip gently SW to SE for a mean calculated bedding of 094/6. The beds are gently folded (warped) along N-NW fold axes.

4.1.2. Pendjari Supergroup

The Pendjari Supergroup in Burkina Faso is divided into the Kodjari and Porga groups. The Kodjari Group is represented by conformable to unconformable diamictite, dolomite and chert members. It forms a discontinuous sequence along the southeastern margin of the Gobnangou and Madjoari massifs (Fig. 3), and between the two massifs where it unconformably overlies the Palaeoproterozoic basement orthogneiss. It is estimated to be approximately 90 m thick (Porter et al., 2004).

In contrast, the Porga Group is represented by disconformable siltstone-shale sequences exposed in isolated low-stand outcrops across a 30 km wide to 100 km long valley (the Pendjari Parcs valley). The group is marked at its base by a 0–30 m thick sequence of phosphatic siltstone-shale. At the villages of Kodjari and Arli, the phosphatic siltstone-shale forms a low-grade phosphate resource to the agricultural industry (Zoungrana et al., 2024).

4.1.2.1. Kodjari Group. In the study area, the Diamictite Member is composed of a <5 m thick lower monogenic diamictite and a 2–10 m thick upper polygenic diamictite. The monogenic diamictite unconformably overlies massive sandstone beds of the Tansarga-Madjoari Formation (Boumbouaka Supergroup). The monogenic diamictite is composed of angular to subrounded and weathered quartzite-greywacke blocks that are centimetric to metric in size (Fig. 5a–b). The blocks form an interlocking mosaic (Fig. 5b) but are set in a matrix of fine to coarse heterolithic-argillitic sand. Striated clasts and a polished pavement veneer as reported by Leprun and Trompette (1969) were not encountered. Indeed, in many sites the monogenic diamictite overlies (1) rippled sandstone beds with intact or partially intact ripples (Fig. 5c), (2) sandstone beds that are partially striated (5–20 % striations), (3) and/or partially polished.

In contrast, the massive structureless polygenic diamictite (Fig. 5d and e) is composed of angular, polyhedral or sub-rounded blocks (1–10 cm diameters in size) of chert, granite, rhyolite, dolerite, amphibolite, gneiss, schist and vein quartz. Angular blocks of sandstone and quartzite of the Tansarga-Madjoari Formation are also present and provide a relative maximum geochronological constraint to the Diamictite Member.

A 1–3 m thick Dolomitic Limestone Member overlies the Diamictite Member in several localities in the study area (Fig. 6a). The unit crops out near the village of Arli between the Madjoari and Gobnangou

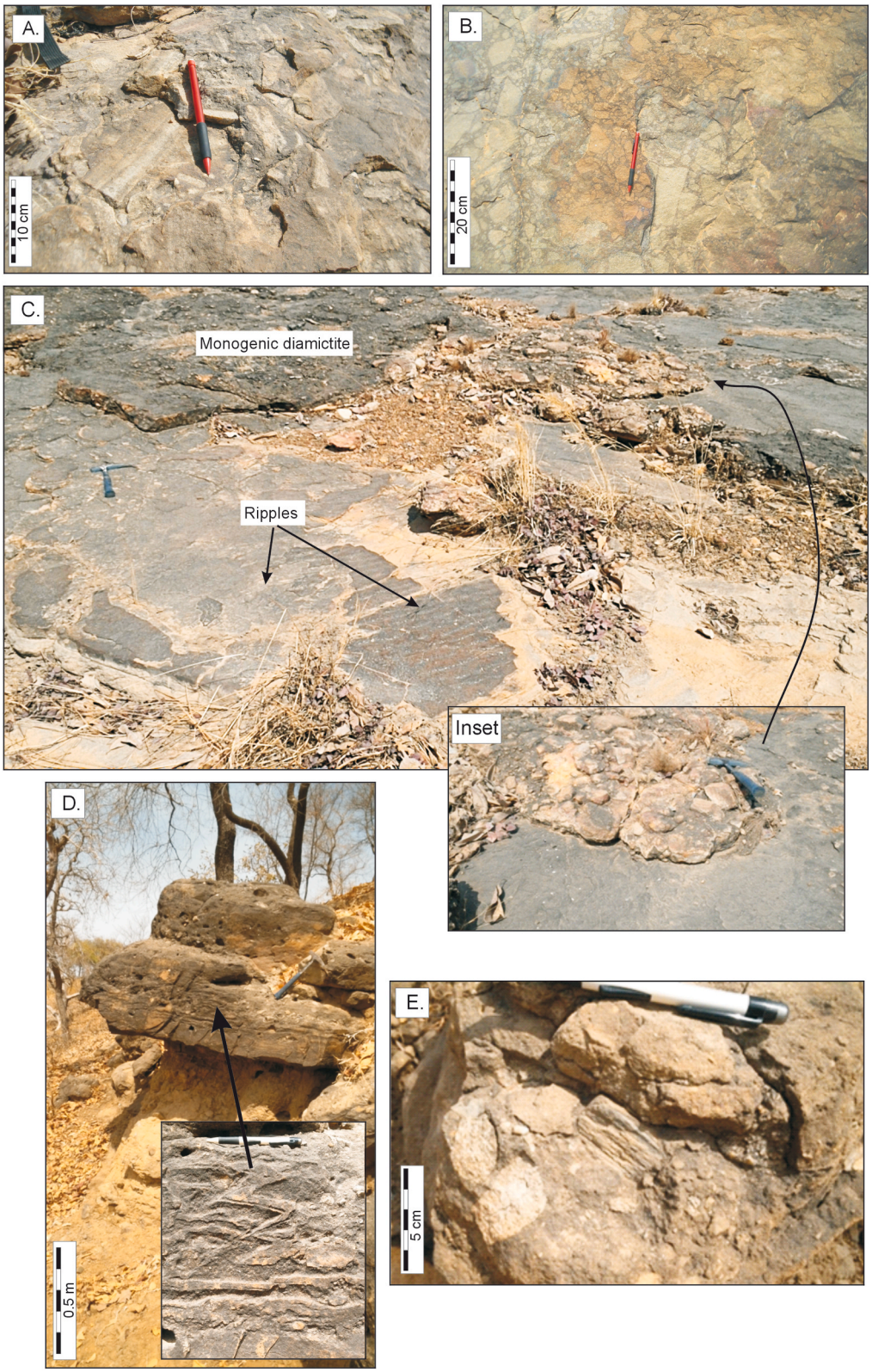


Fig. 5. a. Monogenic diamictite (WGS84 UTM 31 N 378 519 1 311 023) composed of angular to subrounded and weathered quartzite-greywacke blocks.
b. Monogenic diamictite (WGS84 UTM 31 N 379 036 1 309 870). The blocks form an interlocking mosaic set in a matrix of fine to coarse heterolithic-argillitic sand.
c. Monogenic diamictite (WGS84 UTM 31 N 378 519 1 311 023) unconformably overlies sandstone-greywacke of the Tansarga-Madjoari Formation. The monogenic diamictite overlies rippled sandstone beds with intact or partially intact ripples, and striations and a polished pavement surface are not evident (insert).
d. Polygenic sand-clay diamictite (WGS84 UTM 31 N 379 052 1 309 833). The occasional annealed microfaults and small-scale recumbent folds are evident in the inset image.
e. Polygenic diamictite is composed of rounded boulder of granite and schist. (WGS84 UTM 31 N 379 052 1 309 833).

