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Geological mapping for mining development in West Africa

Geological mapping constitutes the basis for a country's subsurface knowledge. It is from geological maps established using approaches that draw upon evolving scientific concepts, sustained by increasingly effective analytical means that countries can obtain the information that will allow them to stimulate exploration, and subsequently exploitation activities of their mineral raw materials, thereby contributing to boosting their economies.

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For nearly a century, prospecting for deposits of mineral resources has been the main driver of the headway made in the knowledge of West Africa's geology. In 1911, the first compilation to 1:5,000,000 scale [Hubert (1911)] left out many *terrae incognitae*, but still provided a fairly accurate distribution between basement and sedimentary basins. In 1948, a new edition of the geological map of Africa to the scale of 1:5,000,000 was presented during the 18th International Geological Congress (IGC) in London, a follow-up to recommendations of the 13th IGC in Brussels in 1922 (*figure 1*). Later, surveys by the French Colonial Administration resulted in partial coverage of West Africa to scales ranging from 1:1,000,000 to 1:200,000. Starting in the years between 1970 and 1980, essentially under projects supported by the French Cooperation, this coverage benefited from large numbers of "mining inventory" or research efforts; new maps were published, while others were considerably revised. In 1989, the map of gold-bearing mineralizations to the 1:2,000,000 scale published by BRGM [Milési *et al.* (1989)] as well as the international geological map of Africa edited by UNESCO to the 1:5,000,000 scale temporarily brought to a close this active phase of geological mapping of West Africa.

Renewed interest in the geological mapping of this part of Africa was displayed at the end of the 1990's, essentially thanks to multilateral institutional funding. Between 1990 and 2010, a number of mapping projects, often with the support of airborne geophysical surveys, accompanied at times by exploratory geochemistry, were thus conducted thanks to funding by the Islamic Development Bank, the World Bank, and more particularly the European Union (the SYSMIN program). These projects involved many countries: the Ivory Coast (BRGM, 1990-1992, then 1993-1995), Guinea (BRGM, 1998-1999, then 2003-2004), Mauritania (BGS, 2000-2003; BRGM, 2000-2008), Burkina Faso (BRGM, 2002-2004), Mali (BRGM, 2003-2006, then 2007; GEOTER, 2006-2007), Ghana (CGS-BRGM-Geoman, 2006-2009) and Senegal (GEOTER-BRGM, 2007-2009 ; BRGM-GEOTER, 2008-2010). The mapping scale was usually 1:200,000 covering a "degree square" area (1° longitude over 1° de latitude). Syntheses at the 1:500,000 or at the 1:1,000,000 scale were often published upon completion of these efforts. All these projects were carried out in collaboration with local geological surveys and were attended by a transfer of competencies in the various domains involved (structural geology, geochemistry, geochronology, geophysics, etc.)

The mining sector has a strong industrial impact in developing nations. Besides bringing in foreign currency, the opening of a mine represents a job source as well as a factor for upgrading infrastructures. The objective of these new geological maps was mainly to promote the mineral resources of the countries concerned and, from this standpoint, progress brought about by the work accomplished between 1990 and 2010 turned out to be pertinent, judging by the number of mineral resource deposits of various substances discovered, and by the ensuing opening of mines.

A constantly evolving discipline

While at the same time endeavoring to stimulate industrial investment, geological maps with a mining inventory vocation are scientific achievements complying with precise evaluation criteria. Fundamentally, a geological map is an ordered representation of the subsurface based on scientific concepts and the preparation of which relies on recognizing constitutive "entities" of the subsurface, determining their geographic distribution and how they relate with each other. Thus, a geological map includes a key describing the formations, a representation providing the projection of these formations onto the topographical surface and cross-sections describing their organization at depth.

Fieldwork is rarely easy; the geologist must supply answers to a host of scientific questions and conduct patient and painstaking investigations in order to ensure

FIGURE 1 / Extract from the 1948 international map of Africa to 1:5,000,000 (by Margerie *et al.*, 1948).

