Geological setting and types of carbonate-hosted gold deposits in the Birimian of West Africa

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Abstract. The Paleoproterozoic domain in the West African Craton (WAC) encompasses numerous world-class gold deposits. These deposits are located in the volcanic and volcano-sedimentary Birimian greenstone belts ante- to syn- Eburnean orogeny in age. The orogenic-type gold mineralizations are coeval with the NW-SE compressive stage (D2) of the Eburnean orogeny. Several deposits are hosted within carbonates showing various purity and deformation degrees in western Ivory-Coast, Guinea and the Senegalo-Malian Kenieba-Kedougou Inlier**.** To date, the role of these lithologies in terms of preferential traps for hydrothermal and/or metamorphic gold-bearing fluids has likely been under estimated. Moreover, the typology of these deposits remains poorly constrained, in part because of their poor outcropping conditions and complex post-emplacement history.

Keywords: Birimian, gold, carbonates

1 Geodynamic evolution of the Birimian

Birimian is a major gold deposits province (Milesi et al. 1989, Milesi. 2001, Beziat et al. 2008) related to the geodynamic evolution of the West African Craton, during early Paleoproterozoic. Birimian consists in supracrustal rocks (volcanic greenstone belts and sedimentary basins) and TTG gneisses, granitoids and granitic intrusions of different ages. Deposition and emplacement of Birimian rocks date **from 2230 Ma to 2060 Ma** (for younger magmatic rocks).
Birimian evolution was driven by a protracted geodynamic evolution characterized by **convergence and subduction processes**. It resulted from the convergence between a southern Guyana shield Craton (Rosa-Costa et al. 2003) and the Kenema-Man Craton of Western Africa. Detailed studies of magmatism particularly in French Guyana (Delor et al. 2001) and Burkina Faso (Thiéblemont, see Castaing et al. 2003), indicate oceanic subduction processes (Ganne et al. 2012) associated with oceanic magmatic arcs. This convergence caused tectono-metamorphic and magmatic events in Western Africa (Delor et al. 2001), termed **Eburnean orogeny** and starting **circa 2220 Ma**. The Eburnean orogeny is related to SE-NW convergence and closure of oceanic domains that led to tectonic accretion of older or younger crustal terranes (micro-continent blocks, volcano-plutonic arcs, etc.) around the edges of a stable Archean continent (Kenema-Man craton). Birimian evolution was a long process taking more than 150 Ma (e.g. Andean realm ~100 Ma) and various stages of evolution can be defined. The **Eburnean D1** tectono-metamorphic **stage** is roughly estimated to date to around 2120 Ma using ages from French Guyana, Ghana and Guinea (Delors et al. 2001, Feybesse et al. 2003, 2006). D1 is associated with reverse faulting, foliation and metamorphism locally reaching upper greenschist to amphibolite facies. In SW Ivory Coast (Ity-Toulepleu), where the San-Pedro Archean terrane is confronted to the Man-Kenema Craton, D1 tectono-metamorphic events are notably intense (Triboulet and Feybesse 1998). The **Eburnean D2 deformation stage**, at about 2100 Ma, was due to an oblique convergence evolution, associated with transcurrent faulting along regional-scale shear zones. During D2, faults and associated folds were generally sub-vertical, with a main sinistral kinematics and epizonal metamorphism (retromorphic when D1 is higher). At a very shallow level, major strike slip faults may generate, pull-apart basins infilled by clastic rocks including sandstones and conglomerates (e.g. Toulepleu conglomerate) and volcanic epiclastic rocks. Upper Birimian sub-marine to aerial volcanism comprising mafic pillows, andesites, tuffs and felsic bodies, is named B2. Indeed B2, which is not deformed by D1 but underwent D2, is geographically associated with these faults. **Later stages of deformation** (e.g. D3: Hein 2004) are limited and heterogeneous in western Africa. Late to post-orogenic magmatism is represented by muscovite-bearing granites (~2080 Ma), differentiated granites and syenites.

2 Birimian gold mineralization

2.1 Early mineralization (ante- 2120 Ma).

Base metal sulfide mineralizations with no significant gold potential, related to active margins have been identified (Schwartz M.O. 2008). Low gold grades Cu-(Mo) porphyry-type mineralization have been identified in Burkina Faso (Goren, Diénémara-Gogondi) (Le Mignot et al. 2013). Massive sulfides bodies (Perkoa, Nabenia Tenga, Burkina Faso), emplaced around 2160 Ma in a back-arc setting (Castaing et al. 2003), are characterized by pyrite-pyrrhotite-sphalerite (Ag, Cu). However, gold is not significantly associated with these mineralizations, except near Nebenia Tenga where gold was probably introduced to the system later (during a D2 gold event, see below).