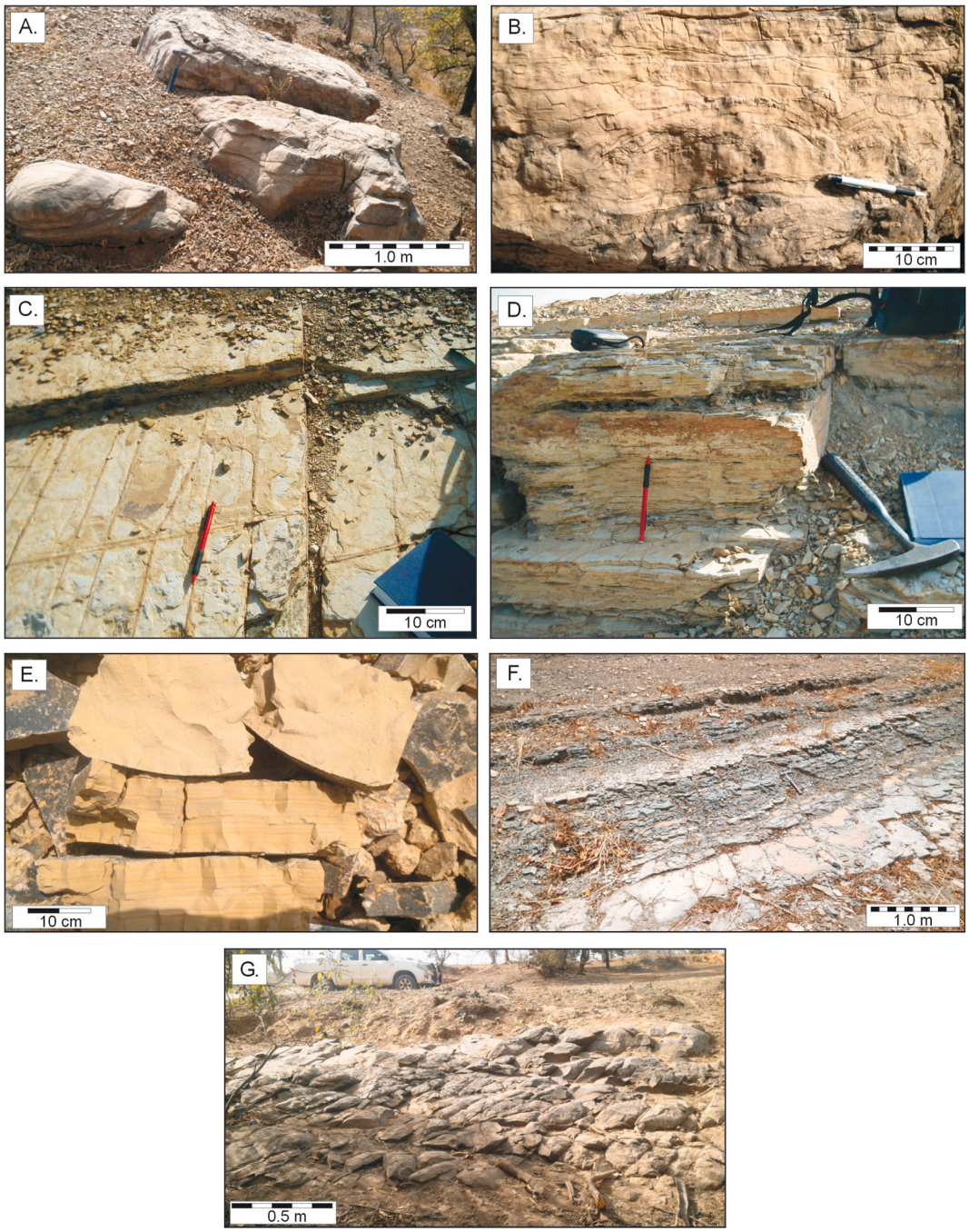


Fig. 6. a. Dolomitic limestones overlying the polygenic breccia at Kodjari. Dolomite Member of the Kodjari Group (WGS84 UTM 31 N 378 962 1 309 546).
b. Pseudo-teepee structure common to the Dolomite Member of the Kodjari Group are probably syn-sedimentary deformation contraction-style thrust-folds (WGS84 UTM 31 N 378 962 1 309 546).
c. & d. Finely bedded siliceous shale within the Chert Member of the Kodjari Group characterized by a fine slaty cleavage and fissility (WGS84 UTM 31 N 377 429 1 307 751) Very low-grade metamorphism.
e. Buff-brown-grey shaly siltstones of the Tambouli Formation at the base of the Porga Group (WGS84 UTM 31 N 376 466 1 305 114)
f. Laminated to turbiditic volcaniclastic siltstone shale beds of the Pielgou Formation of the Porga Group (UTM 327826 1273126).
g. Very fine sandstone of the Kourtiagou Formation at the top of the Porga Group (WGS84 UTM 31 N 377 113 1 279 110).

massifs (Fig. 2), as well as immediately southwest of the Madjoari Massif where it unconformably overlies Palaeoproterozoic basement orthogneiss.

The Dolomitic Limestone Member is pink in color with an ochre to light grey patina. It is finely bedded with rare 2–10 cm high pseudo-teepee structures (Porter et al., 2004) that may represent small-scale contraction-style thrust-folds as syn-sedimentary deformation features (Fig. 6b). The Dolomitic Limestone Member hosts rare quartz gravels and pebbles, and fine glauconitic and ferruginous horizons. Trompette (1981, cited by Porter et al., 2004) noted the presence of barite nodules in this unit, which were not found in the study area.

The Dolomitic Limestone Member is overlain by the Chert Member (silexite in the French literature), which occurs predominantly as long, narrow, discontinuous bands of subcrop, or is found in water-bore and well cuttings. It sometimes forms isolated ridges that rise 5–20 m above the plain to form marker horizons.

The Chert Member unconformably overlies metasandstone/greywacke beds of the Tansarga-Madjoari Formation in several locations along the southeastern margin of the Gobnangou Massif, and occasionally the Madjoari Massif where it forms thin lenses. Between the two massifs and to the south-west of the Madjoari Massif, the Chert Member unconformably overlies the Palaeoproterozoic basement.

The Chert Member is approximately 25–35 m thick. It is laminated, fissile, and sometimes massive, with pronounced slaty cleavage (Fig. 6c–d). It is dominated by siliceous laminations with up to 70 % silica in the form of cryptocrystalline cement.