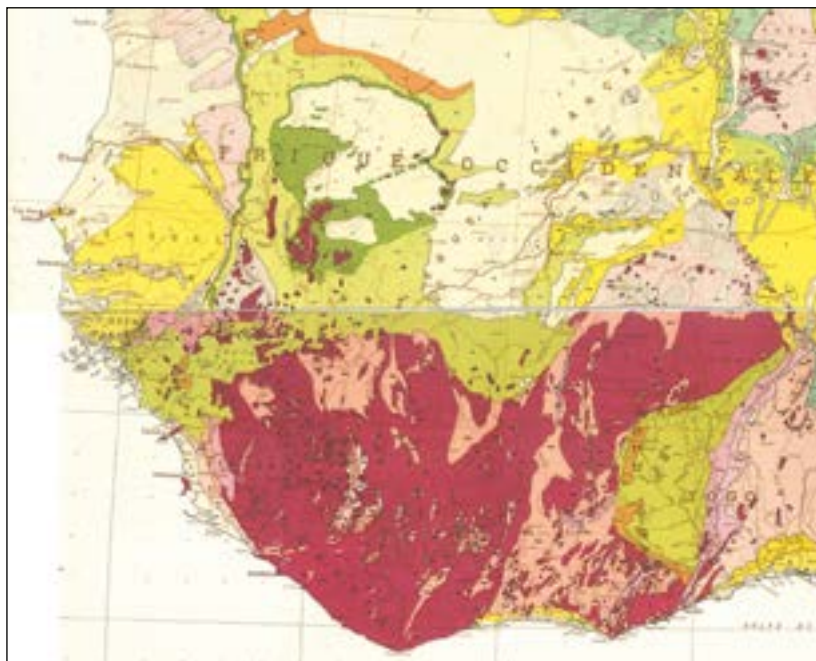


FIGURE 2 / Extract from the new geological map of Africa (Thiéblemont *et al.*, 2016), to be compared with the one portrayed on Figure 1. © CCGM-BRGM

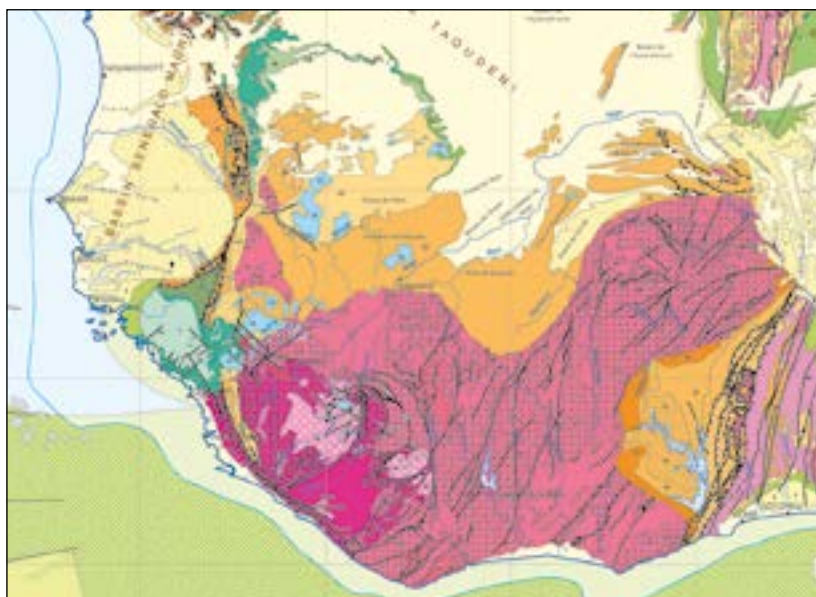


PHOTO 1 / Sedimentary volcanic outcrops in the Birim River, Ghana, origin of the term "Birimian" applied to all West-African Paleoproterozoic formations. © H. THÉVENIAUT, 2008