2.2 Syn-orogenic mineralization (post- 2120 Ma).

Gold mobilization may be coeval to thermal and structural events from D1 to D2 (around 2100 Ma), followed by gold mineralizations coeval to D2 and D3.
Various major types of gold mineralization have been identified (Milesi et al. 1989), each of them associated

with late Birimian evolution (~2100 Ma). These includes: "shear and rock hosted" orogenic type (e.g. Ahafo in Ghana); "Tarkwaian type", related to conglomerates (e.g. Tarkwa district in Ghana); "hypovolcanic associated type" (e.g. Angovia in Ivory Coast); and deposits associated with "intrusive rocks associated type". Orogenic-type mineralization is dominant (Groves et al. 1998). Nevertheless, the influence of deformation on gold deposits and occurrences associated with felsic to intermediate magmatic rocks (sub-volcanic to hypovolcanic, and plutonic bodies) located outside of major D2 shear zones (Milesi, 2003; Robert et al., 2007) is debated.

Additionally, typology and critical parameters controlling emplacement of gold deposits are generally poorly understood, especially the discrimination between "orogenic" and "magmatic" gold end-members. Influence of magmatism on carbonate-hosted gold deposits is still under debate while calc-silicates minerals are diagnostic of magmatic involvement.

3 Carbonate-hosted gold mineralization

Carbonate rocks are very uncommon in the Birimian domain (also in Guyana and Reguibat Shields), even if carbonate rocks can be found close to the Birimian-Archean boundary. Indeed, there is a sub-continuous line extending from Mali (Kenieba-Kedougou Inlier) to the south-west of Ivory-Coast and along the Cestos River in Liberia (Fig. 1). Carbonate layers consist of metamorphosed limestones, impure sandy and possibly greywackeous carbonates, marbles and calc-silicate gneisses probably derived from impure carbonates. The stratigraphic position of such carbonate rocks is poorly understood. However, carbonate rocks seem to be consistently deposited in lower parts of the Birimian (i.e. ante-D1 stage). Carbonate layers underwent medium grade metamorphism and deformation (locally intense with pronounced stretching lineation) during D1 (e.g. Bohodou area in Guinea and Ity in Ivory Coast). Their restricted geographic location, along the Archean-lower