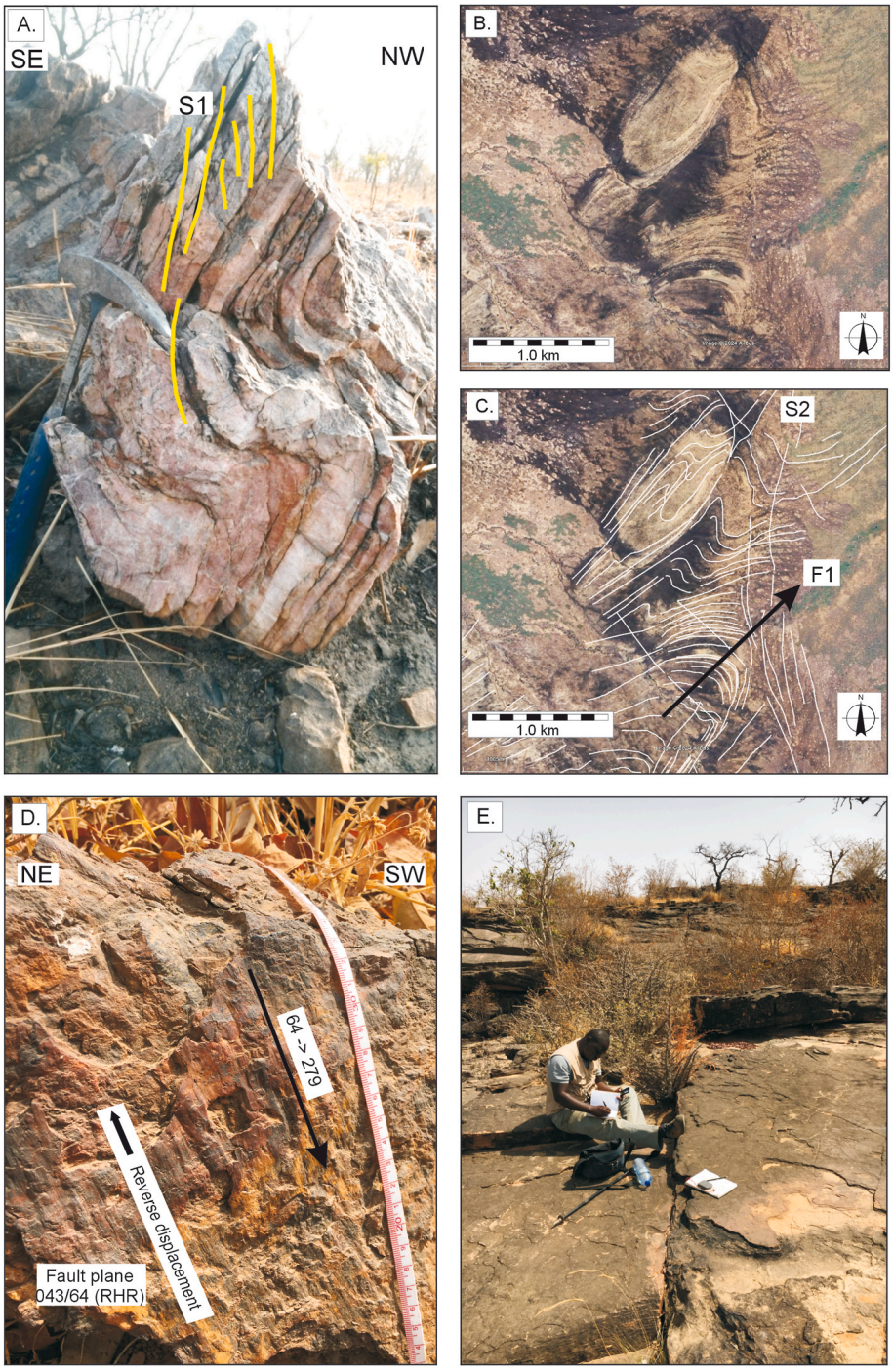


Fig. 7. a. Small-scale S-fold forms at the margin of the Atacora Structural Unit. The axial plane of the folds dip southeast and strike ENE along the overall strike of the Atacora Structural Unit. An early vertical foliation is lost into silicification in the S-fold hinge
b. And c. Example of a low hillock along in the Pendjari Parcs valley from historic remote sensing imagery in Google Earth (WGS84 UTM 31 N 325 089 1 249 992), with bedding and foliation form lines. The folds strike NE with fold closures to the NE and SW.
d. Fe-rich slickensides on an 8 km long NE-striking fault plane in the northeast of the Gobnangou Massif (WGS84 UTM 31 N 382 900 1 313 169). The fault also crosscuts the Palaeoproterozoic basement to the northeast of the village of Kodjari. The structure has an additional 28 km-long expression in magnetic data to the southwest. In this photograph, the fault plane is orientated 043/64 (RHR = right hand rule) with slickenlines at 64->288. Displacement is dextral reverse with northwestern block up.
e. NNW-striking joint that was traced for approximately 750 m across the Gobnangou massifs (WGS84 UTM 31 N 362 517 1 302 404).

4.1.2.2. Porga Group. A 30 m thick sequence of phosphatic siltstone-shale forms the Tambouli Formation at the base of the Porga Group (Table 1, Fig. 6e). The unit dips gently south. Phosphate mineralization occurs in phosphatized (laminites) siltstones, and phospharenites and phosoncoliths near the base of the package (Ouédraogo, 1982; Flicoteaux and Trompette, 1998), i.e., phosphate occurs as diffuse patches through siltstone-shale but also as fine grains, sometimes together with Fe-oxides after pyrite (Lucas et al., 1980). The sequence exhibits rare syn-sedimentary slump folds and faults. A slaty to fracture cleavage is present and shale beds are cleaved and fissile.

Based on their regional persistent granulometric characters observed in scattered outcrops, two additional formations are tentatively assigned to the Porga Group (Table 1), namely the Pielgou and Kourtiagou formations. The Pielgou Formation is dominated by shale interbeds (Fig. 6f), while the Kourtiagou Formation is composed of siltstone to very fine sandstone beds (Fig. 6g). The formations dominate the widest part of the Pendjari Parcs valley (20–25 km) into the Buem Structural Unit, but their continuity was difficult to map due to the poor outcrop across the valley; they are not discussed further.

The sediments of the Porga Group that lie within the Buem Structural Unit in Burkina Faso (Kabore and Ouédraogo, 2006) are dominated by finely bedded arkosic siltstone and shale. These are intercalated with rare lenses of sandstone, greywacke, limestone-dolomite, chert and tuff. The region is marked by a series of low hills in which the siltstone-shale units are silicified, sometimes folded, faulted, and crosscut by moderately penetrative foliations, rare shears and numerous quartz-Fe cataclasite veins.

4.2. Structural geology

Prior to litho-structural mapping, remote sensing imagery (Landsat and Google Earth), and radiometric and magnetic images were studied to extract the position, width and extent of structural attributes (e.g., fold forms, crosscutting lineaments, joints) and formulate domains of equal structural character and property. Published 1:200 000 scale geology maps along the border region with Benin by Anonymous (1989) where used to supplement this work.

4.2.1. Atacora Massif (Atacora Structural Unit)

The metasedimentary sequences of the Atacora Massif (Atacora Structural Unit) are dominated by schistosed quartzite and meta-greywackes in Burkina Faso. The dominate structural attributes include NE-striking tight to isoclinal fold forms, and a series of SSE dipping thrust faults. Metamorphic grade is lower greenschist facies to lower amphibolite facies with development of quartz, chlorite and epidote; the occurrence of kyanite quartzite in Benin (Anonymous, 1989) is consistent with high pressure, low temperature metamorphic conditions proximal to thrust faults. Deformation is ductile-brittle in style. Fold sets include.

(1) Fold 1 – Dominant NE-striking meso-to macroscopic isoclinal folds (F1). Fold limbs are overturned and steeply dipping to the southeast (Fig. 7a). Fold vergence is northwest. S- and Z-fold forms on fold limbs are indicative of flexural-slip shearing.
(2) Drag folds along ENE-striking small-scale shears southwest of the Benin-Burkina Faso international border. The symmetry of fold forms indicates anticlockwise drag rotation (sinistral) on ENE-striking shears.

The folds (F1) give a mean calculated strike and dip of 052/40, with calculated fold plunges to the northeast and southwest of 6–12°, respectively. This is consistent with refolding or periclinal fold-forms as suggested from form-surface mapping. Z- and S-folds indicate flexural-slip shearing during fold formation.

4.2.2. Pendjari Parcs valley

The metasedimentary sequences of the Pendjari Supergroup dominate the wide Pendjari Parcs valley in Burkina Faso and Benin. Remote sensing studies across the valley were critical for lineament extraction and identifying low outcrops. Between the Gobnangou and Madjoari massifs in Burkina Faso and across the Parc National de Pendjari in Benin, outcrops of folded meta-sedimentary rock were evident on Google Earth (Fig. 7b and c) and Landsat imagery. For convenience these are divided into two regions namely.

(1) Region 1 coincides with the Buem Structural Unit. As reported by Anonymous (1989), the Buem Structural Unit is made up of tightly folded quartzites, greywackes and dolerite-basalt in Benin, with numerous quartz-Fe cataclasite veins. Unfortunately, it is poorly exposed in Burkina Faso, but limited outcrops indicate it is composed of folded and schistosed quartzites and siltstones. Metamorphic grade is lower greenschist facies, with the development of quartz-chlorite assemblages.
(2) Region 2 spans the greater part of the Pendjari Parcs valley and is composed of siltstone-shale sequences of the Porga Group.

At least two phases of fold development are evident from imagery across region 2. Dominant NE-striking folds (F1) are refolded by NNW-striking fold axes (F2) to form small-scale domes and basins. F1 folds include open style anticline-syncline pairs with NE-striking (S1) foliation (Fig. 7b and c). The presence of S- and Z-folds is evident along fold limbs and consistent with flexural-slip folding during fold formation. Fold limbs dip gently with measured 5–15 dip angles. The axial plane of F2 folds strike northwest. They are cylindrical and open in form. F2 folds are associated with NW-striking axial planar (S2) foliations that crosscut NE-striking (S1) foliations, disjunctively.

4.2.3. Gobnangou and Madjoari massifs

Steeply-dipping fracture corridors, jointed zones, faults and quartz-Fe cataclasite veins dominate the structural architecture of the meta-sandstone/greywacke beds of the Gobnangou and Madjoari massifs (Fig. 7d–e, 8, 9). As described by Gabrielsen and Braathen (2014) and De Joussineau and Petit (2021) fracture corridors are best defined as closely spaced arrays of sub-vertical, long, narrow and tabular zones of fractures (joints) of significantly increased fracture intensity, which is the classification used herein. In the study area, the fracture corridors are commonly 50 m wide by 15 km long but can attain 300 m in sectional width where they associate with faults and cataclasite veins.

From our field work, the relationship between the fracture corridors, zones of joints and faults indicates that they form progressively because (1) zones of joints and fracture corridors are continuous, (2) faults occur within, along and transect through the fracture corridors, (2) faults interplay along the length of fracture corridors, (3) the faults host quartz-Fe cataclasite breccia veins, and (4) the joints within the fracture corridors are mutually crosscutting. Moreover, NNW-striking joints in the hangingwall of NE-striking fracture corridors are weakly drag folded against the NE-striking faults consistent with (apparent) dextral slip.

