AGES

Support for Groundwater Management in the Niger Basin

Geological map
of the transboundary region Benin, Niger, and Nigeria.

Sedimentary basins:
Southern Iullemmeden, Kandi, and Sokoto

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Abbreviations

ABN	Autorité du Bassin du Niger
AGES	Appui à l'Autorité du Bassin du Niger pour la Gestion des Eaux souterraines
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (Federal Ministry for Technical Cooperation and Development)
BRGM	Bureau de recherches géologiques et minières
CTc	Continental Terminal – complexe de base
CT1	Continental Terminal 1
CT2	Continental Terminal 2
CT3	Continental Terminal 3
DOS	Directorate of Overseas Surveys
EPSG	European Petroleum Survey Group Geodesy
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization of the United Nations
FED	Fonds européen de développement
GIS	Geographic Information System
GIZ	Gesellschaft für Internationale Zusammenarbeit
GSA	Geological Survey of Nigeria (1919-1984)
GSNA	Geological Survey of Nigeria Agency (1984-2006)
IAEA	International Atomic Energy Agency
IGN	Institut Géographique National
IHME1500	International Hydrogeological Map of Europe 1:1 500 000
JICA	Japan International Cooperation Agency
NBA	Niger Basin Authority
NGSA	Nigerian Geological Survey Agency (since 2006)
NIMA	National Imagery and Mapping Agency
QGIS	Open Source GIS programm (formerly Quantum GIS)
SFN	National Focal Structures
SAGA	System for Automated Geoscientific Analyses
SRTM	Shuttle Radar Topography Mission
USGS	United States Geological Survey
Vmap0	Vector Map Level 0

Abstract

Geological baseline information is a fundament for higher-level environmental analyses necessary for natural resource management, groundwater potential and vulnerability assessments, and regional development. Available geological maps differ by purpose and often show divergent interpretations along map sheet boundaries and national borders. For West Africa, no comprehensive, transboundary geological map series exists on the local to regional level (scale <1:1 000 000).

Within the technical cooperation project **“Support for Groundwater Management in the Niger Basin/Appui pour la Gestion des Eaux Souterraines dans le Bassin du Niger“ (AGES)**, the Niger Basin Authority (NBA) and the German Federal Institute for Geosciences and Natural Resources (BGR) joined forces to elaborate an **exemplary transboundary geological map** for the border region of Benin, Niger, and Nigeria. The study region comprises the southern part of the sedimentary Iullemmeden Basin (locally known as Sokoto Basin in Nigeria, respectively Kandi Basin in Benin) and the adjacent basement areas of the Dahomeyan belt and the Nigerian shield.

Geological information from eight different map sources was thematically and geometrically harmonized. Chronostratigraphic units of the original maps were correlated and the stratigraphic framework was summarized in a general legend. Differing lithological descriptions were harmonized following the lithological aggregation scheme proposed for the International Hydrogeological Map of Europe (IHME1500, Duscher et al. 2015). This report outlines the harmonization process and discusses the most important aggregation steps and assignment decisions and points out unresolved geological inconsistencies that call for a renewed effort of geological field mapping. Spatial analyses were performed using the open source geographic information system QGIS (QGIS Development Team 2018).

The “**Geological map of the transboundary region of Benin, Niger, and Nigeria**” presents a thematically and geometrically harmonized geological map with a unified chronostratigraphy and lithology. The map provides geological baseline data for environmental assessments, hydrogeological analyses, and regional planning. Inset maps show important geological cross-sections, lineament distribution, and lithological classifications.

1 Introduction

1.1 Technical cooperation

The project "***A**ppui à la ABN pour la **G**estion des **E**aux **S**outerraines*" (AGES) is a joined project between the cross-national **Niger Basin Authority (NBA)** and **the German Federal Institute for Geosciences and Natural Resources (BGR)** aiming to institutionalize sustainable groundwater management on the regional level of the Niger basin.

The technical cooperation project is part of the "Integrated Water Resources Management NBA" program jointly conducted by the German *Gesellschaft für Internationale Zusammenarbeit* (GIZ) and the German Federal Institute for Geosciences and Natural Resources and funded by the Federal Ministry for Economic Cooperation and Development (BMZ PN: 2013.2465.6). The project supports the Niger Basin Authority regarding:

I. the establishment of groundwater monitoring networks,
II. the development of transboundary groundwater management strategies, and
III. capacity building.

1.2 Motivation

Groundwater management strategies accrue from a sound knowledge of the hydrogeological environment embodied by hydrogeological maps and (conceptual) models on e.g. aquifer productivity, aquifer vulnerability, flow patterns, etc… Prerequisite for any of such hydrogeological analysis is, however, the **understanding of the geological setting**.

Since the early 20th century, colonial and post-colonial geological mapping projects in West Africa provide a wealth of—although often incomplete—map series of different scales, level of geological detail, diverging denomination of (litho-)stratigraphic units, language, and reliability and reflect the evolving geological knowledge and stratigraphic framework. Border regions in particular suffer not only from a lack of coverage but show exemplarily **divergent geological interpretations and denominations along map sheet boundaries** and national borders. Numerous supraregional and Africa-wide geological overview maps exist at scales smaller than 1:1 000 000 thus lacking sufficient detail and accuracy for local to regional planning and management. To address groundwater management demands in transboundary regions of the Niger Basin, unified and harmonized transboundary geological maps are imperative.

The report at hand describes exemplarily the harmonization of geological maps for a transboundary pilot zone of the AGES project (border region of Benin, Niger, and Nigeria). The elaborated harmonized and transboundary geological map represents the base map for the forthcoming hydrogeological analysis and for regional planning purposes. The described harmonization process may be seen as a showcase, exemplary for similar work within and beyond the Niger Basin.

The chapter 1 introduces the project and the study area followed by a short outline of the methodology presented in chapter 2. The report builds on a comprehensive collation of geological maps of the Niger Basin. Strengths and limitations of eight selected geological maps relevant for the pilot zone are discussed in chapter 3. Chapter 4 describes the thematic harmonization of the original eight maps and the unification of legend items within a chronostratigraphic framework summarized in a general legend. Geometric harmonization was necessary to adapt the outline of features that could not reasonably be merged following the general legend. Chapter 5 discusses in detail the geometric harmonization of each geological unit including the rational for individual decisions regarding the feature outlines.

Ancillary data on lineaments, strike and dip, fossil occurrence, and cross sections are presented in chapter 6. The main report finishes with a short summary including a discussion of the limitations in chapter 7.

The appendix comprises: a brief overview on the geological background of the southern Iullemmeden and Kandi Basins (appendix I), a selection of additional maps not used for the harmonization (appendix II), the harmonized general legend for the transboundary geological map (appendix III), the lithological aggregation scheme of the International Hydrogeological Map of Europe (appendix IV), selected cross sections of the study area (appendix V), and a short overview on the implementation of the harmonization process in the free open source GIS program QGIS (appendix VI).

1.3 Study area

Study area is the border region of Benin, Niger, and Nigeria (Fig. 1 & Fig. 2). The region was chosen as the pilot zone n°1 of the AGES project due to:

- its transboundary character involving three of nine member countries of the NBA,
- the importance of the sedimentary aquifers of the Iullemmeden, Sokoto, and Kandi Basins for the drinking water supply of the rural population.

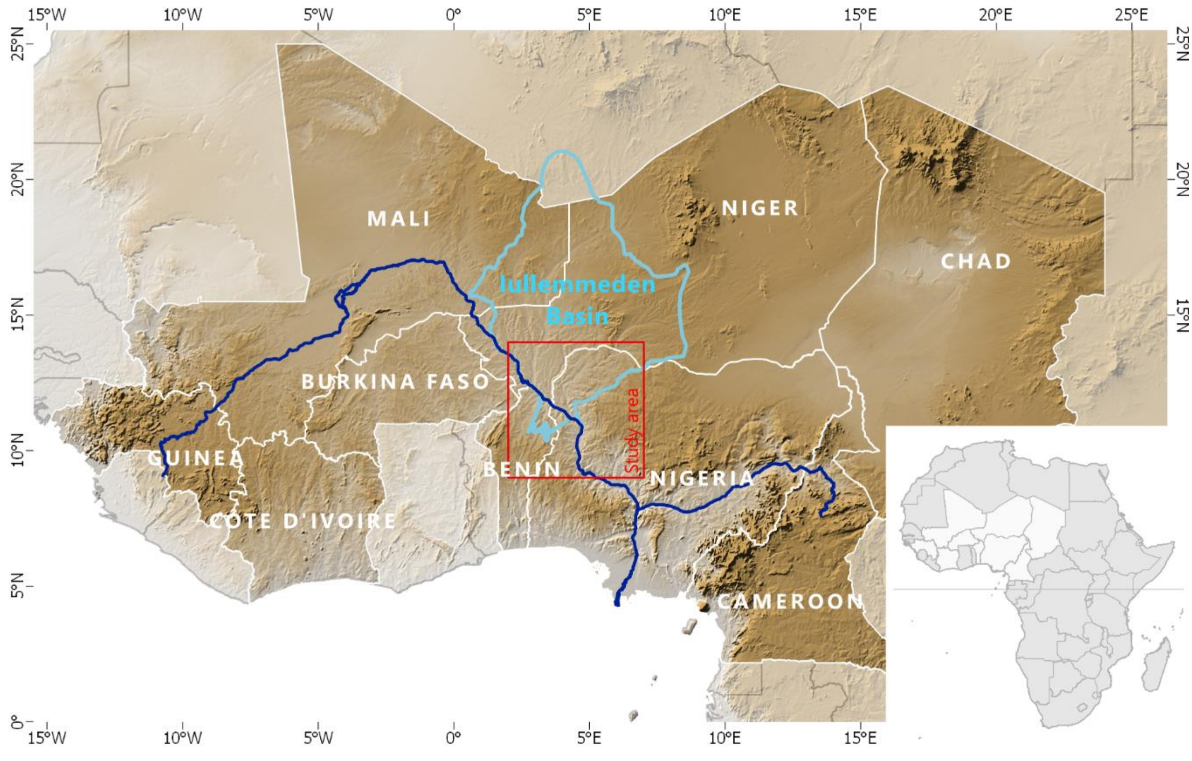

Fig. 1: Member countries of the Niger Basin Authority (NBA), location of the study area and extend of the Iullemmeden sedimentary basin.

The harmonization effort comprises the area between 3°-5°W and 10°-13°N restricted further by the coverage of map sheets and focused on the sedimentary units. The study area is part of the ecoclimatic and biogeographic Sudanian region characterized by an open, moist to dry tree savannah. Rainfall amounts range between the climatic dry frontier (1000 mm)

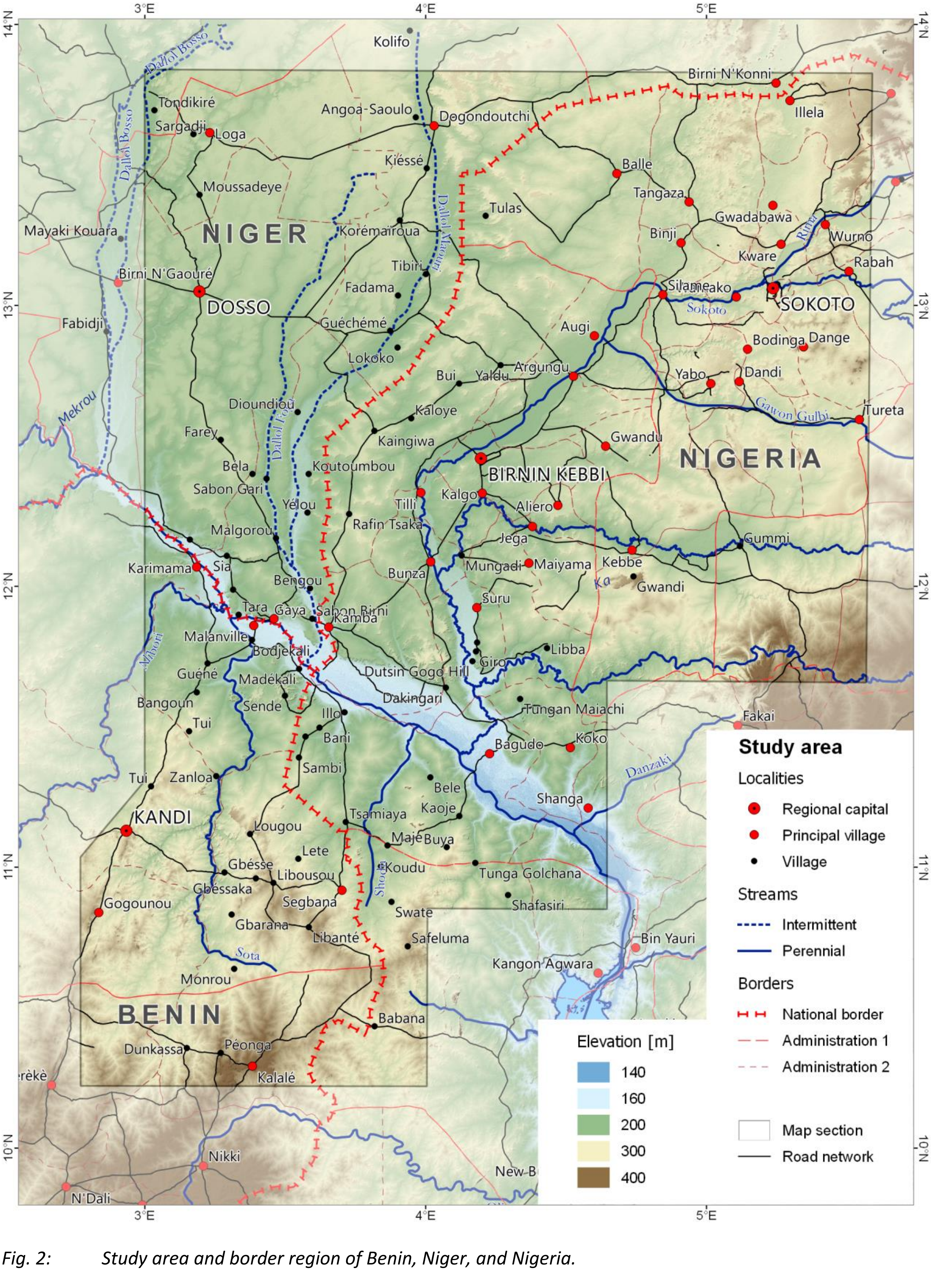

Fig. 2: Study area and border region of Benin, Niger, and Nigeria.

near Kandi and the agronomic dry frontier (500 mm) near Sokoto. Most important rivers beside the Niger River are the perennial right bank tributaries Mekrou, Alibori and Sota (Benin) and the intermittent Shodu (also Choudou or Ouara) in Benin/Nigeria: on the left bank, the perennial Sokoto River (Gublin Kebbi) with its tributaries Rima, Gawon Gulbi (Gaminda), Zamfara, and Gulbin Ka in Nigeria. No regular runoff does occur in the palaeodrainage systems of the Dallol Maouri and Dallol Foga in Niger.

Geologically, the study area is located at the transition between the Dahomeyan basement and the Mesozoic Iullemmeden Basin. The Dahomeyan Belt (Benin, Togo, and Ghana) is the southern part of the Trans-Saharan Mobile Belt—a fold-thrust belt active during the Neoproterozoic Pan-African orogeny (Bumby & Guiraud 2005; Kröner & Stern 2005). The granitoid-gneissic terrane is made up of metamorphic overprinted Paleoproterozoic basement, Neoproterozoic oceanic sediments, and plutonic intrusions recording the ocean opening and subsequent collision-subduction along the West African Craton and the Saharan Metacraton. The Iullemmeden basin is a large epeirogenic continental sag basin that developed from the precursory Palaeozoic sub-basins Tim Mersoï/Tamesna and Kandi to a Cretaceous continental syncline with a total sediment depth of locally over 1000 m of sediments. It formed mainly during the Cretaceous when continental sediments of the so-called “Continental Intercalaire” (Agadez, Irhazer, Tegama groups) were deposited. Marine deposition occurred during the Late Cretaceous global transgressions (late Cenomanian to early Eocene); in the study area, the sediments of the Rima & Sokoto Groups were deposited (Kogbe 1991; Moody 1997). Following the late Eocene Hoggar hot spot swell, the present day drainage pattern established in the early Oligocene (Chardon et al. 2016). Uplift and a slight tilt to the south are responsible for the erosion of Palaeozoic sediments in the northern Tamesna basin and the exposure of progressively younger sediments towards the south. Here, south of 16°N, the final phase of continental sedimentation led to the deposition of the Continental Terminal. During the Oligocene and Miocene, the West African basement experienced repeated phases of planation and erosion that can be directly correlated with the corresponding deposits of the Continental Terminal (Burke & Gunnell 2008; Beauvais & Chardon 2013). Meseta-like remnants of the Continental Terminal 3 found throughout the study area, mark the final stage of deposition during the Late Oligocene followed by surface stability, prolonged weathering and the development of the Intermediate Surface S2 (Chardon et al. 2016).

Subsequent surface stability conserved topography and drainage pattern. The stable present-day topography is shaped by the slow incision of the Niger River and its northern tributaries (Dallol Maouri, Dallol Foga, Sokoto River) into the flat sedimentary plain of the Iullemmeden Basin—build up at the surface by the Continental Terminal 3. The nearly flat sedimentary plain of the Iullemmeden basin tilts from around 300 m a.sl. near Dogondoutchi to about 200 m near Gaya (0.3° slope). In Nigeria, outcropping Cretaceous strata form a sequence of cuestas that give way to an incipient scarpland in the Sokoto Basin, the Nigerian part of the Iullemmeden Basin. In Benin, the Palaeozoic sediments of the Kandi Basin are exhumed and form a levelled plain interrupted by remnants of the Continental Hamadien/Continental Terminal 3 that form meseta-like plateaus with sharp escarpments. Basement areas are characterized by a slightly more varied relief expressed as visible undulations of a flat planation surface. Highest elevations are found in Benin with elevations around 400 m a.s.l. in the area of Kalalé and in the foothills of the Nigerian shield that show elevations between 300-400 m.s.l. The elevation of the Niger valley as the main drainage ranges between 160 m (confluence of the Dallol Maouri) and 140 m near Shanga.

From a hydrogeological point of view, the study region comprises the multi-layered aquifer system of the Iullemmeden/Sokoto Basin with the economically important aquifers of the Continental Terminal 1, 2, and 3 draining into the Niger River from the north and the Palaeozoic Kandi Basin with the semiconfined Wéré Aquifer (formerly subsumed under *Grès de Kandi*) draining into the Niger River from the south.

The area is sparsely populated with a strongly contrasting population density of 50/km² to 100/km² in Dosso region, Niger, and the Kebbi and Niger States in Nigeria but less than 50/km² for the Alibori department in Benin (Brinkhoff 2018).

2 Methodology

Geological maps may differ on different levels: extent of coverage, scale, level of detail, classification, and denomination of (litho-) stratigraphic units, language, and reliability. Harmonization is necessary to obtain a unified geological map. The harmonization process comprises two-stages:

I. thematic harmonization of the map items and descriptions.
   ➔ unified and consistent **(litho-, chrono-) stratigraphic legend**

II. spatial harmonization of the map features.
   ➔ **geometric harmonization** of units between maps and along map boundaries

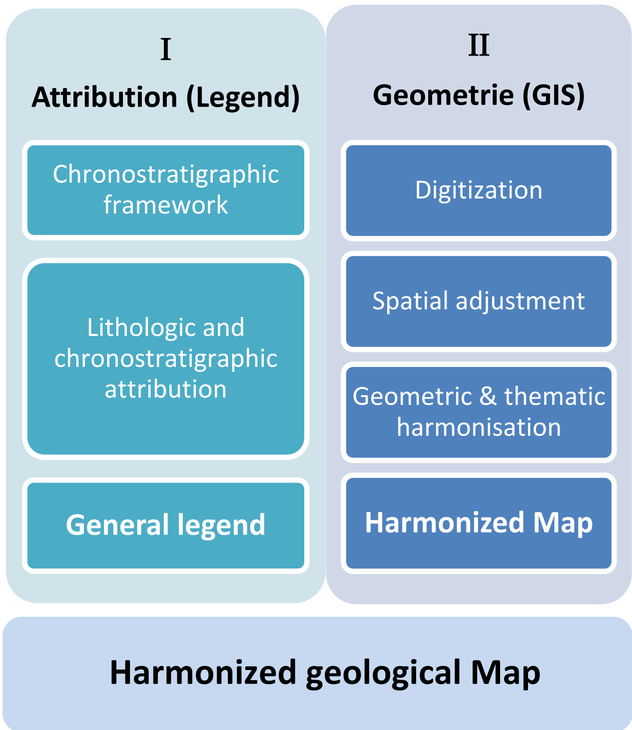

Fig. 3: Harmonization workflow

2.1 Thematic harmonization (general legend)

First step is the creation of a general legend that defines number and content of the final map items. Based on the original map units, a comprehensive chrono- and lithostratigraphic framework is developed by correlating identical and similar stratigraphic units and assigning a common denomination and description. Ancillary geological attributes that can be directly related to a stratigraphic and lithological unit (degree of consolidation, fracturing, etc.) are assigned following information from both the original map legends and auxiliary literature. If necessary, chronostratigraphic units are divided into lithologically distinct facies. Finally, the stratigraphic framework is condensed into a unified general legend that is appended to the GIS layers of the respective maps using the original map legends.

2.2 Geometric harmonization

The second stage is the harmonization of the map geometry. Pre-processing comprises digitization of the original analogue maps, georeferencing, and topological correction. If necessary, the digital datasets are spatially adjusted to a generally accepted topographic base map. To avoid overlapping when merging the GIS layers into a single dataset, the original datasets are cropped to the respective map boundaries.

First step of the geometric harmonization of the GIS layers is to append the new general legend to each digital dataset using the original map items as join fields. Ideally, merging of the datasets using the new general legend results in a harmonized map. Practically, spatial deviations between maps produce a variety of boundary issues that are discussed in chapter 5.

Resolving boundary issues requires manual corrections drawing on expert knowledge—ideally based on geological field expertise or guided by additional information such as remote sensing (topographic features, satellite imagery). A methodological challenge is the merging of overlapping maps. While the additional information allows for crosschecking the reliability of each map product, decisions have to be taken which stratigraphic nomenclature or geometry to use.

2.3 Multi-scale map

Geometric harmonization and aggregation does not change the level of detail nor the scale of the original data. The use of a common scale requires upscaling and geometric generalization oriented towards the smallest scale. More often than not this results in a disproportional loss of detail and information. Alternatively, a multiscale map incorporates all available information at the original level of detail. A spatially varying scale allows maintaining the original heterogeneous level of detail and reflects directly the state-of-art of the available geological mapping. An inset map provides information on the coverage, scale, and the data sources of the original maps.

3 Geological maps of the study area

3.1 Overview

Relevant geological maps covering the study area are listed in Tab. 1. Maps used for harmonization are marked bold and are described in detail below.

Tab. 1: Geological maps of the study area. Maps used for harmonization are marked bold.

	Geological maps		Studies / Explanatory Notes	
Niger	**Greigert (1960)**	**Carte Géologique de Reconnaissance: Dosso, 1:500 000. BRGM**	**Greigert (1961)**	**Notice explicative sur la Feuille Dosso (ND-31-SE)**
	Greigert (1961)	Carte Géologique de Reconnaissance du Bassin des Iullemeden, échelle 1/1 000 000. BRGM	-	-
	Greigert & Pougnet (1966)	**République du Niger. Carte Géologique, 1/2 000 000. BRGM**	**Greigert & Pougnet (1967)**	**Notice Explicative sur la Carte Géologique de la République du Niger à l'échelle du 1/2 000 000. BRGM**
	Machens, E (1966):	Carte Géologique du Niger Occidental 1/200 000. BRGM	Machens, E (1967):	Notice Explicative sur la Carte Géologique du Niger Occidental à l'échelle du 1/200 000. BRGM
Nigeria	**Jones (1940)**	**Geological Map of Sokoto Province, 1:500 000**	**Jones, B (1948)**	***The sedimentary rocks of Sokoto Province*. Bulletin of the Geological Survey of Nigeria N° 18**
	D.O.S. (1965-66):	**Geological Survey of Nigeria, 1:250 000 Series, Directorate of Overseas Surveys.** • **Sheet 1, Tangaza** • **Sheet 2, Sokoto.** • Sheet 3, Shinkafe • **Sheet 6, Birnin Kebbi** • **Sheet 7, Gummi** • Sheet 8, Gusau.		
	Dessauvagie (1974)	Geological Map of Nigeria. The Nigerian Mining, Geological & Metallurgical Society.	-	-
	Geological Survey Division (1965)	Geological Map of Nigeria 1964. Director of Federal Surveys.	-	-
	Geological Survey Division (1974)	Geological Map of Nigeria 1974. Federal Surveys	-	-
	NGSA (2011a)	**Geological and Mineral Resources Map of Kebbi State, Nigeria. 1:500 000. Nigerian Geological Survey Agency.**	-	-
	NGSA (2011b)	**Geological Map of Nigeria. 1:1 000 000. Nigerian Geological Survey Agency**	-	-
Benin	Pougnet (1957):	Kandi-E. Carte Géologique de Reconnaissance de l'A.O.F. Feuille N° NC 31-N.O.-E.34. 1:500000	Pougnet (1957):	Carte Géologique de Reconnaissance á l'échelle du 500.000. Notice explicative sur la Feuille Kandi-Est (N° NC. 31-N.O.-E.34).
	Akibou et al. (1989)	**Carte Géologique. 1 :200 000. Projet FED N° 4105-011-13-20, Istituto ricerche Breda & OBEMINS, Italie.** • Feuille Kandi • Feuille Karimama • **Feuille Malanville** • Feuille Porga	**Istituto ricerche Breda (1989)**	**Notice explicative de la Carte Géologique à 1/200.000. Feuilles: Karimama, Porga, Kandi, Malanville. Projet FED N° 4105-011-13-20, Mémoire N°2, Istituto ricerche Breda & OBEMINS, Italie.**
	Technoexport (1995)	**Carte de Géologie et des Minéraux utiles. Conceil de la Géoscience, Pretoria. 1 :200 000** • **Dunkassa** • Bembèrèkè • Natitingou • Sansanne	**OBEMINES (1995)**	**Notice Explicative de la Carte Géologique à 1:200 000, Feuille Dunkassa. Mémoire N°5, Office béninois des Mines, Pretoria.**
	Konate (1996)	**Carte géologique générale du bassin paléozoïque de Kandi. 1 :400 000, Figure 15.**	**Konate (1996)**	**Évolution tectono-sédimentaire du bassin paléozoïque de Kandi (Nord Bénin, Sud Niger). Un témoin de l'extension post-orogénique de la chaîne panafricaine. Figure 15, Dissertation, Université de Bourgogne, Dijon-Niamey.**

3.2 Niger

For Niger, the base map for geometric harmonization is the high-detail, medium-scale *Carte Géologique de Reconnaissance: Dosso, 1:500 000* of Greigert (1960). It is complemented by the large-scale map *République du Niger. Carte Géologique, 1:2 000 000* (Greigert & Pougnet 1966) to fill gaps and add additional detail along the Niger River and in parts of Nigeria. Most important difference between the two maps is the additional differentiation between Continental Terminal 1 and Continental Terminal—complexe de base.

3.2.1 Greigert (1960): *Carte Géologique de Reconnaissance: Dosso, 1:500 000*

The sheet Dosso (Greigert 1960) is part of the reconnaissance series of the Bureau de Recherches Géologiques et Minières (BRGM) and accompanies the *Notice explicative sur la Feuille Dosso (ND-31-SE). Carte Géologique de Reconnaissance à l'échelle du 500 000* (Greigert 1961b). The map sheet (Fig. 4) covers the Nigerien part of the quadrant ND-31 SE (designation following the Institut Géographique National, IGN) and is dominated by the outcrop of the Continental Terminal 1 and the fossilized quaternary valley of the Dallol Maouri (lower reaches of the Tadiss valley). On the left bank of the Niger River, Greigert reports the unit "Continental Terminal Complexe de base"—described as a conglomerate of rounded pebbles (puddingstone/poudingue) and coarse-grained sandstone—whose lithology and stratigraphic position is not well defined (compare 5.3.2). On the right bank of the Niger River, the *Complexe de base* is not differentiated and forms part of a "Continental Terminal indifférencié". The map depicts in detail formation boundaries and seasonal runoff pathways.

3.2.2 Greigert & Pougnet (1966): *République du Niger. Carte Géologique, 1:2 000 000*

The comprehensive overview map *République du Niger. Carte Géologique, 1:2 000 000* (Greigert & Pougnet 1966) shows the state-of-art geology of the entire Republic of Niger in the mid-70s and is accompanied by a *Notice Explicative sur la Carte Géologique de la République du Niger à l'échelle du 1/2 000 000* (Greigert & Pougnet 1967). The map advances the earlier reconnaissance map *Carte Géologique de Reconnaissance du Bassin des Iullemeden échelle 1/1 000 000* (Greigert 1961a). Greigert's comprehensive regional work has been the base for most of the subsequent regional mapping projects and due to its partly transboundary character it is particularly useful for comparing the extent of geological strata between Niger, Nigeria, and Benin (Fig. 5).

The 1:1 000 000 small-scale overview map was used to complement areas not covered by the *Carte Géologique de Reconnaissance: Dosso* (Greigert 1960). A major revision compared to the earlier reconnaissance map is the mapping of *Continental Terminal 1* on both the right and left bank of the Niger River replacing areas of *Continental Terminal-complexe de base* (left bank) and *Continental Terminal indifférencié (*right bank). Due to the small scale, the *Continental Terminal-complexe de base* is here reduced to a sketchy dotted line along the base of the Continental Terminal escarpment.

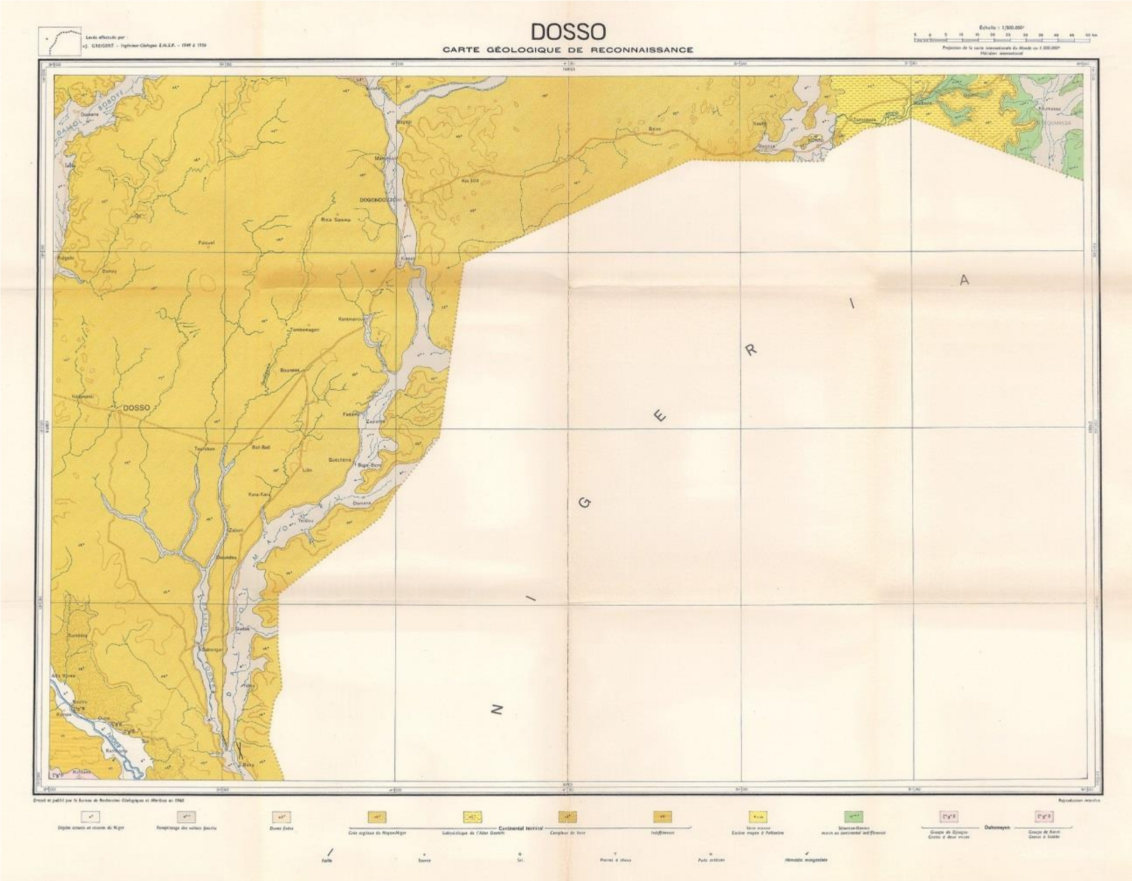

Fig. 4: *The Carte Géologique de Reconnaissance: Dosso, 1/500 000 (Greigert 1960) is used as the base map for the Nigerien part of the study area.*

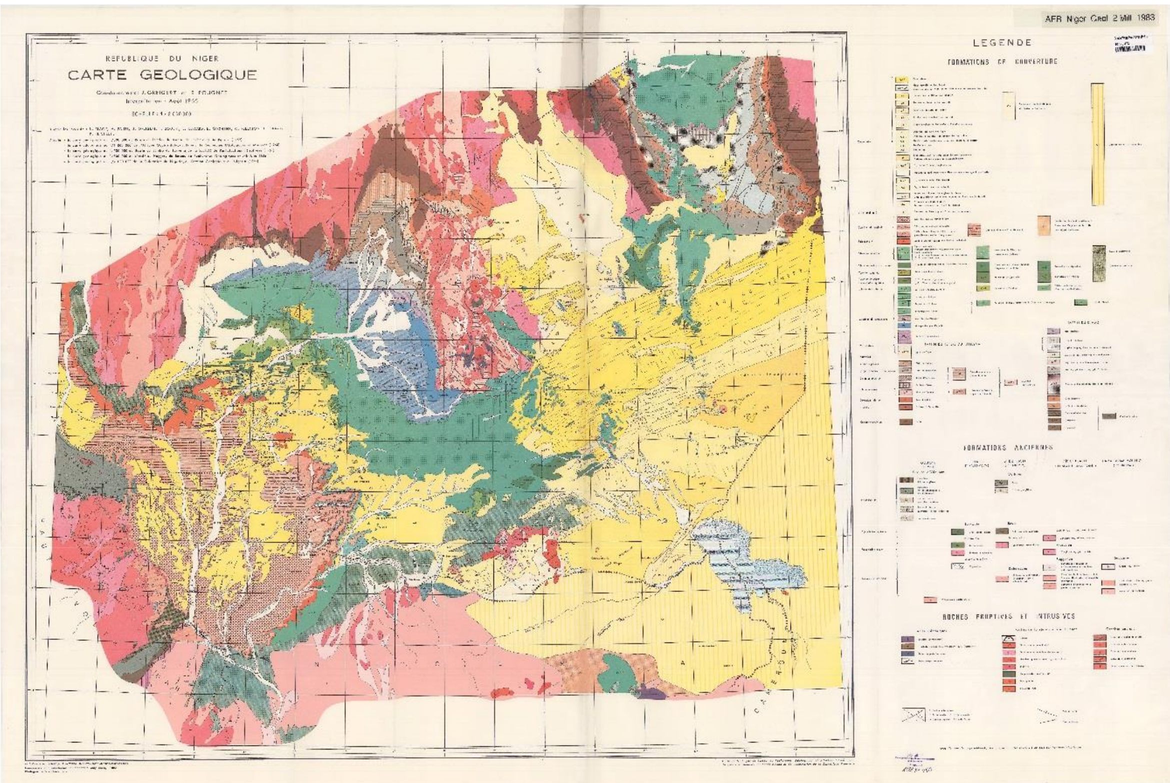

Fig. 5: *Carte Géologique de la République du Niger, 1 :2 000 000 (Greigert & Pougnet 1966) provides a comprehensive overview of the geology of Niger and the Iullemmeden Basin.*

3.3 Nigeria

For Nigeria, the six map sheets of the *Geological Survey of Nigeria maps series 1:250.000* prepared by the Geological Survey of Nigerian (GSN) and the Directorate of Overseas Surveys (DOS) (1965c, 1965a, 1965b, 1966a; 1966) were used as the principal base map for the Sokoto Basin. Despite the limited extent, it is up-to-date the most detailed geological map series available for northwestern Nigeria.

The remaining part of the study area, is covered by two small-scale digital datasets—the *Geological and Mineral Resources Map of Kebbi State, Nigeria* (NGSA 2011a, 1:500.000) and the *Geological Map of Nigeria* (NGSA 2011c, 1:2.000 000). For the areas west of the Sokoto River, maps and geological descriptions of Jones (1948) and Greigert & Pougnet (1966) were deemed more appropriate. These were used to map outcrops of the Gwandu (Continental Terminal), Kalambaina, and Illo Formations as well as the bauxitic clays west of the Sokoto River.

3.3.1 Nigerian Geological Survey Agency (2011a/c): *Geological and Mineral Resources Map series 1:500 000* & *Geological Map of Nigeria, 1:1 000 000*

In 2004, the Geological Survey of Nigeria Agency (GSNA), replacing the Geological Survey of Nigeria (GSN) and renamed in 2006 to Nigerian Geological Survey Agency, NGSA) embarked on a new nation-wide geological mapping project. This resulted in the *Geological and Mineral Resources Map series*, scale 1:500 000 of the 36 states and a nation-wide *Geological Map of Nigeria*, scale 1:1 000 000—both with its own geometries but generally similar legend items. Following information from the Nigerian Geological Survey Agency website (http://ngsa.gov.ng/), both datasets are based on systematic geological mapping on scale 1:1 000 000 by the Geological Survey Department with periodic field checks (for Kebbi State in 1971-75 and 1994-95). The data was collated on state-by-state basis and incorporates data from NGSA records, references from oil companies and publications. Whereas a first publication dates to 2006, the available PDF and digital datasets are dated to the year 2011. Two ArcGIS projects with its respective digital geological datasets were acquired from the headquarters of the Nigerian Geological Survey Agency in Abuja during spring 2017:

- NGSA (2011a): *Geological and Mineral Resources Map of Kebbi State*, 1:500 000
- NGSA (2011c): *Geological Map of Nigeria*, 1:1 000 000

Despite the proclaimed systematic geological mapping, both the map series *Geological and Mineral Resources Maps* at the printed scale of 1:500 000 and the nation-wide *Geological Map of Nigeria* at the printed scale of 1:1 000 000 show ambiguous stratigraphic and/or cartographic elements and are less detailed and less consistent compared to earlier geological maps. Where possible, geometries of the older but more reliable maps were preferred.