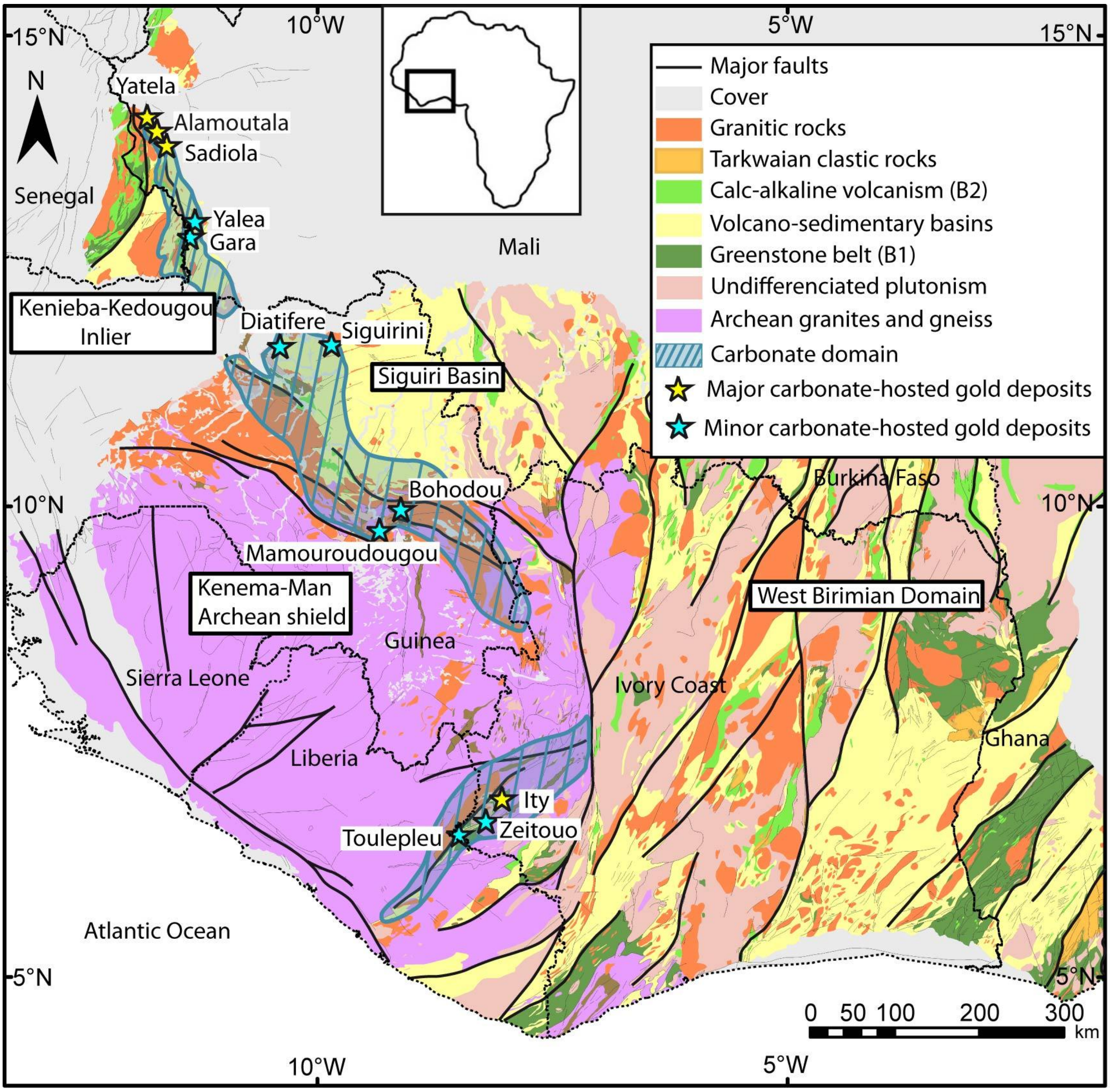

Figure 1. Geological map of the Leo rift system (West African Precambrian).

Birimian boundary, suggests a paleogeographic control. Carbonates are thought to be deposited in discrete episodes, during the lower Birimian, along the shore line bordering the continental domain (Kenema-Man archean eroded craton).

3.1 Kenebia inlier:

The sedimentary Birimian association includes carbonate-bearing layers: calcareous turbidites, impure limestone and marble beds that have been metamorphosed. Close to the major Senegalo-Malian shear zone (SMSZ), gold is frequently hosted by carbonates intruded by late Eburnean magmatic rocks associated to gold-bearing sulfide disseminations.

Sadiola: Gold mineralization is associated with disseminated sulfides in sheared carbonate sediments with subvolcanic intrusive rocks (dioritic sill intrusions, quartz-feldspar porphyry dykes and late dioritic dykes). Carbonate units consist of impure metalimestones interbeded with thin clayey-silty beds and massive metalimestones. Gold is found in association with pyrrhotite, pyrite, arsenopyrite, minor antimony sulfides (stibnite - Sb_2S_3 and gudmundite -FeSbS), chalcopyrite, sphalerite and traces of molybdenite and scheelite. Mineralization hosted by carbonates along the sheared contact is associated with disseminated calc-silicates (porphyroblastic tremolite-actinolite, scapolite, minor epidote and accessory magnetite), albite and carbonate alteration**.**

Alamatoula: In this deposit**,** host-rocks and structures are very similar to Sadiola, and disseminated mineralization is hosted by carbonates. However, at the local-scale (northern part of the open-pit), the massive carbonate lens is skarnified along the contact, and some endo-skarns are located in a granodioritic intrusion.

Yatela: Gold mineralization is related to supergene concentration. The deposit has been interpreted as a paleo-placer deposited in paleo-karst cavities (Hanssen, unpublished 2004), over deeply altered carbonates. Primary disseminated mineralization is hosted by a breccia along the fault zone between carbonate sediments and an intrusive dioritic body, similar to neighboring Alamoutala and Sadiola deposits.

3.2 Siguiri Basin deposits:

Along the southern boundary of Siguiri basin (Guinea) most carbonate rocks are medium to high grade metamorphosed constituting banded paragneiss probably derived from impure carbonates (greywacke and arkosic sandstone) (Feybesse et al. 2004). Rocks consist in a bedded sequence of calc-silicate paragneisses composed of plagioclase, quartz, calcic clinopyroxene (ferrosalite, from diopside-hedenbergite), amphibole, titanite, ± scapolite, ± wollastonite. These rocks host small occurrences (placer and associated primary mineralization) where gold is associated with disseminated sulfides (pyrrhotite, pyrite, and chalcopyrite) in veinlets hosted by calc-silicates gneiss (Mamouroudougou, Bohodou) or in late granitic bodies (Balatindi in Bohodou district). Mineralization is disseminated into intrusions and along the carbonate boundaries without any significant evidences of skarn processes, probably because the calcic gneisses were poorly reactive during the Birimian D2 gold event.