The zones of joints and fracture corridors form 4 sets that include:

Set 1^{MJ} – A dominate NE-striking joint set (and fracture corridors).
Set 2^{MJ}– A subordinate WNW-striking joint set.
Set 3^{MJ} – A subordinate NW joint set.
Set 4^{MJ} - A poorly developed low angle joint set that parallels the orientation of bedding that dips gently south.

The faults form sets that strike NE, NW and WNW, namely.

Set 1^{F} – A dominant NE-striking fault set that occurs within, along and transects through NE-striking fracture corridors. Predominate slickenlines on selected fault planes (mean of 228/78) gave a mean (calculated) plunge and azimuth of 63 -> 278, with up-plunge Fe

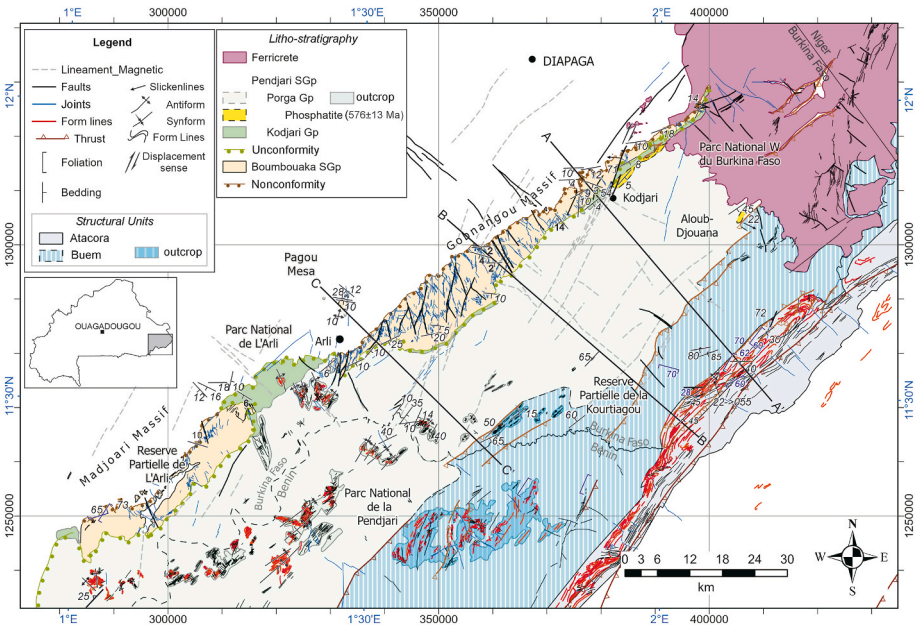


Fig. 8. Litho-stratigraphic map for the Volta Basin in Burkina Faso from this study in WGS84 UTM31N and latitude/longitude. The map presents generalized (1) lithological and structural data collected during field missions, (2) relevant lithologies from the 1:200 000 Parga geological map by the Office Beninois de Mines for northwest Benin and (3) Remote sensing interpretations completed during this study. Magnetic lineaments were extracted from magnetic images of the Volta basin in Burkina Faso. The location of three NW-SE section lines (A-A'. B-B′, C-C′) are marked.

oxide-quartz accretion steps, and up-plunge pluck blocks. Fault displacement was consistently dextral reverse, with west-block up. This fault set crosscuts and displaces the Palaeoproterozoic basement orthogneiss at several locations along the Madjoari Massif.

Set 2^F – A subordinate WNW-striking, moderately south-dipping fault set. Sinistral strike-slip displacement is interpreted from slickenlines of mean (calculated) plunge and azimuth of 9 -> 303, and WNW facing pluck marks. These faults are associated with meter wide zones of cataclasis.

Set 3^F – An ordinate set of NW-striking faults (steeply dipping) that are drag folded along the plane of Set 1^F. Structural data is limited for this fault set; however, the fault set crosscuts and displaces the Palaeoproterozoic basement orthogneiss northwest of the village of Kodjari.

4.3. Radiometric attributes

Radiometric imagery (K, U, Th and total count as raster images) complimented the interpretation of remote sensing and magnetic images and helped to define broad domains in the near surface environment. K is a major constituent of many of these rocks and an important marker of weathering profile. U and Th are generally present in traces, but the U-count proved to be an excellent tracer of the phosphate horizons and thereby the contact of the Porga and Kodjari groups at the local scale. The strongest total count responses defined stream beds and alluvium. Lowest total count occurs (and low U-level) over the Gobnangou-Madjoari massifs in the northwest and the Atacora Massif in the southeast consistent with high silica content.

The Buem Structural Unit which was historically interpreted to be marginal to the Atacora Structural Unit (Barthelet, 1975; Affaton, 1990) is indistinguishable in the radiometric data from the stable domain. However, a series of low intensity radiometric linear anomalies coincide with a silicified thrust zone. This concurs with findings by Barthelet (1975) who mapped a complex mylonitic thrust plane marked by quartz-Fe cataclasite breccia and veinlets at Aloub-Djouana. We mark the contact between Buem Structural Unit and Porga Group along this low intensity radiometric linear anomaly.

The phosphate deposits of Kodjari and Arli correspond to the highest response colors. They could be traced over several kilometers using uranium mapping with shaded relief and NW illumination on the U map; however, in general the contact is not well exposed or absent.

5. Discussion

The results of the integrated field studies across the Volta Basin in Burkina Faso, in combination with data from remote sensing, radiometric and magnetic imagery of Burkina Faso and NW Benin, has facilitated the develop a new geology map for the Volta Basin in Burkina Faso (Fig. 8). Additionally, a geology map of the zones of joints, fracture corridors and faults across the Gobnangou massif is presented in Fig. 9. Three NW-SE cross-sections have been constructed from the combined dataset (Fig. 10) to facilitate comparison with section C32 of Affaton (1975) in Fig. 3. Stereographic projections of bedding, joint and fault datasets from the Gobnangou massif, and with block model schematic representation of the spatial relationship that consequent from the datasets are presented in Fig. 11. A relative chronology of lithostratigraphic and structural events is summarized in Fig. 12. The relative chronology is based on crosscutting relationships in the field and limited absolute geochronology. It provides a framework for the discussion of an event chronology for the Volta Basin in Burkina Faso.

5.1. Litho-stratigraphic character and event chronology

From the combined historic data, field studies, remote sensing and radiometric study, it has been possible to constrain the litho-stratigraphic character and setting of metasedimentary sequences in the Volta basin in Burkina Faso in a fuller way relative to studies by Affaton (1975), and in relationship to sequences in Ghana, Togo and Benin as published by Affaton (1990), Deynoux et al. (2006) and Carney et al. (2010). The nonconformity (AU1) and angular unconformites (AU2-AU4) that separate the supergroups are pronounced in Burkina Faso and contextualize the litho-stratigraphy (Table 1, Fig. 12). The lowest stratigraphic sequence is defined by feldspathic sandstone and greywacke beds of the Tansarga-Madjoari Formation (Mont Boumbouaka Group, Boumbouaka Supergroup) (Fig. 8). The sequence overlies high-grade metamorphosed plutonic-volcanic rocks of the 2.0–2.2

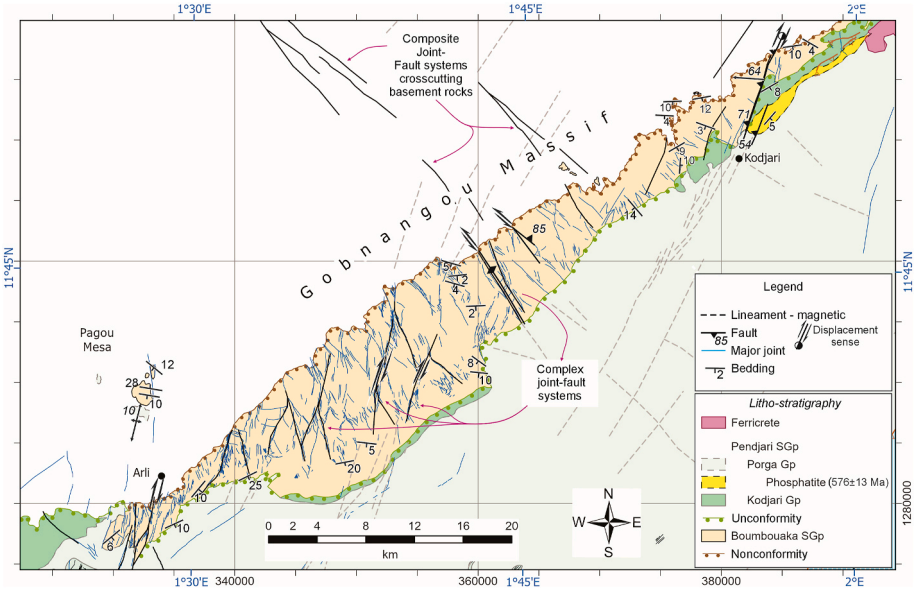


Fig. 9. Map of joints, fracture corridors, and fracture-faults that are evident from remote sensing images across the Gobnangou Massif in WGS84 UTM. Certain fracture corridors and faults coincide and crosscut the Palaeoproterozoic basement in several locations. Magnetic lineaments extracted as linear attributes from magnetic imagery coincide with fracture corridors suggesting that the corridors could be up to 50 km in strike length.