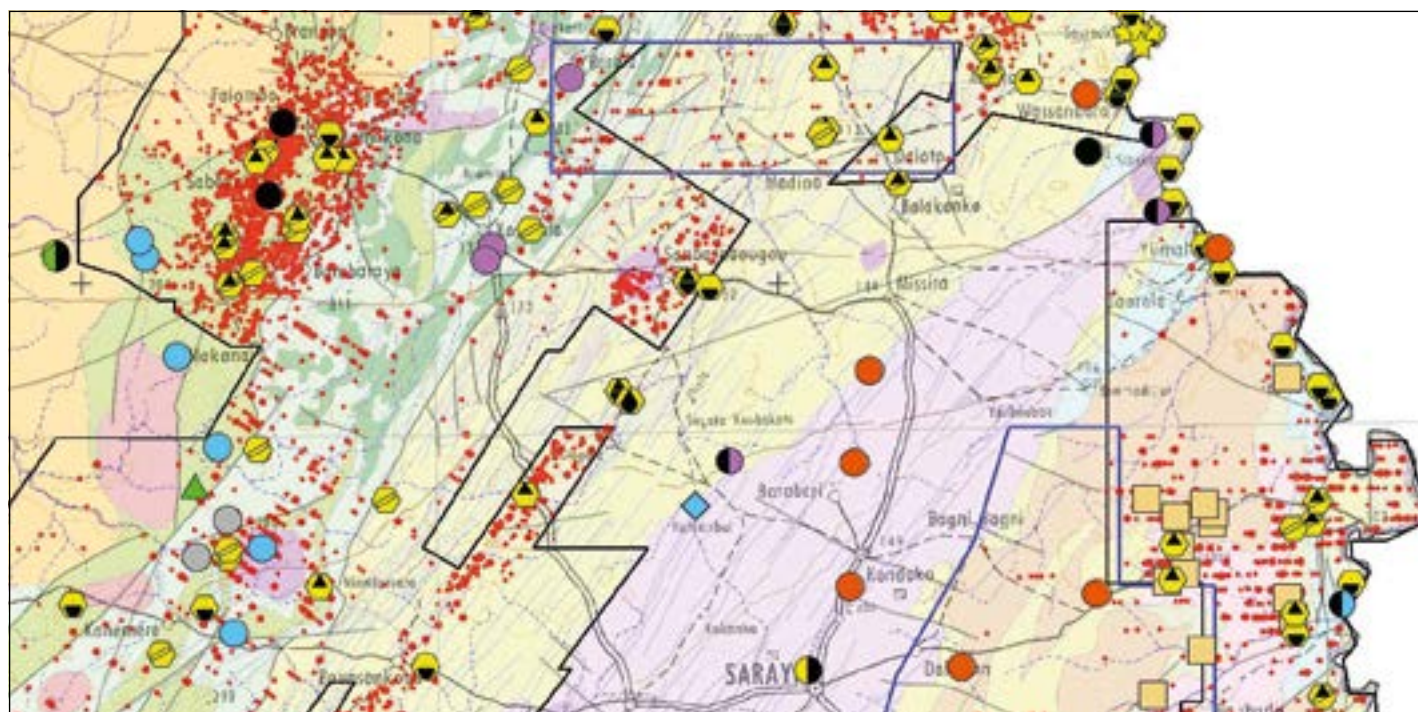


FIGURE 3 / An extract from the “map of gold deposits and abundance” in eastern Senegal (Morisseau *et al.*, 2010).

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that the data gathered and their interpretations articulate coherently with each other. In this effort, analytical methods (geochemistry, geophysics, isotopic dating...) are becoming increasingly important. Thus, information and sample-gathering in the field is just one of the elements in the chain that associates a composite of specialists and tools, ranging from the simplest to the most complex. This said, fieldwork and the geologist's rigor and intuition still constitute the foundation of knowledge.