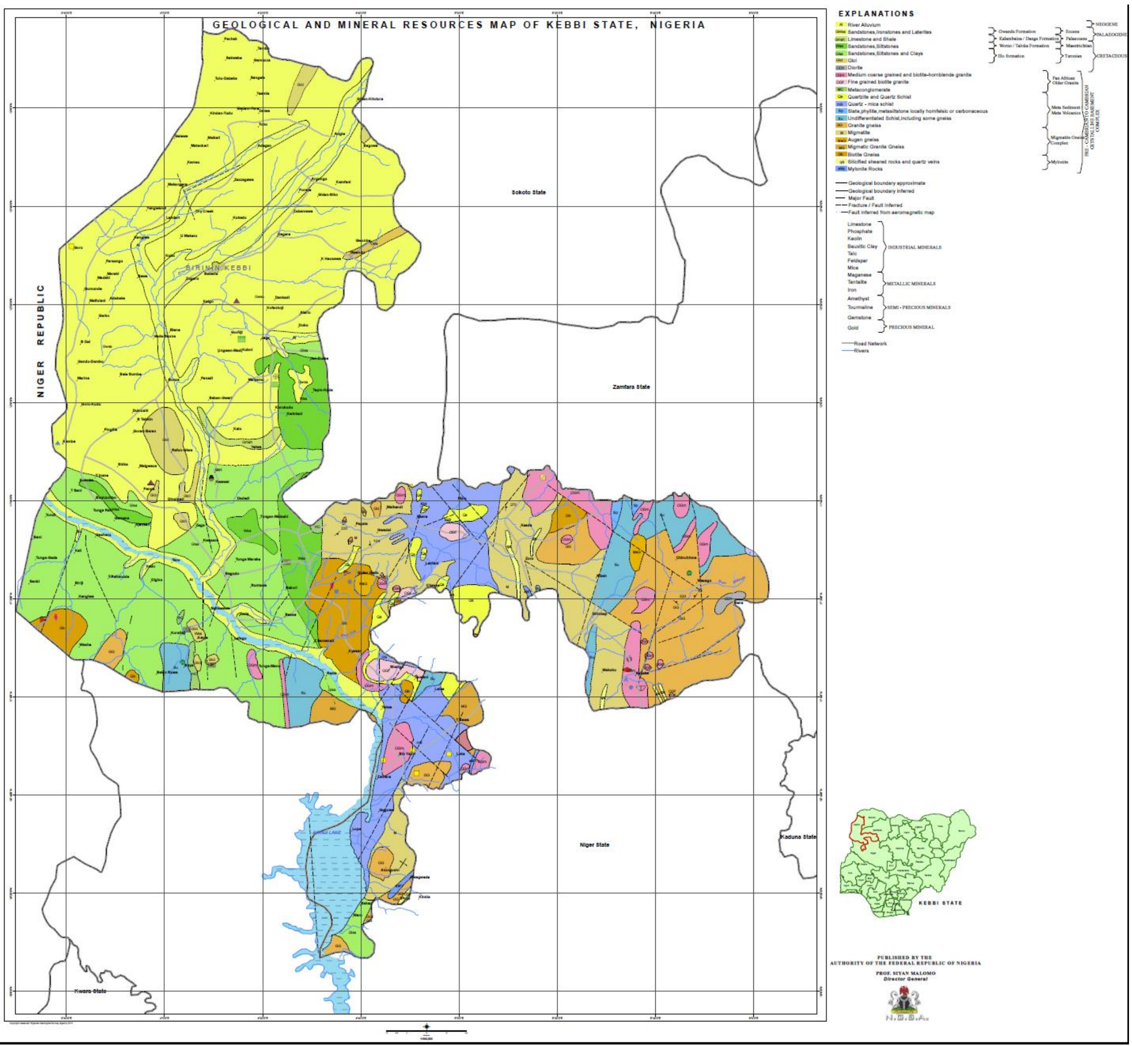

Fig. 6: Geological and Mineral Resources Map of Kebbi State, Nigeria, 1:500 000 (NGSA 2011a).

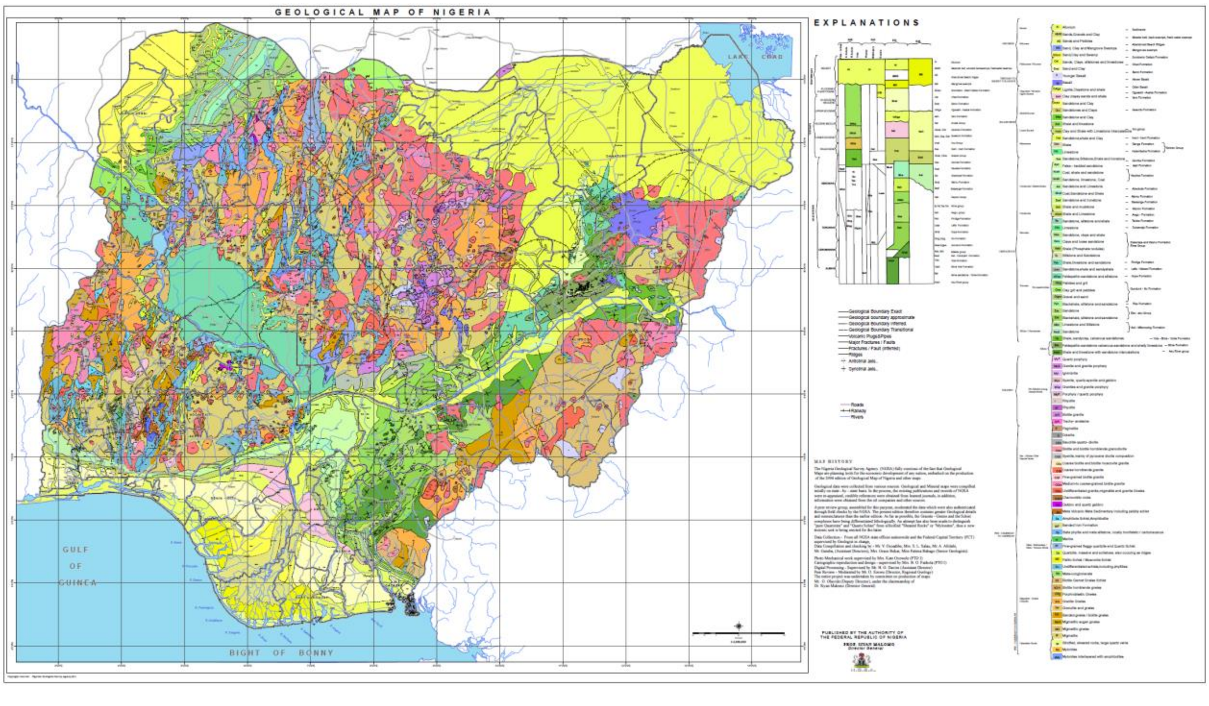

Fig. 7: Geological Map of Nigeria, 1:1 000 000 (NGSA 2011c)

3.3.2 D.O.S. (1965-66): *Geological Survey of Nigeria map series 1:250 000*

The *Geological Survey of Nigeria map series 1:250 000* was published in 1956-1966 by the Geological Survey of Nigeria (GSN) and the Directorate of Overseas Surveys (D.O.S.). Up-to-date, the six map sheets surveyed between 1958 and 1965 by D.H. Parker, D. Carter, M.N. Fargher, and D. C. Turner provide the most detailed geological map series available for northwestern Nigeria: Sheet 1 - Tangaza (D.O.S. 1966a), Sheet 2 – Sokoto (D.O.S. 1965a), Sheet 3 – Shinkafe (D.O.S. 1965b), Sheet 6 - Birnin Kebbi (D.O.S. 1965c), Sheet 7 – Gummi (D.O.S. 1966b), Sheet 8 – Gusau (D.O.S. 1966c). The following four analogue map sheets were digitized:

- Sheet 1: Tangaza (D.O.S. 1966a)
- Sheet 2: Sokoto (D.O.S. 1965a)
- Sheet 6: Birnin Kebbi (D.O.S. 1965c)
- Sheet 7: Gummi (D.O.S. 1966b)

Printed in the scale 1:250 000, the maps show a high degree of detail and a very good accuracy regarding topographic features such as stream networks and ferricrete outcrops. Being the product of an integrated mapping approach that included geological, topographical and hydrological features, the information on the map is the best available. In addition, each map provides a simple geological cross section. In 1973, the USGS study *Aquifers in the Sokoto basin, northwestern Nigeria, with a description of the general hydrogeology of the region* (Anderson & Ogilbee 1973) used the Geological Survey of Nigeria series as base map for their *Geologic Map of the Sokoto Basin, Northwestern Nigeria* and respective hydrogeological studies. Later, nation-wide geological maps that touch the areas such as the *Geological Map of Nigeria 1964, 1:2 000 000* (Geological Survey Division 1965), the *Geological Map of Nigeria, 1:1 000 000* (Dessauvagie 1974) or the *Geological Map of Nigeria 1974, 1:2 000 000* (Geological Survey Division 1974) built on the seminal work of Parker and colleagues. For the northwestern part of the study area, this map series is given preference over the latest release of digital datasets by the Nigerian Geological Survey Agency.

3.3.3 Jones (1940): *Geological Map of the Sokoto Province*

Jones *Geological Map of the Sokoto Province* (Jones 1940) was published as a supplement to the report *The Sedimentary rocks of Sokoto Province* (Jones 1948) and provides the first comprehensive description of the geology of the Sokoto basin (Fig. 9). Since, his map and his stratigraphic framework have been revised repeatedly. However, he provides the only detailed description of the *Pisolithic and nodular clays* within the Illo Formation. Here, we adopted his original outline of this important stratigraphic marker horizon.

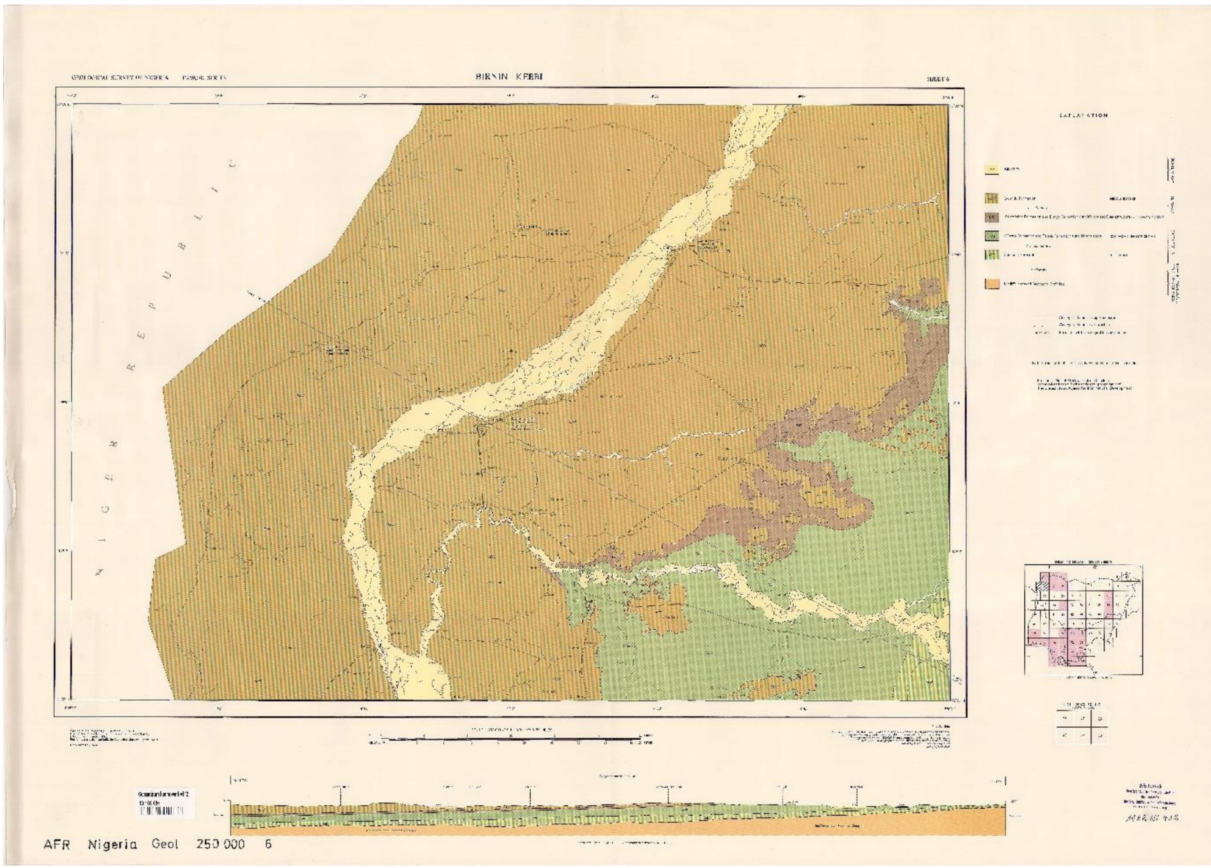

Fig. 8: *Geological Survey of Nigeria map series 1 : 250.000, Sheet 6, Birnin Kebbi published by the Directorate of Overseas Surveys (D.O.S. 1965c).*

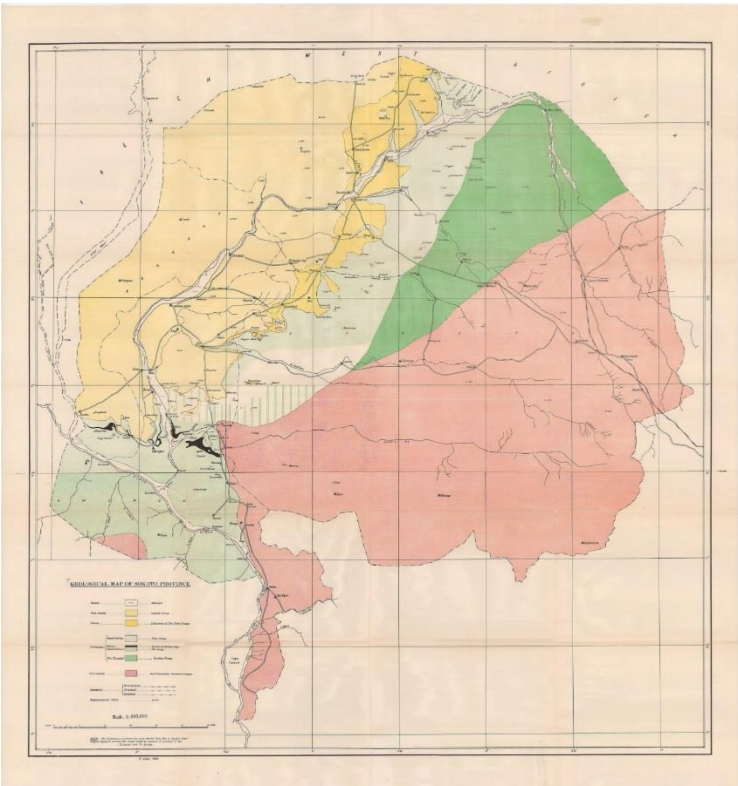

Fig. 9: *Geological Map of the Sokoto Province (Jones 1940) published within The Sedimentary rocks of Sokoto Province (Jones 1948), the first comprehensive geological study of the area.*

3.4 Benin

The Kandi Basin in Benin is covered by the map series of the Italian Istituto Ricerche Breda *Carte Géologique - Feuilles Karimama, Porga, Kandi, and Malanville, 1:200 000* (Akibou et al. 1989c, 1989b, 1989a, 1989d), the Russian Technoexport map series *Carte de Géologie et des Minéraux utiles, Dunkassa, Sansanné-Mango, Natitingou, and Bembèrèkè 1:200 000* (Technoexport 1995b, 1995a), and the geological work of Alidou (Alidou & Lang 1983, 1983; Alidou 1987) and Konaté Konaté (1996; Konaté et al. 2003a, 2006).

The harmonization approach draws on all available datasets but follows in nomenclature and (chrono-) stratigraphic interpretation the work of Konaté and co-workers (Konaté 1996; Konaté et al. 2003a, 2006). To incorporate most of the field detail, the outline and special extent of geological units is taken generally from the detailed, 1:200 000 large-scale map series of the Istituto Ricerche Breda (Akibou et al. 1989c, 1989b) and Technoexport (1995b).

Konaté (1996).

3.4.1 Istituto Ricerche Breda (1989): *Carte Géologique. Feuilles : Karimama, Porga, Kandi, and Malanville, 1:200 000*, Project F.E.D

Up to the present day the map series *Carte Géologique – Feuilles Karimama, Porga, Kandi, and Malanville* of the Italian Istituto Ricerche Breda is the most widely known geological map of the Kandi Basin (Akibou et al. 1989c, 1989b, 1989a, 1989d). Field work was conducted between 1980 and 1982 within the F.E.D. project *Étude de la Cartographie Géologique et Prospection Minière de Reconnaissance au Nord du 11ème parallèle* (4105-011-13-20). The *Notice Explicative de la Carte Géologique à 1/200.000. Feuilles: Karimama, Porga, Kandi, and Malanville* accompanies the map series (Istituto ricerche Breda & OBEMINS 1989). The work of Istituto Ricerche Breda partly incorporates results of the concurrent sedimentological and dating research (Alidou et al. 1986; Alidou 1987; Seilacher A & Alidou S 1988) but differs in the assignment of the superficial deposits of the Kandi Basin. On the Feuille Malanville, the dominant surface geology is described as 30 m thick coarse sandstones with silt and clay intercalations of a cretaceous flood plain environment (unit C)—corresponding to the Illo Formation in Nigeria (Akibou et al. 1989c).

Within the Palaeozoic, three successive facies are differentiated comprising alluvial fan deposits (K1), floodplain deposits (K2) and marine-lacustrine environments (K3). The unit K1 "conglomérats, brèches, grès avec silts et argiles subordonnés" is interpreted as an alluvial fan environment with matrix supported flash flood, debris flows, stream channel and bahada deposits. Where conglomerates and breccia dominate, a separate unit K1 (dotted) is shown. The unit K2 comprises "grès moyen, silts, argiles" reflecting a generally fluvial depositional environment similar to a floodplain with braided rivers (plaine d'inondation) but also comprises a transition from a fluvial to a more lacustrine milieu. The upper unit K3 is made up of "grès fins, silts, argiles" and is described as a shallow marine environment with transitional characteristics between floodplain, lacustrine, and deltaic environments ("dépôts paraliques").

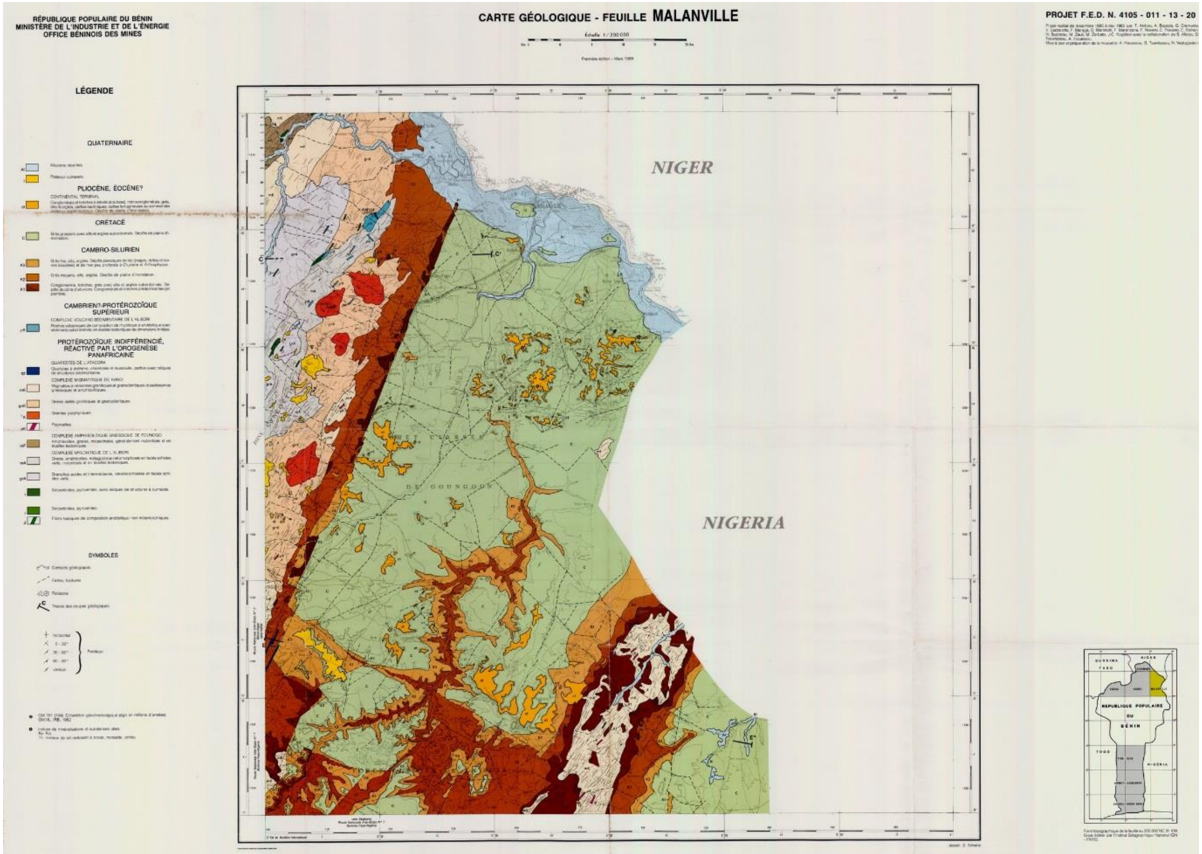

Fig. 10: Carte Géologique–Feuille Malanville elaborated in 1989 by the Istituto Ricerche Breda (Akibou et al. 1989c).

3.4.2 Technoexport (1995): *Carte de Géologie et des Minéraux utiles, Dunkassa, 1:200 000*

The geological map sheets between 10°N and 11°N were elaborated by geologists of Technoexport from the Sovjet Union and the Office Béninois des Mines (OBEMINES) following the Contract n° 55-036/4500; 1977-1994 – contemporaneous with the geological mapping north of the 11°N parallel by the Italian Istituto Ricerche Breda. The map sheets Sansanné-Mango, Natitingou, and Bembèrèkè were mapped between 1977 and 1980; the map sheet *Carte de Géologie et des Minéraux utiles, Dunkassa, 1:200 000* (Technoexport 1995b) between 1981-1984. The resulting map series was published in 1995 by the Council of Geoscience in South Africa and comprises four maps. The two accompanying reports—Mémoire 4 for the Dunkassa sheet (OBEMINES 1995a) and Mémoire 5 for the adjoining map sheets (OBEMINES 1995b)—are based on unpublished reports of Technoexport (1980, 1984).

The maps series focuses primarily on the Proterozoic basement. Nevertheless, the Dunkassa sheet differentiates four units of Palaezoic sediments (total thickness between 60-115 m) of the southern part of the Kandi Basin (Technoexport 1995b).

The Wéré Formation ($PZ_{1-2}W$)–or marginal zone–is described by the English map legend as “Gritty sandstones, micropuddingstone, conglomerate”. Occuring generally as subhorizontal witness buttes within the Precambrian basement, the Wéré Formation passes gradually into the sandstones and siltstones of the Zougou Formation of the basin center. The maximum thickness is estimated as 60 m.

The Zougou Formation ($PZ_{1-2}Z_{1-3}$) comprises three morphologically and geochemically distinct facies described as “Sandstone of varying grain sizes, often gritty interlayered with micropuddingstone” (Zougou 1, $PZ_{1-2}Z_1$), “Siltstone, less frequently fine-grained sandstone” (Zougou 2, $PZ_{1-2}Z_2$), and “Siltstone and ferruginous sandstone” (Zougou 3, $PZ_{1-2}Z_3$). Zougou 1 (15-25 m) is a transitional facies and replaces laterally the Wéré Formation. It can be further devided into a lower level of unsorted, rusty reddish-brown micropuddingstone and yellowish brown sandstones and an upper level of well-sorted, medium to coarse-sized, cross-stratified sandstone with intercalated beds of siltstone. Siltstones and fine sandstones of Zougou 2 (35-50 m) show fine ondulating stratifications and rest concordant over Zougou 1. Traces of *Arthrophycus alleghanéensis* (*Harlania*) along the Sota River place the light to variegated sediments in a marine Palaeozoic environment. Remnants of Zougou 3 (observed 15-20 m, up to 40 m assumed) are described as dark red-brown, ferrugineous, compact, quartzitic and micaceous silt- and sandstones.

3.4.3 Konaté (1996): *Carte Géologique Générale du Bassin Paléozoïque de Kandi, 1:400 000,*

Based on extensive fieldwork on the lithostratigraphy and structural geology of the Kandi Basin, dissertation and resulting papers of Moussa Konaté are the most reliable and up-to-date source on the geology of the Kandi Basin (Konaté et al. 1994; Konaté 1996; Konaté et al. 2003a, 2003b, 2006). Building on previous work by Alidou (1987) he revised the lithostratigraphy, highlighted the Late Devonian glacial character of the Wéré Formation and investigated the tectonic evolution. The resulting 1:400 000-overview map of the Kandi Basin is generally based on the geometry of the Istituto Ricerche Breda map and only touches the Russian work for the Dunkassa and Bembereke sheets. Based on his fieldwork, Konaté refined and unified the different existing terminologies proposed by Alidou and coworkers and the mapping projects of BREDA and Technoexport. His new nomenclature distinguishes in the first order the coarse terrestrial deposits of the Late Ordovician Wéré Formation (Wa/Wb members) from the finer sediments of the Kandi Formation comprising deposits of the Upper Ordovician-Lower Silurian marine transgressions (Ka/Kb members). For a more detailed overview on his lithostratigraphic classification, see chapter I.I.

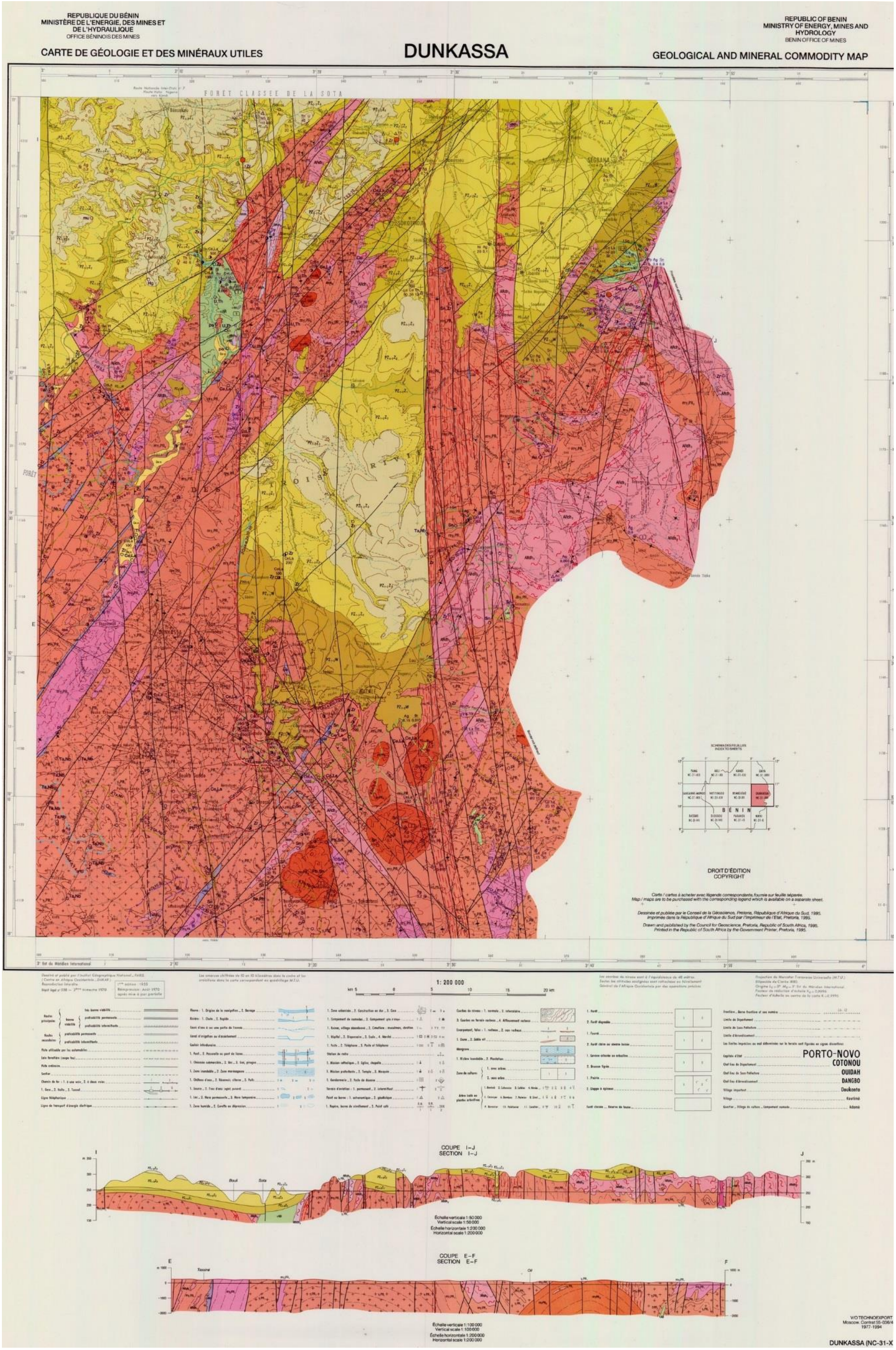

Fig. 11: Carte de Géologie et des Minéraux utiles, Dunkassa, 1:200 000 (TECHNOEXPORT 1995a).

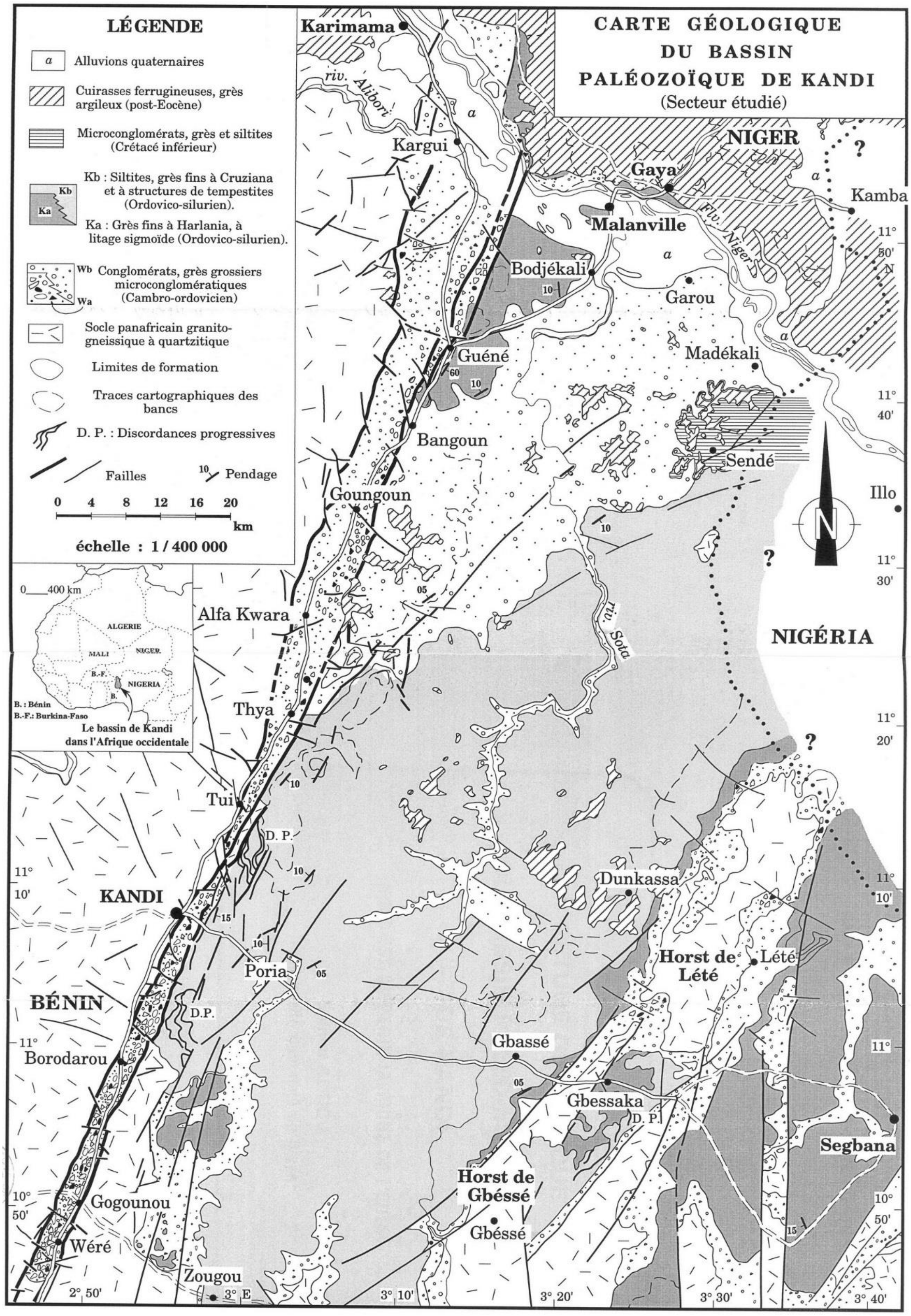

Fig. 12: *Carte géologique du bassin paléozoïque de Kandi, 1:400 000, (Konaté 1996)*

4 General legend

4.1 Chronostratigraphic framework

The chronostratigraphic framework builds on existing stratigraphic overviews for the Iullemmeden, Sokoto, and Kandi Basins evolved from the geological research of the last century. In Niger, early work of Pougnet (1949) was summarized by Greigert (1968) in the geological and hydrogeological work *Les Eaux Souterraines de la République du Niger*—that later feed into the *Atlas des Eaux Souterraines du Niger* (Greigert 1978) and set the basis for the hydro-geological study of the Iullemmeden basin. The early geological research in the Sokoto basin builds on the Braeburn and Tattam (1930), Tattam (1943), and was summarized by Jones (1948). Decades later Kogbe, with a more transboundary view, revised the stratigraphy of the Sokoto and Iullemmeden basin and set the basis for the present day understanding (Kogbe 1981, 1991; Kogbe & Burollet 1990). Continent-wide reviews were prepared by Lang, Moody and coworkers (Lang et al. 1990; Moody & Sutcliffe 1991; Moody 1997). For hydrogeological purposes, a summary was prepared during a workshop of the International Atomic Energy Agency (IAEA) in Cotonou (Tab. 5). Further stratigraphic overviews are given for example by Moumouni et al. (2016) as well as in the grey literature, in doctoral theses, and reports (FAO 1970; Anderson & Ogilbee 1973; JICA 1990; OSS 2011; ANTEA Group & JMB Consult 2012). For the Kandi Basin, the stratigraphic framework developed by Alidou and coworkers (Alidou & Lang 1983; Alidou 1987; Alidou et al. 1991) and revised by Konaté (Konaté 1996; Konaté et al. 2003a) was adopted.

The unified stratigraphic framework is in form of a general legend appended for each geological unit (see Appendix III, Tab. 11). This general legend juxtaposes the legend items of the consulted original maps and the elaborated harmonized map allowing the comparison of abbreviation codes and lithological descriptions. Tied into a chronostratigraphic chart (Tab. 2) the general legend synthesizes the available information on both the national level and on the level of the study area (see examples for the Continental Hamadien,Tab. 3, and the Paleozoic Wéré/Kandi Formations,Tab. 4). During the AGES workshop *La situation actuelle des piézomètres et des cartes thématiques dans le Bassin du Niger* in May 2015 at Niamey, a draft of the general legend was discussed with representatives of the Niger Basin Authority, the Nigerien *Direction générale des ressources en eau* of the *Ministère de l'Hydraulique et de l'Assainissement*, and the National Focal Structures (SFN) of all nine member countries of the Niger Basin Authority.