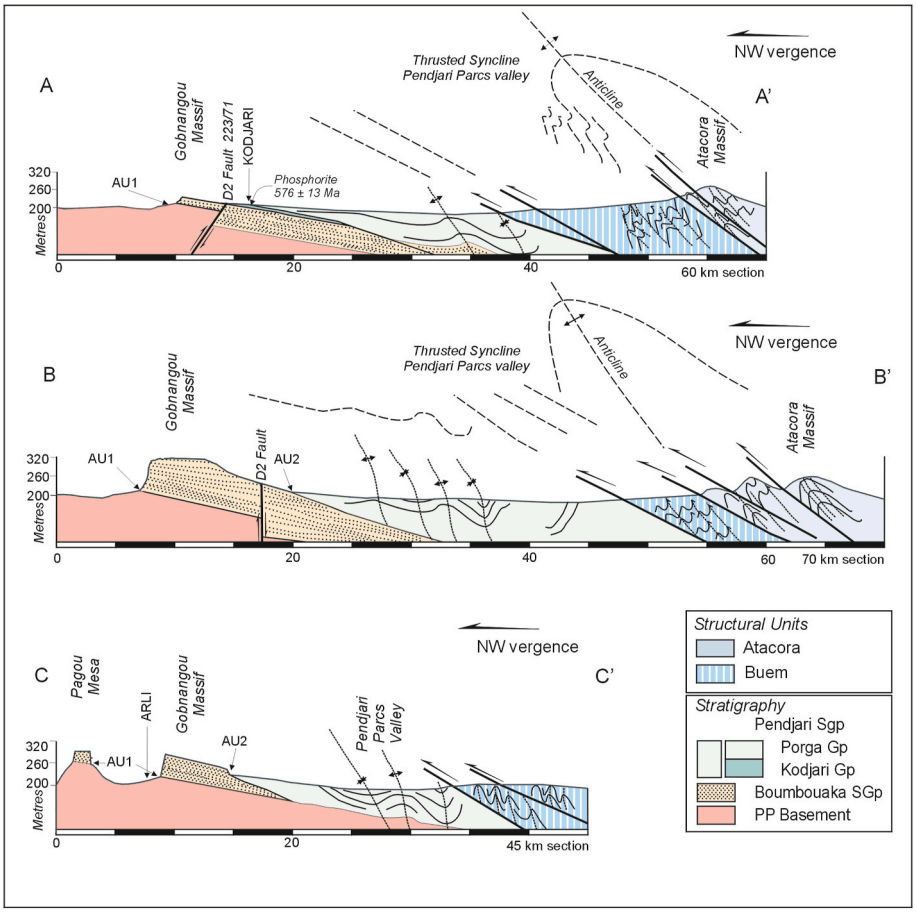


Fig. 10. Schematic cross-sections A-A'. B-B′and C-C′ for the Volta Basin in Burkina Faso. The cross-sections present the interpreted trace of beds, thrusts and the form of folds in the Pendjari Parcs valley, Buem and Atacora structural units. The Atacora Structural Unit is defined by a macroscopic anticline. The Buem Structural Unit is interpreted as the overturned northwestern limb of the anticline. It is important to note that the felspathic sandstone-greywacke beds of the Boumbouaka Supergroup in the Gobnangou massif and Palaeoproterozoic basement are unconformably overlain by siltstone-shale sequences of the Pendjari Supergroup that are folded, thrust-faulted and sheared.

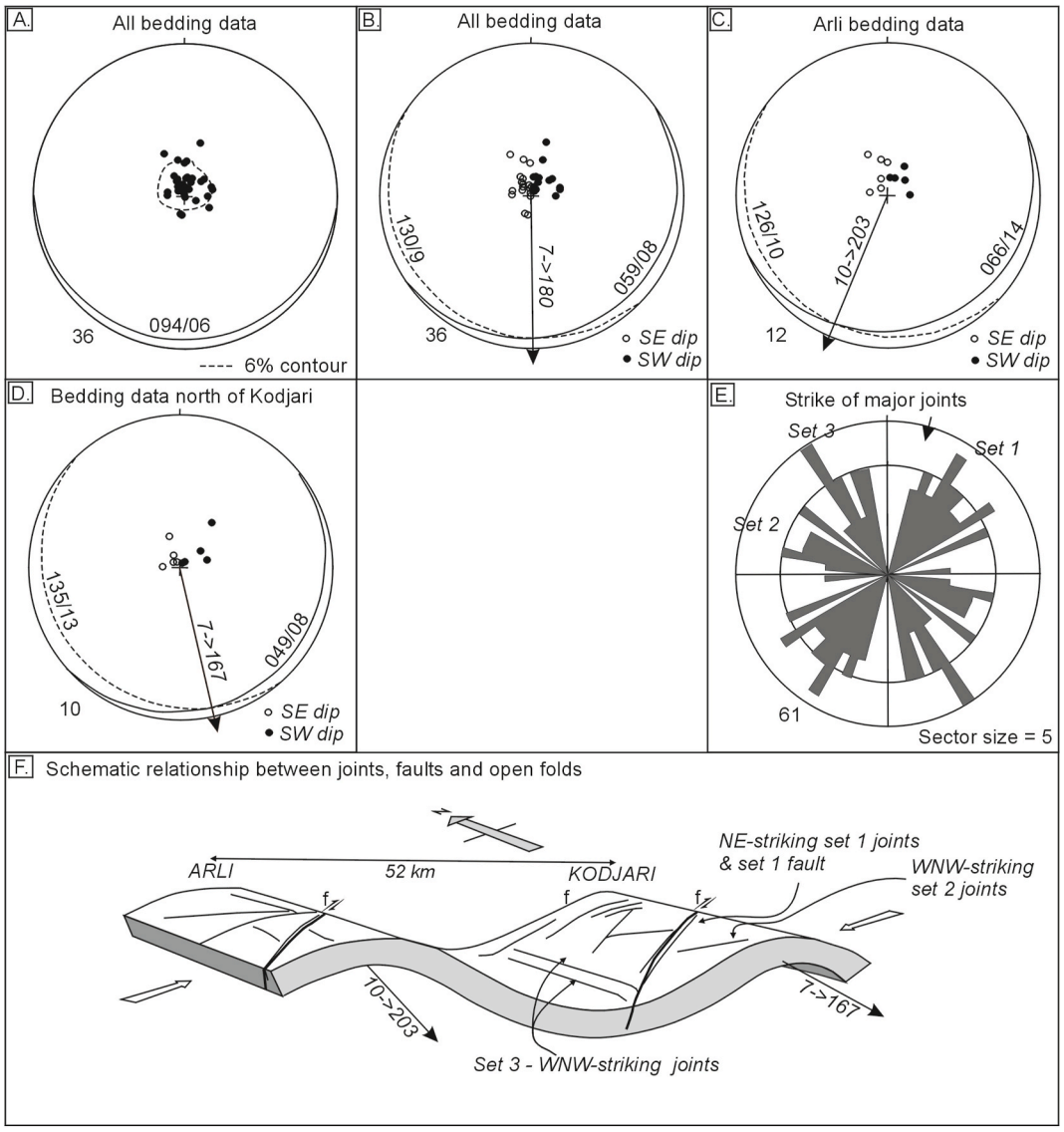


Fig. 11. Equal area stereographic projections, rose and schematic block model for the Boumbouaka Supergroup along the Madjoari and Gobnangou massifs.
a. Bedding data with calculated mean at 094/06, 36 measurements.
b. Bedding data divided into southwest and southeast calculated means. Mean calculated fold plunge is 7->180.
c. Bedding data divided into southwest and southeast calculated means for the region close to the village of Arli. Mean calculated fold plunge is 10->203.
d. Bedding data divided into southwest and southeast calculated means for the region north of the village of Kodjari. Mean calculated fold plunge is 7->167.
e. Rose plot of the strike of single Master Joints, which are near vertical. Sets 1–3 are consistent across the massifs.
f. Block diagram for the Gobnangou Massif over 52 km resolves gentle folding of the sandstone-greywacke and quartzite beds of the Tansarga-Madjoari Formation. Master joints and faults are interpreted to have formed during folding and progressive deformation in D2.