Today, geological maps are fully computerized and integrated into a geographical information system (GIS) that affords access to the entire set of geological data in the form of distinct and superimposable “layers”. The resolution, or precision, of this information depends on the scale. At the 1:1,000,000 scale, a geological formation outcropping in the field over a width of 100 m represents 1/10 of a millimeter on its mapped representation, i.e., a barely perceptible line, whereas at the 1:1000 scale, the same formation is depicted by a 10-cm-wide band. A map at the 1:200,000 scale is accordingly ill suited for representing the geometry of deposits with surface areas rarely exceeding one hundred meters or so, but it is still indispensable for detecting mineral indices and understanding the relationships among the various formations, some of which are known to contain potential deposits of mineral resources.

The purpose of geological maps is thus not only to determine the contours of formations and to locate deposits within these, but more particularly to take into account the subsurface organization. For this reason, further mapping is fundamental, and corresponds to the expectations of the international institutions funding the programs of geological infrastructure: it is by going back into the field that the data can be brought up to date, synchronizing these with the evolution of geological techniques and concepts.

Metallogenic concepts

The study of mineral deposits derives from the science of metallogeny and consists of superimposing on the GIS a specific layer of information comprising all the known mineral deposits within the map's zone of coverage. These mineral deposits are indices, which become deposits once a significant mass of economically exploitable metal is proven, and mines when the deposit is worked industrially.

This exploitation also depends on economic parameters (the level of market prices for raw materials), or social and political, determining profitability.

The status of index or deposit for a mineral depends upon a number of parameters, which are linked not only to the evolution of knowledge. Improvements in techniques

and extraction processes, and also quite largely to the rule of marketplace, strongly influence the mining sector: today's deposits were often, yesterday, only indices or even outcrops deemed devoid of interest. Thus, for gold, mining targets prior to 1975 contained over 10 tons of gold, with a content of at least 10 g/t (deposits termed "low tonnage and high content"); today, exploitable gold, owing in particular to the considerable appreciation of its price, sometimes only represents several g/t in deposits termed "high tonnage and low content".

These changes have altered the parameters taken into consideration in geological maps. In the instance of low-content deposits, the gold may not be visible, but be present in "halos" (zones bearing the traces of chemical weathering of the rocks), which reflect the activity of hot fluids, called hydrothermal (water + various chemical elements: chlorides, sulfates, etc.) which circulated and transported the precious metal. The identification of these halos on the map is accordingly indispensable even if the gold has not been observed directly. Thus, today's map includes the description of mineralized occurrences, but additionally a set of information that is pertinent with regard to the existence of one type of deposit or another.

The maps provide an inventory of deposits and indices, which they situate in an appropriate layer. This information (*figure 3*) concerns the type, the form, the economic size and the geometry of the deposits and, more exceptionally, their situation with respect to geological history.

The definition of the typology of a deposit derives from the observation of a certain number of characteristics including lithological (the nature of the rocks), geometric, morphological... Massive clusters of sulfide minerals (mainly pyrite and chalcopyrite) in association with certain submarine volcanic rocks are thus ascribed to the type known as volcanogenic massive sulphide (VMS). Worked for the sulphur and the base metals, but which likewise present strong potentials for tin and gold.

A deposit's morphology plays a role in defining its type, but likewise its volume. A deposit may be vein-like, stratiform (interlayered between geological strata), disseminated (a mineral substance impregnating a rocky substratum), etc. The economic size of a deposit may be large, intermediate or small in terms of the conventions of international lexicons. The deposit's geometry defines the dimension and the type of exploitation. A detailed study of the deposit's extent in depth, of its slope, of the presence of faults... is a determining factor for its profitability.

Determining a deposit's position in relation with the regional geological history consists in ascribing it to a "mineralizing event" that shows evidence of a particular geological process: intrusion of a certain type of granite, fracturing following certain directions...