Tab. 2: Stratigraphic overview

Chronostratigraphy				Lithostratigraphy				
Erathem	**Systeme**	**Serie**	**Stage**	**Environment (Kilian, 1931)**	**Environment**	**Transgressions**	**Group**	**Formation**
Cenozoic	**Quaternary**	**Holocene**			terrestrial		***Quaternary deposits***	Aeolian deposits
								Recent fluvuial deposits
		Pleistocene/ Holocene						Ancien alluvial and fluvial deposits
	Neogene	**Pliocene**						Unconformity
		Miocene						
	Paleogene	**Oligocene**		***Continental Terminal***	terrestrial, lacustrine		**Continental Terminal**	Continental Terminal 3: *Grès argileux du Moyen-Niger*
								Unconformity
								Continental Terminal 2: *Série argilo-sableuse a lignites*
								Continental Terminal 1: *Série sidérolithique de l'Adar Doutchi*
								Continental Terminal 1: *Complexe de base* (Conglomerates)
		Early Eocene		***Serie hamadianne***	marine	4. & 5. transgressions	**Sokoto (Garadawa)**	Unconformity
		Paleocene / Eocene						Gamba (Barmou) *Schistes papyracés supérieurs*
								Kalambaina (Tamaské)
		Paleocene						Dange Formation (Kao) *Schistes papyracés inférieurs*
		Danian/ Montian						Unconformity
Mesozoic	**Cretaceous**	**Upper Cretaceous**	Maestrichtian		marine	3. & 4. transgressions (*Libycoceras*)	**Rima (Majia)**	Wurno (Im'Wagar) *Upper Sandstones*
								Dukamaje (Farin Doutchi) *Mosasaurus shales*
			Coniacian-Santonian-Campanian					Taloka (Alambanya) *Lower Sandstones*
			Turonian			1. & 2. trans. (*Nigericeras*, N Niger)		
			Cenomanian					
		Lower Cretaceous	Albian	***Continental intercalaire***	terrestrial		**Continental Intercalaire/Hamadian**	Unconformity
			Aptian					Sendé / Illo / Gundumi Formations Nupe Sandstone
			Barremian					
	Jurassic							Unconformity / Hiatus
	Triassic							
	Permian							
	Carbo-niferous			***Serie post-tassilianne***	marine transgression			
	Devonian							
Palaeozoic	**Ordovico-silurian**			***Couverture tassilianne***	marine transgression		**Grés de Kandi / Zougou**	Kandi B
								Kandi A
				Continental de base	fluvio-glacial (terrestrial)		**Wéré**	Were B
								Were A
	Cambrian							Unconformity
Neoproterozoic					*Pan-African orogeny II*			**Trans-Saharan mobile belt:** Dahomeyides, Nigerian shield, Pharusian/Hoggar-Iforas, Quagarta, Anti-Atlas, Rokelides
Mesoproterozoic					*Pan-African orogeny I*			Kibaran orogeny
Paleoproterozoic					*Eburnean orogeny*			Suggarian, Liptakoian, Birimian and Tarkwaian sediments
Archean					*Craton formation*			Reguibat Shield, Leo-Man Shield

Tab. 3 Excerpt from the General Legend: Aggregation of the Continental Hamadien (Gunumi/Illo/Sende groups)

Stratigraphie			Lithostratigraphie			Konate (1996): Carte géologique du Bassin Paléozoïque de Kandi		Société Istituto Ricerche Breda (1989): Notice Explicative de la Carte Géologique à 1/200.000 Feuilles: Karimama, Porga, Kandi, Malanville		Greigert (1966): Carte Geologique Republique du Niger. 1:2.000.000		D.O.S. (1965/6): Geological Survey of Nigeria, 1:200.000 map series		NGSA (2011) Geology and Mineral Resources Map of Nigerian States & Geological Map of Nigeria		Lithologie harmonisée		
Eratheme	Systeme	Serie / Stage	Trans-gression		Group	Code	Lithologie	Code	Lithologie	Code	Nom	Code	Nom	Code	Lithologie	Code	Formation	Lithologie
Mésozoïque	Crétacé inférieur	**Albien, Aptien, Barrémien** (originalement: pre-Maastrichtian, often Cretaceous superieur (p.e. Cénomanien to Senonian; Turonian Campano-Maestrichtian)	*Continental intercalaire*	*1st / 2nd marine transgression in north Niger (not Nigeria)*	**Continental hamadien**			C	Grès grossiers avex silts et argiles subordonnés. Dépôts de plaine d'inondation.							Io	**Illo Group**	cross-bedded, fine to coarse often angular sandstones; kaolinitique matrix, interbeddedd clays and microconglomerates, siltits, variegated clays
						S	Microconglomérats, grès et siltites (Crétacé inférieur) [evtl. Sende], fluviatil distal											
										Csc	Continental hamadien							
														Glloss	Sandstones, siltstones and clays			
										Csc bp	Continental hamadien. Bauxite pisolithique					I^{bx}	**Illo - Bauxite pisolithique**	pisolitic and nodular low-grade, bauxitic white clays
												GD	Gundumi Formation	Glss	Clay, grit and pebbels (Sokoto, Nigeria);	Gu	**Gundumi Group**	Medium to coarse-grained sandstones intercalated with variegated clays and clayey sandstones. Towards the contact with the basement
												GD	Gundumi Formation	Glgss	Gravel and sand			
												GD	Gundumi Formation	Glcg	Pebbels and grits			
														ssf	Ferrugenious sandstone	N	**Nupe Sandstone**	Sandstone

Tab. 4: Excerpt from the General Legend: Aggregation of the Paleozoic formations of the Kandi Basin (Wéré & Kandi groups)

Stratigraphie			Konate (1996): Carte géologique du Bassin Paléozoïque de Kandi		Société Istituto Ricerche Breda (1989): Notice Explicative de la Carte Géologique à 1/200.000 Feuilles: Karimama, Porga, Kandi, Malanville			Technoexport (1994) Carte de Géologie et des Minéraux utiles: Dunkassa (NC-31-X), 1:200.000			Harmonized lithology		
Eratheme	**Systeme**	**Group**	**Code**	**Lithologie**	**Code**	**Formation**	**Lithologie**	**Code**	**Formation**	**Lithologie**	**Code**	**Lithologie (eng)**	**Environment**
Paléozoïque	**Ordovico-silurien**	**Kandi** (Grés de Kandi/Zougou)	**Kb**	Siltites, grès fins à *Cruziana* et à structures de tempestites	**K3**	**Formation Kandi supérieur**	Grès fins, silts, argiles. Dépôts paraliques de lac (plages, deltas et varves lacustres) et de mer peu profonde à *Cruziana et Arthrophycus.*	PZ_{1-2} Z_3	**Zougou**	Siltstone et grès ferrugineux	**Kandi B**	Siltstone facies with hummocky cross-stratfication, siltstone strata interbedded with micaeous fine sandstone in undulating beds several decimeters to a meter thick; upper offshore environemt; traces fossils: *Cruziana*	upper offshore environment (hummocky cross-stratified sandstones); clay and sand, marine environment
					K2	**Formation Kandi inférieur**	Grès moyens, silts, argiles. Dépôts de plaine d'inondation.	PZ_{1-2} Z_2		Siltstone, plus rarement grès à grain fin; toujours Ka, parfois (centre) Kb	**Kandi A**	medium- to fine-grained sandstone deposits displaying sigmoidal bedding and herringbone cross-bedding, tidal origin; trace fossils *Harlania / Arthrophycus*	Milleu paralique (lac, delta & mer peu profonde), shoreface barrier & tidal environment
			Ka	Grès fins à *Harlania* , à litage sigmoïde ou ondulés									
		Wéré	**Wb**					PZ_{1-2} Z_1		Grés à graulométrie variable, souvent graveleux, intercalé de micropoudingue	**Wéré B**	granule-rich coarse sandstones with tabular to through cross-bedding	Dépôts de plaine d'inondation & dynamique fluvial, braided river sediments
				Grès grossiers à moyens microconglomératiques à grands litages obliques plans et en auges				PZ_{1-2} Z_1		Grés à graulométrie variable, souvent graveleux, intercalé de micropoudingue			
					K1	**Wéré-Goungoun**	Conglomérats, brèches, grès avec silts et argiles subordonnés. Dépôts de cône d'alluvions	PZ_{1-2} W	**Wéré**	Grés graveleux, micropoudinque, conglomerats: toujours Wa, parfois Wb (Segbana)		Conglomerates, breccia with sandstones, siltits and clays. Dotted: Conglomerates dominant.	
			Wa	Conglomérats, grès grossiers microconglomératiques a gros blocs, litages obliques plans ou en auges. La coleur est généralement rouge-brun	**K1 dots**	**Wéré-Goungoun**	Conglomérats, brèches, grès avec silts et argiles subordonnés. Dépôts de cône d'alluvions. Conglomérats et brèches prédominantes (en pointillé)				**Wéré A**	diamictite and breccia medium- to coarse-grained sandstones with quartzitic boulders and faceted pebbles ...	Dépôts de cône d'alluvions & dépôts glacial (tillites), glaciofluvial outwash, perglacial sediments

Tab. 5: Stratigraphic overview elaborated an IAEA workshop (Cotonou, 2014)

Age		Algérie		Mali		Niger		Bénin		Nigeria	
		Groupe	Formation	Groupe	Formation	Groupe	Formation	Groupe	Formation	Groupe	Formation
Quaternaire		Quaternaire	Alluvions de fonds de vallées	Quaternaire	Alluvions, dunes **Aquifère**	Quaternaire	Alluvions, dunes **Aquifère**	Quaternaire	Sables fins, Aquifère	Quaternary	Alluvium **Aquifère**
Tertiaire	Pliocène	Discordance		Continental Terminal	sablo – gréseux et argileux **Aquifère**	Continental Terminal CT_3	Série des grès argileux du Moyen Niger **(Aquifère)**	Continental Terminal	conglomérats brêches, microconglomérats, grès, silts et argiles Aquifères	Continental Terminal	Gwandu **Aquifère**
							Aquitard				
	Miocène					Continental Terminal CT_2	Série argilo-sableuse à lignite - **Aquifère**				
							Aquitard				
	Oligocène					Continental Terminal CT_1	Série Sidérolithique - **Aquifère**				
	Eocène			Eocène moyen	schistes		Schistes papyracés supérieurs - **Aquitard**	Discordance		Sokoto	Kalambaina
	Paléocène			Paléocène terminal	calcaire et marno – sableux avec niveau phosphaté	Formation de Garadawa -	Calcaires - **Aquifère**				Dange **Aquitard**
				Paléocène inférieur	calcaire - sable	Paléocène marin	Schistes papyracés inférieurs - **Aquitard**				
Crétacé - Jurassique	Crétacé Supérieur			Maestrichtien - Cénomanien	grès – argileux **Aquifère**	Grès supérieur	Grès d'Im Wouagar			Rima (Mæstrichtien)	Wurno **Aquifère**
						Sénonien Moyen	Argiles de Doutchi Zana - **Aquitard**				Dukamaje **(Aquitard)**
						Sénonien Moyen (Grès Inférieur)	Silts de Bouza				Taloka **Aquifère**
						Sénonien inférieur	Argiles du Sénonien Inférieur - **Aquitard**				
						Turonien	Calcaires blancs				Basal Clayey
						Cénomano-turonien	Argiles Sénomano-turoniens - **Aquitard**				
	Crétacé Inférieur			Continental intercalaire	Grès quartzitique, micro conglomératique, arkoses, sable, argiles Tégama **Aquifère**	Continental intercalaire (Jurassique-Albien) **Aquifère**	Continental Hamadien	Grès de Kandi	Grès grossiers, silts et argiles, Aquifères	Continental intercalaire / Continental Hamadien	Gundumi & Illo **Aquifère**
							Argiles du Farak				
							Grès de Tégama				
Trias-Jurassique				Permien Trias Jura	Grès aquifères	Néocomien	Argiles de l'Irhazer			?	
Paléozoique	Permien					Trias-Jurassique	Grès d'agadez Serie d'Izegouandane				
						Namurien	Serie de Tagora				
						Viseen	Serie de Talack et grès de Farazet				
		Devonien	Grès aquifères	Devonien	Grès aquifères	Devonien	Grès d'Amesgueur				
		Cambro - ordovicien	Grès aquifères	Cambro - ordovicien	Grès aquifères	Cambro - ordovicien	Grès de timesger	Cambro-Silurien	Conglomérats brêches, grès, silts et argiles Aquifères	?	
Précambrien		Précambrien	Précambrien	Précambrien	Birrimien	Précambrien	Précambrien	Précambrien	Panafricain	Précambrien	Précambrien

4.2 Lithological attribution

Harmonization of lithological classes comprises thematic and semantic generalization as well as aggregation. Duscher et al. (2015) proposed a hierarchical lithological aggregation scheme to harmonize the lithological information of the 30 map sheets of the *International Hydrogeological Map of Europe 1:1 500 000* (IHME1500). This hierarchical, taxonomic classification scheme allows differentiation on five aggregation levels (cf. Appendix IV, Tab. 12). The upper most level differentiates between consolidated, unconsolidated, and hybrid rocks (partly consolidated). The following levels are differentiated based on main, secondary, and accessory components separated by comma. Subordinate components are joined using "with"; "and" is used to separate consolidated and unconsolidated lithology in the hybrid classes.

The lithological descriptions available from map legends were enhanced by additional information from the literature and classed according to the lithological aggregation scheme of the IHME1500. Categorization beyond IHME aggregation level 3 is ambiguous due to lack of detailed information and strongly depends on the expert's knowledge and decision.

The advantage of the IHME1500 lithological classification scheme is also its main limitation. While allowing unification of information, specific information necessary for differentiation between strata is lost. Such information is often conveyed by flexible facies description and geological termini (till vs gravel, bauxitic clay vs. layered shale). For an overview of the lithological variation in the study area, the aggregation level 3 is most convenient and comprises in the study area 16 different classes. However, on this level no clear differentiation between important continental sediment types is possible, resulting in the incapacity to differentiate on the basis of map lithology between aquifers and aquitards. For lower levels, expert bias increases substantially, while the rapidly increasing number of classes complicate presentation on a map.

The maps of Fig. 13 show the resulting distribution of lithological classes for the level 4, level 3, and level 2 of the IHME1500 aggregation scheme.

Tab. 6: IHME1500 lithological aggregation levels. The number of lithological classes occurring in the study area and three naming examples for each of the three classes of aggregation level 5.

Aggregation level	N° of classes	Examples of class denominations		
Level 5	3	**Unconsolidated**	**Partly consolidated**	**Consolidated**
Level 4	8	Coarse sediments	Clastic rocks and fine sediments	Clastic rocks
Level 3	16	Sands	Sandstones and sands	Sandstones
Level 2	28	Sands, gravels	Sandstones and sands, clays	Sandstones, claystones
Level 1	37	Sands, gravels, silts	Sands, clays and sandstones	Siltstones, claystones, sandstones

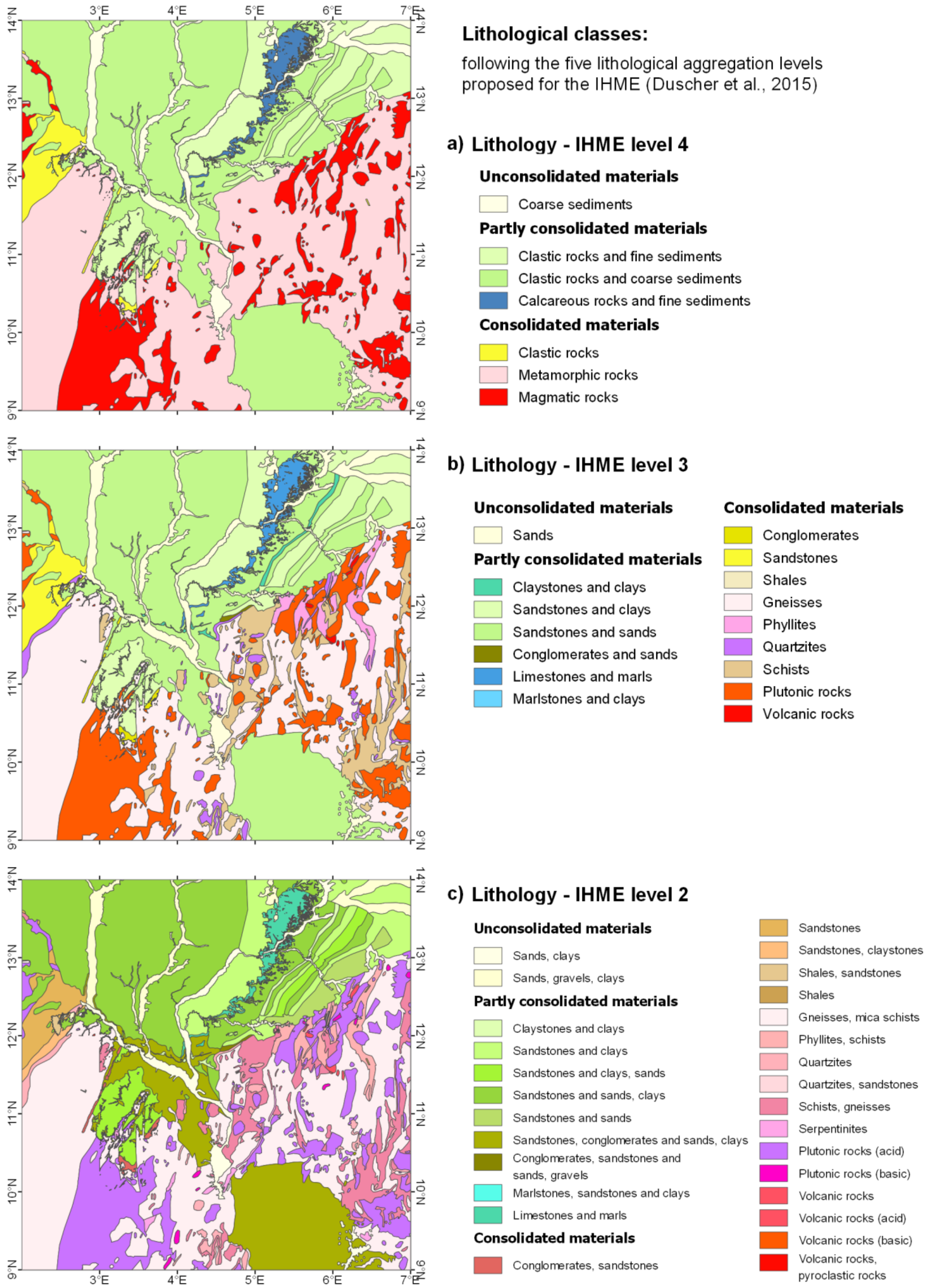

Fig. 13: Lithological aggregation levels 4, 3, and 2 following the lithological classification scheme of the IHME1500 (Duscher et al. 2015).

4.3 Geological attributes

Geological attributes of the sedimentary units are provided as ancillary digital datasets. The information is compiled from maps, explanatory notes, and literature. The available data allows for broad categorizations of the attributes:

- Consolidation (unconsolidated/partly consolidated/consolidated),
- Porosity (porous/mixed/fissured),
- Aquifer type (aquifer/aquitard).

For further attributes only local or exemplary information is available:

- Deposition environment,
- Thickness of strata,
- Economic potential,
- Occurrence of karst features,
- Fracturing, and
- Cementation.

4.3.1 Consolidation/Cementation

The degree of consolidation—unconsolidated, partly consolidated, unconsolidated—is required for aggregation within the IHME1500 lithological classification scheme. Classification as consolidated or partly consolidated is rarely explicitly stated in map legends or the lithological reports and descriptions are often biased by outcrop conditions as well as the field geologist's expertise. In general, outcrop and borehole descriptions of terrestrial deposits report weakly cemented material as reflected by terms such as sand or clay, instead of sandstone or claystone. Explicitly, JICA (1990, Tab 4-1) describes all tertiary and cretaceous formations in the study area as "semi-consolidated".

The geological strata outcropping within the study area were never buried deep and phase out towards the Nigerian and Beninese basement areas. The Continental Terminal 3 comprises sediments deposited prior to the onset of the present day erosion regime and has not been buried at all. Where outcropping and representing the present-day surface lithology, the stratigraphically underlying strata (Continental Terminal 2 & 1, Sokoto & Rima Groups, and Continental Hamadien) were covered by a comparably thin and now eroded overburden, only. Consequently, cementation by clay, iron, and locally silica were the dominant consolidation processes while compaction was rather weak due to the limited overburden.

Quaternary sediments are classed as unconsolidated. Older terrestrial deposits were classified as partly consolidated. The chemical sediments of marine origin of the Palaeocene–Eocene Sokoto Group (marls, shales, limestones) are classed as consolidated. The Rima Group, composed of mixed chemical/clastic sediments are described here as partly consolidated.

4.3.2 Fracturing

The degree of fracturing is rarely documented in lithological descriptions. Observations on tectonic fracturing/deformation are reported from the Continental Terminal 1; all older strata may show fracturing. The attribute gives a generalized summary on fracturing and deformation but are neither comprehensive nor representative.

4.3.3 Porosity

The type of porosity is inferred from the degree of consolidation and fracturing. The recent sandstone sequence of the Continental Terminal—despite being partly consolidated and cemented—is still assumed to be dominated by porous flow. Despite frequent reports of joints and small faults. Clastic and chemical sediments of the Sokoto and Rima Groups are classed as either mixed porous/fissured media or in the case of limestone or shales as fissured media. Fracturing becomes more important in older (and more consolidated) sediments. Precambrian clastic sediments as well as the Proterozoic basement complex are classed as fractured.

5 Harmonization of the transboundary geological map

5.1 Pre-processing

5.1.1 Digitization

Geological maps were digitized by the DGIS Service GmbH, Radeberg, Germany. The data was delivered as georeferenced ESRI shapefiles including all geologically relevant information depicted on the maps—excluding topographic elements.

5.1.2 Geographic coordinate systems

Colonial maps generally lack information on the geographic coordinate system used. During the early and mid-20th century, a wealth of geographic coordinate system were in use, each based on a different ellipsoid, fundamental point, and adjustment factors. A summary on geographic datums are given by Clifford for Benin (Clifford 2003), Nigeria (Clifford 2009), and Niger (Clifford 2011) freely available under https://www.asprs.org/asprs-publications/grids-and-datums. The georeferenced maps were assigned the most likely corresponding geographic coordinate systems (see Tab. 7) before re-projection into the common geographical coordinate system *World Geodetic System 1984* (WGS84). The possible error margin of assigning the erroneous geographic coordinate system ranges between 80 m to over 150 m.

Given the time of preparation, the Point 58 datum is assumed for the Nigerien maps of Greigert (1960) and Greigert & Pougnet (1966). Neither the *Geological Survey of Nigeria map series* nor the ArcGIS projects provided by the Nigerian Geological Survey Agency (NGSA) specify the used coordinate system. The latter being provided in an unspecified geographic coordinate system. Due to the time of publication in 1966, the *Geological Survey of Nigeria map series* is most likely prepared in the Minna geographical datum. Being specifically constructed for country-wide Nigerian maps the same is assumed for the present-day GIS projects.

The Beninese map of Istituto Ricerche Breda (Akibou et al. 1989c, 1989b) and Technoexport (1995b), are oriented along the grid of the 1:200 000 maps series *Carte de l'Afrique de l'Ouest* of the French Institute Géographique National (IGN) that was based on the Clarke 1880 ellipsoid. The unspecified Clarke 1880 (IGN)—EPSG 4011 was assumed for these map series.

5.1.3 Spatial adjustment

Topographic elements like river courses, escarpments, roads and places depicted on correctly georeferenced scanned maps frequently show deviations from up-to-date topographic data such as topographic maps, the Vector Map Level 0 (vmap0; NIMA (National Imagery and Mapping Agency) 2001), or Open Street Map (https://www.openstreetmap.org). Spatial adjustment of the scanned raster dataset or the vectorised data to a topographic base map is a common approach to minimize (systematic) offsets of the thematic data.

Tab. 7: Geographic coordinate systems assigned to the georeferenced geological maps prior to transformation into the WGS84.

Original maps			Assigned Geographic Coordinate System (GCS)				
	Map	**Map GCS**	**GCS / Datum**	**Fundamental point**	**Year**	**Ellipsoid**	**EPSG**
Niger	**Greigert, J (1960):** Carte Géologique de Reconnaissance Dosso, 1:500.000. BRGM.	none	Point 58	near Dosso 12°52'44.045''N 3°58'37.040'' E	1969, IGN	Clarke 1880	4620
	Greigert, J & Pougnet, R (1966): République du Niger. Carte géologique, 1/2 000 000. BRGM.	none					
Nigeria	**Directorate of Overseas Surveys (1965):** Geological Survey of Nigeria, 1:250,000 Series, Sheet 2 Sokoto, Sheet 3 Shinkafe, Sheet 6 Birnin Kebbi	none	Minna 1928	Minna base 9°38'09.000'' N 6°30'59.000'' E	1928	Clarke 1880	4263
	Directorate of Overseas Surveys (1966): Geological Survey of Nigeria, 1:250.000 Series, Sheet 1 Tangaza, Sheet 7 Gummi	none					
	Nigerian Geological Survey Agency (2011a): Geological and Mineral Resources Map of Kebbi State, Nigeria. Digital dataset.	unspecified GCS					
	Nigerian Geological Survey Agency (2011b): Geological Map of Nigeria. Digital dataset						
Benin	**Akibou, et al. (1989):** Carte Géologique - Feuille Malanville (NC-31-XXII) & Karimama (ND-31-III/IV., Istituto ricerche Breda & OBEMINS	Based on IGN	Clarke 1880 (IGN)	Based on IGN map NC 31-XXII /ND-31-III/IV	-	Clarke 1880	4011
	Technoexport (1995): Carte de Géologie et des Minéraux utiles, Dunkassa (NC-31-XVI). Conceil de la Géoscience, Pretoria.	Clarke 1880 proj. not specified	Clarke 1880 (IGN)	-	-	Clarke 1880	4011
	Konate, M (1996): Carte géologique générale du bassin paléozoique de Kandi. Figure 15, Université de Bourgogne, Dijon-Niamey.	none	WGS 84	geozentric	1984	WGS 84	4326

For the here presented harmonized lithological map, no comprehensive spatial adjustment was conducted, due to two main reasons:

1. Lack of a generally accepted base map prevented the spatial adjustment to topographic features (lack of a comprehensive topographic digital dataset, low accuracy and gaps of the VMap level 0). During the project, quality and coverage of the Open Street Map data set (OSM, openstreetmap.org) advances rapidly. Up-to-date, OSM provides the most adequate digital topographic data set and is worth evaluating for spatial adjustment purposes.
2. The available medium and small-scale maps (<1:250 000) are strongly generalized. Outline and location of topographic features are of an indicative accuracy only.

Given the small scale and the low level of detail in the study region, the maps of Greigert (1960), Greigert & Pougnet (1966), and Konaté (1996) were not spatially adjusted. The 1:200.000 map series of the Directorate of Oversea Surveys (1965a, 1965c, 1965b, 1966a; 1966), the series of Istituto ricerche BREDA (Akibou et al. 1989c, 1989b), as well as the map sheet of Technoexport (1995b) are reasonable well georeferenced and spatial adjustment was not deemed necessary.

5.2 Cover layers

Cover layers are superficial geological units that are assumed to be dry or to be of negligible importance for a regional hydrogeological assessment. Due to either a small spatial extent, their localized occurrence, or a generally shallow depth, superficial layers do not harbour own groundwater resources. In the study area, three types of cover layers are differentiated: quaternary aeolian sand deposits, remnants of the Continental Terminal, and lateritic ironcrusts (ferricretes).

5.2.1 Quaternary aeolian cover layers

Quaternary aeolian dunes are classed as cover layers and are not included in the solid geology dataset. Aeolian cover layers comprise both active and ancient dunes and sand fields (ergs) that cover vast regions in the northern part of Niger and Nigeria. Extended areas of aeolian cover layers—particularly the *Erg ancient à dunes longitudinales et non-orientées*—are mapped on Nigerien maps (Greigert 1960; Greigert & Pougnet 1966). In Nigeria, small areas of aeolian sands are shown on the map series published by the Directorate of Overseas Surveys (1965a, 1965c, 1966a; 1966). Considering the generally localized occurrence and shallow manifestation, superficial aeolian sand deposits are considered to be dry and will not be retained in the geological map of solid rocks. The respective areas were manually attributed according to the surrounding solid geology – in Niger mainly Continental Terminal 3, in Nigeria adjacent outcrops of cretaceous sediment series where extrapolated.

5.2.2 Remnants of Continental Terminal

At the end of the Miocene, a shallow sheet of Continental Terminal sediments covered most of the study area extending far into Nigeria and the Beninese Kandi Basin. Today, these deposits have been mostly eroded. The remaining vestiges occur as mesas and buttes, generally too small to host own aquifers. Isolated occurrence of Continental Terminal south of the Niger River in Benin and Nigeria are classed as cover layers. The large contiguous tableland south of Karimama is assumed to be large enough to host an own groundwater resources.

5.2.3 Ferricrete plateaus

The top layer of the Continental Terminal sediments are generally consolidated by a strongly iron-enriched ferricrete typically incorporating sedimentary oolithic layers. Lateritic ferricretes on the other hand occur at similar topographic positions within the basement areas. On the sheets *Malanville* and *Kandi*, Istituto Ricerche Breda differentiates between Continental Terminal within the tectonic Kandi Basin and *Plateaux cuirasses* on basement. The ferricretes represent probably the Eocene to Pliocene stages S2 – S4 of the intermediate post-African palaeosurfaces (Chardon et al. 2016). The indurated lateritic ferricretes are important hydro (-geo) logical surface features and are mapped as independent cover layers.

5.3 Solid geology

5.3.1 Quaternary alluvial deposits

Alluvial valley sediments often form prolific near-surface aquifers and are - despite their shallowness and localized occurrence - important groundwater reservoirs particularly in desert areas. Alluvial sediments have been included in the lithological map although many palaeochannels (e.g. the Dallols in Niger) may not host own groundwater resources but form the upper part of more extensive aquifer systems being fed by artesian groundwater from the Continental Terminal 1 and Continental Terminal 2.

The observations of meanders and oxbow lakes indicates an active floodplain environment. Solid geology units protruding into the large floodplains of the Niger and its tributaries were manually adapted and the extent of alluvial sediments was adjusted according to Landsat satellite imagery (NASA EOSDIS Land Processes DAAC 2018) and the digital elevation model SRTM v3 (NASA Jet Propulsion Laboratory 2013).

On the left bank of the Niger, several kilometre-wide palaeovalleys occur in both Niger and Nigeria. Alluvial deposits of the Dallol Maouri shown on the *Carte Géologique de Reconnaissance: Dosso* (Greigert 1960) are, however, not mapped neither on the *Carte Géologique de la République du Niger* (Greigert & Pougnet 1966) nor on the Nigerian maps. Truncated alluvium (e.g. tributaries of the Dallol Maouri) was manually extended into Nigeria where necessary guided by satellite images and a digital elevation model. In Nigeria, the Nigerian Geological Survey Agency (NGSA 2011a, 2011c) maps several large alluvial features near Yaldu, Balle, and Tangaza not shown on the Geological Survey of Nigeria map series of the Directorate of Overseas Surveys (1965c, 1965a, 1965b, 1966a; 1966). These shallow depressions are unlikely to harbour extensive alluvial sediments and their extent has been manually reduced and adjusted guided by the digital elevation model (Fig. 14).

On the right bank of the Niger, tributaries drain areas of higher and more reliable rainfall in Benin and Nigeria. Permanent and seasonal water courses show defined (but narrower) channels that were not mapped explicitly on the maps of Istituto Ricerche Breda (Akibou et al. 1989c) and Konaté (1996). Technoexport (1995b), on the other hand, mapped valley sediments consistently. Consequently, valleys and alluvial layers are not comprehensively mapped throughout the study area. Discontinuous valley sediments may be depicted south of 3°N.

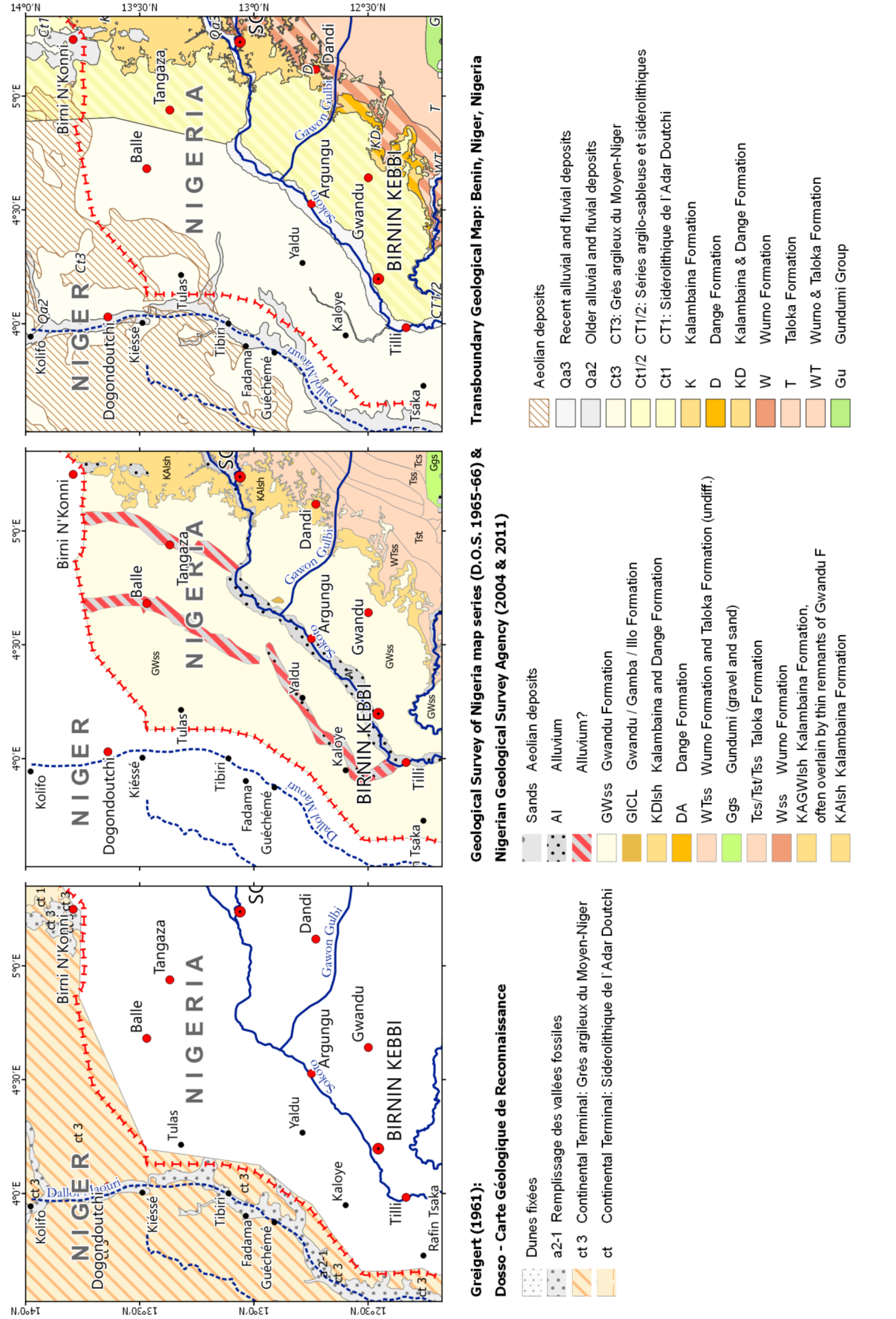

Fig. 14: *Manual adjustment of alluvial deposits along the Dallol Maouri and near Birnin Kebbi and Birnin N'Konni. Elimination of irrelevant and/or unreliable units mapped by NGSA (2011a, 2011c).*

5.3.2 Continental Terminal

Continental Terminal 1 and Continental Terminal 2

Outcrops of the Continental Terminal are limited to the Continental Terminal 3, the Continental Terminal 1, and the early conglomeratic facies *Complexe de base du Continental Terminal*. Surface occurrence of the Continental Terminal 2 is not reported from within the study area. In Niger, the Continental Terminal 2 is believed to phase out between Dioundiou (FAO 1970, p. 19) and Yelou (Guero 2003, p. 42); in Nigeria it has not been mapped explicitly. The FAO published several cross sections along and across the Dallol Maouri (see Appendix V) and generally suggests a wedging out of the Continental Terminal 2 between Yelou and Bengou within the palaeovalley of the lower Dallol Maouri (FAO 1970; Coupe 1, Planche 2). On a general scale, this is in accordance with the outcropping of Continental Terminal 1 on the escarpments around Bengou. Further south, the cross sections of FAO (1970) indicate—depending on the cross section—occurrences of CT3, (CT?), CT1 on the hills between Gaya and the Dallol Maouri—contrasting with the available geological maps suggesting Continental Hamadien.

The Continental Terminal triad 1, 2, and 3, common place in Niger, has not been adopted to describe the corresponding Gwandu Formation in Nigeria. Despite a commonly accepted division of the Gwandu Formation in an upper unconfined member, a confining middle clay member and a confined lower sandy zone (Anderson & Ogilbee 1973; JICA 1990), none of the existing Nigerian maps ventures to depict any superficial subdivision of the Gwandu formation in Nigeria (D.O.S. 1965c; Anderson & Ogilbee 1973; Kogbe 1981; JICA 1990; NGSA 2011a, 2011c). Following the *Hydrogeological Cross Sections for the Sokoto basin* (JICA 1990; Fig. 8, Transect C-C'), the Sokoto River forms a divide between the upper member (CT 3 ?) to the west and the clay-rich middle member (CT 2 ?) to the east (see Fig. 16). Outcrops of the basal member are suggested to occur only along a small fringe overlaying the Kalambaina Formation of the Sokoto Group. The harmonized map shows a continuous Continental Terminal 3 (=upper member) in Niger and Nigeria and maps the areas east of the Sokoto River as CT 1-2 undiff. to reflect the lacking spatial differentiation between CT 1 and CT 2 on Nigerian territory (Fig. 14, Fig. 17). Between the Sokoto River and the Dallol Maouri, the harmonized map follows Greigert & Pougnet (1966), who depict a continuous band of Continental Terminal 1 outcropping in a fringe along the northern bank of the Niger River and continuing into Nigeria (Fig. 15).

Geometric harmonization of the state-wide maps of the Nigerian Geological Survey Agency (2011c, 2011a) and Greigert & Pougnet (1966) encounters a stratigraphic unsatisfactory break of the Continental Terminal and Eocene-Palaeocene units due to diverging interpretations on the national map series. Instead of the Niger-Nigerian boundary, the break was shifted to the Sokoto River giving prevalence to the more intuitive outcrop stratigraphy of Greigert & Pougnet (1966).

Further major differences in the extent of Continental Terminal 1 are observed outside the study area along the Nigerien-Nigerian boundary near Birni-N'Konni. Where Greigert & Pougnet (1966) map the Continental Terminal 1, the field studies of the Directorate of Overseas Surveys (D.O.S.) indicate large areas of outcropping Kalambaina Formation. Here, the detailed and fieldwork-based series of the Directorate of Overseas Surveys (1965a) is deemed more reliable than the probably inferred geometry proposed by Greigert & Pougnet (1966).

On the right bank of the Niger River, Continental Terminal sediments only occur fragmentary. An exception being the large areas around Kirimama where Continental Terminal deposits occur outside the Kandi Basin and overlay more or less directly the basement separated only by thin layers of locally Palaeozoic and Cretaceous sediments. The stratigraphic position has not been investigated in depth. Whereas Greigert (1961b) on his early map *Carte Géologique de la Feuille de Dosso* does not differentiate the Continental Terminal facies, the *Carte Géologique de Reconnaissance du Bassin des Iullemmeden* suggest Continental Terminal 1 together with the widespread occurrence of a *Complexe de base* (Greigert 1961a). The latest map *Carte Géologique: Republique du Niger* shows Continental Terminal 3 (Greigert & Pougnet 1966).

To the south of Benin, fragments of Continental Terminal become less frequent and more and more shallow. No occurrences of Continental Terminal are reported south of Kandi and Lété. No subdivision or correlation with Continental Terminal 1 or 3 has been proposed for these widely eroded remnants of Continental Terminal in Benin. For the harmonized map, the outline of (undifferentiated) Continental Terminal in Benin follows the comprehensive mapping of the Istituto Ricerche Breda (Akibou et al. 1989c) later adopted by Konaté (1996).

Complexe de base du Continental Terminal

The earliest map, the *Carte Géologique de Reconnaissance Dosso, 1:500.000* (Greigert 1960) differentiates between *Continental Terminal 1* (CT 1), *Continental Terminal – complexe de base (CT b)* and an undifferentiated (not studied?) *Continental Terminal (CT)* on the right bank of the Niger River. On their 1966 map *Republique du Niger-Carte Géologique, 1:2.000 000*, Greigert & Pougnet (1966) depict schematically (crossed signature) a small band of *Continental Terminal—complex de base (CT 1 c)* along the foothills of the cliffs flanking both the right and left bank of the Niger River.

For the Nigerien part of the harmonized map, the additional differentiation between *Continental Terminal 1 (CT 1)* and a *Continental Terminal 1—complex de base (CT 1-b)* as suggested by Greigert & Pougnet (1966) was adopted. The outline was adjusted to the more detailed lithological boundaries between CT b and Alluvium, respective CT b and CT3, as shown in the earlier 1:500 000 map of Dosso (Greigert 1960). The boundary between the alluvial floodplain and the rock outcrops were corrected based on digital elevation data and satellite imagery. South of the Niger River, *Continental Terminal 1—complex de base* was omitted. Here, the unclear stratigraphic position of the undifferentiated Continental Terminal south of the Niger River, the unknown extent of the Continental Hamadien, and the possible local occurrence of the *complexe de base* call for a stratigraphic fieldwork.

The more recent map of the Kandi Basin (Konaté 1996, Fig 15) emphasizes on Palaeozoic sediments and only peripherally shows the north bank of the Niger River. Nevertheless, it provides a detailed geometry for the undifferentiated Continental Terminal and outcrops of the Palaeozoic rocks. These were deemed more appropriate and were incorporated where necessary (Fig. 15).