Ga basement (Kabore and Ouédraogo, 2006) above an important nonconformity (AU1). AU1 marks the end of the Mesoproterozoic 'boring billion' of Xiao and Tang (2018) into the formation of the Rodinia supercontinent (Antonio et al., 2021) and in the field juxtaposes very low-grade (anchimetamorphic) rocks of the Boumbouaka Supergroup against felsic granulite, orthogneiss, and quartzo-feldspathic paragneiss of the 2.2–2.0 Ga Palaeoproterozoic basement (Hein et al., 2018) across a 1.0 Ga stratigraphic hiatus of seemingly no deposition or tectonic activity (Xiao and Tang, 2018).

The lower formations of the Boumbouaka Supergroup reported by Affaton (1990), Deynoux et al. (2006) and Carney et al. (2010) from Ghana, Togo and Benin (Table 1) are absent in the study area leaving a 100–120 m thick sequence of metasandstone/greywacke beds as the Tansarga-Madjoari Formation. The absence of the lower formations is interpreted to be the result of no-deposition or reworking and erosion prior to the deposition of the Tansarga-Madjoari Formation. In either case, the metasandstone/greywacke beds exposed along the Madjoari-Gobnangou massifs in Burkina Faso correlate with a thicker sequence (500–700 m) reported by Affaton (1990) in Ghana. Moreover, the beds represent remnants of what would have been a much wider basin in Burkina Faso because we find outcrops of the Boumbouaka Supergroup atop the Pegou Mesa 7.5 km and up to 11 km northwest of the cliff faces at the village of Arli.

In comparison, modal and petrofacies analyses for the Boumbouaka Supergroup in Ghana give a continental granitoid provenance for the sedimentary rocks of the Boumbouaka Supergroup (Anani et al., 2017), which is consistent with our studies and petrography. The sedimentary textures exposed along the Madjoari-Gobnangou massifs, such as ripples, mud cracks, and massive cross-lamination indicate deposition took place in a shallow marine to lagoonal settings along a continental passive margin.

Selected age dating from equivalent stratigraphy to the Boumbouaka

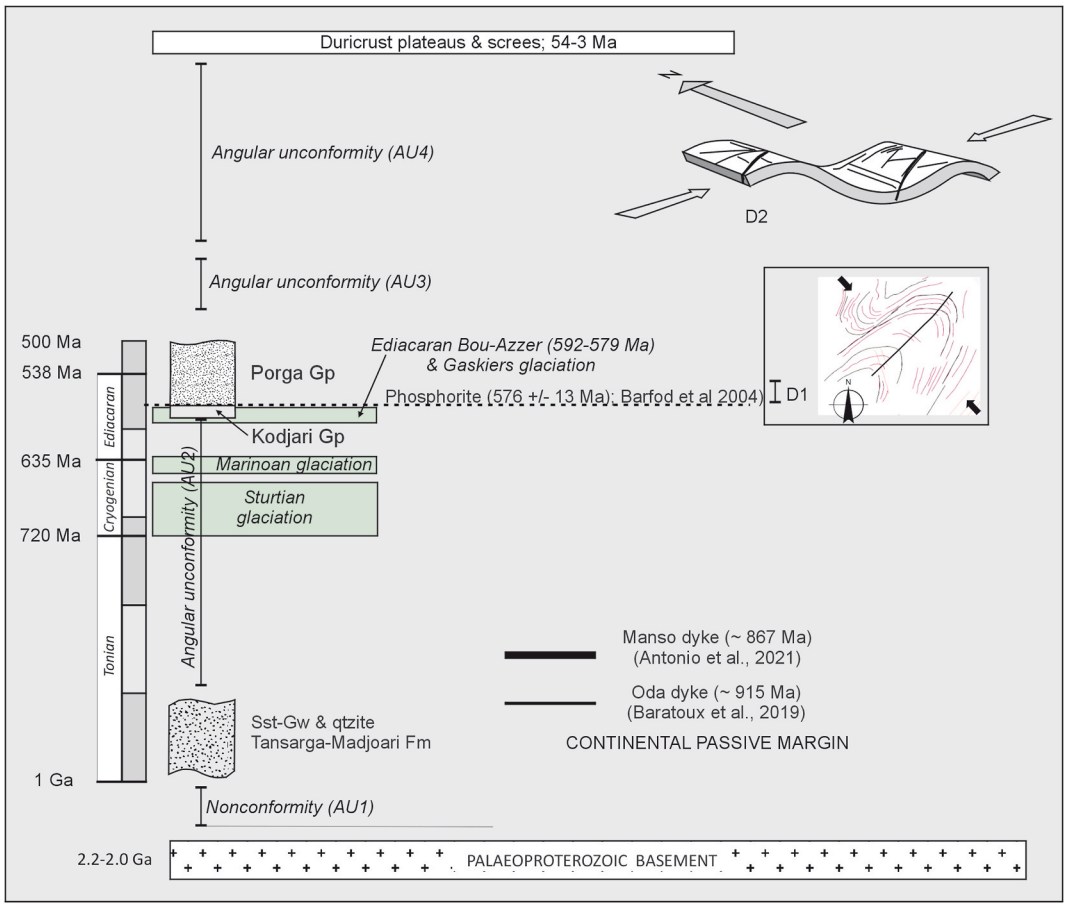


Fig. 12. Schematic event diagram that incorporates stratigraphic and tectonics elements for the Volta Basin in Burkina Faso. D1 deformation is constrained by the Boumbouaka and Pendjari Groups because the rocks are comprehensively folded and faulted along NE-striking axes. D2 deformation event crosscuts D1. The Oda and Manso dyke swarms crosscut the equivalent of the Tansarga-Madjoari Formation (Boumbouaka Group) in Ghana and the age constraint applies to the Volta basin in Burkina Faso by Baratoux et al. (2019) and Antonio et al. (2021). The age of Sturtian, Marinoan and Ediacaran Bou-Azzer and Gaskiers glaciations are by Williams et al. (2008), Pu et al. (2016), Letsch et al. (2018), Wang et al. (2023). Age constraints for the Pendjari Group are by Bozhko et al. (1971, 1974), Clauer (1976), Clauer and Deynoux (1987), Barfod et al. (2004), Kalsbeek et al. (2008), Ganade et al. (2016), and Antonio et al. (2021).

Supergroup in Ghana by Clauer (1976; Rb-Sr clay), Clauer and Deynoux (1987; illites in shale), Kalsbeek et al. (2008; Pb-Pb detrital zircon), and Antonio et al. (2021; U-Pb baddeleyite and U-Pb apatite) indicate deposition took place along a continental passive-margin in the early Tonian Period (ca. 1000-720 Ma) between 1000 and 855 Ma. This is consistent with studies by Evans (2000) of the climate paradox during the Neoproterozoic when continental deposits were laid down on the southern Rodinia sub-continent at high palaeo-latitudes during the Tonian Period. Moreover, geochronology-palaeomagnetic studies by Baratoux et al. (2019) and Antonio et al. (2021) of the Oda and Manso dyke swarms in Ghana (915 ± 7 Ma, Oda swarm, 867 ± 16 Ma, Manso swarm; U–Pb TIMS on baddeleyite) suggest that the continental passive-margin may have been active early in the Tonian Period (pre 900 Ma), because the dykes crosscut the Boumbouaka Supergroup in Ghana.

Deposition in the Tonian Period gave way to ca. 270 Ma period of erosion marked by the AU2 unconformity and a significant stratigraphy hiatus (Table 1, Fig. 12). The hiatus spans the Sturtian and Marinoan glaciation cycles and significant global climate change in the Cryogenian Period (720–635 Ma) as discussed by Williams et al. (2008) and Halverson et al. (2020) but extends to the middle Ediacaran Period (635-538 Ma). In the study area, AU2 ends with the (unconformable) deposition of monogenic and polygenic diamictite beds that mark the base of the Kodjari Group (Pendjari Supergroup) (Table 1, Fig. 8).