This information is stored in databases which supply the name of the deposit and its description. Maintaining these bases presupposes a continual updating of the information, as well as adapting the digital architectures in keeping with the evolution of computer software.

Geological maps and mineral resources

Modern geological maps distinguish particular layers and structures (known as "of metal-bearing value" or "metallotect"), the study of which has revealed a preferential association with mineralizations. The representation of these metallotects enriches the geological map and materializes metal-bearing potentials. Their definition depends strongly on the expertise of the geologists and the metallogenic concepts used.

Identifying zones possessing a metal-bearing potential requires modelling the geological, geotectonic, geophysical and geochemical parameters associated with the metallotects and governing the distribution of the deposits already recognized. But it is also necessary to extrapolate these parameters to the scale of the map so as to identify analogous areas.

Modelling consists of establishing a combination of elements related to varied levels of information and allowing a mineralized zone to be distinguished, thereby assigning it its own signature. Extrapolation consists in seeking this signature inside areas with no known deposit, which calls for computer tools allowing the management of geographical data, and the cross-comparison of these data, as well as a solid expertise in geology.

Experts define the processing procedures, select, quantify the criteria to be taken into account and validate the results by taking into account methodological limitations. The results depend on scale; an approach at 1:200,000 scale enables favorable sectors for launching a "strategic-scale" campaign to be identified (a search grid on the order of a km²); on the contrary, implanting drilling is based on a tactical approach with an application scale which is that of the deposit (1:1000 at most).

More generally, the results obtained from multi-criteria processing reveal the close control exerted on the mineralizations by the strictly geological parameters and establish the notion of "marker of metal-bearing value". At the same time, analysis of the geological history enables a dynamic significance to be assigned to the markers by connecting them with a specific geological environment.

“Geological maps with a mining inventory vocation are scientific achievements respecting precise evaluation criteria”

► THE YATELA GOLD DEPOSIT (SOUTH WEST MALI): SUPERGENE GOLD ENRICHMENT IN A SURFICIAL KARST

Most of West Africa's mineral wealth derives from its Precambrian basement of Palaeoproterozoic age, commonly referred to as the "Birimian". From 200 Ma and the subsequent opening of the Atlantic Ocean onward, weathering processes have made a major contribution to the concentration of certain mineral resources, such as gossans, bauxites or mineralized karsts. Birimian carbonates, for example, which are rarely observed in outcrop, are frequently affected by dissolution phenomena; such is the case of the Yatela karst.

The Yatela gold deposit is located in the north of the Kedougou-Kenieba inlier in South West Mali. It is hosted by Birimian limestones in contact with a diorite intrusion and which are overlain discordantly by the Neoproterozoic Seroukoto sandstones. The primary mineralization consists of pyrite+chalcopyrite+arsenopyrite and is essentially hosted by dolomitized carbonates [Masurel *et al.*, (2016)]. Supergene ore is associated with a broad karstification surface (coalescent dolines attaining

depths of up to 200 m) with stratified fill [Hanssen *et al.* (2009); Figure]. Four units are distinguished in the latter; from base to top, they are:

- 1 / A basal ferruginous, powdery, sandy to clayey unit containing lithic fragments, derived from the Birimian and the overlying Neoproterozoic formations. These include vein quartz, carbonate rock, diorite saprolite and Seroukoto sandstone. Locally, this unit is referred to as the "mixed zone", which carries the supergene Yatela gold ore.
- 2 / A thick unit of coarse sands with abundant angular blocks of variable size (up to several tens of meters), derived from the Seroukoto sandstones. These blocks have generally undergone superficial weathering processes and crumble easily.
- 3 / A fine sandy unit, derived from the same Seroukoto sandstones. The sands alternate with beds of lateritic pisoliths and other fragments of lateritic crust. The upper lateritic beds are subhorizontal, whereas the lower beds display an increasing dip towards the center of the dolines with

depth. This points to draw-down during karstification, suggesting gradual infill of the dolines as they deepen.