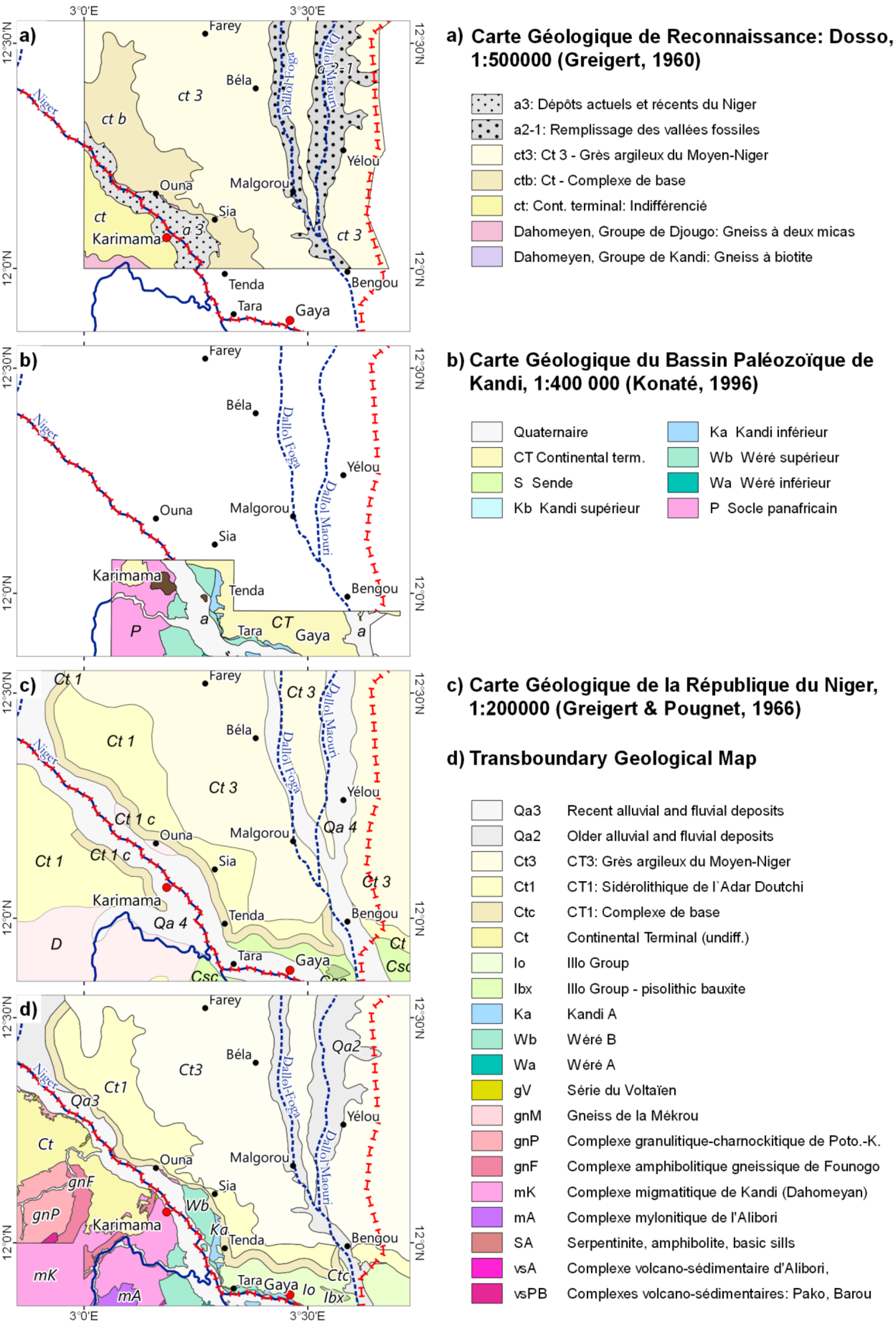

Fig. 15: Harmonization of Continental Terminal 1 & Complexe de base along the Niger River

5.3.3 Sokoto Group (Gamba/Kalambaina/Dange F.) & Rima Group (Wurno/Dukamaje/Taloka F.)

Near the Sokoto River, the ***Paléocène Zone à Operculinoïdes et à Lockhartia haimei*** Geigert & Pougnet (1966) described in Nigeria as Eocene-Palaeocene Sokoto Group (Gamba, Kalambaina, Dange Formations) slides in between the Cretaceous Illo-Gundumi Formations (Continental Hamadien in Niger) and the Miocene Continental Terminal.

On the early maps of Jones (1948) and the Geological Survey of Nigeria map series (D.O.S. 1965c), outcrops of the Sokoto Group are restricted to areas north of the Zamfara River. On the later maps of Geological Survey of Nigeria (1965), Greigert & Pougnet (1966), and Dessauvagie (1974), the Kalambaina Formation (or *Paléocène Zone à Operculinoïdes et à Lockhartia haimei* sensu Geigert & Pougnet (1966)) wedges out further south on the right bank of the Sokoto River near Dakingari.

The recent compilations of Nigerian Geological Survey Agency (2011c, 2011a), however, did not retain the geometries of the original maps. Both the spatial information on the *Geological Map of Nigeria* and the *Geological and Mineral Resources Map of Kebbi* display distinct geometries of the geological units and often lack reliable legend entries and/or legend assignment. For example, differing descriptions of the GIcl unit as “Sandstones and clays of the Gwandu Formation” on the *Geological Map of Nigeria* (NGSA 2011c) and as “Shales of the Gamba Formation” on the *Geological and Mineral Resources Map of Kebbi* (NGSA 2011a) shed doubt on the spatial extent and the thematic reliability of this unit. The first description corresponds to the Gwandu Formation (Gwss) the second suggests extension of the Sokoto Group. The abbreviation itself, however, suggests a “Gundumi-Illo clay” unit and perhaps is equivalent to the bauxitic clay mapped by Jones (1948). The stratigraphically inconsistent location of the outcrop within the Continental Terminal 3 instead of within the Illo Formation raises further questions regarding the reliability of the digital dataset provided by the Nigerian Geological Survey Agency.

The **Kalambaina Formation (K)** is most extensive north of the Sokoto River, where it is partly overlain by thin remnants of Gwandu sediments. The Kalambaina Formation (KA) of Geological Survey of Nigeria (D.O.S. 1965a) corresponds to the Dange/Kalambaina Formation (DKsh) of the *Geological Map of Nigeria* (NGSA 2011c). The original subdivision of the Kalambaina Formation by NGSA into a “Limestone and shale” unit—Dange/Kalambaina, abbreviated as DKsh (NGSA 2011c) or Gmsh (NGSA 2011a) and a “Sandstone, siltstone” member (abbreviated as DKss or DKls but named Wurno Formation on the state map of Sokoto (NGSA 2011b)) was abandoned due to a high level of uncertainty and geometric inconsistencies. South of Argungu, Kalambaina and Dange Formation (KD *sensu* D.O.S.) and Dange/Kalambaina Formation (DKsh *sensu* NGSA) are in both maps undifferentiated.

Between Dakingari and Jega, the Kalambaina/Dange Formation KD follows the map *République du Niger. Carte Géologique, 1:2 000 000* of Greigert & Pougnet (1966). The direct limit between the Continental Terminal and the Continental Hamadien/Illo Formation as suggested by the Nigerian Geological Survey Agency (2011c, 2011a) was abandoned and the latter was substantially extended from Dutsin Gore/Giro north beyond the village of Suru. The disjunct occurrence of the Gmsh unit (Limestone and shale of the Kalambaina/Dange Formation) is preserved as stratigraphically younger erosive remnant overlying the

Continental Hamadien instead of a older sediment preserved in a low position within the Continental Terminal.

The Geological Survey of Nigeria map series by the Directorate of Overseas Surveys (1965c, 1965a, 1965b, 1966a; 1966) suggests an explicit division of the **Wurno (W)** and **Taloka (T) Formations** only north of the Sokoto River. Here the Wurno-Taloka boundary of the Geological Survey of Nigeria map series—with local intercalations of the Dukamaje Formation—was retained. The outline of the Dukamaje Formation follows the *Geological Survey of Nigeria map series* instead of the much more extensive "Limestone of the Dukamaje Formation"—confusingly labelled Glls—as proposed by the Nigerian Geological Survey Agency.

South of the Sokoto River, the *Geological Survey of Nigeria map series* proposes a single undifferentiated unit "Wurno Formation and Taloka Formation" (WT). The areas was subdivided into a transitional unit Wurno/Taloka Formation (Wss) of sandstones and an underlying upper Siltstone member of the Taloka Formation (Tst) based on an the units proposed by the Nigerian Geological Survey Agency (NGSA 2011c). The sketchy limits depicted by the Nigerian Geological Survey Agency were adjusted to avoid stratigraphic inconsistences around the frequent remnants of younger sediments (Gwandu, Dange, Kalambaina) mapped on the Geological Survey of Nigeria map series. For the Taloka Formation itself, the Nigerian Geological Survey Agency (NGSA 2011c) suggests six lithological subdivisions. The two classes proposed by the *Geological Survey of Nigeria map series*—Wurno Formation and Taloka Formation (WT) and an undifferentiated Taloka Formation (T)—were abandoned in favour of an apparently more detailed lithostratigraphic subdivision of the Taloka formation interpreted as lithological facies. Supporting information for such a facies-based subdivision of the Taloka Formation but also a potential source for a possible mix up of geological layers provide the *Hydrogeological Cross Sections for the Sokoto basin* (JICA 1990; Fig. 8, Transect C-C') that show a "Basal Clay bed of the Rima Group" overlying the Gundumi Formation for areas north of the Zamfara River.

5.3.4 Continental Hamadien (Gundumi/Illo/Sendé Formations)

The Continental Hamadien, in Benin known as Sendé Formation, is subdivided in Nigeria into the northern **Gundumi Formation** and the southern **Illo Formation**. The dataset of the *Geological Map of Nigeria* (NGSA 2011c) differentiates three facies of the Gundumi Formation: "GIcg—Pebbels and grits", "GIgss—Gravel and sands", "GIss—Clay, grit and pebbles", representing roughly a lowermost conglomeratic sandstone and an upper mixture of gravel and sands; the third unit being an undifferentiated local unit east of Libba. The occurrence of a second conglomeratic strata (GIcg) at the top of the Gundumi Formation as suggested by the *Geological Map of Nigeria* (NGSA 2011c) is not reflected in the *Geological and Mineral Resource map of Kebbi State* (NGSA 2011a) nor the geological literature.

A single unit GIls described as "Limestone of the Dukumaje Formation" is wedged between outcrops of the two facies of the Gundumi Formation (GIss & GIpg), respective Taloka and Gundumi Formation (Tst & GIpg). This is litho-stratigraphically questionable as a limestone member of the continental Gundumi Formation has not been reported. The small area between Libba and Gummi was eliminated and grouped with the nearby areas of the sandstone facies of the Gundumi Formation (GIss).

The spatial extent of the stratigraphic important marker horizon ***Pisolitic and nodular bauxitic clay*** occurring as a middle member of the Illo Formation follows the original field work of Jones (1948). JICA (1990) mapped the outcrops of "white bauxitic clay" as part of the Kalambaina Formation, whereas NGSA (2011c, 2011a) mapped these areas as "Wss—Sandstones, clays and shale of the Dukamaje and Wurno Formation" (NGSA 2011c) or "Sandstones, siltstones of the Wurno/Taloka Formation" (NGSA 2011a). The assignments are erroneous as the Kalambaina, the Dukamaje and partly the Wurno Formations are limestone deposits and stratigraphically and sedimentological inconsistent with the field reports describing a kaolinite dominated bauxitic deposit.

East of the Sokoto River, near Tungan-Malashi and Koko, the shape of outcrops mapped as "Wss—Sandstones and clay of the Gwandu Formation" (NGSA 2011c) or "Sandstones, Siltstones of the Wurno/Taloka Formation" (NGSA 2011a)—resembles allusively the Jones (1948) unit of *Pisolitic and Nodular Clays* but is far off the original location. Without accompanying explanations of the geological units, the inconsistent denominations and doubtful geometries of the digital datasets probably indicate a mix-up of units and legend entries thus shedding further doubt on the general reliability of the recent compilations.

In Benin, the small extent of the **Sendé Formation** is backed by the spatially restricted records of Cretaceous fossilized wood limited to the Nigerian border region (Appendix I.II.IV). Recent fieldwork by Konaté, Issifou Fatiou, and the author, however, has shown that thin strata of Cretaceous Sendé sediments crop out on footslope positions of buttes covered by erosion resistant Continental Terminal in most of northern Benin. For the time being, the shallow thickness of Cretaceous Sendé justifies its classification as a potential—but unmapped—cover layer and its omission on the here presented map of solid rocks.

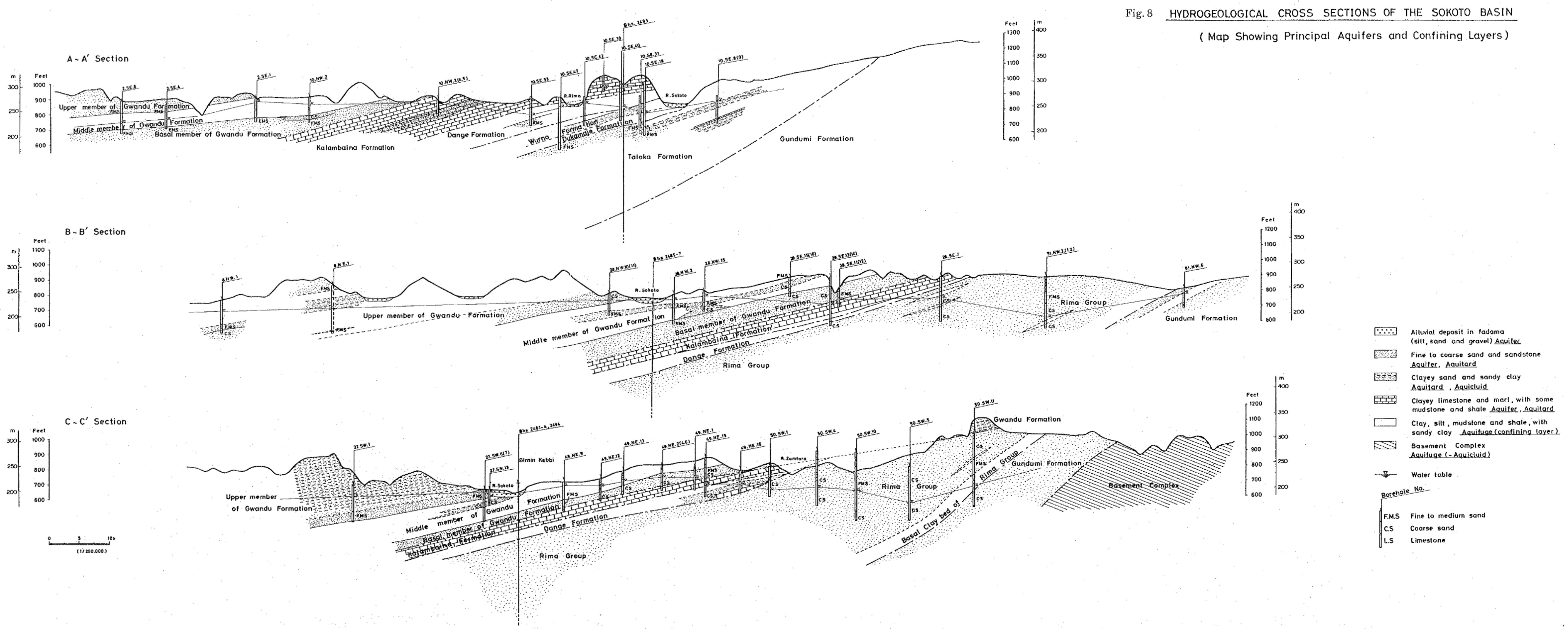

Fig. 16: Cross sections NW-SE through the Sokoto Basin (JICA 1990; Fig. 8)

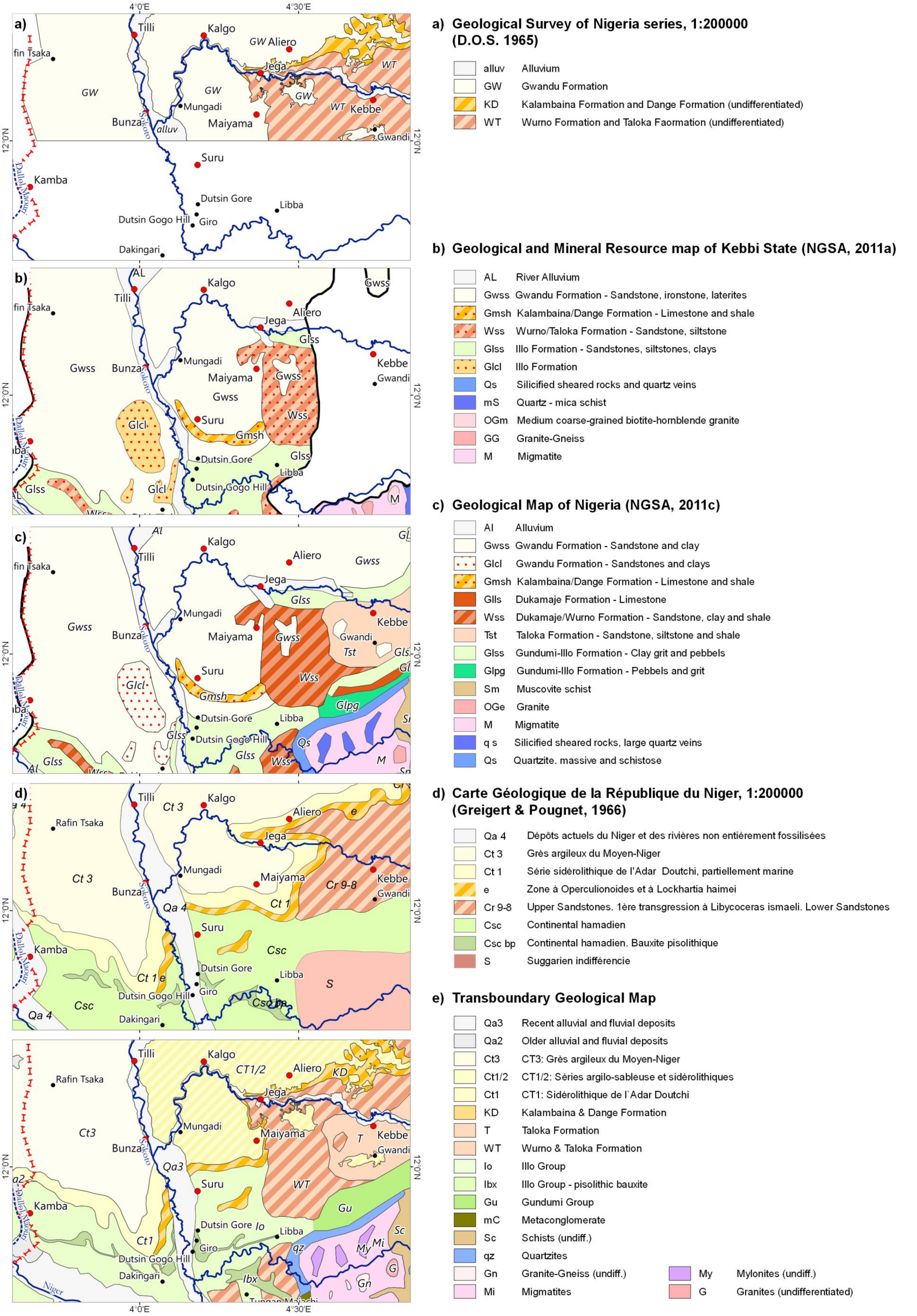

Fig. 17: *Harmonization of differing geometric and thematic map content for the Eocene-Palaeocene (Sokoto & Rima Group) and Cretaceous (Illo-Gundumi Formation) strata.*

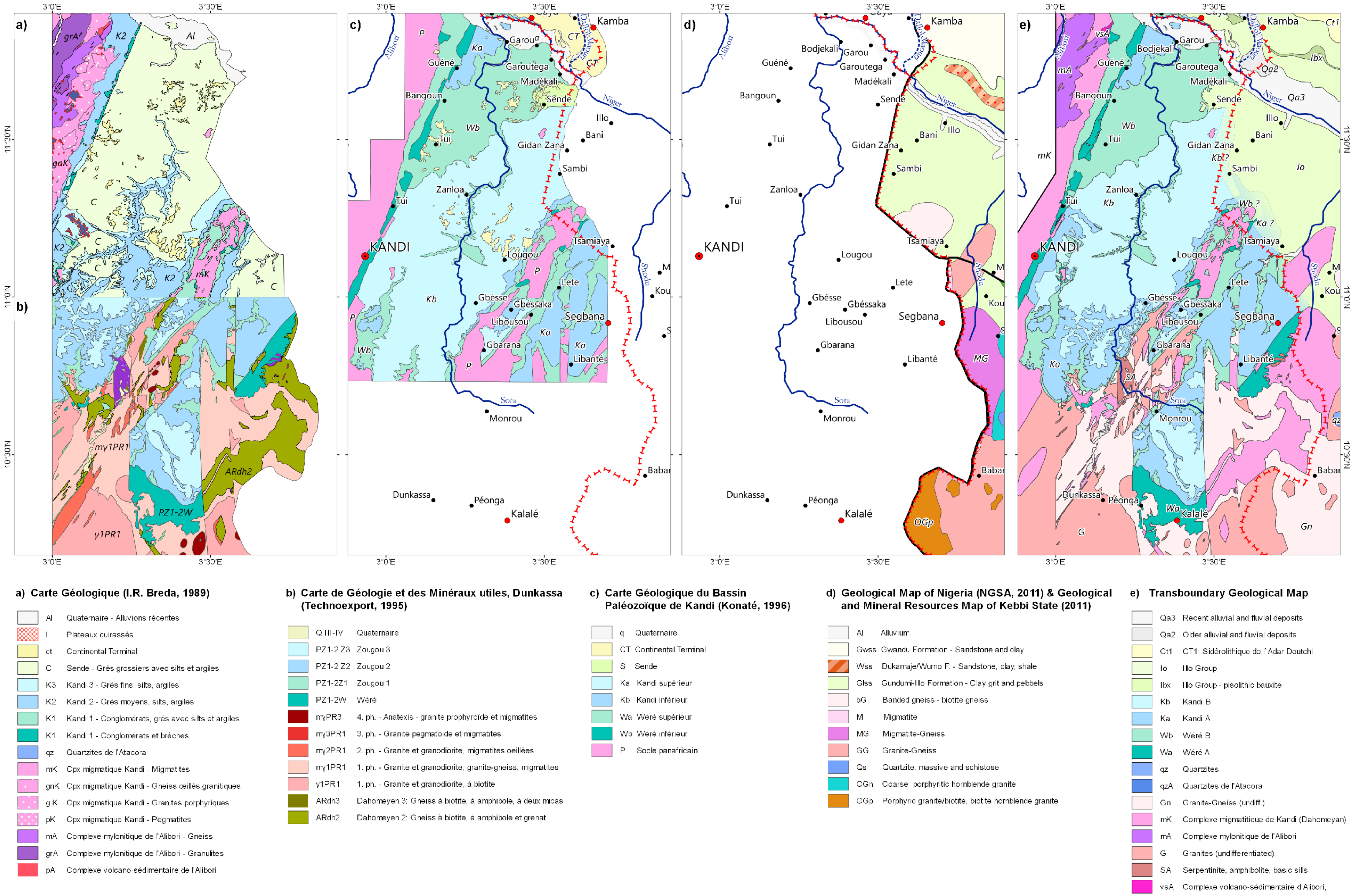

Fig. 18: Harmonization of the Kandi Basin and the Benin-Nigerian border region. The transition from Paleozoic Wéré and Kandi Formations to the Cretaceous Sendé along the international border of Benin and Nigeria has never been mapped and is indicated tentatively, only.

5.3.5 Palaeozoic Kandi group

Wéré Formation

Wéré A member (Wa)

The **Wéré A member** is a poorly-sorted polymictic breccia with boulders in a coarse-grained massive sandstone matrix interpreted as glacial drift and glacio-fluvial sediments. The unit corresponds to the *Wa member* of Konaté (1996), the units *K1 (dotted)* and *K1* of the Istituto Ricerche Breda (only the K1 units along the Kandi fault!), and the *Wéré Formation* ($PZ_{1\text{-}2}W$) of Technoexport (1995b). K1 (*dotted)* is described as "Conglomérats, bréches, grès avec silts et argiles subordonnés. Dépôts de cône d'alluvions. Conglomérats et bréches predominantes (en pointillé)" corresponds very well with the extent of the Wa member *sensu* Konaté (1996).

On the Dunkassa sheet of the Technoexport map series, the Wéré Formation ($PZ_{1\text{-}2}W$) is defined as "Gritty sandstones, micropudingstones, conglomerate" and corresponds rather to the fluvial Wb member. Undisputable Wéré A sediments along the Kandi Fault at Goungoun shown on the adjoining map sheet Bembèrèkè (Technoexport 1995a) led, however, to a the classification of unit $PZ_{1\text{-}2}W$ as Wéré A member.

Following Technoexport (1995b), $PZ_{1\text{-}2}W$ sediments occur also disjunct in the grabens of the Segbana (Segbana/Lété/Libanté) and Kalalé (Kalalé/Péonga/Monrou) sectors. The distant and disjunct occurrence questions at these locations the classification of $PZ_{1\text{-}2}W$ as Wéré A—particularly if following Konaté descriptions of the Wa member as a periglacial basin-margin facies deposited along the Kandi Fault, in the deepest point of the Kandi half-graben, and filling fault-bounded palaeovalleys during the early phase of faulting. Alidou & Lang (1983), on the other hand, describe a 125 m deep profile near Kalalé as "conglomérats induré" (lower 20 m) and "des grès et des siltites micacées et ferrugineuses avec des stratifcation entrecroisées" near Kalalé that might support a disjunct occurrence of Wéré A sediments. The distribution, as here suggested, warrants further investigation.

Wéré B member (Wb)

Wéré B member is a granule-rich coarse sandstone showing trough cross-bedding often in fining-upwards sequences. It is interpreted as a Wéré facies deposited in a periglacial braided-stream environment. Wéré B corresponds to the Wb member of Konaté (1996) and comprises most of Istituto Ricerche Breda's unit K1 with parts of unit K2 as well as the Zougou 1 Formation ($PZ_{1\text{-}2}Z_1$) of Technoexport. Compared to the map of Konaté outcrops of Wéré B have been refined and extended based on the extent of the Breda unit K1 along the Sota River. The Horst of Lété was mapped by Konaté homogenously as basement, whereas Istituto Ricerche Breda differentiated several small remnants of unit K1. Giving this apparent field evidence for sediments, the remnants were included and attributed as Wéré B. Following Konaté (1996), large areas of unit K2 west of Lété were surmised under Wéré B.

Wéré B and Kandi A members mapped by Konaté (1996), were geometrically reasonable prolonged to cover low-lying areas north of the Niger River (east of Karimama) although subrecent meanders and oxbow lakes indicate at least a shallow cover layer of floodplain deposits.

Kandi Formation

Kandi A member (Ka)

Kandi A corresponds to the Ka member of Konaté (1996). The fine-grained siltstones with rhythmic laminations represent the tidal shore face facies of the Kandi Group. The Kandi A member comprises the following units of Istituto Ricerche Breda: the Cretaceous unit C in the areas of Bodjékali and Guéné, the unit K2 east of Kandi, east of Guéné-Laga, and east of Lété, and the unit K3 between Guéné Laga and Lougou. On the map sheets of Technoexport (1995b, 1995a), the Kandi A member corresponds directly to the Zougou 2 Formation ($PZ_{1\text{-}2}Z_2$). Towards the basin centre, the shore face facies Kandi A grades into the offshore facies Kandi B. Although Konaté (1996) recorded several continuous profiles from Kandi A to Kandi B in the Poria area (Kandi-Tui-Kouta Kroukou), the basin centre is not expected to show a continuous sequence from shore face (Kandi A) to offshore environments (Kandi B). The harmonized map reflects this notion and follows Konaté (1996), who suggested a direct transition from terrestrial Wéré B to offshore Kandi A in the basin centre. Accordingly, the sequence from Wéré B to Kandi B exposed along the Sota River was not subdivided as suggested by the sequence of units K2, K3, to C on the maps of Istituto Ricerche Breda.

Towards the south-eastern limits of the basin, the Kandi A member of the harmonized map extends beyond the areas suggested by Konaté (1996) following the more detailed subdivision of Istituto Ricerche Breda (Akibou et al. 1989c) and Technoexport (1995b).

Kandi B member (Kb)

The **Kandi B member** corresponds to the Kb member of Konaté (1996) and comprises siltstones of variable colour deposited in a marine, upper offshore environment. The Kandi B Formation comprises the following units of the Istituto Ricerche Breda (Akibou et al. 1989c): the entire Cretaceous unit C, parts of unit K2 (south of a line between Kandi and Lougou, but except the areas along the Kandi Fault system, along the Sota River, and near Lété where the unit K2 is assigned to Wéré B), and the unit K3 (except the areas east of Tui and around Lété where it is assigned Ka). On the map sheets of Technoexport (1995b, 1995a), the Kandi B Formation corresponds directly to the Zougou 3 Formation ($PZ_{1\text{-}2}Z_3$).

The most obvious differences between the maps of Konaté (1996) and the Istituto Ricerche Breda (Akibou et al. 1989c) are:

a) restriction of the Cretaceous Sendé Formation to a small area near the Benin-Niger border,
b) diagonal division of the basin centre in Wéré B and Kandi A, and
c) the sequence outcropping along the Sota River.

The Cretaceous Sendé Formation, mapped throughout the basin by the Istituto Ricerche Breda (Akibou et al. 1989c) has been revised in favour of a Palaeozoic basin as shown by Alidou et al. (1986) and Konaté (1996) (cf. chapter 5.3.4). The former Cretaceous strata is now described as either terrestrial Wb member (between Bodjekali and Guéné and east of Lété) or as the upper Kb member of the marine Kandi Formation (basin centre).

The diagonal division between continental Wéré B in the north-west and marine Kandi B in the south as suggested by Konaté (1996) is based on conjectures. The intermediate Kandi A member has not been mapped and is omitted on the map. Its apparent lack is explained by lateral facies change between the two formations. Rather than representing a continuous (chrono-)stratigraphic sequence, the Kandi A and Kandi B members embody two endmember facies reflecting within the Kandi Group the facies change from a tidal shoreface environment to a subtidal upper offshore environment. The two formations may (around Poria cf. Konaté 1996; Konaté et al. 2003a) or may not (as assumed for the basin centre?) occur in a chronostratigraphic sequence.

Technoexport (1995b) and Istituto Ricerche Breda (Akibou et al. 1989c) likely used topographic elevation and aerial images as proxies to delimit unit boundaries. The result was a high level of detail particularly along the valley flanks of the Sota River and its tributaries where the homogeneous Kb member is dissected and unit K2 (Wéré B), unit K3 (Kandi A? or Kandi B), and Zougou 2 (Kandi A) crop out. Such an exposure of the entire sequence is reasonable, given an incision of the Sota River of about 50 m to 100 m into the sediments of the Kandi Group estimated to have a thickness of around 60 m. Presuming that Kandi A and Kandi B are concurrent lateral variations representing a basin-margin and a basin-centre facies, the detailed lithological subdivision as suggested by the Istituto Ricerche Breda for the exposed units K2 and K3 was not incorporated into the harmonized map. This led to a major generalization of the units K2 and K3 to the member along the Sota River and south of the line Kandi-Lougou. To avoid map sheet boundary problems along the 11°N between the map series of Technoexport and the Istituto Ricerche Breda, several minor occurrences of the Zougou 3 Formation were suppressed and/or adjusted.

Spatial assignment

The correlation of units between Konaté and Istituto Ricerche Breda is based on the available maps. This results not only in cartographic imprecisions but also in thematic differences for example for the unit K2 of Istituto Ricerche Breda. While the presence of *Harlania* is indicative for a marine environment of the Kandi Formation (Ka/Kb members; Konaté 1996 p.32), the description of a fluviatile environment with floodplains and braided rivers for unit K2 by the Istituto Ricerche Breda suggests an environment Konaté proposes for the Wb member.

Detailed inset maps for the areas of Kandi and Tui (Konaté 1996; Konaté et al. 2003a) may differ from the overview map *Carte Géologique Générale du Bassin Paléozoïque de Kandi*. The inset maps have not be taken into account for the elaboration of the present map.

The *Carte de Géologie et des Mineraux utiles* elaborated by the Russian Technoexport in the years 1981-1984 was only partly incorporated into the work of Konaté. Nevertheless, the spatial extents of the combined Zougou 2 ($PZ_{1\text{-}2}Z_2$) and Zougou 3 ($PZ_{1\text{-}2}Z_3$) Formations agree well with the Kb member. Being described in the map as “Siltstone and ferruginous sandstone” and “Siltstone, less frequently fine-grained sandstone”, respectively, they agree well with Konaté’s description of a “siltstone facies with hummocky cross-stratification, siltstone strata interbedded with micaeous fine sandstone in undulating beds several decimetres to a meter thick”. However, both Technoexport and Istituto Ricerche Breda share the notion of a subdivision of the Kandi B member in a finer upper deposit—“Siltstone and ferruginous sandstone”, respective “Grès fins, silts, argiles. Dépôts paraliques de lac (plages, deltas et varves lacustres) et de mer peu profonde à *Cruziana* et *Arthrophycus*” including the wrongly mapped Cretaceous unit)—and a coarser lower deposit: “Siltstone, less frequently fine-grained sandstone”, respective “Grès moyens, silts, argiles. Dépôts de plaine d'inondation”.

5.3.6 Basement units

Basement units were aggregated following litho- and chronostratigraphic descriptions on the original map legends. For Nigeria, only lithological descriptions were available. For Benin, the regional chronostratigraphic denominations were maintained, if possible. The chronostratigraphic terms provide additional information useful for differentiation on a regional level. For Niger, the study area does not comprise any noteworthy basement areas.

The 83 different basement units were aggregated to **26 classes** comprising both:

- purely lithological denomination—particularly maps provided by the Nigerian Geological Survey Agency,
- regional chronostratigraphic units available from maps of the Istituto Ricerche Breda and Technoexport for Benin.

Similar basement units were identified and grouped within the general legend before merging using the respective GIS features in QGIS. For example, the group “Granites undiff.” comprises six finely differentiated varieties of biotite granite and granodiorite but also small occurrences of quartz-syenite, diorite and dolerite (cf. Tab. 8). The aggregated units are—following the number of subunits—Granites undiff. (20), *Complexe migmatitique de Kandi* (7), Amphibolite & Serpentinite (7), Banded biotite (6), Biotite and muscovite schist (5), Granite-gneiss (4), Migmatite (3), Mylonite (3).

Tab. 8: Excerpt from the General Legend: Aggregation of the unit: Granites (undiff.)

Harmonized map	Société Istituto Ricerche Breda: Akibou et al. (1989): Carte Géologique à 1/200.000 Feuilles: Karimama, Porga, Kandi, Malanville		Technoexport (1994) Carte de Géologie et des Minéraux utiles: Dunkassa (NC-31-X), 1:200.000		Greigert (1966): Carte Geologique Republique du Niger. 1:2.000.000		D.O.S. (1965/6): Geological Survey of Nigeria, 1:200.000 map series		NGSA (2011) Geology and Mineral Resources Map of Nigerian States & Geological Map of Nigeria	
	Abbrev.	Lithology	Abbrev.	Lithology	Abbrev.	Lithology	Abbrev.	Lithology	Abbrev.	Lithology
Granites indifférenciés / Granites (undiff.)	γ	Granites indifférenciés								
			γPR3	Formations palingéno-métasomatiques. Granite prophyroïde et migmatites						
			γ3PR1	Troisième phase : Granite pegmatoïde et migmatites						
			ρPR1	Troisième phase : Granite pegmatoïde et migmatites ; filons de pegmatite						
			γ2PR1	Deuxième phase : Granite et granodiorite grossiers						
			(m)γ2PR1	Deuxième phase : Granite et granodiorite grossiers, migmatites œillées						
			γ1PR1	Première phase : Granite et granodiorite à grain moyen et fin, à biotite						
					gs	Granites syntectoniques				
					gpt	Granites postectoniques				
					g	Granites anciens indifférenciés				
							P	Pegmatite, granite and aplite complex (quatzo-feldspathic rocks with epidote	OGp	porphyric granite / coarse porphyritic biotite and biotite hornblende granite
							Ogh	Biotite- and biotite-hornblende-granite, medium grained	Oge / Ogm	Medium to coarse grained biotite granite
									OGf	Fine-grained biotite granite
									OGh	Coarse, porphyritic hornblende granite
									OGd	Biotite and biotite hornblende granodiorite, quartz diorite
									OGu	Undifferentiated granites and granite gneiss and migmatite
									OSq	Quartz-syenite
							D	Dyke-complex, including dacite, micro-granite and micro-granodiorite	ODh	Diorite
			γ1PR1	Formations Palingéno-Metasomatiques. Première phase : Diorites						
									D	Dolerite

Issues along map sheet boundaries

Along the map boundary of Benin and Nigeria, thematic harmonization and spatial adaptation resulted in three transboundary units (Fig. 18): the *Complexe migmatique de Kandi* (mK), undifferentiated Granites (G), Granite—gneiss (Gn). Following the map series of the Istituto Ricerche Breda (Akibou et al. 1989c, 1989b), the *Complexe migmatique de Kandi* (mK) crops out disjunct in the Lété horst and the western margins (gnK) of the Palaezoic Kandi Basin and corresponds to the Archean-Dahomeyen unit $ARdh_2$ (gneiss with biotite, biotite with garnet, amphibole and garnet, amphibolite with pyroxene and garnet) of Technoexport (1995b). In Nigeria, the Horst of Lété is mapped as Gb (banded gneiss - biotite gneiss) and the western extension as MG (Migmatite-granite-gneiss). These two Nigerian units Gb and MG are condensed into the Beninese *Complexe migmatique de Kandi*. Along the Shodu (Ouara) River, the Nigerian maps propose a granite-gneiss (GG) outcrop stretching into Benin north of Segbana. This prominent basement outcrop is not reported on earlier Nigerian maps nor does it stretch into Benin. Within the horst-and-graben structures (Horst of Lété to the west and unnamed basement outcrops to the south and the east), a further palaezoic basement outcrop is reasonable—although its limit paralleling the Benin-Niger international border raises questions regarding the accuracy of the field mapping. The geological formations along the international border are tentative at best and call for geological reconnaissance mapping.

South of 11°N, the *Complexe migmatique de Kandi* limits with the units GG (Granite-gneiss) and Ogp (porphyric granite/biotite and biotite hornblende granite). Both of these Nigerian units fall into the first phase of granite intrusion *sensu* Technoexport (1995b) and are only differentiated by the occurrence of gneiss and migmatites. Spatially, they correspond to the unit $_{m\gamma1}PR_1$ *(First* phase: Granite-gneiss; plagiogranite-gneiss; migmatites) and $_{\gamma1}PR_1$ (First phase: Fine- and medium-grained granite and granodiorite, with biotite), respectively. The first unit $_{m\gamma1}PR_1$ was subsumed under Granite-gneiss (Gn), the second as undifferentiated granites (G: Granites undiff.). As a chronostratigraphic correlation of these units for the Nigerian shield is beyond the scope of the present map, the chronostratigraphic denominations were dropped.