The diamictite beds in the Volta Basin in Burkina Faso and Ghana are interpreted as glacial tillite based originally on the studies by Koert (1906 cited in Bell, 1964) who mapped the geology of the Buem Structural Unit in Ghana and reported boulder and pavement striations. Koert's interpretation was carried through to Burkina Faso by Leprun and Trompette (1969), Lucas et al. (1980), Trompette et al. (1980), Affaton (1990) and Porter et al. (2004) for diamictite beds at the Kodjari village near the Kodjari phosphate deposit, with reports of striated pavements. This was despite objections by Bell (1964) who could not validate the original field observations of Koert (1906). Gaisie and Winter (1974) cautioned that the rocks of the original field area in the Buem Structural Unit in Ghana included deformed and metamorphosed rocks up to greenschist facies.

We concur with Bell (1964) and Gaisie and Winter (1974) and recommend caution when interpreting the Diamictite Member in Burkina Faso as tillite because field evidence for '*tillite on a straited pavement*' is inconsistent, i.e., the monogenic diamictite unconformably overlies (1) rippled sandstone beds with intact or partially intact ripples, (2) sandstone beds that are partially striated (5–20 % striations), (3) and/or partially polished (Fig. 5c). Unfortunately, the formation of striations and polished surfaces are not unique to single geological process(es) even in glacial environments. In addition, the formation of diamictites as the products of mass-wasting are also not unique to a single dynamic process (Eyles and Lazorek, 2014). Perhaps the monogenic diamictite is best described as *glacial-associated* given that it was deposited during or after Cryogenian-Ediacaran glacial cycles.

Moreover, the polygenic diamictite above the monogenic diamictite is sourced from all underlying rocks units including Palaeoproterozoic

basement supracrustal rocks. We found little evidence for the boulder striations mentioned by Leprun and Trompette (1969) and many boulders that make up the polygenic diamictite are schistosed and gneissic in texture. The Diamictite Member may be simply the product of mass-wasting as screes in a glacial environment, but requires further study.

The Diamictite Member is overlain by Limestone and Chert members in the Kodjari Group. The Limestone Member has been interpreted as a cap carbonate to the Diamictite Member by Porter et al. (2004) who undertook chemo-stratigraphic studies of samples from the Limestone Member near the villages of Kodjari and Arli in the study area, and in northeast Togo. The authors compared sample compositions and $\delta^{13}C$-isotopes and interpreted that the Limestone and Diamictite members formed together during glaciation cycles at ca. 650-635 Ma, or are glacial-associated.

The Diamictite, Limestone and Chert members are disconformably overlain by phosphorite, argillite and sandstone units of the Porga Group (Pendjari Supergroup) in the study area. The phosphorite forms a marker bed that was readily mapped, geologically and radiometrically. Lu–Hf dating of the phosphorite from Kodjari by Barfod et al. (2004) yielded an age of 576 ± 13 Ma (MSWD = 0.21, n = 6), which provides a minimum age constraint to the Diamictite, Limestone and Chert members of the Kodjari Group. However, it also provides a maximum age constraint to the sedimentary sequences of the Porga Group in the study area to ca. 589-563 Ma and places the phosphorite marker in the middle Ediacaran Period (ca. 635-538 Ma) (Fig. 12; Table 1). This is consistent with ca. 620-570 Ma age by Bozhko et al. (1971, 1974; K/Ar method on glauconite) and Clauer (1976, Rb-Sr clay).

Ironically, the 576 ± 13 Ma age for phosphorite deposition in the Ediacaran Period also concurs with studies by Vernhet et al. (2012) and Letsch et al. (2018; U-Pb zircons) for the Ediacaran/Bou-Azzer glaciation as interpreted from the Anti-Atlas belt in Morocco, and Pu et al. (2016) and Wang et al. (2023) for the Gaskiers glaciation of Newfoundland at ca. 592-579 Ma (Fig. 12). Given the importance of the Ediacaran Period to the ca. 575-541 Ma radiation of Ediacara Biota (Droser and Gehling, 2015), the lower Porga Group in Burkina Faso warrants further investigation.

In terms of event chronology, phosphorite deposition in the Ediacaran Period indicates a shift towards higher temperatures, limited detrital input, a larger marine layer and transition to more oxidizing conditions in the ocean and atmosphere (Planavsky et al., 2010), and is therefore consistent with a period of deglaciation at ca. 576 Ma in the middle Ediacaran Period. The transition to deposition of siltstone-shale sequences after phosphorite corresponds with a shift in the depositional environment from shallow marine to offshore marine.

With regards to AU3 and AU4 unconformities in the study area, these are combined because the Tamale Supergroup is absent from the litho-stratigraphy (Table 1). Thus, the AU3-AU4 unconformity at the base of the ca. 54-3 Ma ferricrete plateaus (see Fig. 8) marks an approximately 450 Ma stratigraphic hiatus.

In summary, the litho-stratigraphic studies across in the study area have shown that.

1. Feldspathic sandstone and greywacke beds of the Boumbouaka Supergroup were deposited in the shallow marine to lagoonal setting along a continental (Rodinia) passive margin early in the Tonian Period (ca. 1000-855 Ma) and probably during breakup of the Rodinia land mass. Sediment provenance was from a granitoid hinterland. The Boumbouaka Supergroup in Burkina Faso represents a 100–120 m relic of the 500–700 m thick sequence seen in Ghana.
2. Tonian continental sediments were unconformably overlain (200 Ma later) by diamictite, dolomite and chert beds in the middle Ediacaran Period (ca. 635-538 Ma) and at the end of Cryogenian-Ediacaran glacial cycles. Deposition was probably by mass-wasting processes and glacial-associated and/or within shallow marginal marine environment.
3. A significant global climatic shift in the middle Ediacaran accompanied deposition of phosphate horizons at ca. 576 Ma with a concomitant shift to higher temperatures, rising sea level and oxidizing conditions. The subsequent disconformable deposition of shale-siltstone sequences of the upper Porga Group occurred in the offshore marine environment.

5.2. *Structural character*

The metasedimentary rocks in the Volta Basin in Burkina Faso were deformed during D1 and D2. D1 is represented in the Atacora Structural Unit by NE-striking tight to isoclinal and recumbent fold forms, Z- and S-folds, flexural-slip shearing, NW vergent thrust faults, and axial planar (S1) foliation. In the Buem Structural Unit, D1 is represented by close to tight mesoscopic disharmonic fold forms, and numerous quartz cataclasite veins, while across the Pendjari Parcs valley, mesoscopic NE-striking open to close-style folds and quartz-Fe cataclasite veins are well developed.

The intensity of D1 deformation and metamorphic grade decreases across the Volta Basin in Burkina Faso from ductile-(brittle) in the Atacora Structural Unit in the southeast to brittle-(ductile) near the Madjoari-Gobnangou massifs in the northwest, as noted by Grant (1969) and Bozhko (1969b). The intensity is highest in the Atacora Structural Unit where F1 fold forms are inclined and isoclinal (NW vergence). The presence of S- and Z-folds along all fold limbs indicates generalized flexural-slip shearing (sinistral and dextral) during fold formation.

Near the inferred contact of the Buem Structural Unit, disharmonic folding above thrust faults (Barthelet, 1975) gives way to brecciation and brittle-ductile deformation in quartzite units in the footwall of the thrust. Across the Pendjari Parcs valley, quartz-Fe cataclasite veins, and mesoscopic to macroscopic NE-striking open to close-style folds are well developed. Although the siltstone-shale sequences are consistently folded, thrust-faulted (mylonitic) and sheared, the intensity of deformation is low grade. D1 deformation is not well resolved or absent in the felspathic sandstone-greywacke beds of the Boumbouaka Supergroup in the Madjoari-Gobnangou massifs.

The decrease in intensity of D1 deformation is illustrated in the schematic cross-sections in Fig. 10.

1. A macroscopic anticline in the Atacora Structural Unit is paired with a macroscopic synform in the Pendjari Parcs valley.
2. The Buem Structural Unit represents the overturned limb of the macroscopic anticline-syncline pair and is thrust faulted. Fold-thrust vergence is towards the northwest.
3. The metasedimentary sequence across the Pendjari Parcs valley, the Madjoari-Gobnangou massifs and Pagou Mesa lie on the recumbent northwestern limb of the macroscopic synform.