In the Siguiri basin, due to tropical weathering, outcrops of carbonate are uncommon, except in the Léro-Fayalala gold district where carbonate-hosted gold deposits are known near Siguirini (Firifirini and Toume ore bodies). Gold is associated with skarn related to monzodioritic intrusions into carbonates. Skarn lenses are composed of garnet, clinopyroxene-diopside, epidote, magnetite and sulfides (pyrrhotite and pyrite) associated with disseminated gold.

The weathered Diatiféré deposit (70 km west of Siguirini, Guinea) is presented as a residual deposit (similar to Yatela) probably derived from a primary mineralization hosted by skarn in carbonate rocks intruded by a “dioritic body” (Feybesse et al. 2004).

3.3 Toulepleu-Ity domain:

The **Ity deposit** is a gold-bearing skarn enriched by weathering associated with karstification processes. Primary mineralization is composed of skarn lenses, garnetite masses, magnetite and sulfides (pyrite-chalcopyrite) but also of veins and veinlets of various types. The carbonate unit is composed of calcic marbles, calc-magnesian hornfelds and metasomatic skarns. Limestones and impure carbonates are interleaved (tectonic D1 contacts) in a sequence of lower Birimian beds that underwent D1 mesozonal metamorphism and deformation. Mineralization occured during D2 with an early orogenic stage cross-cut less than 10 Ma later by monzogranite to granodiorite intrusions developing high temperature alterations and associated exo-skarns (Billa et al. 2000). Skarn lenses are composed of garnet, clinopyroxene-diopside, epidote and magnetite (± carbonate, quartz, chlorite, pyrrhotite and pyrite). Veinlet networks and disseminations are more complex and are characterized by an assemblage dominated by pyrite and pyrrhotite, with minor amounts of chalcopyrite, molybdenite, electrum, gold inclusions, and traces of sphalerite, arsenopyrite, galena rich in tellurides (altaïte, volynskite) and Cu-As-Sb sulfosalts (tennantite – tetraedrite series) inclusions. The Zeitouo and Toulepleu occurrences are very similar and are characterized by a more pronounced orogenic style than the Morgan or Doui deposits.

4 Conclusions

Carbonate rocks are very uncommon in the Birimian domain, except along the western part of the Archean craton boundary, where they appear as a sub-continuous band from Mali to Ivory-Coast and possibly Liberia. Such specificity suggests a paleogeographic control on carbonates deposition, along the shore line bordering the Archean continental domain. These rocks were deposited before the D1 orogenic stage (i.e. before ~ 2120 Ma) and underwent metamorphism and deformation. The pure carbonaceous marbles, in particular, played a crucial role in trapping any gold-bearing fluids (metamorphic or magmatic).

More than ten deposits and occurrences are known locally in this geological setting, demonstrating a close relationship between early Birimian carbonates, 2100 Ma shear zones, and later Birimian intrusive rocks. The typology of these deposits is hotly debated due to limited information on their non-oxized part. For some highly weathered deposits, interpretations are limited to the description of supergene enrichment of a concealed primary mineralization (e.g. Yatela deposit in a karst setting).

Three hypotheses can be proposed for primary gold mineralization hosted by carbonate rocks: (i) sensu stricto orogenic-type, (ii) skarn-type related to a magmatic intrusion and associated fluids, or (iii) a combination of orogenic and magmatic types.

The preferred interpretation concerning the so-called “skarns-type” is the interaction of an early “classical” orogenic gold mineralization related to the 2100 Ma deformation stage reworked by younger magmatic intrusions and their associated high temperature fluids. Such an interpretation has been proposed by Lawrence et al. (2013) to explain the differences observed between the Yalea and Gara deposits in Loulo camp (Kenieba-Kedougou inlier, Mali).

In Kenieba-Kedougou and Siguiri gold districts, the influence of the magmatism appears limited. This is contrary to Ity–Toulepleu district where the role of magmatism is evident, forming a single orogenic and magmatic hydrothermal event, coeval with a short temporal window (less than 10 Ma) during which gold of any mineralization type is deposited (reduced vs oxidized magmatism clan, Robert et al. 2007).

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