Harmonization of Beninese maps

The detailed basement differentiations of the Istituto Ricerche Breda map series (Akibou et al. 1989c, 1989b) and Technoexport (1995b) were generalized prior to harmonization (cf. chapter 4.1 & Appendix III). Areas west of the Kandi Basin were not differentiated further as the geological map sheets Kandi and Bembèrèkè were not digitized. The *Complexe migmatique de Kandi* (now cpK) comprises the main unit mK (Migmatites à néosomes granitiques et granodioritiques et paléosomes gneissiques et amphibolitiques) as well as all subordinated units such as gnK (Gneiss œillés granitiques et granodioritiques), γK (Granites porphyriques), and pK (Pegmatites). Further, the unit cpK has been merged with the two corresponding Technoexport's units Archeen-Dahomeyen 2 ($ARdh_2$: Gneiss with biotite, with biotite and garnet, amphibole and garnet; amphibolite with pyroxene and garnet) and $ARdh_3$ (Gneiss with biotite, with biotite and amphibole, with two micas; amphibolite).

The *Complex mylonitique de l'Alibori* of Istituto Ricerche Breda has been retained as a separate unit but has not been further differentiated into mA (Gneiss, amphibolites, métagabbros retromorphosées en faciès schistes verts; mylonitisés et en écailles tectoniques.) and grA(Granulites acides et intermédiaires, retromorphosées en faciès schistes verts).

Proterozoic intrusive rocks of the first anatectic phase (γ_1PR_1 : Première phase : Granite et granodiorite à grain moyen et fin, à biotite ; diorites (δPR_1)) are subsumed under the generic unit G (Granites undiff.). The metamorphic facies of the same anatectic phase ($m\gamma_1PR_1$: granite-gneiss; plagiogranite-gneiss; migmatites) was grouped under the generic unit Gn (Granite-Gneiss undiff.). Thematic overlap between the different granite-gneiss, gneiss, and migmatite units, particularly the *Complexe migmatique de Kandi,* cannot be ruled out.

Spatially adaption was required to harmonize the outline of the younger basement units Voltaen, Buem & Atakorien as depicted on the map of Greigert and Pougnet (1966) with the more detailed outlines shown on the maps series of the Istituto Ricerche Breda.

6 Accessory datasets

6.1 Tectonic structures: Lineaments, faults, and fractures

Faults, fractures, and tectonic contacts have been compiled from geological maps and were combined with a recent remote sensing study in the Dosso region (Ibrahim et al. 2016). The lineament dataset has to be evaluated with caution as the density and direction of lineaments differs between authors indicating different mapping approaches and levels of detail (Fig. 19).

The most striking tectonic feature within the study area is the Kandi Fault or the "Kandi shear zone", part of the transcontinental Sobral (NE Brazil) - Hoggar shear zone (4°50' fault) of Neoproterozoic age (Pan-African orogeny). This major suture zone between the West African and the Congo tectonic domains is traceable throughout Benin; farther north, it is covered under the sediments of the Iullemmeden Basin. Reactivated in the Palaeozoic, the Kandi Fault marks the abrupt boundary between the Neoproterozoic basement and the Palaeozoic sediments of the Kandi Basin.

On the Dunkassa sheet, OBEMINES and Technoexport (OBEMINES 1995a) discern three main tectonic accidents (*accidents cassants*) with their respective rejuvenation phases:

- Archean-Early Proterozoic (northeast): restricted to the southern part of the Dunkassa sheet and do not affect the sedimentary units.
- Archean-Palaeozoic (northeast): rejuvenated during the Palaeozoic they contribute to the delimitation of horst structures.
- Proterozoic-Palaeozoic (centre & north-west): resulted from lateral sublatitudinal compression during the Eburnean orogeny (Proterozoic) often associated with mylonitization. Nord-west oriented secondary (shear) fractures are of secondary nature.

The dominant lineament direction of the basement areas on the Technoexport map sheets south of 11°N is primarily S175°E and secondarily N45°E. Technoexport (1995b) mapped a dense network of (probably largely generalized) *tectonic contacts* (observed/inferred—incorporated as: *Lineaments observed/inferred*), *geological contacts* (geological unit boundaries), *fissures* (incorporated as: *Fissures*), and *structural form lines*. Structural form lines (only recorded by Technoexport) and generic geological contacts/unit boundaries were not incorporated in the *Lineaments* dataset.

The sedimentary Palaeozoic Kandi Basin and the adjoining basement areas north of 11°N were mapped by the Istituto Ricerche Breda (Akibou et al. 1989c, 1989b) and Konaté (1996). Both report the strike of the Kandi fault N20°E as the main lineament direction and a perpendicular secondary S110°E direction. Similar directions dominate on the overview maps of Greigert (1960), Greigert & Pougnet (1966), and the Nigerian maps (NGSA 2011a, 2011c) for basement and to a lesser extent for the sedimentary basins in Nigeria and northern Niger.

For the Continental Terminal, the data of Ibrahim et al. (2016) suggest a main lineament direction of NE-SW (widespread between 0°E to 60°E)—probably corresponding to a (Miocene?) rejuvenation of the Kandi fault direction—and secondary directions of N90°E, and S150°E.

The striking differences between the three datasets strongly cautions against the indiscriminate use of the data for analysis (cf. Fig. 19). The difference might be partly related to the changing tectonic stress field and different sets of fractures in the Dahomeyan basement, the Palaeozoic basin, and the Neogene sediments—but more likely arises from different mapping approaches thus reflecting a strong author bias.

The approach of Technoexport resulted in a dense network of lineaments with a high number of lineaments and a high degree of abstraction and generalization. The resulting lineament pattern differs from the more fragmentary—thus more plausible—mapping approach applied by the other studies.

Data of the different sources was merged and an attempt was made to harmonize the differing datasets. To attenuate the strong difference between map sheets, several *tectonic contacts* within the Palaeozoic sedimentary cover that are not directly related to unit boundaries were omitted for the final map. Duplicates or features indicating the same geological feature were manually removed. Preference was given to features from the same data source as the underlying lithological data while harmonizing line and polygon data. The manual cleaning included minor geometric corrections. Where available, information on observed and inferred faults and fractures is conserved (field: *certainty*). The *Geological Map of Nigeria* (2011c) differentiates between major and inferred faults/fractures. For consistency, major faults/fractures were reclassed in the category: Lineaments (observed)

The shapefile *Lineaments* presents four types of structural elements. Of these, only observed and inferred lineaments are displayed in the final map.

- Lineament (observed),
- Lineament (inferred),
- Lineament (omitted),
- Fissures

6.2 Mineral Ressources

The occurrence of major mineral resources are shown on the maps of of Istituto Ricerche Breda (Akibou et al. 1989c, 1989b), the Nigerian Geological Survey Agency (NGSA 2011a, 2011c), as well as on the map of Greigert (1960). Despite being named *Geological and Mineral Resources map of the Kebbi State*, the map of the Nigerian Geological Survey Agency only depicts major mineral deposits. Using a more explorative approach, the map by Technoexport (1995b) reports in detail the distribution of mineral occurrences often with an estimation of the mineral content. Mineral occurences are displayed “as is” in Fig. 21.

6.3 Strike and Dip

The orientation of geological structures in space are described by the attitude of the geological layer expressed as the strike and dip of the geological surface. Strike describes the intersection of the tilted/inclined layer with the horizontal plane, whereas the dip indicates angle of maximum inclination of the layer. Strike direction is given as the angle of the strike to the North; dip is the angle of the tilted layer to the horizontal plane. Dip angles are often reported as a range and displayed as such. All reported values were incorporated (Fig. 21).

Limitations of data quality

Quality and density of the structural elements strongly reflect the different mapping approaches and thus limited the possibilities for harmonization. The four datasets—lineaments, mineral resources, strike-and-dip, and fossils—are provided “as is” and are only suitable for overview purposes regarding data quality and quantity. Given the heterogeneous quality of the data sources no harmonization was attempted. Spatial analysis should not be performed on these datasets.

Tab. 9: Accessory datasets: Distribution of original data

	Niger			Benin				Nigeria	
	Greigert (1966)	**Greigert (1960)**	**Ibrahim et al.(2016)**	**BREDA (1989)**	**Technoexport (1995)**	**Konate (1996)**	**IGIP/GIZ (2012)**	**NGSA (2011a)**	**NGSA (2011b)**
Strike & Dip	-	-	-	24	148	12		-	5
Faults / Fractures - observed	-	3	3274	432	318 111 (Fissures)	285	30	671	42
- inferred	-	3	-	378	242 76 (Fissures)	234	3	193	42

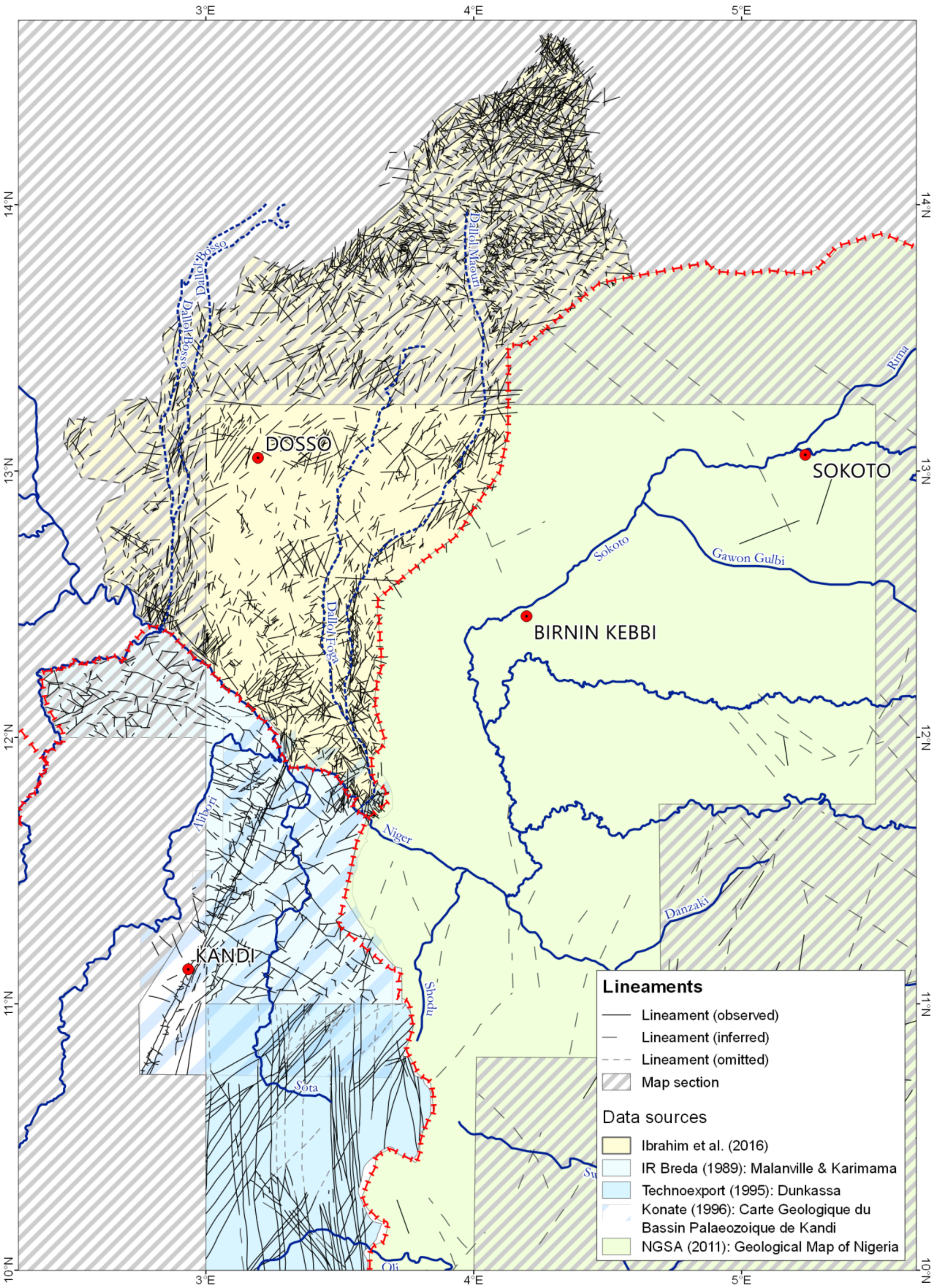

Fig. 19: Available lineament datasets show diverging lineament density, level of continuity, and strike direction indicating different mapping approaches.

6.4 Fossil sites

The data layer *Fossils* has been compiled using three maps published by a) Alidou et al. (1986), b) Alidou (1987), and c) Konaté et al. (2003a). All of these maps are sketch maps thus only the approximate location of fossil sites can be indicated (Fig. 28). Growing numbers of fossil sites allowed the evolvement of the geological maps of the Kandi Basin. Whereas Konaté (1996) mapped the area between Kandi and Poria as Early Silurian Kandi B member, determination of fossils allowed Konaté et al. (2003a) to differentiate between sediments of the Kandi A and Kandi B member based on traces of *Cruziana petraea* (Late Ordovician, Kandi A) and *Cruziana acacencis* (Early Silurien, Kandi B).

6.5 Cross Sections

Cross sections were compiled from the literature (Tab. 10 & Fig. 22) and are collated in the Appendix. V. The compilation comprises generalized geological sections with low (Geological Survey of Nigeria map series by the D.O.S.) to medium detail (Istituto Ricerche Breda & Technoexport & JICA) as well as superficial sections (Continental Terminal) published by the FAO (1970) for the Dallol Bosso in Niger and geophysical sections in northern Benin (Bouzid 1971).

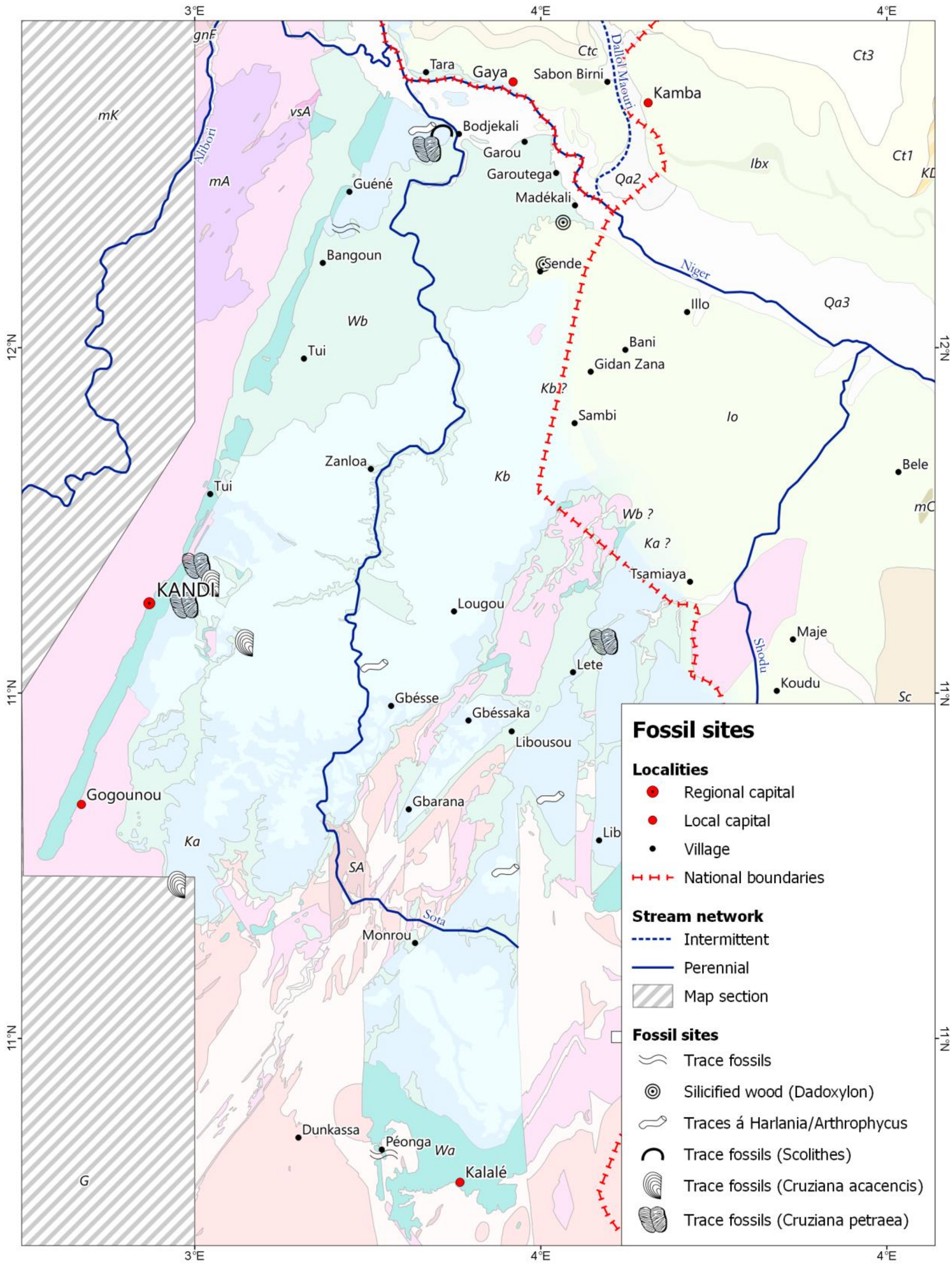

Fig. 20: *Fossil and trace fossil sites compiled from Alidou et al. (1986), Alidou (1987), and Konaté et al. (2003a). For geological background information, see the attached harmonized geological map.*

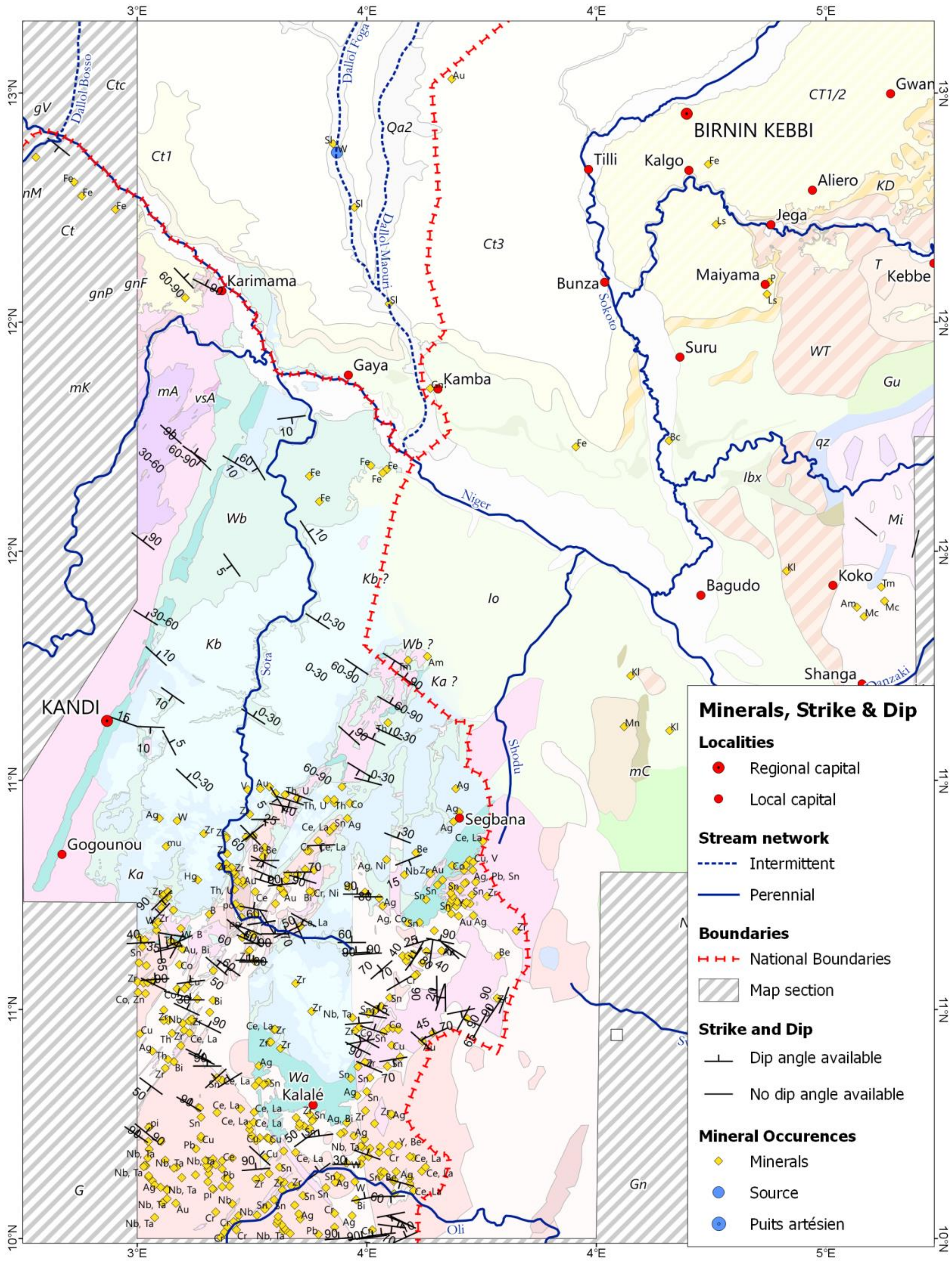

Fig. 21: Mineral occurrences and strike & dip information. For geological background information, see the attached harmonized geological map.

Tab. 10: Geological cross-sections: Overview and sources

Source	Section	Label
FAO (1970) Mise en valeur du Dallol Bosso, Fig 14a	Fig 14a	Fig 14a
FAO (1970) Mise en valeur du Dallol Bosso, Fig 14b	Fig 14b	Fig 14b
FAO (1970) Mise en valeur du Dallol Bosso, Planche N° 2, Coupe I	Planche 2, Coupe I	FAO (1970), Planche 2, Coupe I
FAO (1970) Mise en valeur du Dallol Bosso, Planche N° 2, Coupe II	Planche 2, Coupe II	FAO (1970), Planche 2, Coupe II
FAO (1970) Mise en valeur du Dallol Bosso, Planche N° 2, Coupe III	Planche 2, Coupe III	FAO (1970), Planche 2, Coupe III
FAO (1970) Mise en valeur du Dallol Bosso, Planche N° 2, Coupe IV	Planche 2, Coupe IV	IV
FAO (1970) Mise en valeur du Dallol Bosso, Planche N° 3, Coupe J	Planche 3, Coupe J	J
FAO (1970) Mise en valeur du Dallol Bosso, Planche N° 3, Coupe H	Planche 3, Coupe H	H
FAO (1970) Mise en valeur du Dallol Bosso, Planche N° 3, Coupe G	Planche 3, Coupe G	G
FAO (1970) Mise en valeur du Dallol Bosso, Planche N° 3, Coupe F	Planche 3, Coupe F	F
FAO (1970) Mise en valeur du Dallol Bosso, Planche N° 3, Coupe E	Planche 3, Coupe E	E
FAO (1970) Mise en valeur du Dallol Bosso, Planche N° 3, Coupe C	Planche 3, Coupe C	C
FAO (1970) Mise en valeur du Dallol Bosso, Planche N° 3, Coupe B	Planche 3, Coupe B	B
FAO (1970) Mise en valeur du Dallol Bosso, Planche N° 3, Coupe A	Planche 3, Coupe A	A
FAO (1970) Mise en valeur du Dallol Bosso, Planche N° 3, Coupe longitudinal du Dallol	Planche 3, Coupe Longitudinale Dallol	FAO (1970), Planche 3, Coupe Longitudinale Dallol
DOS-GSN (1965) Geological Survey of Nigeria, Tangaza	-	DOS (1965), Tangaza
DOS-GSN (1965) Geological Survey of Nigeria, Sokoto	-	DOS (1965), Sokoto
DOS-GSN (1965) Geological Survey of Nigeria, Shinkafe	-	DOS (1965), Shinkafe
DOS-GSN (1965) Geological Survey of Nigeria, Birnin Kebbi	-	DOS (1965), Birnin Kebbi
DOS-GSN (1966) Geological Survey of Nigeria, Gummi B-B	B-B'	DOS (1966), Gummi B-B
DOS-GSN (1966) Geological Survey of Nigeria, Gummi A-A	A-A'	DOS (1966), Gummi A-A
DOS-GSN (1965) Geological Survey of Nigeria, Gusau	-	DOS (1965), Gusau
DOS-GSN (1960) Geological Survey of Nigeria, Potiskum	-	DOS (1960), Potiskum
DOS-GSN (1960) Geological Survey of Nigeria, Kusheriki	-	DOS (1960), Kuseriki
DOS-GSN (1960) Geological Survey of Nigeria, Gombe	-	DOS (1960), Gombe
DOS-GSN (1960) Geological Survey of Nigeria, Lau	-	DOS (1960), Lau
Anderson & Ogilbee (1973): Aquifers in the Sokoto basin, northwestern Nigeria, Plate 3	Plate 3	USGS (1973), Plate 3
JICA (1990) The study of groundwater development in Sokoto State, Vol. 1, Fig. 08, B-B'	Vol. 1, Fig. 08, B-B'	JICA (1990), Vol. 1, Fig. 08, B-B'
JICA (1990) The study of groundwater development in Sokoto State, Vol. 1, Fig. 08, A-A'	Vol. 1, Fig. 08, A-A'	JICA (1990), Vol. 1, Fig. 08, A-A'
JICA (1990) The study of groundwater development in Sokoto State, Vol. 1, Fig. 08, C-C'	Vol. 1, Fig. 08, C-C'	JICA (1990), Vol. 1, Fig. 08, C-C'
Bouzid (1971): Développement de l'utilisation des eaux souterraines, Dahomey. Hydrogéologie.	Carte/Planche 3, A	Bouzid 3A
Bouzid (1971): Développement de l'utilisation des eaux souterraines, Dahomey. Hydrogéologie.	Carte/Planche 3, B	Bouzid 3B
Bouzid (1971): Développement de l'utilisation des eaux souterraines, Dahomey. Hydrogéologie.	Carte/Planche 3, C	Bouzid 3C
Bouzid (1971): Développement de l'utilisation des eaux souterraines, Dahomey. Hydrogéologie.	Carte/Planche 3, D	Bouzid 3D
Breda (1989) Note explicative de la Carte Géologique à 1/200.000, Malanville	Malanville E'-E''	Malanville E'-E''
Breda (1989) Note explicative de la Carte Géologique à 1/200.000, Malanville	Malanville C-C'	Malanville C-C'
Breda (1989) Note explicative de la Carte Géologique à 1/200.000, Kandi	Kandi E-E'	Breda (1989), Kandi E-E'
Breda (1989) Note explicative de la Carte Géologique à 1/200.000, Kandi	Kandi C-C'	Breda (1989), Kandi C-C'
Breda (1989) Note explicative de la Carte Géologique à 1/200.000, Karimama	Karimama B-B'	Breda (1989), Karimama B-B'
Breda (1989) Note explicative de la Carte Géologique à 1/200.000, Karimama	Karimama A-A'	Breda (1989), Karimama A-A'
Breda (1989) Note explicative de la Carte Géologique à 1/200.000, Porga	Porga D-D'	Breda (1989), Porga D-D'
Technoexport (1995) Carte de Géologie et des Minéraux utiles, Bembereke	Bembereke, C-D-E	Technoexport (1995), C-D-E
Technoexport (1995) Carte de Géologie et des Minéraux utiles, Dunkassa	Dunkassa, E-F	Technoexport (1995), E-F
Technoexport (1995) Carte de Géologie et des Minéraux utiles, Dunkassa	Dunkassa, I-J	Technoexport (1995), I-J
Technoexport (1995) Carte de Géologie et des Minéraux utiles, Natigingou	Natigingou, B-C	Technoexport (1995), B-C
Technoexport (1995) Carte de Géologie et des Minéraux utiles, Natigingou	Natigingou, G-H	Technoexport (1995), G-H

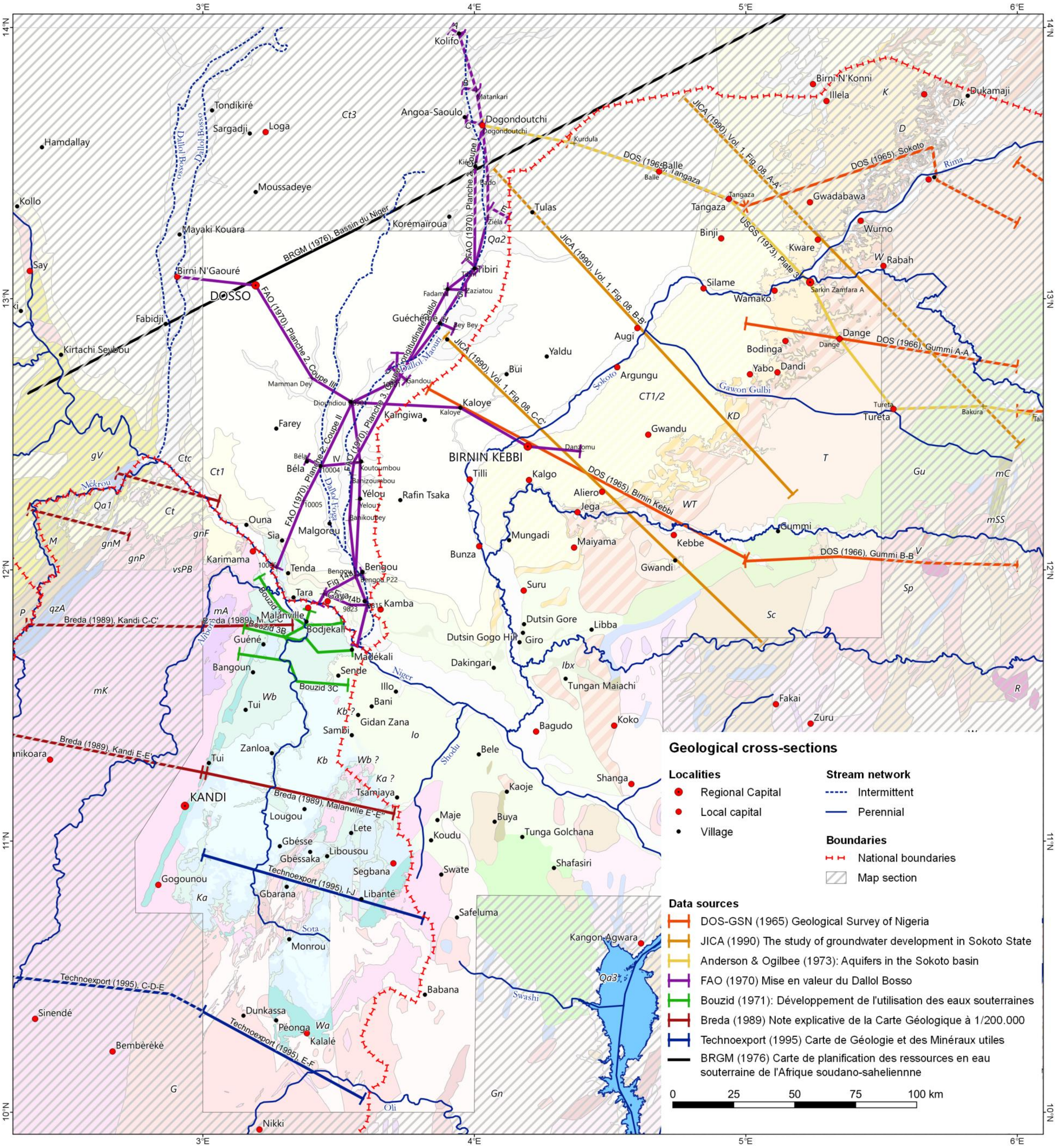

Fig. 22: Geological cross sections compiled from different sources. See Appendix V for a selection of cross sections. For geological background information, see the attached harmonized geological map.

7 Conclusions

7.1 General Remarks

Geological maps of the boundary region of Benin, Niger, and Nigeria have been thematically and geometrically harmonized. The harmonized transboundary geological map

- is a **multiscale map**, that displays spatial information on different scales depending on the coverage of the original maps.
- collates and incorporates the **most detailed available information** for each region.
- is a two-dimensional **solid rock map** and presents information on the **outcropping, uppermost geological layer**. Cover layers and drifts are summarized in a cover layer. For information on thickness of strata, the reader is referred to the auxiliary geological literature.
- focuses on the sedimentary basins. Differentiation of basement units is limited to broad categories.
- **highlights unresolved stratigraphic issues** along map boundaries to flag up areas and topics for future geological research.
- provides the **spatial baseline information** for further geoscientific analyses e.g. hydrogeological assessments.

The harmonization of eight geological maps in the study area has shown:

- the previous lack of transboundary geological mapping at scales >1:1 000 000 in West Africa,
- divergent geological interpretations between map series and map authors,
- the need for targeted geological fieldwork to resolve known inconsistencies between maps.

7.2 Limitations & unresolved issues

7.2.1 Map sheet boundary Benin–Nigeria

The revised litho- and chronostratigraphy of the Kandi Basin suggests Palaeozoic strata stretching from Benin into adjacent Nigeria while the sedimentary cover in the Nigerian regions of Bagudo, (department Kebbi) and Borgu (department Niger) has been assumed to belong to the Illo Formation (Jones 1948) or the Continental Hamadien (Greigert & Pougnet 1966). Having been neglected by both colonial and Nigerian geologists, mining companies, and (inter-)national development projects, the geology of the right bank of the Niger in the departments of Kebbi and Borgu has been subject to speculation on all subsequent geological maps. The exact eastward extent of the Palaeozoic Kandi Basin can only be delimited by thorough geological field mapping. Tentative transition areas have been delimited following the given unit boundaries and supported by satellite imagery. The units *Ka?,* respective *Wb?,* highlight the lack of reliable geological information and call for detailed geological fieldwork.

7.2.2 Quality of available datasets

The digital datasets—G*eological and Mineral Resources Map of Kebbi State* NGSA (2011a) and the *Geological Map of Nigeria* (NGSA 2011c)—provided by the Nigerian Geological Survey Agency show several shortcomings such as a faulty GIS topology, strongly simplified feature outlines, technical mistakes, and thematic inconsistencies. Thematic inconsistencies are mismatches in the map legend and the mix-up of legend codes, stratigraphically inconsistent assignment of units, and errors in the legend descriptions. Particular, the nation-wide *Geological Map of Nigeria* (NGSA 2011c) required manual adjustment.

Least reliable are the datasets in the area between the Niger, Sokoto, and Zamfara Rivers. Here in particular, further geological fieldwork is required to establish a consistent and reliable picture of the geological environment. The most relevant issue concerns the delimitation of the Continental Hamadien and its limits with the Continental Terminal and the Wurno Formation in the triangle between Jega, Dakingari, and Koko. Particularly the outcrops of the interposed Palaeocene Kalambaina Formation and the bauxitic clay layer of the Continental Hamadien are contradictory.

Despite these limitations, the official data of the Nigerian Geological Survey Agency enriched the transboundary geological map through the differentiation of the Gundumi and Taloka Formations in the northeastern part of the Sokoto basin

7.2.3 Complexe de base du Continental Terminal vs Continental Hamadien

The region south of the Niger River, has persistently been the transition zone between erosion processes on the basement and deposition processes in the Iullemmeden/Sokoto/Kandi Basins and marked the southern limit for both continental and marine deposition. Terrestrial deposits of the Continental Hamadien and the Continental Terminal are reported as shallow and nowadays widely eroded cover layers. Outcrops of the intermediary marine sediments—reflecting the late Cretaceous marine transgressions—have not been reported east of the Sokoto River. The lack of reliable continuous sections recording both the Continental Hamadien and its transition (or the hiatus) to the Continental Terminal facilitated contradictory assignments of the same strata to different geological formations. The *Continental Terminal-complexe de base* is described as a conglomeratic facies of the Continental Terminal but strongly resembles the descriptions of the Continental Hamadien (Sendé/Illo/Gundumi Formation): “A ces poudingues s’ajoutent des grès siliceux à grains de toutes tailles, classés ou non, des arkoses, des argiles kaoliniques bariolées.” (Greigert 1961b). Even Greigert himself hints the possibility of two different series.

Locally, areas mapped as *Continental Terminal-complexe de base* have later been revised and classed as the conglomeratic Wéré B member (Konaté 1996). For example the low-lying region near Tenda upstream of Gaya described as “des poudingues à stratification entrecroisée, à blocs de quartzites ou des quartz laiteux, peu uses pouvant atteindre 10 cm longueur ... parfois franchement anguleux … dans un ciment qui est un grès siliceux” (Greigert & Pougnet 1967).

Given a) their similar lithology, b) the lack of intermediate marine sequences, and c) the lack of strong stratigraphic markers, differentiation between the *Continental Hamadien* and the *Continental Terminal-complexe de base* is not straight forward. Perhaps the *Complexe de base* is not a substrata of the Continental Terminal but a margin facies of the Cretaceous

Continental Hamadien. Thorough lithostratigraphic fieldwork is necessary to describe, differentiate, and map the two continental sediments—taking also into account reports of a basal conglomerate near Niamey (Machens 1967).

7.2.4 Illo Formation-Nupe Sandstone transition

The transition between the Illo Formation of the Iullemmeden/Sokoto Basin and the Nupe Sandstone (Bida Sandstone) of the Bida Basin is handled differently between cartographers. Both are terrestrial sediments of the Cretaceous. Dessauvagie (1974) uses a single signature class for the entire Cretaceous using different labels but without spatially delimiting each formation. The *Geological Map of Nigeria* (NGSA 2011c) shows a transition between Nupe Sandstone and Illo Formation near the Niger–Sokoto confluence, and the *Geological and Mineral Resources Map of Kebbi State, Nigeria* (NGSA 2011a) classes the entire Early Cretaceous as Illo Formation. The elaborated transboundary geological map shows the Illo Formation on both the right and left bank of the Niger River. The transition to the Nupe Sandstone is assumed at about 11°N in the bedrock narrow between Tunga Golchana and Shafasiri—given the lack of sound evidence, the Kebbi State boundary has been chosen as a convenient limit—an arbitrary decision that awaits further revision by field studies.

7.2.5 Basement complex

Aggregation of basement units followed the lithological descriptions of the map legends. Differentiation into (chrono-) stratigraphic units was only feasible for Benin. For Nigeria such information was not available. Please refer to the corresponding literature for further and detailed information on basement geology.

8 References

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9 Digital data sets

Digital data sets used for the elaboration and layout of the geological map:

Administration: GADM28 (2018), https://www.gadm.org (modified)

DEM: NASA JPL (2013). NASA Shuttle Radar Topography Mission Global 30 arc second. NASA EOSDIS Land Processes DAAC. doi: 10.5067/MEaSUREs/SRTM/SRTMGL30.002

Localities: OpenStreetMap (2018), www.openstreetmap.org (modified)

Stream network: internal data from Niger Basin Authority (NBA), 2016, modified

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I Geology of the southern Iullemmeden Basin

The following chapters provide a short overview of the geological history of the study area and describe the most important geological units.

I.I Mesozoic and Palaeozoic Kandi Basin

The Kandi Fault is an old Pan-African overthrust suture between the West African craton and the Congo Craton—called Amguid in the Hoggar and prolonging into Brazil as the Sobral fault. At the end of the Late Ordovician (Hirnantian) glaciation, isostatic uplift, and extensional stress might have triggered the reactivation of the Kandi fault in a normal motion resulting in an extensive half-graben (Fig. 23 & Fig. 25). Oriented N20°E, the Kandi Fault is a marked geological feature that sharply limits the Kandi Basin—a half graben with several fault block mountains namely the Lété, Imina, Ouana, and Poria horsts, separating three minor graben structures in the area of Kalalé (Kalalé, Péonga, Monrou), Segbana (Segbana, Lété, Libanté) and Gébessaka. The Kandi Basin extends about 160 km north-south and 50 -100km east-west and covers and area of about 9000 km². The sedimentary filling is estimated to have a maximum of about 600 m thickness.