In concert, metamorphic grade decreases in intensity and transitions from greenschist facies (quartz-epidote-chlorite) and low-grade amphibolite facies in the Atacora Structural Unit to very low grade (anchimetamorphic) near the Madjoari-Gobnangou massifs. Quartz-chlorite schist in the Atacora Structural Unit transitions across the Pendjari Parcs valley to slaty cleavage in siltstone-shale beds of the Porga Group (Fig. 7c–g) near the Madjoari-Gobnangou massifs.

In general, the D1 structural-metamorphic character of the Volta basin in Burkina Faso matches the summaries and interpretations given by Affaton (1990) and Kwayisi et al. (2020) for the foreland fold-thrust External Dahomeyide in Ghana, Togo and Benin. However, there is a contradiction in some senses between what constitutes a '*stable* domain of undeformed geology' in the foreland arc as established by Affaton (1975) and the evidence from our study area in Burkina Faso, i.e., in D1 metasedimentary sequences are deformed to varying intensities, and metamorphism grade transitions from greenschist-amphibolite in the Atacora to anchimetamorphic facies in the Madjoari-Gobnangou massifs. This is best addressed by considering the zonal divisions made by

Affaton (op cit.) in his original work where he described folded and *unfolded* portions in the *stable* domain (Fig. 2). We content that the '*folded*' portion remain internal to the fold-thrust belt because it represents a mappable 'leading edge' to the deformation front. In Burkina Faso, the 'leading edge' is located along the southeastern edge of the Madjoari-Gobnangou massifs.

In addition, the rheological heterogeneity of the stratigraphic sequences may have played a role during D1 to limit the advance of the 'leading edge'. Given the effective competency contrast between incompetent siltstone-shale sequences of the Pendjari Supergroup (an effectively inhomogeneous package) and competent sandstone-greywacke sequence of the Boumbouaka Supergroup, strain was likely partitioned into the siltstone-shale sequences. The massive sandstone-greywacke sequences of the Boumbouaka Supergroup in the Madjoari-Gobnangou massifs would have resisted deformation.

With regards to tectonic setting, the overall structural architecture for D1 is consistent with interpretations by Bozhko (1969b) and Simpara et al. (1985) for fold-thrust tectonics in the Pan-African Dahomeyide belt in Ghana and Togo. D1 also corresponds with regional events of Affaton (1990) and Kwayisi et al. (2020, 2023) for the greater Volta basin. Affaton (1990) described four stages (P1-P4) for progressive fold-thrust development during NW-SE compression and shortening across the Dahomeyides, which correspond well with D1-D3 events of Kwayisi et al. (2020, 2023). These events are identical to D1 in the Volta basin in Burkina Faso, which is constrained to younger than ca. 576 Ma (or mid Ediacaran) by Lu–Hf dating of phosphorite from the Kodjari and Arli villages by Barfod et al. (2004) (Fig. 9). By extrapolation, this age also provides a maximum age constraint to foreland fold-thrust development in the Pan-African Orogeny in Burkina Faso and correlates well with foreland arc development at ca. 610-570 Ma as proposed by Ganade et al. (2016) for the Dahomeyide fold-thrust belt across Ghana and Brazil.

In contrast to D1, D2 deformation in the Volta Basin in Burkina Faso reflects a period of brittle-(ductile) deformation as characterized by the progressive development of zones of joints, fracture corridors and faults in the sandstone-greywacke sequences of the Boumbouaka Supergroup along the Madjoari-Gobnangou massifs. Analysis of bedding data collected across the Gobnangou massif indicates that metasandstone/greywacke beds are weakly folded (warped), for a mean calculated fold plunge and azimuth of 7->180, with 10 -> 203 around the village of Arli and 7 -> 167 in the region north of the village of Kodjari (Fig. 11a–e). The folds associate with joint sets, fracture-corridors and faults that crosscut the massif, as illustrated in the schematic block diagram in Fig. 11f.

(1) Fracture corridors and joint sets 1^{MJ} and 2^{MJ} form diagonal/cross joints.
(2) The WNW joint set 3^{MJ} forms longitudinal/tension joints that parallel fold axes.
(3) The low angle joint Set 4^{MJ} represents offloading joints that probably formed during folding.

Arguably, D2 brittle deformation across the Gobnangou massif was progressive such that the development of joints into fracture-corridors and into fracture-faults continued towards development of open folds. This is consistent with progressive evolution of joint-fault-fold formation by increasing incremental strain, as reported by Gabrielsen and Braathen (2014) for joint swarms in Norway.

Evidence for ductile behaviour in D2 includes the presence of NW-striking open (F2) folds between the Madjoari and Gobnangou massifs (Fig. 9) and NNW-striking open (F2) folds in the Pendjari Parcs valley that refold NE-striking F1 folds, as extracted from remote sensing data (Fig. 7b–c). The intersection of F2 on F1 forms open style basins and domes.

The combined D2 structural architecture suggests a period of approximately east-west brittle-(ductile) shortening and/or (weak) dextral wrench. The chronological age of D2 structures is not known, but Kwayisi et al. (2023) mapped east-west and NNW-SSE striking faults and joints in Ghana, whose orientation approximately match fault and joint sets 1^{F}, 3^{F}, 1^{MJ} and 3^{MJ} for our study in the Volta basin in Burkina Faso. This suggests that D2 may be a regional deformation event that should be investigated further.

6. Conclusions

By using integrated litho-stratigraphic and structural geology field studies that are combined with interpretations of high-resolution Google Earth imagery, Landsat, radiometric and magnetic imagery, the litho-stratigraphy and character of deformation of the Volta basin in Burkina Faso has been revised, and the geodynamic evolution has been evaluated taking into account revisions to the deformation history of the Volta basin in Ghana by Kwayisi et al. (2020, 2023).

Tonian sandstone/greywacke beds of the Boumbouaka Supergroup exposed along the cliffs of the Madjoari-Gobnangou massifs were deposited ca. 1000-855 Ma on a Palaeoproterozoic basement (ca. 2.25–2.10 Ga) within a tidal to marine lagoonal environment probably along the margin of Rodinia continent. The massive cross-bedded sandstone and greywacke beds correlate with the approximately 700 m thick sequences seen in Ghana and reflects erosion of the granitoid hinterland across the wider Volta Basin. The Tonian beds were unconformably overlain (ca. 270 Ma later) by diamictite, dolomite and chert beds of the Kodjari Group of the Pendjari Supergroup, and disconformably overlain by phosphorite and thick sequences of siltstone-shale of the Porga Group. A time marker of 576 ± 13 Ma for phosphorite (Lu–Hf dating by Barfod et al., 2004) constrains the stratigraphy above and below the phosphorite layer to the middle Ediacaran Period (ca. 635-538 Ma), and after the Ediacaran glacial cycle perhaps during deglaciation. We recommend caution when interpreting the diamictite as glacial tillite in Burkina Faso because the primary features that suggest tillite are not always consistent in the field.

The integrated studies indicate that the Volta Basin in Burkina Faso is located within the marginal foreland of the Dahomeyide fold-thrust belt, and all rocks units were deformed in D1 and D2. The progressive encroachment of the fold-thrust belt onto the southeast margin of the Volta basin in Burkina Faso (and northwest Benin) was a ductile-brittle deformation (D1). Encroachment in D1 occurred during the late Ediacaran and after the ca. 576 Ma phosphorite timeline. The character of D1 deformation, metamorphism and decreasing in intensity across the basin (from SE to NW) places the leading edge of the fold-thrust belt in the Volta basin in Burkina Faso proximal to the Madjoari-Gobnangou massifs.

A younger (undated) east-west directed brittle deformation (D2) is responsible for refolding of sedimentary sequences to form small-scale basins and troughs. D2 is associated with gentle warping, progressive formation of joints, fracture corridors and faults that crosscut the sandstone and greywacke beds of the Boumbouaka Supergroup, leading to open folding (warping) of the sedimentary sequences possibly during dextral wrench tectonics.

CRediT authorship contribution statement

Kim A.A. Hein: Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis. **Stephan Séjourné:** Writing – original draft, Formal analysis. **Clément Ouédraogo:** Writing – review & editing, Investigation, Formal analysis. **Gnissa Sidibé:** Investigation. **Richard Dahl:** Validation, Investigation. **Guy Kevin Coulibaly:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

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Data availability

Data will be made available on request.

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