- 4 / An alluvial unit consisting of coarse lithic elements (pisoliths, fragments of lateritic crust and Seroukoto sandstone) in a series of shallow cross-cutting alluvial channels.

Karstic dissolution/concentration led to supergene gold enrichment in the basal ferruginous unit, where the latter overlies sub-economic mineralized carbonate rock. Economic-grade supergene gold mineralization represents a dissolution residue of weakly mineralized carbonate. This is an atypical deposit which, due to its nature represents a hidden exploration target. —

Eric HANSSEN

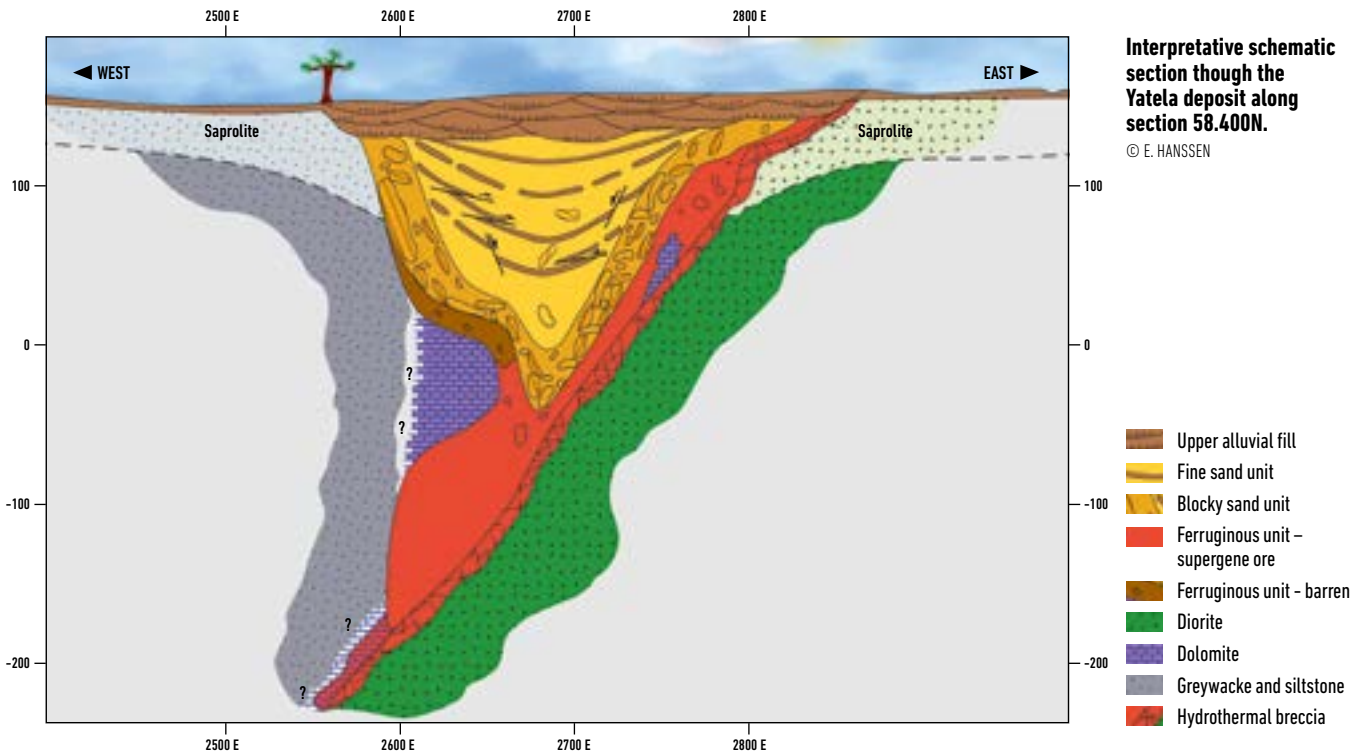
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