The geological study of the Kandi Basin commences with the visit of Hubert between 1904-1906 (Hubert 1908). In 1957, Pougnet describes the *Grès de Kandi* as the dominant sediments within the Kandi Basin based on reports from the areas around Kandi and Zougou. Along the route federal, he further differentiates conglomerates around Wéré (Ouéré) as well as fine to coarse sandstones. Following Jones (1948) and Tattam (1943), he assumes an early or perhaps late Cretaceous age for the sediments of the Kandi Basin. Bouzid conducted first geophysical investigations to assess suitability of groundwater abstractions (Bouzid 1971) and estimated the maximum sediment depth to about 500 m. In the 1980s and 1990s two mapping projects by the Italian Istituto Ricerche Breda (Akibou et al. 1989c; Istituto ricerche Breda & OBEMINS 1989) and the Russian Technoexport (Technoexport 1995b, 1995a) provided first large-scale 1:200 000 maps of the Kandi Basin. Comprehensive geological field work by Alidou (1987) and Konaté (1996) set the basis for the present litho- and chronostratigraphy of the Kandi Basin. The here presented summary follows the subdivision proposed by Konaté (1996) and later refined by Konaté et al. (2003a, 2006)

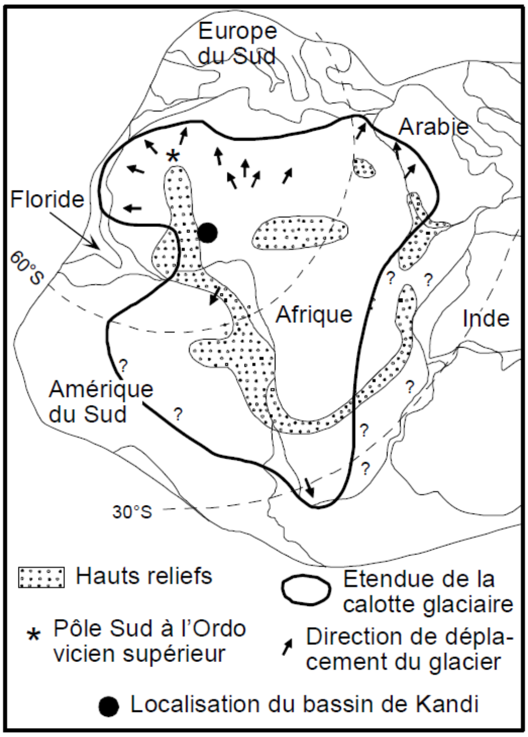


Fig. 23: Maximal extent of the late Ordovician ice sheet (Konaté et al. 2006)

I.I.I The Wéré (Ouéré) Formation

The continental Wéré Formation (up to 500 m) comprises a succession of reworked peri-glacial deposits. The **Wa member** comprises reworked tills, glacial outwash deposits and alluvial fans; the **Wb member** fluvio-glacial sediments of braided river systems. Deposition took place at the end of the Late Ordovician (Hirnantian) glaciation (440-460 Ma) that was centered on Westafrica and is suspected to be responsible for the second-largest extinction event in Earth's history. Syntectonic sedimentation suggests an isostatic uplift that led to an extensional reactivation of the Kandi Fault concurrent with the deglaciation and a progressive deepening and infilling of the basin from west to east evidenced by strongly tilted sediments near the Kandi Fault as well as tilted unconformities in and between lithostratigraphic members (Fig. 25 & Fig. 24). The syntectonic deposition in first a glacial environment (Wa) and later a fluvio-glacial braided river system (Wb) followed by storm to tidal (Ka) and offshore sediments (Kb) reflects a single tectonic accident and the respective depositional response. A major unconformity suggested by gullying indicates a prolonged hiatus and erosion prior to the marine transgression in the early Silurian.

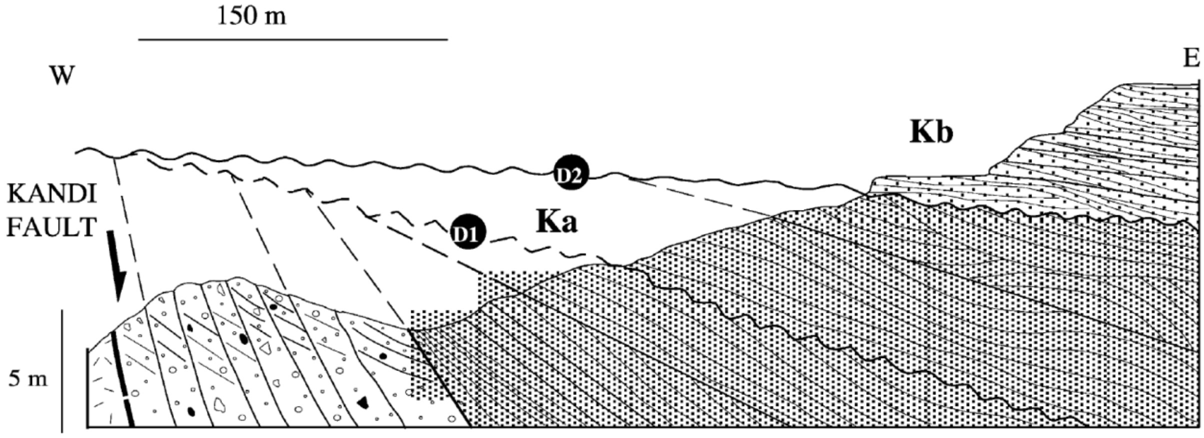


Fig. 24: Syntectonic deposition of the Wéré Formation shown by tectonic-conditioned alluvial fans and large-scale progressive unconformities and generally post-tectonic deposition of the Kandi Formation in the area of Tui (from Konaté et al. 2003a)

Wéré A (Wa member)

The Wa member (up to 150 m) is described as either a diamictite/breccia or a medium to coarse-grained sandstone showing tabular to trough cross-bedding with angular quartzitic boulders and faceted pebbels (Fig. 26) The poorly sorted polymictic breccia with erratic decimeter-sized boulders scattered within a fine-grained massive sediment resembles dropstones typical for glacial drifts. In 2003, Konate refined his early interpretation of the clastic Wéré Formation and interpreted these matrix-supported breccia/conglomerates as glacial till with dropstones occurring side by side with glacio-fluvial sediments, sandurs, boulder clays, and channel deposits. The deposits show large-scale channel structures and erosional truncation. The Wa member crops out in a narrow (<5 km) strip along the Kandi fault and is interpreted as glacial drift deposits that filled a fault-bounded palaeovalley incised along the Kandi Fault structure—perhaps excavated by the Ordovician ice sheet and filled by glacial tills and outwash deposits. Towards the east, the Wa facies grades laterally into the Wb facies. The Wa member is a basin-margin facies restricted to the south-west and grades vertically (Goungoun) and laterally (basin centre) into the Wb member.

Outside of the conservative Kandi Basin studied by Alidou (1987) and Konaté (1996), Technoexport (1995b) mapped three smaller graben structures filled by deposits of the Wéré Formation ($PZ_{1\text{-}2}W$): the Gébessaka trench—east of the Horst de Lété/Gbessé, the Segbana basin and further south the Kalalé-Péonga-Monrou basin. Due to its one-to-one spatial accordance with the Wéré A member along the Kandi Fault, and its description as "gritty sandstones, micropudingstones and conglomerates", the unit $PZ_{1\text{-}2}W$ was deemed the equivalent to the Wéré A member of Konaté et al. (2003a).

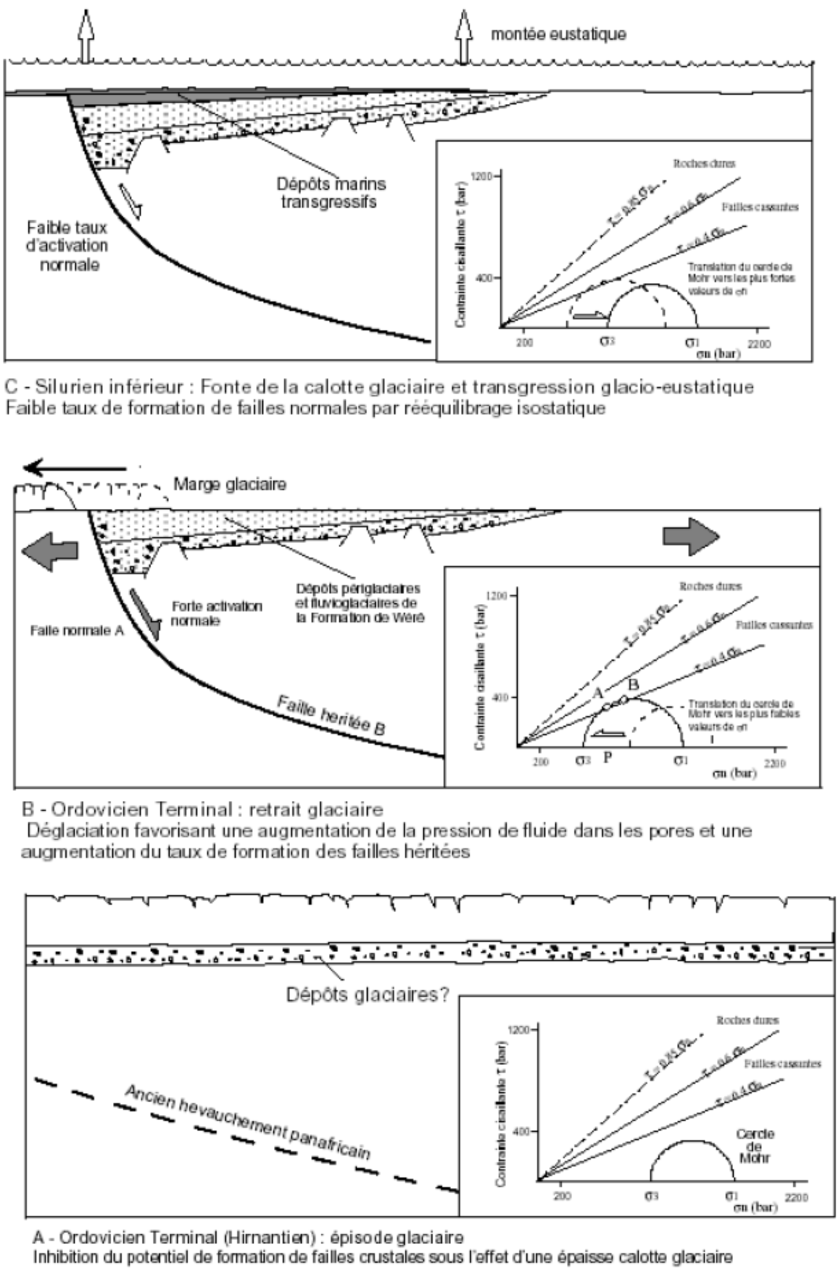


Fig. 25: Post-glacial reactivation of the normal Kandi Fault as a half-graben following the retreat of the Hirnantian ice cap (Konaté et al. 2006)

Wéré B (Wb member)

Wéré B member (up to 350 m) occurs as a granule-rich coarse sandstone or a matrix-supported, poorly sorted breccia. The sandstone is nearly structureless but may display tabular and trough crossbedding often in fining-upwards sequences. The Wéré B member is interpreted as a braided-stream environment marked by an irregular flow regime.

I.I.II Kandi Formation

Melting of the Hirnantian ice cap and eustatic see level rise at the end of the Late Ordovician glaciation triggered a marine transgression and the flooding of the Kandi Basin from the north. The transgression is recorded by 75 m of sediments of the marine Kandi Formation. Fine sandstones and siltstones with sigmoidal bedding indicate a tidal and shoreface barrier environment for the Ka member and hummocky cross-stratified siltstone and fine sandstones suggest storm deposits and a near offshore environment for the Kb member. The Kandi Formation rests with a major unconformity characterized by rounded granules over the periglacial sandstone deposits of the Wb member. In contrast, to the Wéré Formation evidence for synsedimentary tectonics decrease, particularly within the Kb member.

Kandi A (Ka member)

The lower deposits of the Ka member (around 40 m) are fine-grained siltstones showing rhythmic laminations and bioturbation features which grade into white, fine- to medium-grained sandstones with an erosional hummocky cross-stratification. Characteristic are the occurrence of kaolinitic clay beds and on the top of the banks soft angular to smooth clay pebbles. Typical sediment structures are tidal bundle structures, erosional hummocky cross-stratification, and herringbone cross-bedding indicative for a shore face environment under tidal influence. The Ka member is observed in the northern and southeastern sectors of the basin.

Kandi B (Kb member)

The Kb member (30 m) comprises the finer upper sediments reflecting an offshore environment. Siltstones of variable color (from white, yellow to violet) are intercalated with undulating beds (up to 1 m) of micaceous fine sandstone. Ichnofossils of *Cruziana*, *Arthrophycus* (*Harlania*) as well as *Curvolithos* and *Scolicia* are present. The typical sedimentary structures are lens-shaped erosional troughs and hummocky cross-stratification indicative of storm deposits. Together with the fine-grained texture, the sediments are interpreted to reflect an upper offshore environment.

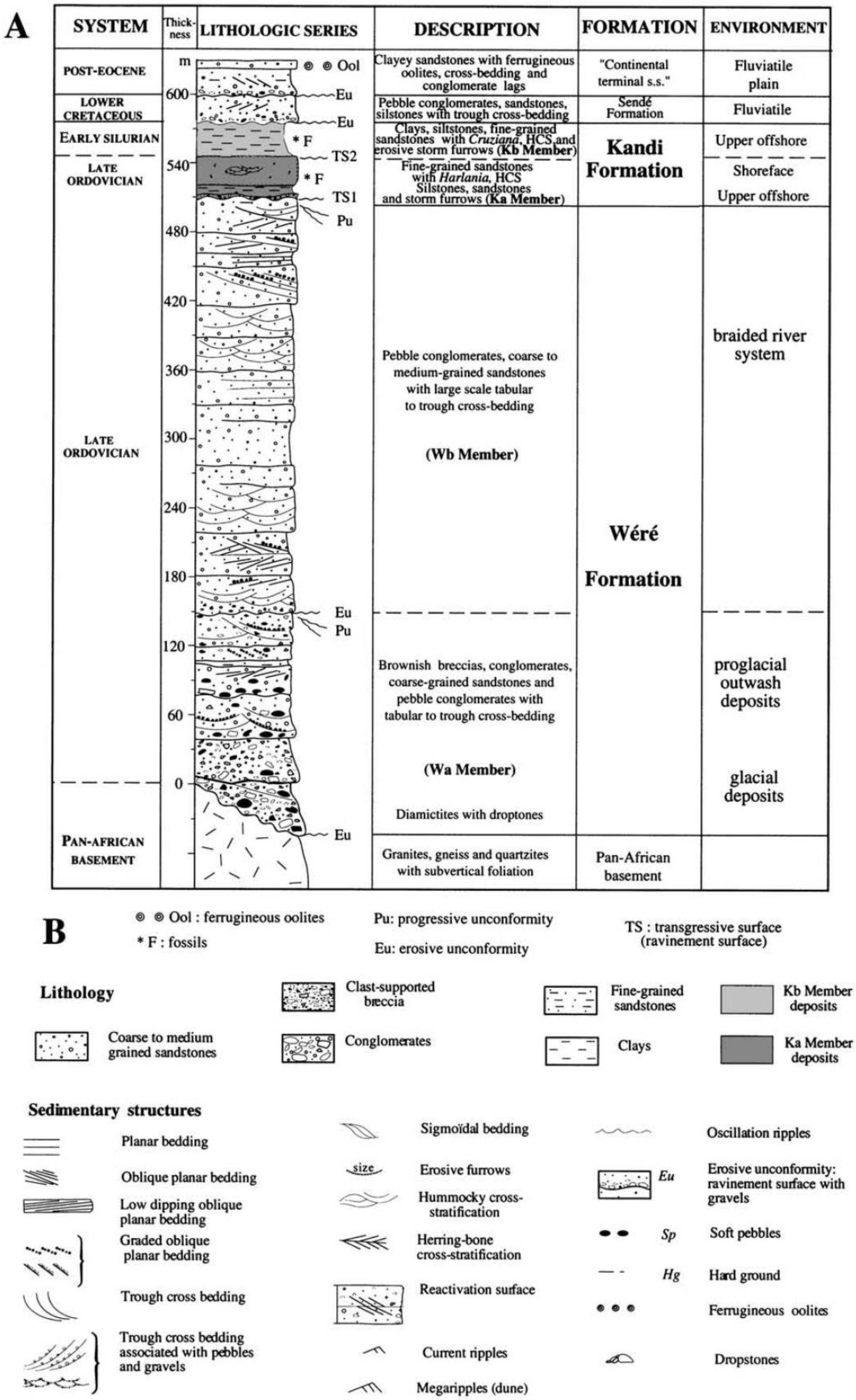


Fig. 26: Lithostratigraphy of the Palaeozoic sedimentary series of the Kandi Basin (from Konaté et al. 2003a)

I.I.III Chronostratigraphy revised

Dating—absolute or relative—is fundamental for the placement of geological units within a chronostratigraphic framework. Early on Jones (1948) and Tattam (1943) assume an early or perhaps late Cretaceous age for the sediments of the Kandi Basin. Alidou (1987) refined the lithostratigraphy of the Kandi Basin and used trace fossils to establish the present chronostratigraphy of the Palaeozoic-Mesozoic Kandi Basin (Alidou et al. 1986).

Trace fossils or ichnofossils are the imprints of past biological activity recorded in the geological archive such as burrows, footprints, and root cavities. Trace fossils (ichnofossils) of *Cruziana* (trilobites) and worm burrows *Arthrophycus* (*Harlania*) as well as unspecific vertical burrows of the *Skolithos* type are reported from both Kandi members (Fig. 28 & Fig. 27). Small evolutionary variations allowed Seilacher and Alidou (1988) not only to date the Kandi Formation but inclusive to differentiate between *Cruziana petraea* and linear and protrusive worm burrows of the Upper Ordovician Kandi A member and *Cruciana acacensis* and deep palmate and retrusive worm burrows of the Lower Silurian Kandi B member. This placed the bulk of the sediments within the Kandi Basin into the Palaezoic.

I.II Continental Intercalaire/Continental Hamadien

The descriptive term “Continental Intercalaire” as defined by Kilian (1931) comprises the continental sediments deposited between the Carboniferous marine transgression (Variscan orogenese, Devon-Trias) and the Upper Cretaceous marine transgression (Late Cenomanian-Maastrichtian). The Cretaceous marine transgressions repeatedly established a Transsaharan seaway from the northern Tethys to the Gulf of Guinea (Kogbe 1981, 1991) but did not reach the south and northwest areas of the Iullemmeden Basin. Important terrestrial sediments of the Continental Intercalaire comprise the *Grès du Tegama* in northern Niger, the *Koutous Formation* in Chad, and the *Bima/Nupe sandstone* of north-eastern/central Nigeria. Continental sediments deposited concurrent with the Late Cretaceous marine transgressions at the basin margins are known as “Continental Hamadien” (Guero 2003).

In the study area, terrestrial deposits along the basement margins are known as Sendé Formation in Benin, Continental Hamadien in Niger and correspond in Nigeria to the Illo Formation in the southern and the Gundumi Formation in the northern Sokoto Basin. Being generally unfossiliferous, the age of these sediments has been inferred from their stratigraphic position. Overlain by Upper Cenomanian marine sediments (pre-Maastrichtian, pre-Turonien, etc – depending on the author and study area), a Late Jurassic-Early Cretaceous age is assumed. Fragments of silicified wood were found within outcrops of the Sendé Formation in the north-eastern part of the Kandi basin (Alidou et al. 1979; Alidou & Lang 1983) and were identified as a gymnosperm with Araucaria-type structures, probably *Dadoxylon*. Similar silicified wood assigned to *Dadoxylon* has been reported from the Nigerian Illo-Gundumi Formations (Kogbe & Lemoigne 1976 discussed in Kogbe, 1981; and Alidou et al. 1986) and most occurrences of the Continental Intercalaire such as the *Grès de Tegama* in Niger (Faure 1966).

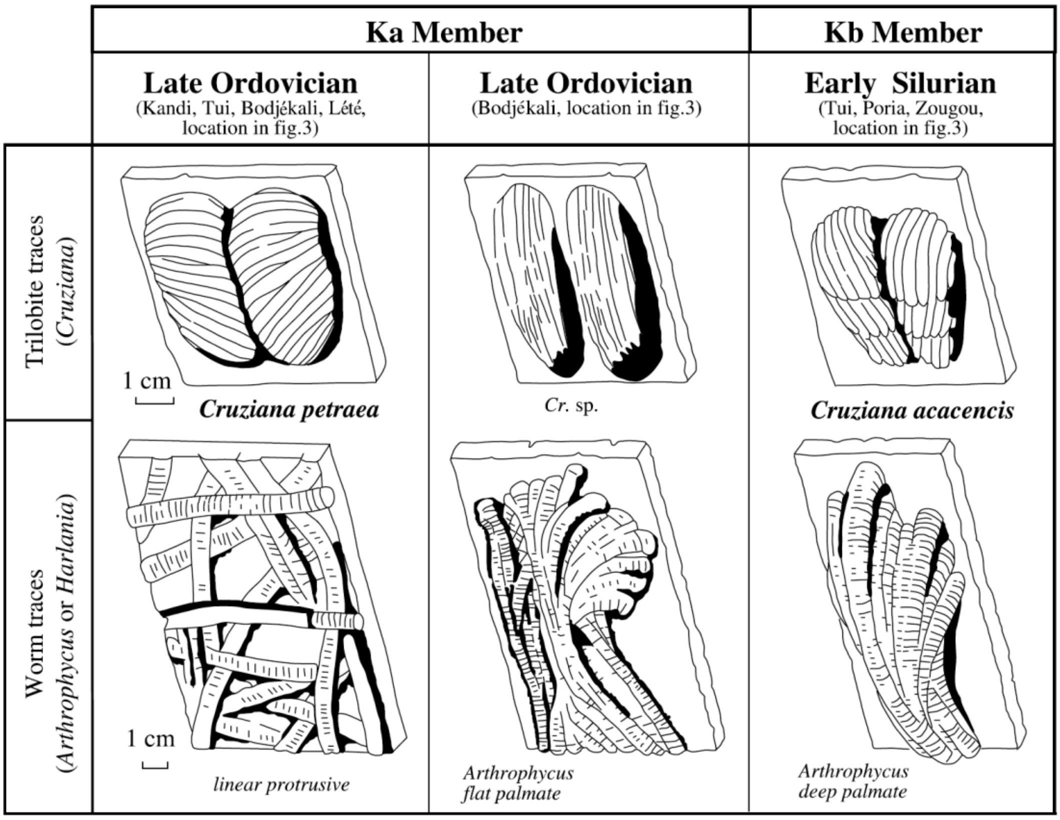


Fig. 27: Trace fossils of the Kandi Formation and its chronostratigraphic classification (Seilacher A & Alidou S 1988 modified by Konaté et al., 2003)

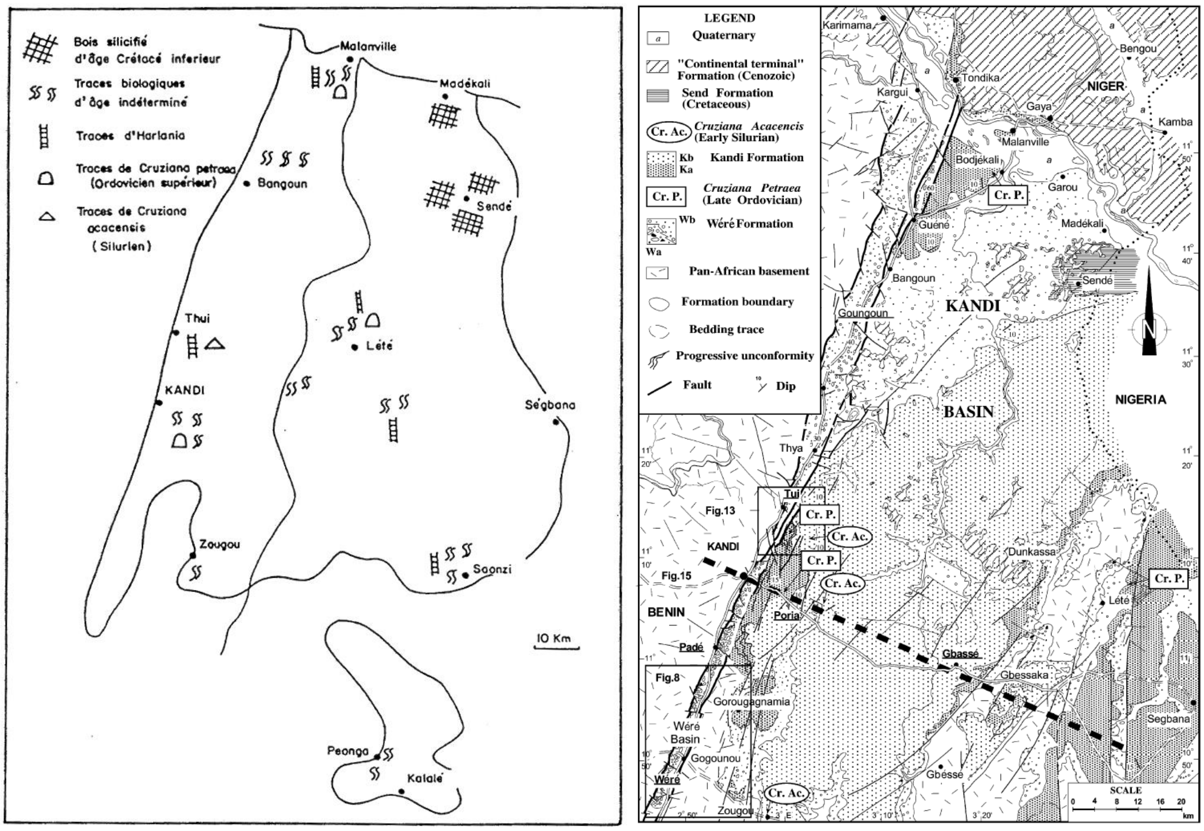


Fig. 28: Fossil sites mapped by Alidou (1987) (left) and Konaté et al. (2003a) (right)

Given the lack of robust absolute dating, the exact chronostratigraphy of the Sendé/Illo-Gundumi Formation is subject to further research and the allocation to either the "Continental Intercalaire" or the "Continental Hamadien" differs between authors. The facts that the Sendé/Illo-Gundumi Formation underlies the Late Cretaceous to Palaeocene marine sediments and the occurrence of *Dadoxylon* suggest concomitant deposition with the Tegama Sandstone and justifies the classification as "Continental Intercalaire" (Kogbe & Lemoigne 1976; Alidou et al. 1986; Kogbe & Burollet 1990). The term Continental Hamadien, however, has been used frequently by scholars working on the Nigerien parts of the Iullemmeden basin to refer to Sendé/Illo-Gundumi Formations (Greigert & Pougnet 1967; FAO 1970 and others; see discussion by Guero 2003). The report at hand follows this habitual use and employs the term "Continental Hamadien" without the implication of any absolute age attribution.

Lithologically, the Continenental Intercalaire/Hamadien comprises poorly fossiliferous, continental deposits laid down in a fluvial to fluvio-lacustrine environment with braided rivers. It rests in the east and south-east unconformable over the Pre-Cambrian basement of Nigeria (Gundumi and Illo Formations) where the variation in thickness may correspond to the infilling of ancient river channels in the bedrock. In the Kandi Basin (Sendé Formation)—and further to the centre of the Iullemmeden basin—the Continental Intercalaire tops Paleozoic sediments. Originally described separately, both Jones (1948) and Kogbe (1981) combine the Illo and Gundumi Formation – and by inference the Beninese Sendé Formation – based on:

- occurrence of basal conglomerate with well-rounded pebbles, cross-bedding,
- clay mineral assemblage of predominantly kaolinite and illite,
- a similar heavy mineral assemblage,
- bands of feruginized sandstone,
- absence of oolithic ironstone.

Finer sandstones and more sub-rounded pebbles suggest that the Illo Formation was deposited further from the potential source rocks--which Kogbe (1981) locates in the Nigerian basement complex—than the Gundumi Formation. The presence of pisolitic and nodulare clays is a further particularity of the Illo Formation

On Jones (1948) map *Geological Map of Sokoto Province*, both formations wedge out in an area delimited by the Zamfara River (Gummi) to the north and Libba in the south. Jones explains the lack of mapped outcrops by the drift-covered country, a view adopted by Anderson & Ogilbee (1973) who indicate with broken lines a direct connection between the deposits of the Gundumi and Illo Group. From a tectonic viewpoint, Buser (1966) suggests, that the Bussa basement ridge as a NNE-SSW striking high zone between Jega and Dakingari was responsible for either an original lacunae or the posterior removal of sediments.

I.II.I Gundumi Formation

Outcrops of the Gundumi Formation are mapped in a triangular area in NW Nigeria. The Gundumi Formation dips with about 4 m per kilometre and reaches a thickness between 250-300 m at the Niger-Nigerian border (Anderson & Ogilbee 1973), about 250 at the type section of Dutsin Dambo (Kogbe 1981), and wedges out on the Nigerian basement.

The Gundumi Formation comprises continental, fluvio-lacustrine deposits of a heterogeneous nature that shows a high lateral variation of facies and variegated colours. It is described by Brynmor Jones as cross-bedded “clayey grits and clays with basal conglomerate” (Jones 1948) resting unconformable over the basement or as a “sequence of interbedded sandstones, arkoses and shales with strong lateral variations” (Buser 1966). At the base of the formation, “a conglomerate of rounded quartz pebbles up to 1½ inches in diameter” occurs intercalated with sand and gravel beds “composed chiefly of angular and subangular quartz grains … as well as rock fragments” (Anderson & Ogilbee 1973). At the type section at Dustin Dambo (near Bukara) this unit attains 42 m thickness. It is followed by finer units of 52 m of a compact silty clay, 36 m of poorly consolidated clayey sandstone, 34 m of clay and 100 m of a semi-consolidated, medium to coarse-grained ferruginized sandstone capped by 23 m of highly indurated (ironstone), cross-bedded, ferruginized sandstone (Kogbe 1981). The Gundumi Formation does not necessarily show a distinct boundary to the overlying Taloka Formation but can be distinguished from the younger strata by its much coarser material and thin beds.

I.II.II Illo Formation

The Illo Formation formed in a continental, fluvio-lacustrine depositional environment and represents the southwestern prolongation of the Gundumi Formation. The Illo group, named after the Illo village south of the Niger River, rarely exceeds 40 meters thickness (Kogbe 1981) and shows three typical members (Jones 1948):

- iii Upper sandstone member (“Upper Grits”), thickness of 7-100 m
- ii Middle pisolitic member (“Pisolitic and Nodular Clays”), thickness of 3-10 m
- i Lower sandstone member (“Lower Grits”), thickness 10-130 m

The Lower Grits are a white, friable, cross-bedded clayey medium to coarse-grained sandstone (“grit”) “studded with quartz pebbles”. The typical pebbles are small (~0.5 cm), subangular and quarzitic. Intercalated within the sandstones are variegated clays and clayey grits (white, red, yellow, purple) as well as fine-grained sandstones (Jones 1948). Often loose, friable and poorly cemented, towards the basement at Libba quarry, the (sub-) rounded quartz pebbles (up to 6 cm) are indurated and cemented by a calc-silicic agent (Kogbe 1981). Thin bands of consolidated, ferruginized sandstone (ironstone) may occur throughout (Kogbe 1981). Similar to the Gundumi Group is the occurrence of “mottled clay-grits”.

The “Upper Grits” are coarse, friable, varicolored, cross-bedded grits and sandstones with subordinate clay layers.

The middle member of the Illo group is a stratigraphic marker horizon described as “**Pisolitic and Nodular Clays**” (Jones 1948). Outcrops show massive white clays with a chalky or finely granular structure. The clay is non-plastic and occurs mainly as concentric pisolites (~ 5mm) or nodules ranging from oval to irregular (1 – 15 cm). Jones suggests, that the highly aluminous clay is a low-grade bauxite. Kogbe (1981) observes that the pisolithic clay generally overlies the nodular clay and exhibits a lateritic ironstone capping. Mapped only for Nigeria, Jones (1948) mentions similar observations by Hubert (1908) at Gaya.

I.II.III Nupe Sandstones

The Nupe or Bida Sandstone is the lateral equivalent of the Continental Hamadien in the Bida Basin of Nigeria. Within the study area only the northern most occurrences of a marginal and residual facies of the Nupe sandstones of the Bida Basin with a thickness of <30 m can be found. Typical is a residual concretionary ironstone.

I.II.IV Sendé Formation (Benin)

The Sendé Formation is the Beninese term for the prolongation of the Nigerian Illo Formation that stretches into northwestern Benin. Between Madékali and Sendé and occurs as a shallow (20 m) cover layer outcropping along the escarpments of extensive tableland—often capped by even more shallow remnants of the Continental Terminal. Elsewhere it crops out on the footslopes of the numerous mesa-like buttes where the weathering resistant Continental Terminal preserved the poorly consolidated deposits of its predecessor the Contental Hamadien (Fig. 29). Evidences for a Plaeocene-Eocene shoreline and corresponding marine sediments as suggested by Kogbe (1981) are not reported from Benin.

Alidou describes the lithology of the Sendé Formation as a poorly consolidated conglomeratic sandstone more or less whitish and with an argillo-ferruginous matrix (Alidou 1987). At the base, a locally silicified and consolidated conglomerates of rounded quarzitic pebbles (“conglomérats à galets quartzeux roulés de 5 cm de longueur moyenne”) hosts the diagnostic silicified wood fragments of *Dadoxylon*. Above, rests a weakly consolidated argillous sandstone. Interbedded are kaolinitic clay layers with a pisolithique texture, possibly an rudimentary equivalent to the “Pisolitic and Nodular Clays” of Jones (1948).

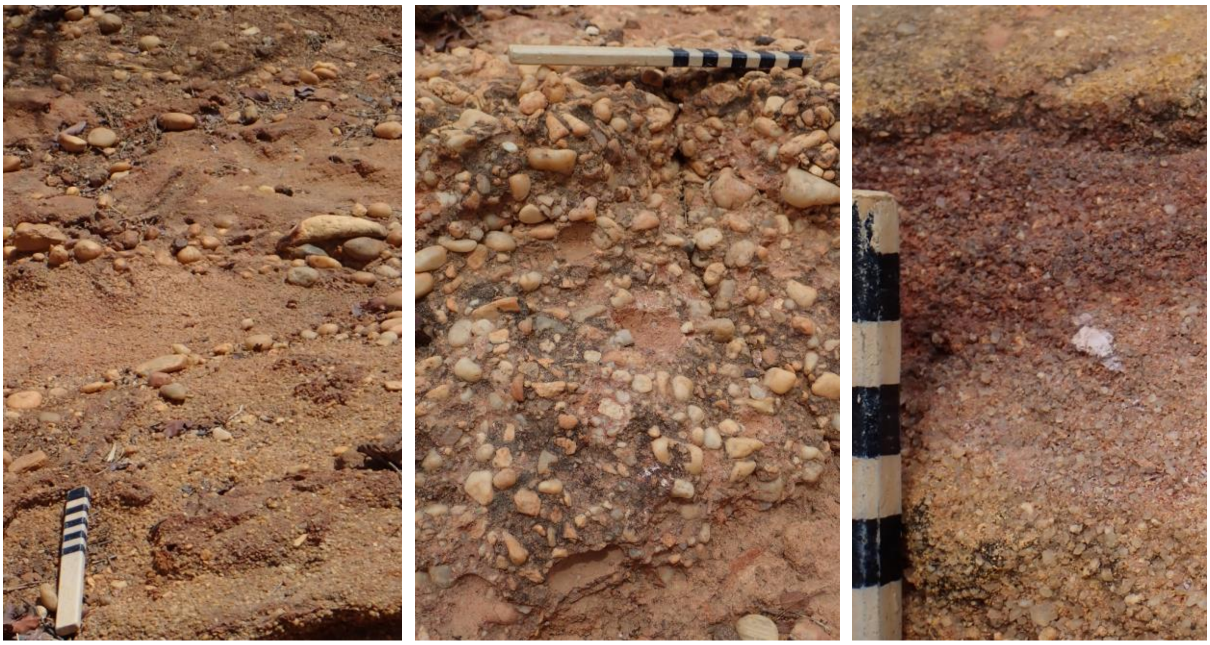


Fig. 29: Facies of the Sendé Formation. Rounded clast-supported quartz pebbles (2-4 cm] forming thin cross-bedded strata within a fine to coarse-grained sandstone characteristic for the continental depositional environment of the Sendé Formation. Right: near Karimama; middle: near the village Sendé Peul. Left: coarse-grained quarzitic sandstone at Sendé Peul. Photographs by the author.

I.III Upper Cretaceous-Palaeocene marine transgression

I.III.I Rima Group

The Rima Group was deposited unconfomably on the Lower Cretaceous terrestrial sediments of the Continental Intercalaire. It corresponds to the third and forth marine transgression in the Iullemmeden Bassin and the establishment of the Transsaharan seaway. The sediments have not been absolutely dated. Marked by the widespread occurrence of *Libycoceras* a Senonian (Coniacian, Santonian, Campanian, Maastrichtian) and particularly Maastrichtian age is assumed by most authors. Jones (1948) subdivided the Rima Group into *Lower Sandstones and Mudstones*, *Mosasaurus Shales*, and *Upper Sandstones and Mudstones* corresponding to the Wurno, Dukamaje, and Taloka Formations proposed by Parker and collegues for the *Geological Map Series of Nigeria* (D.O.S. 1965a). The Rima Group is characterized by fine-grained, friable sandstones and siltstones of the Taloka (*Lower Sandstones*) and the Wurno (*Upper Sandstones*) Formations separated by the organic and fossil rich *Mososaurus shales*—the Dukamaje Formation that report the first transgression with the occurrence of *Libycoceras spp.*

The marine strata are tilted. They crop out in Nigeria and dip towards the centre of the basin with a total thickness of about 300 m at Balle (Anderson & Ogilbee 1973). In Niger, the marine sequences phase out around Bana in the Dallol Maouri and Kawara Débé in the Dallol Foga (FAO 1970).

Taloka Formation

The Taloka Formation—the *Lower Sandstones* of Jones (1948) —is a white fine-grained, friable sandstone with siltstones and intercalated carbonaceous mudstones or shales (Kogbe 1991).. The Formation crops out over large areas east of Sokoto. A subdivision is proposed by the Nigerian Geological Survey Agency (NGSA 2011c) differentiating basal clays and sand (Tcs), the main sandstones unit (Tss) and upper siltstone (Tst) and shale (Tsh) units. Coarse, gravelly sand from boreholes in Sokoto and Dogwandaji indicate a transition to the underlying Gundumi Formation (Anderson & Ogilbee 1973). In the northern Sokoto Basin, the Taloka Formation reaches maximum thicknesses of about 120 m.

Dukamaje Formation

Known as *Mososaurus Shales* (Jones 1948), the Dukamaje Formation is a shallow (6-12 m) layer that is only documented north of Rabah. The Formation consists of dark grey organic-rich and carbonaceous shales, banked limestone, mudstones (Kogbe 1991). The base shows a bone bed (*Mosasaurus* spp.) interpreted as the former shoreline. Shrimp burrows (*Callianassa spp.)* are common. The Dukamaje Formation reports the first transgression characterized by the Maastrichtian ammonite *Libycoceras spp.*

Wurno Formation

The Wurno Formation or *Upper Sandstones* consist of pale and friable, fine-grained, banked sandstones and siltstones intercalated with sandy mudstones (Kogbe 1991). Characterisitc are ferruginous levels with ooliths, carbonaceous material, gypsum, and finely disseminated iron sulphides (pyrite). The ammonite *Libyococeras spp* is present. The thickness of the lossley consolidated Wurno Formation varies between 50 m at Balle, 20 m at Wurno. It thins south of the Sokoto River, where the Dukamaje Formation is absent and the Taloka and Wurno Formation cannot be distinguished.

I.III.II Sokoto Group (Palaeocene-Eocene)

The Sokoto Group comprises both the Clay-shale group and the Calcareous Group of Jones (1948) and corresponds to the *Série marine: Zone à Operculionoïdes et à Lockhartia haimei* sensu Greigert & Pougnet (1967). Deposited during the Paleocene and the early Eocene, the Sokoto Group represents the fifth and last marine transgression and shows three phases: It consists of a limestone facies (Kalambaina Formation, 35 m) framed by two series of grey laminated carbonaceous shale ("schistes papyracées" in the French literature: Dange, respective Gamba Formation, ~10m).

Dange Formation

The outcrop of the Dange Formation can be traced in the landscape along the so-called "Dange scarp". The bluish-grey shale with interbedded thin layers of limestone shows bands of fibrous gypsum and phosphatic nodules, as well as abundant vertebrate fossil remains (Kogbe 1991). The Dange Formation rests unconformably over the Rima Group; erosion at the Cretaceous-Tertiary boundary being indicated by a conglomeratic lag deposit.

Kalambaina Formation

The Kalambaina Formation is a white, clayey limestone with the occurrence of shales and calcareous marls and phosphates and is rich in invertebrate fossils, foraminiferas, and ostracods. The limestone of the Kalambaina Formations shows evidence of karstification and solution and—following Kogbe (1991)—fracture zones. Its original thickness is estimated to about 20 m. 5 m are observed at Dange, 18 m at Birnin Kebbi, 50 m at Balle, and 4 m at Argungu. In Niger, Greigert & Pougnet (1967) differentiate a lower *Zone à Operculinoïdes* and an upper *Zone á Lockartia-haimi* corresponding laterally to the Kalambaina and Gamba Formations, respectively (Moody 1997)

Gamba Formation

The Gamba Formation is a grey laminated, fossiliferous, phosphatic shale characterized by a marker bed of phosphatic pellets and small coproliths. In the French literature it is described as "schistes carton jaunes". Due to the solution of the underlying calcareous Kalambaina Formation, it often seems to be "folded". With a thickness of about 10 m it corresponds well with the confining "gray clay layer" at the base of the Gwandu Formation/Continental Terminal discussed by Anderson & Ogilbee (1973). At the same stratigraphic position as the Gamba Formation, this "gray clay layer" was recorded in the boreholes Sabla and Janzomo whereas a lignite and peat horizon was described at the boreholes Tangaza and Ruawuri—both directly overlying the Kalambaina Formation.

I.IV Continental Terminal

The "Continental Terminal" was proposed by Kilian (1931) as the third and last detritic, continental series that followed the third phase of marine transgressions ("Série hamadienne", Late Cretaceous to Paleogene) in the Central Sahara. The term has been used inflationary to describe any altered sediments and even altered marine sediments showing ferralitic weathering and the occurrence of kaolinite and ferruginous concretions with the Saharan and coastal basins of West Africa. In the Iullemmeden Basin, the Continental Terminal *sensu stricto* comprises continental sediments of Eocene to Miocene age that have undergone advanced chemical alteration prior to —and possibly after—deposition (Lang et al. 1990) often termed "Sidérolithique" (Lang et al. 1986).

The final uplift of the Hoggar mountain (Late Eocene to Early Quaternary) led to the latest continental deposition period of the "Continental Terminal" that covers the centre of the Iullemmeden syncline centred between the 3°E and 4°E meridians. With a total thickness of 450 m between Koléfou, Kiessé and Dogondoutchi (Greigert 1978), the Continental Terminal makes up half of the estimated 1000 m thickness of Mesozoic sediments in the Iullemmeden Basin (Kogbe 1991).

Lithologically, the Continental Terminal is characterised by alternating successions of ferruginous sandstones, silts, and often variegated clays. A characteristic marker that may occur throughout the Continental Terminal an differentiates it from previous terrestrial sediments is the occurrence of ferruginous layers made up of loose to densely-packed oolithic to pisolithic ironstone. Oolithic ironstone forms in shallow (saline?), lacustrine or nearshore environments (Kogbe 1981; Young 1989; Mücke 2000). Often associated with oolithic ironstone is the widespread occurrence of (lateritic) ferricretes within the ferruginous sandstones. Within the series, the lack of distinct chronostratigraphic markers hampers the unambiguous assignment of outcrops or borehole logs to one of the three units.

Based on an offset of about 100 m between the boreholes Koutumbou (IRH n°10007) and Sabon Gari (IRH n°10004), FAO (1970) infers a hypothetical strike-slip fault between the Dallol Foga and the Dallo Maouri striking in the main direction of the Iullemmeden syncline and the Kandi fault (FAO 1970, p20 & planche 2,coupe IV). However, being described as quite a monotone depositional environment; large tectonic displacements are not anticipated. Only for the oldest Continental Terminal 1 slight ductile tectonic deformation is reported (Konaté, pers. communication). The lack of further (surface and borehole) indications renders such strong and Miocene tectonic unlikely and suggests revision of the respective borehole interpretations.

Traditionally, and from a hydrogeological viewpoint, the Continental Terminal is divided into three main lithological units:

- Continental Terminal 1 – CT1: *Série Sidérolithique de l'Adar Doutchi*
- Continental Terminal 2 – CT2: *Série argilo-sableuse à lignites*
- Continental Terminal 3 – CT3: *Les Grès Argileux du Moyen Niger*

I.IV.I Continental Terminal I (CT1) : *Série Sidérolithique de l'Adar Doutchi*

The *Série Siderolithique* is formed by often banked ferruginous sandstones and kaolinitic clays. Characteristic are large deposits of goethitic ooliths and pisoliths that may reach thickness up to several meters. The ooliths may occur loose forming sandy banks or are solidified by ferruginous, often phosphor rich, silts, and sands.

Borehole and geoelectric surveys in the Dosso region indicate that the CT1 consist of two units, a lower unit of loose sandstone and fine sands topped by a grey-blue clay with increasing sandy intercalations to the south (FAO 1970; Tab. 15, Fig. 17). Maximum thickness and depth are recorded from the centre of the syncline at Koléfou (176-282 m, thickness of about 100 m) decreasing to the south (e.g. 74-94 m at Koutoumbou, Fig. 30 & Fig. 31). The Continental Terminal 1 crops out at Bangou where it has been mapped by in detail by Greigert (1961a) but is absent in the area of Gaya and Benin where remnants of the Continental Terminal 3 discordantly rest on top of the Continental Intercalaire/Hamadien. FAO (1970) points out two important marker horizons:

- Levels of oolithic ironstone at Banikoubeye, and in boreholes at Bana, Fasaka, Malgorou and at the escarpment of Bangou Béri.
- White clay, potentially kaolinitic: between Bengou and Sabon Birni.

Generally, the *Siderolithique* rests in concordance over the shale *schiste papyracés du Lutetien* and shows a continued deposition marked by the presence of reworked shale fragments within the CT1. Small fragments of silicified wood as well as foraminifers known from the Palaeocene-Ypresien have been recorded in boreholes (Greigert & Pougnet 1967).

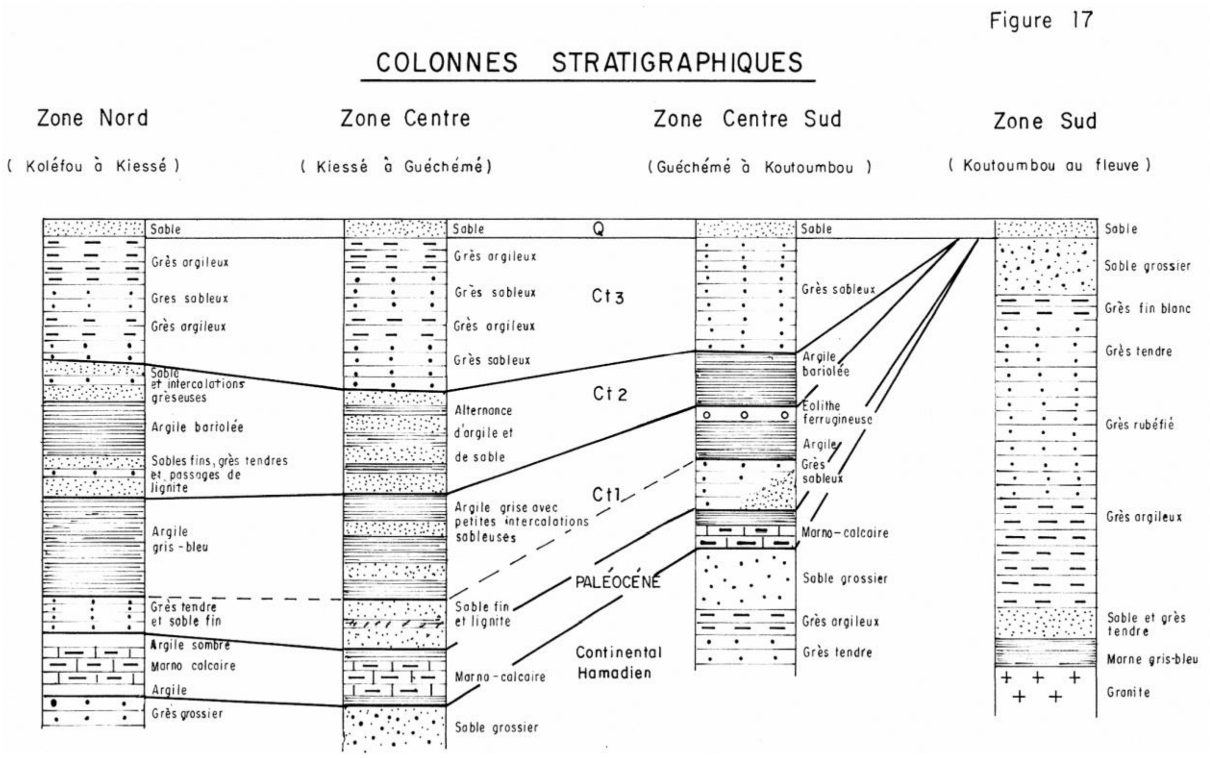


Fig. 30: Stratigraphic north-south transect along the Dallol Maouri (FAO 1970).

Contrary to the younger members of the Continental Terminal, the *Siderolithique* has undergone slight tectonic deformation and is characterized by the occurrence of numerous north-south and east-west oriented joints.

Tableau 15

VARIATIONS DE FACIES ET D'EPAISSEUR DU Ct_1 DE KOLEFOU A YELOU

ZONE NORD Koléfou à Ziela		ZONE CENTRE Ziela à Lokoko		ZONE SUD Lokoko à Yélou	
Faciès	Epaisseur	Faciès	Epaisseur	Faciès	Epaisseur
Argile gris-bleu	50 - 60 m	Argile grise avec petites intercalations sableuses	60 - 70 m	Oolithe ferrugineuse	2 - 20 m
Grès tendres et sables fins	40 - 50 m	Sables fins avec intercalations argileuses et passages à lignites	15 - 40 m	Argile sombre au nord, blanche au sud	8 - 24 m
				Grès sableux passant à des sables au sud	15 m

Tableau 16

VARIATIONS DE FACIES ET D'EPAISSEUR DU Ct_2

ZONE NORD Koléfou à Kiessé		ZONE CENTRE Kiessé à Guéchémé		ZONE CENTRE SUD Guéchémé à Koutoumbou	
Faciès	Epaisseur	Faciès	Epaisseur	Faciès	Epaisseur
Sables avec passages gréseux	20 - 30 m				
Argile bariolée avec passages sableux	20 - 60 m	Alternance d'argiles et de sables	40 - 80 m	Argile bariolée	0 - 30 m
Sables fins, grès tendres, silts et passages de lignite	40 - 75 m				
Note : Un niveau semble assez constant du nord au sud: les argiles bariolées jaune, brun, vert et surtout violet.					

Fig. 31: Continental Terminal 1 & 2: Variation of thickness along the Dallol Maouri (FAO 1970; Tab. 15 & 16).

I.IV.II Continental Terminal II (CT2): *Série argilo-sableuse à lignites*

The *Série argilo-sableuse à lignites* is characterized by the intercalation of well-sorted fine to coarse sands and variegated clays or dark-coloured mud. The sandy series is often topped by ferruginous sandstones, while the clays show ferruginous oolithic/pisolithic layers (Guero 2003). The grey to black, fine-grained sediments, claystones, and mudstones of the CT2 seem to have accumulated in local basins. Coalified wood (lignite) and vegetation remains are common. (Greigert (1965).

Following FAO (1970; Tab. 16), the Continental Terminal 2 is most pronounced in the northern zone of the Dallol Maouri (thicknesses between 80 m to 160 m at Koléfou to Kiéssé, Fig. 31) much less prominent between Tibiri/Kiéssé and Guéchémé (40-80 m) and fades out south of Dioundiou (0-30 m between Guéchémé and Koutoumbou).

I.IV.III Continental Terminal III (CT3): *Les Grès Argileux du Moyen Niger*

Les Grès Argileux du Moyen Niger are a monotone series of alternating loosely consolidated ferruginous sandstones, silts, and reddish clays. The sandstones are often banked, their upper parts are generally made up of an oolithic layer also described as goethitic ironstone (Greigert & Pougnet 1967). A peculiarity of the clay layers of the Continental Terminal 3 is the occurrence of a so-called *facies termitière*—a network of cavities and tubular structures coated and solidified with iron oxides—the fossilized remnants of former termite activity. FAO (1970) describe alternating sequences of "grès argileux" and "grès sableux". Based on a particularly well developed strata of "grès sableux" at Kisamou (70 m thick), they postulate a "basin grèseux" between Dioundoiou and Tibiri that thins towards the north.

Like the entire Continental Terminal, the *Grès Argileux du Moyen Niger* thins out to the south. Around Yelou, no deposits of the Continental Terminal 3 are found in the valley of the Dallol Maouri (FAO 1970) while they continue to form the ferricrete-topped mounds and hilltops of the plateau. Remnants of Continental Terminal south of the Niger River in Benin are likely Continental Terminal 3, however, no subdivision of is put forward in the available literature.

I.IV.IV Complexe de base du Continental Terminal

The *Complexe de base du Continental Terminal* is a conglomeratic sandstone with cross-bedded stratification mapped at the base of the Continental Terminal escarpment along the Niger River. It has been described in the region between Gaya and Ouna (Greigert 1961b)—on both banks of the Niger River (cf. *Carte Géologique de Reconnaissance du Bassin des Iullemmeden* (Greigert 1961a)—but also in the Dallol Bosso (Greigert & Pougnet 1967) and further north near Boubon along the route Niamey-Tillabéry (Machens 1967).

Greigert (1961b) describes outcrops around Gaya, where cross-stratified, unsorted quarzitic conglomerates ("poudingues") with up to 10 cm large blocks of quartz occur in a matrix of silicified, locally ferruginous sandstone with angular grains up to 5 mm in size. The conglomerates are accompanied by sorted and unsorted silicified sandstones and variegated kaolinitic clays. In their map, Greigert & Pougnet (1967) describe the occurrence of a siliceous cross-stratified conglomerate/breccia at the base of the Continental Terminal 1 near Gaya and along the Dallol Bosso. They interpret the deposits as the remnants of a north-draining valley coming from the Dahomeyan basement in the south. For the area of Niamey, Machens (1967) reports a very thin conglomeratic layer at the base of the Continental Terminal, here directly overlaying the basement.

The available descriptions may actually describe lag deposits and/or a high-energy environment along an erosive discordance between basement respectively Cretaceous Continental Hamadien prior to the deposition of the Continental Terminal. On the other hand—and particularly in the region of Gaya—the *Complexe de base du Continental Terminal* may correspond to the Palaeozoic Wéré Formation—as suggested by Konaté (1996) for the area between Sia and Gaya—or this conglomeratic facies may correspond to the underlying *Continental Hamadien*. This point of view is supported by the transects of FAO (1970) that show the rise and outcrop of the *Continental Hamadien* in the area of Gaya (Fig. 46 & Fig. 47) and discusses outcrops of the *Continental Hamadien* beneath *Continental Terminal* along the escarpment of the Dallo Maouri (Fig. 32).

I.IV.V Continental Terminal in Nigeria : The Gwandu Formation

In Nigeria, the subdivision of the Continental Terminal is reflected by a similar tripartite subdivision of the Gwandu Formation although no researcher has ventured to directly correlate the respective units. Moumouni et al. (2016) argues that the Gwandu Formation can be directly correlated with the Continental Terminal 3.

Oteze (1971 cited in JICA, 1990) differentiates four sand zones or aquifers within the Gwandu Formation: an unconfined Upper Zone 1, a confined Upper Zone 2, a Middle Zone and a Lower Zone. Later works have picked only three of these zones up. Anderson & Ogilbee (1973) differentiate two aquifers: an unconfined upper aquifer and a thick lower confined aquifer ("sandy zone") separated by a confining clay. The three strata increase to the northwest and at the Niger border the clay layer is about 75 m (250 feet) thick whereas the "sandy zone" shows a thickness of about 60 m (200 feet). More importantly, facies changes are documented that show an increasingly finer texture and abundant clay and lignite beds in the western part of the "sandy zone". Based on this facies change, the occurrence of lignite beds, and similar thickness of the respective Continental Terminal 1 & 2 in the area of Dogondoutchi (see Fig. 30; Fig. 31) the three zones can confidently be correlated with the Continental Terminal 1, 2, and 3. JICA (1990) follows the three layer interpretation and differentiates an Upper, Middle, and Basal Member on its three detailed east-west transects (Fig. 16)—but lacks a detailed geological description.

The different units of the Gwandu Formation have never been mapped. Only Greigert & Pougnet (1966) assume outcrops of Continental Terminal 1 overlying the late Paleocene *Zone à Operculinoïdes et à Lockhartia haimei*, known in Nigeria as Sokoto Group (Gamba, Kalambaina, Dange Formations). Anderson & Ogilbee (1973), however, describe a "conspicuous ridge west of the Sokoto-Illela road" as the outcrop of the confining clay layer (middle member) and the *Hydrogeological Cross Sections for the Sokoto basin* (JICA 1990; Fig. 8, Transect C-C') give some rough indications for the outcrop areas of the Middle and Basal member (i.e. Continental Terminal 1 & 2).

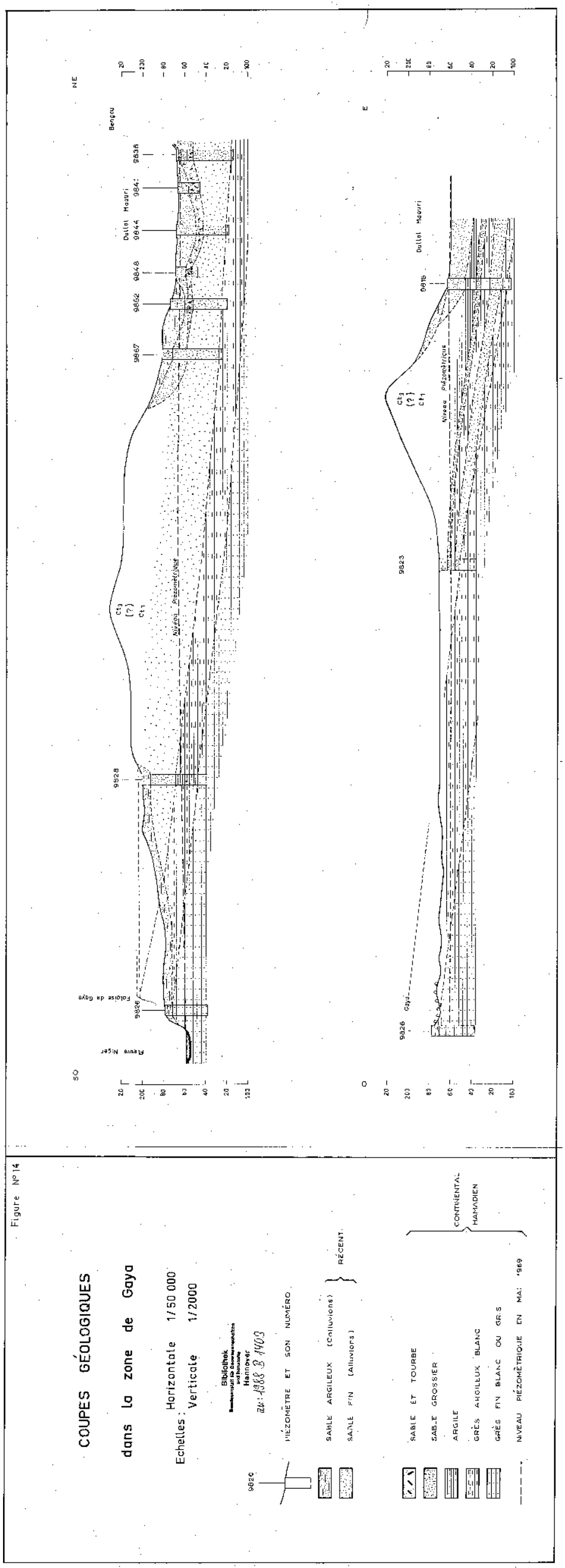


Fig. 32: Transect through the outcrop area of the Continental Terminal 3 & 1, and the Continental Hamadien between the Dallo Maouri and Gaya (FAO 1970, Fig. 14)

II Further maps of the study area

Additional maps cover parts of the study area. Selected maps that did not contribute substantially to the elaboration of a harmonized geological map are listed here:

II.I *Carte Géologique de Reconnaissance á l'échelle du 500.000* (Pougnet 1957b)

The *Carte Géologique de Reconnaissance á l'échelle du 500.000* (Pougnet 1957b) with its accompanying *Notice explicative sur la Feuille Kandi-Est (N° NC. 31-N.O.-E.34)* (Pougnet 1957a) cover parts of the Nigerien and Beninese basement areas west of the Kandi Fault (Fig. 33).

II.II *Carte Géologique du Niger Occidental 1/200 000* (Machens 1966)

Contemporaneous with Greigert overview map of Niger, Machens (1966) published the *Carte Géologique du Niger Occidental 1/200 000* and its accompanying *Notice Explicative sur la Carte Géologique du Niger Occidental à l'échelle du 1/200.000* (Machens 1967). The map covers the Liptako basement area up to the Niger River but is tangent to the study area and thus not included in the present work Fig. 34.

II.III *Carte Hydrogéologique: Bassin sédimentaire de Kandi à l'echelle 1/200.000* (Achidi et al. 2012)

In 2011, the Ingenieur-Gesellschaft für internationale Planungsaufgaben mbh (IGIP) on behalf of the Gesellschaft für Internationale Zusammenarbeit (GIZ) elaborated hydrogeological map (Fig. 35) for the sedimentary coastal basin and the Kandi Basin (Achidi et al. 2012). The accompanying Explanatory Note *Notice Explicative de la Carte du Bassin sédimentaire de Kandi à l'échelle 1:/200 000* provides a good overview on the existing geological maps. The hydrogeological map is based on the mapping efforts of Istituto Ricerche Breda (Akibou et al. 1989c, 1989b, 1989a, 1989d) and assumes a Cretaceous uppermost aquifer for the entire Kandi Basin. Building on the work of Alidou (1987) and Konaté (1996), the present map shows a Plaeozoic Kandi Basin and does not incorporate the geology of the 2011 map of IGIP-GIZ.

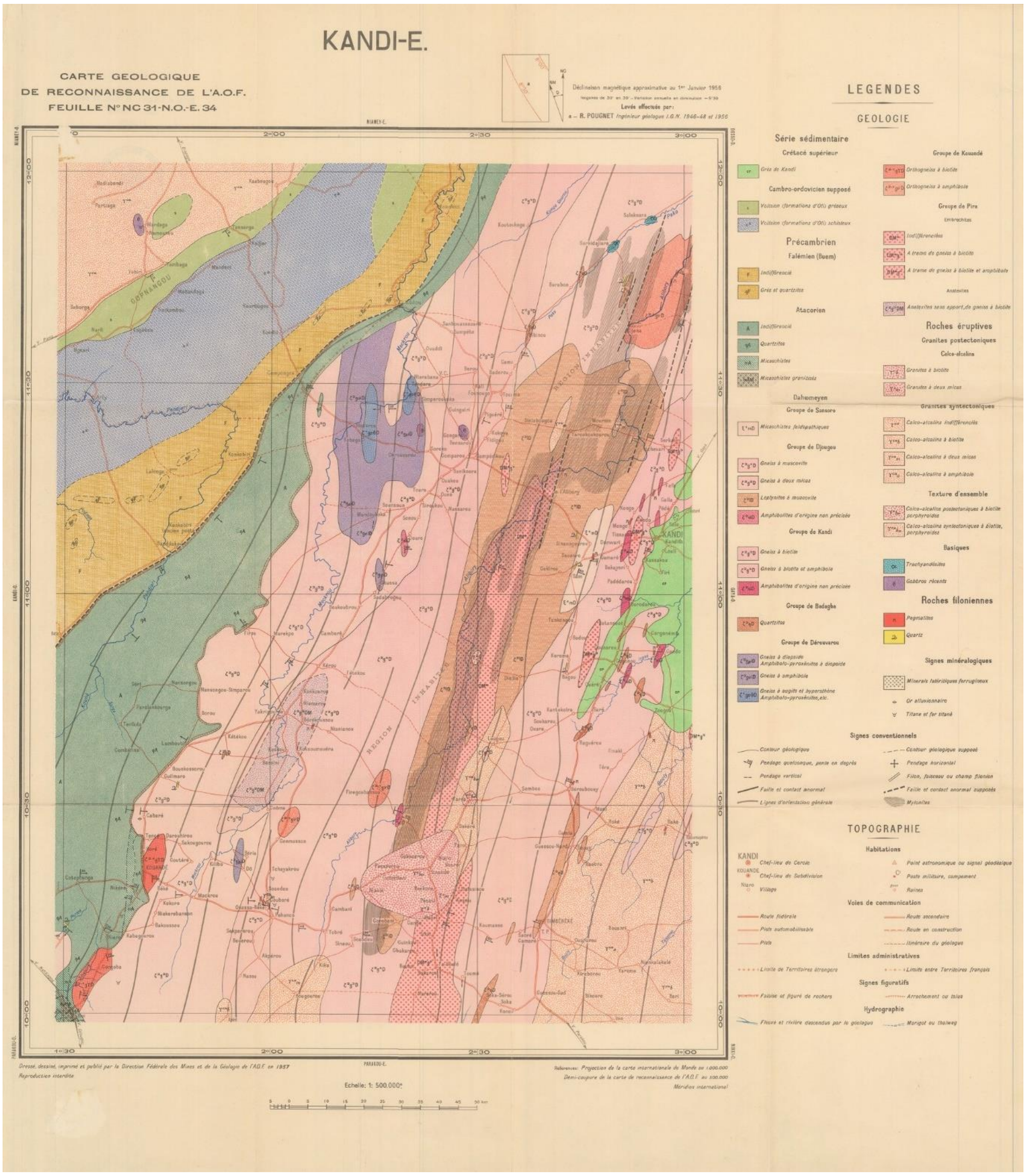
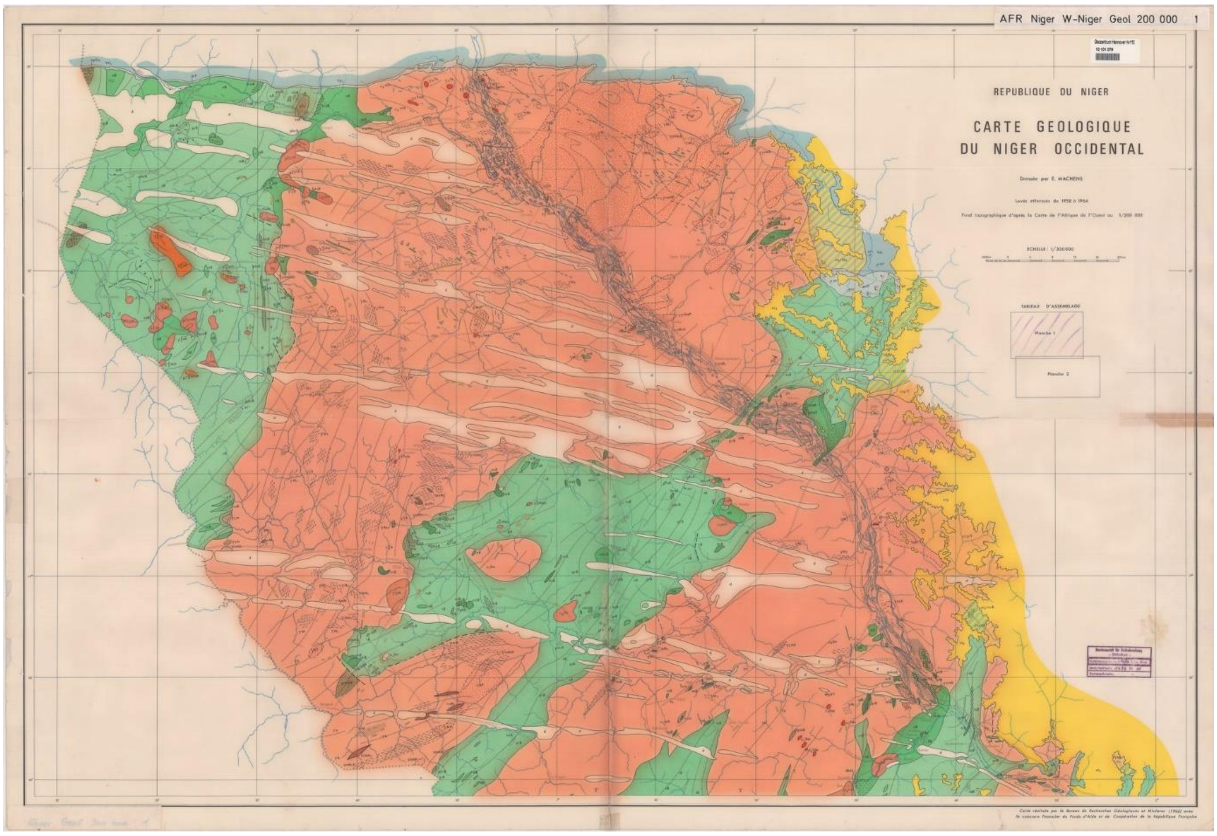


Fig. 33: *Carte Géologique de Reconnaissance á l'échelle du 500.000 (Pougnet 1957b)*



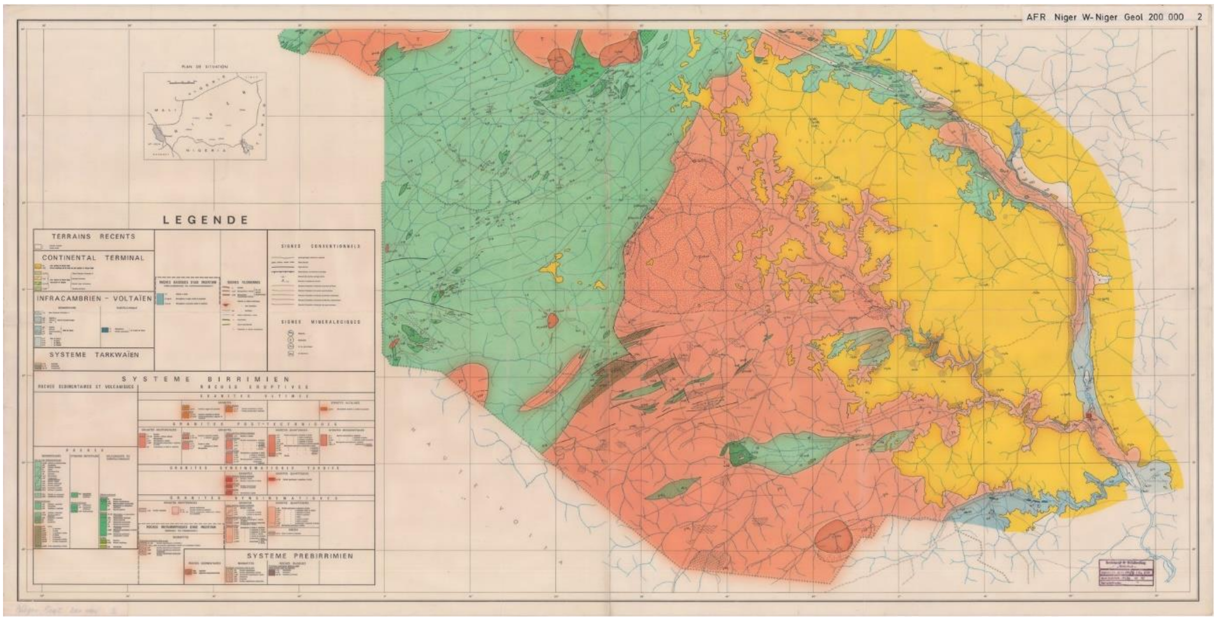


Fig. 34: Carte Géologique du Niger Occidental 1/200 000, feuille 1 & 2 (Machens 1966)

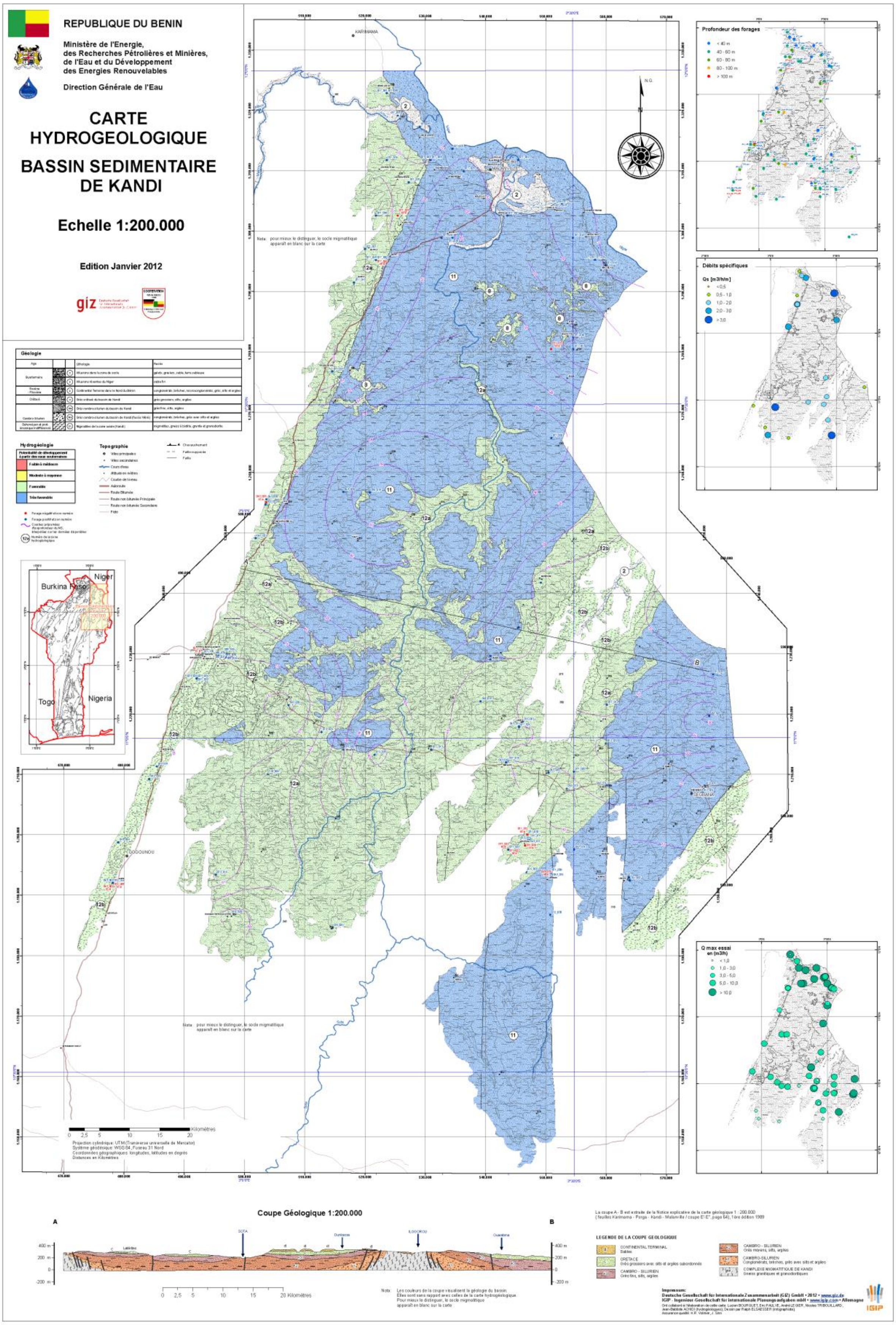


Fig. 35: Carte Hydrogéologique: Bassin sédimentaire de Kandi à l'echelle 1/200.000 (Achidi et al. 2012)

III General Legend

Tab. 11 *General Legend and stratigraphic framework of the harmonized map. The table shows the original legend items and the respective the harmonized stratigraphy, item code, general description, geological attributes, and the reclassed lithology following the IHME1500 aggregation scheme.*

Stratigraphic framework - General Legend

Harmonized Lithology

Code	Formation	Lithologie (fr)	Lithologie (eng)	Lithology (detailed)	Environment	Epaisseur	Economy	Fracturation
	cover layer	Dépôts éoliens fixés	Fixed eolian deposits		dépôts éoliens			pas fracturé
Qa3	**Dépôts fluviales récentes**	Dépôts alluviales et fluviales récentes	Recent alluvial and fluvial deposits		dépôts fluviaux, alluviaux et colluviaux			
Qa2	**Dépôts alluvial et fluvial anciennes**	Dépôts alluviales et fluviales anciennes	Older alluvial and fluvial deposits					
Qa1	**Dépôts alluvial et fluvial anciennes (Pre-Pléistocène?)**	Dépôts alluviales et fluviales anciennes (Pre-Pléistocène?)	Ancient alluvial and fluvial deposits (Pre-Pleistocene?)	Comblement alluviales et colluviales des vallées fossilisées Terrasses anciennes du Ténéré du Tamesna. Alluvions anciennes à galets.				
	Discordance							
Ct	**Continental Terminal (indiff.)**	Série de grés hétéro-granulaires, argileux rougeâtre parfois kaolinitique, peu cimenté, faiblement consolidé, niveaux oolitiques ferrugineux; base conglomeratique, plateaux des cuirasses ferrugineuses	Heterogranular sandstones series, reddish often caolinitic clays, slightly cimented and weakly consolidated, intercalations of ferrugineous oolithic strata; ferrugineous ferricretes on plateaus; base conglomeratic basal sediments.		mainly terrestrial, lacustrine environement (ooliths)	150 W - 450 O (Iullemmeden)		pas fracturé
Ct3	**Continental Terminal 3: *Grès argileux du Moyen-Niger***	Série monoton de grés hétéro-granulaires, argileux rougeâtre par fois kaolinitique, peu cimenté, faiblement consolidé, niveaux oolitiques ferrugineux; plateaux des cuirasses ferrugineuses	Monoton series of heterogranular sandstones, reddish often caolinitic clays, slightly cimented and weakly consolidated, intercalations of ferrugineous oolithic strata; ferrugineous ferricretes on plateaus		mainly terrestrial, lacustrine environement (ooliths)	20 m at type section	High water table, prone to pollution	pas fracturé
	Discordance	**surface d'érosion et de péneplanation**	**erosion and peneplanation surface**					
Ct2	**Continental Terminal 2: *Série argilo-sableuse a lignites***	Alternance de séries sableuses et argileuses; sables fins à moyens bien classés plus o moins argileux, friables, lentilles argileuses; carapaces de grès ferrugineux et dans les argiles des niveaux ferruginisés à ooliths ou pisolithes	Alternating sandy and clayey series; well-sorted, fine to medium sands more or less clayey, friable, clay lenses; ferricretes of ferrugineous sandstone and within the clays ferrugineous levels of ooliths or pisoliths, levels of lignite and peat.		terrestre/marine		main aquifer used for large-scale water extraction	pas fracturé
		Série argilo-silteuse/sableuse (N 13°) absente dans le bas-dallol Maouri (au Sud de Koutoumbou) et dans la partie sud-ouest de la zone d'étude (W Sabongari)	Série argilo-silteuse/sableuse (N 13°) absente dans le bas-dallol Maouri (au Sud de Koutoumbou) et dans la partie sud-ouest de la zone d'étude (W Sabongari)			max 30m (DD), 5-20m (D. Foga, Mamandeye)		
		Série argilo-sableuse à lignites: sables fins à moyens bien classés à quartz no usés plus o moins argileux, lentilles argileuses; carapaces de grés ferrugineux; niveaux ferruginisés à ooliths ou pisolithes	Série argilo-sableuse à lignites: sables fins à moyens bien classés à quartz no usés plus o moins argileux, lentilles argileuses; carapaces de grés ferrugineux; niveaux ferruginisés à ooliths ou pisolithes			0m (D. Maouri), 60m (Dogond.)		
		Argiles grises à lignites et tourbes; èpaisseur variable; par endroits faciès sableux/silteux; sablo-argileux / argilo oolithique, lignites, pyritee à grès tendres oolithiques et lignties (W D. Foga, Mamandeye)	Argiles grises à lignites et tourbes; èpaisseur variable; par endroits faciès sableux/silteux; sablo-argileux / argilo oolithique, lignites, pyritee à grès tendres oolithiques et lignties (W D. Foga, Mamandeye)			0 (D. Maouri, S Yelou, Sabongari) - max 65m (Dogond.)		
		Série argilo-sableuse et série sidérolithique dans le Détroid soudanais, argiles bariolés, grès et de sables, niveaux ferrugininsés à structure oolithique	Série argilo-sableuse et série sidérolithique dans le Détroid soudanais, argiles bariolés, grès et de sables, niveaux ferrugininsés à structure oolithique			20-50		
Ct1/2	**CT1/2: *Séries argilo-sableuse et sidérolithiques***	Série indifferencié du CT2 et CT2: Séries argilo-sableuse à lignites et tourbes (CT2) au-dessus du Serie sidérolithique sableuse à alternance de argiles (CT1); niveaux ferruginisés à ooliths	Undifferenciated series of CT1 and CT2: Sandy-clayey series with lignites and peat (CT2) overlying the sandy siderolithic series with intercalations of clays (CT1); oolithic levels		terrestre			pas fracturé
Ct1	**Continental Terminal 1: *Série sidérolithique de l'Adar Doutchi***	Série sableux moyen à grossiers passe à des alternance de sables fins argileux et d'argiles sableuse, argiles kaoliniques ferruginisés, dépôts à ooliths de goethite	Series of medium to coarse sands alternating with fine, clayey sands and sandy clays, ferrugineous kaolinitic clays, deposits of goethitic ooliths		terrestre	Max 80m Dogond.; 0m (Bana, D. Maouri), 75m (Dogondoutchi), moyenne 26m; Nigeria: 2-5 m		légerement fracturé
Ctc	**Continental Terminal 1: *Complexe de base* (Conglomérats)**	Poudingue à stratification entrecroisée, cimenté pour un grés siliceux à grains anguleux (5 mm) ferrugineux; parfois blocs de quartzites anguleux (à 10 cm)	Microconglomerates with cross-stratification, cimented by a siliceous sandstone of cimenté pour un grés siliceux, ferrugineous of angular sand grains (5 mm); often angular quartzitic blocs (10 cm)		terrestre	2 W - 40 m E (Machens, 1967, fleuve niger); Nigeria: 2-5 m		légerement fracturé
	Discordance							
So	**Sokoto Group (Gamba, Kalambaina & Dange Formations) / (Garadawa?)**	**Série marine:** *Zone à Operculinoïdes et zóne à Lockartia-haimi*; 35m de calcaire récifaux encadrés par 2 séries de marno-calcaires en palques et de schistes papyracés épaisses d'une dizaine de mètres. Nodules phosphatés et gypse. Concordance avec Upper Sandstone	**Série marine:** *Zone à Operculionoïdes et à Lockhartia haimei*; Limestone (35m) framed by two series of grey laminated carbonaceous shale *(schistes papyracé,* ~10m), occurence of gypsum, & phosphatic nodules. Concordanz with Upper Sandstone		marine environment (nearshore to open marine)			fracturé
-	**Gamba / (Barmou?) Schistes papyracés supérieurs**	Schistes carton jaunes (attapulgite), nodules phosphatés, gypse, sel, ooliths de goethite au sommet; al la base une zone à Lockhartia haimei (~10m); tassement pour dissolution des calcaires sous-jacentes	Grey laminatedphosphatic shale, marker bed of phosphatic pellets and small coproliths; "folded" due to dissolution of underlying limestone		nearshore facies, withdrawl of sea	4 - 10 m (Nigeria); 0m (S D. Mauouri, Bana), 50m (Dogond., Bonkoukou, 100m (Digdiga); 35m (Greigert, Dosso) (10 - 30 - 10 m, Greigert, 1967)		deformé
KD	**Kalambaina & Dange Formations**	**Série marine:** *Zone à Operculionoïdes et à Lockhartia haimei*; Limestone framed by two series of grey laminated carbonaceous shale *(schistes papyracés)*, occurence of gypsum, & phosphatic nodules	**Série marine:** *Zone à Operculionoïdes et à Lockhartia haimei*; Limestone (35m) framed by two series of grey laminated carbonaceous shale *(schistes papyracé,* ~10m), occurence of gypsum, & phosphatic nodules. Concordanz with Upper Sandstone					?
KD								
K	**Kalambaina Formation / (Tamaské?)**	Calcaires blancs et marnes calcaires; abondante faune; zones à *Linthia sudanensis, Plesiolampas saharae, Operculinoides* (~30m)	White, clayey limestone and shale, calcareous marls; phosphates, fossiliferous		open marine	12 - 20 m		fracturé
K	**Kalambaina Formation**							
D	**Dange Formation / (Kao?) Schistes papyracés inférieurs**	Schistes carton jaunes ou bleus avec des intercaltions de calcaires; nodules des phosphatés et des gypses; débutant par des marnes sableuses (~10m)	Bluish-grey shale, interbedded with thin layers of limestone (fibrous gypsum, phosphatic nodules); alternative: Clay shales with thin bands of intercalated limestone		transition phase to marine	~ 20 m (50 at Balle, 4 m at Argungu (south centre)		?
	Discordance		Thin bed of conglomerate (coproliths, gypsum, molluscs) & erosion of top of Wurno F.		terrestrial / erosion			
Ri	**Rima / Maji Group (Wurno, Dukamaje, Taloka Formations)**	**Rima / Maji Group:** Upper & Lower Sandstones: Première transgression à *Libycoceras ismael*; *Mosasaurus* shales; marin ou continental indifférencié	**Rima / Maji Group:** Upper & Lower Sandstones, first marine transgression à Libycoceras ismaeli; *Mosasaurus shales*		low-energy marine, tidal-flat environement		-	?
WT							-	?
WT								
W	**Wurno / Im'Wagar *(Upper Sandstones)***	Marnes sableuses, grès en bancs réguliers, friables; intercalations des niveaux ferrugineux à oolithes, gypse et pyrite; *Libycoceras*	Sandy mudstones/marls interaclated with friable, fine-grained banked sandstones, siltstones; ferrugineous levels with ooliths, gypsum and pyrite; *Libyococeras*	pale, friable, fine-grained sandstones, siltstones and intercalated mudstones (dark coloured in boreholes due to carbonaceous material & finely disseminated iron sulphides)	low-energy marine, tidal-flat environement	20 m (50 m at Balle)	-	?
Dk	**Dukamaje / Farin Doutchi (*Mosasaurus shale*)**	*"Mosasaurus shales"* (Jones, 1948) Bancs calcaires fins separé des sables/argiles à débris végétaux - ou - shale avec calcaires et marls; lit à ossements *Mosasaurus; Libyococeras*	*"Mosasaurus shales"* (Jones, 1948) shales with some limestones and mudstones, bone bed at the base (shoreline); *Libycoceras sp, Mosasaurus;* Niger: banked limestone separated by vegetation rich mudstones	Bancs calcaires fins separé des sables/argiles à débris végétaux - ou - shale avec calcaires et marls; lit à ossements *Mosasaurus; Libyococeras* - Mosasaurusshales (bone bed) with limestones and mudstones, Libycoceras sp. - Bancs calcaires fins separé des sables/argiles à débris végétaux - ou - shale	marine	6-12 m (Nigeria)	Limestone resources	?
T	**Taloka / Alambanya *(Lower Sandstones)***	Grés fin et friable avec siltits intercalé avec marls et shales calcaires	White, fine-grained, friable sandstones and siltstones with thin intercalated, hard mudstones and carbonaceous mudstones or shales	fine-grained, friable sandstones & siltstones	Niger (north): marine Niger/Benin: continental/erosion	~ 60 m (Nigeria)	lignite resources	?
T		Shales et marls calcaires et intercalées	Thin intercalated (carbonaceous) mudstones or shales	thin intercalated (carbonaceous) mudstones or shales				?
T		Grés fin et friable avec siltits et marls intercalé avec marls et shales calcaires	Fine-grained, friable sandstones & siltstones, thin intercalated (carbonaceous) mudstones or shales	fine-grained, friable sandstones & siltstones, thin intercalated (carbonaceous) mudstones or shales				?
T		Grés à dragées du CI (Niger: Gaya Est, sud du 12°, Pougnet) & schiste calcaires foncé et grés bariolé (Nigeria)	Sandstones similar to CI (Gaya Est, sud du 12°, Pougnet) & darky grey, carbonaceous shale and yellowish brown variagated sandstones (Nigeria);	Grés à dragées du CI (Gaya Est, sud du 12°, Pougnet) darky grey, carbonaceous shale and yellowish brown variagated sandstones (Nigeria);				?
	Unconformity ?							
Ch	**Continental hamadien**	Grès fins à grossiers à ciment kaolinique et de sables moyens à grossiers plus ou moins consolidé, microconglomeratique, argiles bariolés; intercalation major de argile pisolitique et nodulaire bauxitique	Cross-bedded, fine to coarse often angular sandstones; kaolinitique matrix, interbeddedd clays and microconglomerates, siltits, variegated clays; major intercalation of white bauxitic, nodular and pisolitic clay	Cross-bedded fine to coarse-grained (grids), angular sandstones; interbedded clays and grits; major intercalation of white bauxitic, nodular and pisolitic clay; occurence of variegated clays and multicolored ferrugineous deposits;	terrestrial: fluviatil to fluvio-lacustrine	< 240 m (7-100m / 3-10m / 10- 130m)		fracturé
Io	**Ch: Illo Group**	Grès fins à grossiers à ciment kaolinique et de sables moyens à grossiers plus ou moins consolidé, microconglomeratique, argiles bariolés	Cross-bedded, fine to coarse often angular sandstones; kaolinitique matrix, interbeddedd clays and microconglomerates, siltits, variegated clays	Grès fins à grossiers à ciment kaolinique et de sables moyens à grossiers plus ou moins consolidé (Dallol Maouri); S plus grossiers/homogène; N plus fins et argileux, alternance (Guero (2003) / Sables, argiles et calcaires à Dinosauriens et Unios / cross-bedded, fine to coarse sandstones; microconglomerates, siltits, variegated clays	terrestrial: fluviatil to fluvio-lacustrine	< 240 m (7-100m / 3-10m / 10- 130m)		fracturé
I^{bx}	**Illo Group - Bauxite pisolithique**	Argile blanche bauxitique, pisolithique et nodulaire	Pisolitic and nodular low-grade, bauxitic white clays		terrestrial	3 - 10 m		fracturé
Gu	**Ch: Gundumi Group**	Grés moyene à grossier intercalé avec d'argile bariolé, vers le socle conglomerates de base (<6cm), graviers, induré (calcsilicic)	Medium to coarse-grained sandstones intercalated with variegated clays and clayey sandstones. Towards the contact with the basement basal conglomerates (<6cm), indurated (calcsilicic)	Basal conglomerates (<6cm), indurated (calcsilicic) towards the contact with basement	terrestrial			
				Gundumi Group (clay, grit, pebbels): Clay, grit, pebbels; poorly fossiliferous, high-enetgy environement, fluviatil and lacustrine / Medium to coarse-grained sandstones intercalated with clays and clayey sandstones	poorly fossiliferous, high-enetgy environement, fluviatil and lacustrine	< 350 m		fracturé
				Gundumi Group (gravel & sands): Gravel & sands	terrestrial			fracturé
				Gundumi Group (metaconglomerate): Meta-conglomerate (Sokoto m	terrestrial			fracturé
N	**Nupe Sandstone**	Grés	Sandstone		terrestrial	-		fracturé
	Discordance / Hiatus	**surface d'érosion subaérien**						
Kb	**Kandi B**	Siltites intercalé avec grès fins, argiles; traces à *Cruziana*; structures de tempestites; stratification entrecroisée.	Siltstone facies with hummocky cross-stratfication, siltstone strata interbedded with micaeous fine sandstone in undulating beds several decimeters to a meter thick; upper offshore environemt; traces fossils: *Cruziana*	Siltites, grès fins à *Cruziana* et à structures de tempestites / Siltstone facies with hummocky cross-stratfication, siltstone strata interbedded with micaeous fine sandstone in undulating beds several decimeters to a meter thick;; upper offshore environemt	upper offshore environment (hummocky cross-stratified sandstones); clay and sand, marine environment upper offshore environment (hummocky cross-stratified sandstones); clay and sand, marine environment			fracturé
Ka	**Kandi A**	Grès fins o/ou siltstone, argiles, litage sigmoïde ou ondulé; traces à *Harlania/Arthrophycus*	Medium- to fine-grained sandstone deposits displaying sigmoidal bedding and herringbone cross-bedding, tidal origin; trace fossils *Harlania / Arthrophycus*	Grès fins à *Harlania*, à litage sigmoïde ou ondulés / medium- to fine-grained sandstone deposits displaying sigmoidal bedding and herringbone cross-bedding, tidal origin	Milleu paralique (lac, delta & mer peu profonde), shoreface barrier & tidal environment			fracturé
					Milleu paralique (lac, delta & mer peu profonde), shoreface barrier & tidal environment			fracturé
					Milleu paralique (lac, delta & mer peu profonde), shoreface barrier & tidal environment			fracturé
Wb	**Wéré B**	Grès grossiers à moyens microconglomératiques, litages obliques plans et en auges	Granule-rich coarse sandstones with tabular to through cross-bedding	Grès grossiers à moyens microconglomératiques à grands litages obliques plans et en auges / granule-rich coarse sandstones with tabular to through cross-bedding	Dépôts de plaine d'inondation & dynamique fluvial, braided river sediments			fracturé
					Dépôts de plaine d'inondation & dynamique fluvial, braided river sediments			
		Conglomérats, brèches, grès avec silts et argiles subordonnés. Dépôts de cône d'alluvions. Conglomérats et brèches prédominantes (en pointillé)	Conglomerates, breccia with sandstones, siltits and clays. Dotted: Conglomerates dominant.		Dépôts de plaine d'inondation & dynamique fluvial, braided river sediments			
Wa	**Wéré A**	Conglomérats, grès grossiers microconglomératiques a gros blocs, litages obliques plans ou en auges. La coleur est généralement rouge-brun	Diamictite and breccia medium- to coarse-grained sandstones with quartzitic boulders and faceted pebbles ...	NW: consolidé (silice) autrement: non consolidé	Dépôts de cône d'alluvions & dépôts glacial (tillites), glaciofluvial outwash, perglacial sediments			fracturé

Stratigraphic framework - General Legend

Stratigraphy and original geological maps

Eratheme	Systeme	Serie / Stage	Transgressions (Kilian, 1931)	Group	Konate (1996): Carte géologique du Bassin Paléozoïque de Kandi – Code	Formation	Description	Société Istituto Ricerche Breda (1989): Notice Explicative de la Carte Géologique à 1/200.000 Feuilles: Karimama, Porga, Kandi, Malanville – Code	Formation	Description	Technoexport (1994) Carte de Géologie et des Minéraux utiles: Dunkassa (NC-31-X), 1:200.000 – Code	Formation	Description	Greigert (1966): Carte Geologique Republique du Niger. 1:2.000.000 – Code	Description	D.O.S. (1965/6): Geological Survey of Nigeria, 1:200.000 map series – Code	Description	NGSA (2011) Geology and Mineral Resources Map of Nigerian States & Geological Map of Nigeria – Code	Description
Basement																			
Paleozoic	Cambrian		Pan-African orogenies (Trans-Saharan mobile belt, Dahomeyan)	Serie du Voltaïen										Vs	Voltaïen: Schistes, argilites				
														Vg	Voltaïen: Grès				
								gV	Série du Voltaïen	Grès quartzites cimentés. Dépôts sub- et intertidals									
				Serie de la Mékrou				gM	Série de la Mékrou	Silts, argiles avec intercalation de grès phosphaté à ciment siliceux. Dépôts néritiques									
								pM	Série de la Mékrou	Argiles et silts prédominants avec rares intercalation gréseuses. Dépôts néritiques									
																mc	Meta-conglomerate	MC	Metaconglomerate
																p	Meta-sandstone	Mt	Meta-sandstone
																sp	Shale, phyllite and meta-siltstone	Sp	Slate, phyllite, metasiltstone, locally hornfelsic or carbonaceous
																		Sf	Biotite and musovite schist
																		Sm	Muscovite schist and quartzite
																		Su	Undifferentiated muscovite and feldspathic schist
																		Speg	Schist with pegmatites
		Siderian / Rhyacian	Eburneen orogenese	Birrimian / Pharusian										Bs	Birmian: Schistes, grauwackes				
	Neoproter		Pan-African orogeny (Trans-Saharan	Buem				jP	Série de la Podiega	Jaspes rouges et violets, généralement très cataclastiques									
								pP	Série de la Podiega	Siltites et schistes argileux									
														Bu	Buem: Schistes, grès-quartzites				
											PR_3tg	Atacora / Tagayéyé	Quartzite, schiste, schiste séricito-quartzeux	Sq	Quartzites, schistes				
											PR_3kd	Atacora / Kouandé	Quartzite, schiste à quartz et muscovite			qs orange	Large quartz veins	MC	Quartzite
								qz	Quartzites de l'Atacora	Quartzites à disthène, chloritoïde et muscovite, parfois avec reliques de structures sédimentaires									
								qzA	Quartzites de l'Atacora	Quartzites fins, parfois micacés, schisteux et plissités (Atacora)									
														A	Atacorien: Quartzites, micaschistes				
																		bG	Biotite Gneiss or banded gneiss
																		bS	Biotite Garnet Gneiss Schist
																		OPg	porphyroblastic Gneiss
	Paleoprot.		Eburneen											S	Suggarien indifférencie				
																GG	Granite-gneiss	GG	Granite-gneiss
											my_1PR_1	Formations Palingéno-Metasomatiques	Première phase: Granite-gneiss ; plagiogranite-gneiss ; migmatites						
																		MaG	Augengneiss
								gnM	Gneiss de la Mékrou	Paragneiss à muscovite et parfois staurotide avec filons pegmatiques à tourmaline									
								grP	Complexe granulitique-charnockitique de Pototoumana-Kompagorou	Granulites basiques. Granoblastites et charnockites dans la partie méridionale									
								mF	Complexe amphibolitique gneissique de Founogo	Amphibolites, gneiss, micachistes, généralement mylonitisés et en écailles tectoniques									
																		MG	Migmatite-granite-gneiss
																		M / Mi	Migmatite
		Antebirrimian												M	Migmatites				
								mK	Complexe migmatitique de Kandi	Migmatites à néosomes granitiques et granodioritiques et paléosomes gneissiques et amphibolitiques									
								gnK	Complexe migmatitique de Kandi	Gneiss œillés granitiques et granodioritiques									
								Gamma K	Complexe migmatitique de Kandi	Granites porphyriques									
								pK	Complexe migmatitique de Kandi	Pegmatites									
											$ARdh_3$	Dahomeyan	Gneiss à biotite, à biotite et amphibole, à deux micas, amphibolite						
											$ARdh_2$	Dahomeyan	Gneiss à biotite, à biotite et grenat, amphibole et grenat ; amphibolite à pyroxène et grenat						
											$ARdh_1$	Dahomeyan	Amphibolite à pyroxène, à pyroxène et grenat ; gneiss à biotite et grenat, leptynite						
					Socle	Socle panafricain	Socle panafricain granito-gneissique à quartzitique												
	Mesoproteroz		Pan-African orogeny (Trans-Saharan mobile belt)	Groupe de Djougo &										D	Dahomeyen, Groupe de Djougo & Kandi: Gneiss à deux micas & Gneiss à biotite				
														D	Dahomeyen, Groupe de Djougo & Kandi: Gneiss à deux micas & Gneiss à biotite				
Precambrian (Basement)																		My	Mylonites
																		aMy	Mylonite interlayered with amphibolites
																		qS / Qs / qs	Silicified and sheared rocks, large quartz veins
			Pan-African orogeny (Trans-Saharan mobile belt,					mA	Complexe mylonitique de l'Alibori	Gneiss, amphibolites, métagabbros retromorphosées en faciès schistes verts; mylonitisés et en écailles tectoniques.									
								grA	Complexe mylonitique de l'Alibori	Granulites acides et intermédiaires, retromorphosées en faciès schistes verts.									
								Gamma	Granites indifférenciés	Granites indifférenciés									
											γPR_3	Formations Palingéno-Metasomatiques	Formations palingéno-métasomatiques. Granite porphyroïde et migmatites						
											γ_3PR_3	Formations Palingéno-Metasomatiques	Troisième phase : Granite pegmatoïde et migmatites						
											γPR_3	Formations Palingéno-Metasomatiques	Troisième phase : Granite pegmatoïde et migmatites ; filons de pegmatite						
											γ_2PR_2	Formations Palingéno-Metasomatiques	Deuxième phase : Granite et granodiorite grossiers						
											$(m)\gamma_2PR_2$	Formations Palingéno-Metasomatiques	Deuxième phase : Granite et granodiorite gneissiques, migmatites œillés						
											γ_1PR_1	Formations Palingéno-Metasomatiques	Première phase : Granite et granodiorite à grain moyen et fin, à biotite						
														gs	Granites syntectoniques				
														gpt	Granites posttectoniques				
														g	Granites anciens indifférenciés				
																P	Pegmatite, granite and aplite complex (quartzo-feldspathic rocks)	OGp	porphyric granite / coarse porphyritic biotite and biotite hornblende granite
																Ogh	Biotite- and biotite-hornblende-granite, medium grained	Ogp / Ogm	Medium to coarse grained biotite granite
																		OGf	Fine-grained biotite granite
																		OGh	Coarse, porphyritic hornblende granite
																		OGd	Biotite and biotite hornblende granodiorite, quartz diorite
																		OGu	Undifferentiated granites and granite gneiss and migmatite
																		OSq	Quartz-syenite
																D	Dyke-complex, including dacite, micro-granite and micro-granodiorite	ODh	Diorite
											γ_1PR_1	Formations Palingéno-Metasomatiques	Première phase : Diorites						
																		D	Dolerite
																		aS	Amphibolite schist / amphibolite
											σAR	Roches intrusives	Pyroxénites amophibolisées, serpentinites, hornblendites, roches à trèmolite, talc-trémolite et chlorito-trémolite						
											νAR	Roches intrusives	Amphibolite apogabbroïque et apodiabasïque, gabbro-diabase amphibolitisés						
								Epsilon	Serpentinites, pyroxénites.	Serpentinites, pyroxénites.									
								Epsilon Dots	Serpentinites, pyroxénites, avec reliques de structures à cumulats.	Serpentinites, pyroxénites, avec reliques de structures à cumulats.									
								b	Filons basiques de composition andésitique non métamorphiques	Filons basiques de composition andésitique non métamorphiques									
																		MV / E	Metagabbro and hornblende schist
																		BIF	Banded iron formation
																v	Acid lavas interbedded in the shale, pyhllite, meta-siltstone series	V	Meta-volcano sedimentary series
																		r	Rhyolite
																B	Olivine basalt	-	-
								pA	Complexe volcano-sédimentaire de l'Alibori	Roches volcaniques de compostion de rhyolitique à andésitique avec sédiments subordonnés; en écailles tectoniques de dimensions limitées									
								Beta PK	Complexe volcano-sédimentaire de la Pako	Roches volcaniques de composition basaltique-andésitique avec structures "pillow lavas", brèches volcaniques et rares sédiments pélitiques siliceux associés									
								Beta B	Complexe volcano-sédimentaire de la Barou	Roches volcaniques de composition basaltique-andésitique, et sédiments pélitiques siliceux associés									

Harmonized Lithology, Aquifer parameters, Lithological classification following the aggregation scheme of the International Hydrogeological Map of Europe (IHME1500), Zone Pilote, IAEA (2014): Synthèse stratigraphique, Cotonou

Code	Formation	Lithologie (fr)	Lithologie (eng)	Lithology (detailed)	Environment	Epaisseur	Economy	Fracturation	Cimentation	Consolidation	Karst	Porosité	Aquifer type	IHME_L5	IHME_L4	IHME_L3	IHME_L2	IHME_L1	Zone Pilote	Age	Group	Formation	Hydrogeo.
	Discordance - Basement	surface d'érosion subaérien	Erosion surface																				
gV	Série du Voltaïen	Grès quartzites cimentés. Dépôts sub- et intertidals	Quartzitic cemetned sandstones. Intertidal to subtidal deposits.					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Clastic rocks	Sandstones	Sandstones	Sandstones, phyllites, quartzites					
M	Série de la Mékrou	Silts, argiles avec intercalation de grès, dépôts néritiques	Siltstones, claystones with intercalation of sandstones, neritic deposits.					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Clastic rocks	Sandstones	Shales, sandstones	Shales, sandstones					
mC	Metaconglomerate	Métaconglomérat	Metaconglomerate	Metaconglomerate				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Quartzites	Quartzites	Quartzites, conglomerates, sandstones, shales (jointed)					
mSS	Meta-sandstone	Métagrès	Meta-sandstone	Meta-sandstone				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Quartzites	Quartzites, sandstones	Quartzites, sandstones					
Sp	Slate & phyllite	Ardoises & phyllite	Slate & phyllite	Slate, phyllite, metasiltstone, locally hornfelsic or carbonaceous				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Phyllites	Phyllites, schists	Phyllites, schists, quartzites					
Sc	Schistes (indiff.)	Schistes (indiff.)	Schists (undiff.)	Biotite and musovite schist				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Schists	Schists, gneisses	Schists, gneisses					
				Quartz-muscovite schist																			
				undifferentiated schist including phyllites and gneiss																			
				Schist with pegmatites																			
				Birmian: Schistes, grauwackes																			
P	Série de la Podiega (Buem)	Siltites et schistes argileux; grès-quartzites	Siltstones and clayey schists; sandstone-quartzites					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Clastic rocks	Sandstones	Sandstones and claystones	Siltstones, claystones, sandstones					
qz	Quartzites	Quartzites	Quartzites					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Quartzites	Quartzites	Quartzites					
qzA	Quartzites de l'Atacora	Quartzites	Quartzites					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Quartzites	Quartzites	Quartzites					
Gn	Granite-Gneiss (indiff.)	Granite-Gneiss (indiff.)	Granite-Gneiss (undiff.)	Biotite Gneiss or banded gneiss				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, amphibolites					
				Biotite Garnet Gneiss Schist				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, amphibolites					
				porphyroblastic Gneiss				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, amphibolites					
				Suggarien indifférencie				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, amphibolites					
								fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, amphibolites					
								fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, amphibolites					
				Augengneiss				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, amphibolites					
gnM	Gneiss de la Mékrou	Paragneiss à muscovite et parfois staurotide avec filons pegmatiques à tourmaline	Paragneiss to muscovite, often staurolite with sills of pegmatites and tourmaline					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, amphibolites					
gnP	Complexe granulitique-charnockitique de Pototoumana-Kompagorou	Granulites basiques. Granoblastites et charnockites dans la partie méridionale	Basic granulites. Granoblastites and charnocktites					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, amphibolites					
gnF	Complexe amphibolitique gneissique de Founogo	Amphibolites, gneiss, micachistes, généralement mylonitisés et en écailles tectoniques.	Amphibolite, gneiss, micachists, generaly myolonitic.					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, amphibolites					
Mi	Migmatite	Migmatite	Migmatites					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, migmatites					
mK	Complexe migmatitique de Kandi (Dahomeyen)	Migmatite: gneiss à biotite, amphibole, grenat; neosomes œillés granitiques et granodioritiques	Migmatite: gneiss to biotite, amphibolite, garnet; neosomes granitic and granodioritic (augengneiss)					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, migmatites					
								fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, migmatites					
								fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, migmatites					
								fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, migmatites					
								fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, migmatites					
								fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, migmatites					
								fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, migmatites					
								fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, migmatites					
				Dahomeyen, Groupe de Djougo & Kandi: Gneiss à deux micas & Gneiss à biotite				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, migmatites					
				Dahomeyen, Groupe de Djougo & Kandi: Gneiss à deux micas & Gneiss à biotite				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Gneisses	Gneisses, mica schists	Gneisses, mica schists, migmatites					
My	Mylonites (undiff.)	Mylonites (indiff.)	Mylonites (undiff.)	Mylonites (undiff.)				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Schists	Schists, gneisses	Schists, gneisses					
				Mylonites (undiff.)																			
				silicified, sheared rock, large quartz veins																			
mA	Complexe mylonitique de l'Alibori	Gneiss, granulites, schistes verts	Gneiss, granulite, greenschists					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Schists	Schists, gneisses	Schists, gneisses					
G	Granites indifférenciés	Granites indifférenciés	Granites (undiff.)	Première à troisième phase : Granite parfois biotitique et granodiorite, granite pegmatoïde et migmatites				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Magmatic rocks	Plutonic rocks	Plutonic rocks (acid)	Plutonic rocks (acid to intermediate)					
				Première à troisième phase : Granite parfois biotitique et granodiorite, granite pegmatoïde et migmatites																			
				Première à troisième phase : Granite parfois biotitique et granodiorite, granite pegmatoïde et migmatites																			
				Première à troisième phase : Granite parfois biotitique et granodiorite, granite pegmatoïde et migmatites																			
				Première à troisième phase : Granite parfois biotitique et granodiorite, granite pegmatoïde et migmatites																			
				Première à troisième phase : Granite parfois biotitique et granodiorite, granite pegmatoïde et migmatites																			
				Première à troisième phase : Granite parfois biotitique et granodiorite, granite pegmatoïde et migmatites																			
				Première à troisième phase : Granite parfois biotitique et granodiorite, granite pegmatoïde et migmatites																			
				Première à troisième phase : Granite parfois biotitique et granodiorite, granite pegmatoïde et migmatites																			
				Première à troisième phase : Granite parfois biotitique et granodiorite, granite pegmatoïde et migmatites																			
				Première à troisième phase : Granite parfois biotitique et granodiorite, granite pegmatoïde et migmatites																			
				Première à troisième phase : Granite parfois biotitique et granodiorite, granite pegmatoïde et migmatites																			
				Première à troisième phase : Granite parfois biotitique et granodiorite, granite pegmatoïde et migmatites; medium to coarse grained biotite granite																			
				Fine-grained biotite granite																			
				coarse, porphyritic hornblende granite																			
				Biotite and biotite hornblende granodiorite, quartz diorite																			
				undifferentiated granite, granite gneiss, migmatite																			
				Quartz-syenite				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Magmatic rocks	Plutonic rocks	Plutonic rocks (basic)	Plutonic rocks (basic)					
				Diorites				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Magmatic rocks	Plutonic rocks	Plutonic rocks (basic)	Plutonic rocks (basic)					
				Diorites																			
				Dolerite				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Magmatic rocks	Plutonic rocks	Plutonic rocks (basic)	Plutonic rocks (basic)					
SA	Serpentinites, amphibolites, filons basiques	Serpentinites, amphibolites, filons basiques	Serpentinite, amphibolite, basic sills	Serpentinites, amphibolites, filons basiques				fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Metamorphic rocks	Schists	Serpentinites	Serpentinites, ophiolitic series					
				Serpentinites, amphibolites, filons basiques																			
				Serpentinites, amphibolites, filons basiques																			
				Serpentinites, amphibolites, filons basiques																			
				Serpentinites, amphibolites, filons basiques																			
				Serpentinites, amphibolites, filons basiques																			
				Metagabbro and hornblende schist																			
BIF	Banded iron formation	Formations de fer rubanées	Banded iron formation					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Clastic rocks	Shales	Shales	Shales					
V	Meta-volcano sedimentary series	Série sedimentaire meta-volcanique	Meta-volcano sedimentary series					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Magmatic rocks	Volcanic rocks	Volcanic rocks	Volcanic rocks, shales, sandstones, conglomerates, claystones, limestones					
R	Rhyolite	Rhyolite	Rhyolite					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Magmatic rocks	Volcanic rocks	Volcanic rocks (acid)	Volcanic rocks (acid)					
E	Olivine basalt	Basalte à olivine	Olivine basalt					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Magmatic rocks	Volcanic rocks	Volcanic rocks (basic)	Volcanic rocks (basic)					
vsA	Complexe volcano-sédimentaire d'Alibori,	Roches volcaniques de compostion de rhyolitique à andésitique	Rhyolitic to andesitic volcanic rocks					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Magmatic rocks	Volcanic rocks	Volcanic rocks, pyroclastic rocks	Volcanic rocks (acid), pyroclastic rocks, sandstones, shales					
vsPB	Complexes volcano-sédimentaires: Pako, Barou	Roches volcaniques de composition basaltique-andésitique	Basaltic to andesitic volcanic rocks					fracturé	-	consolidé	-	fracturé	Aquifère local	consolidated	Magmatic rocks	Volcanic rocks	Volcanic rocks, pyroclastic rocks	Volcanic rocks, pyroclastic rocks					

IV Lithology classification of the IHME1500

Tab. 12: Aggregation scheme of the IHME1500 lithology classification for the three consolidation levels unconsolidated, partly consolidated, and consolidated (taken from Duscher et al. 2015).

Level 5: Unconsolidated materials

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4
Gravels, sands	Gravels, sands	Gravels	Coarse sediments
Valley fillings	Gravels, sands	Gravels	Coarse sediments
Gravels, sands covered by clays, silts	Gravels, sands, clays	Gravels	Coarse sediments
Gravels, sands, clays	Gravels, sands, clays	Gravels	Coarse sediments
Sands	Sands	Sands	Coarse sediments
Sands (glauconitic)	Sands	Sands	Coarse sediments
Sands, clays	Sands, clays	Sands	Coarse sediments
Sands, silts, clays	Sands, clays	Sands	Coarse sediments
Sands, gravels	Sands, gravels	Sands	Coarse sediments
Sands, gravels, boulders, clays, silts	Sands, gravels	Sands	Coarse sediments
Sands, gravels covered by clays, silts	Sands, gravels, clays	Sands	Coarse sediments
Sands, gravels, silts, clays	Sands, gravels, clays	Sands	Coarse sediments
Clays	Clays	Clays	Fine sediments
Clays, marls with gypsum	Clays	Clays	Fine sediments
Clays, boulder clays, silts, sands, gravels	Clays, boulder clays	Clays	Fine sediments
Clays, sands	Clays, sands	Clays	Fine sediments
Clays, sands, gravels	Clays, sands	Clays	Fine sediments
Clays, silts, sands	Clays, silts	Clays	Fine sediments
Clays, silts, sands, gravels	Clays, silts	Clays	Fine sediments
Marls, clays	Marls, clays	Marls	Fine sediments
Silts, clays, gravels, boulders	Silts, clays	Silts	Fine sediments
Silts, clays, sands	Silts, clays	Silts	Fine sediments
Fine sands	Silts, sands	Silts	Fine sediments
Fine sands, silts, clays, gravels	Silts, sands	Silts	Fine sediments
Silts, fine sands	Silts, sands	Silts	Fine sediments

Level 5: Partially consolidated materials

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4
Limestones and sands	Limestones and sands	Limestones and sands	Calcareous rocks and coarse sediments
Limestones, conglomerates, sandstones, marlstones and sands			
Dolomitic limestones, marlstones, siltstones, sandstones and sands	Limestones, marlstones and sands		
Limestones (sandy), sandstones and sands, silts	Limestones, sandstones and sands		
Limestones, sandstones and sand, gravel			
Limestones, sandstones and sands, clays			
Limestones, sandstones and sands, clays with gypsum			
Limestones, sandstones and sands, silts, clays			
Marlstones, limestones, sandstones and sands, clays, marls	Marlstones, limestones and sands, clays	Marlstones and sands	
Marlstones, sandstones and sands, clays	Marlstones, sandstones and sands, clays		
Clays and dolomitic limestones	Limestones and clays	Limestones and clays	Calcareous rocks and fine sediments
Gypsum, anhydrite and clays			
Limestones and clays, fine sands			
Clays, marls and limestones	Limestones and clays, marls		
Limestones, conglomerates, sandstones and clays	Limestones, conglomerates and clays		
Clays, sands and dolomitic limestones, marlstones, sandstones	Limestones, marlstones and clays, sands		
Dolomitic limestones, marlstones and clays with gypsum			
Limestones, marlstones and clays, sands, silts with gypsum			
Clays and limestones, sandstones	Limestones, sandstones and clays		
Clays, sands, gravels, marls and limestones, sandstones, conglomerates, pyroclastic rocks			
Limestones, sandstones, conglomerates, ophiolitic series and clays			
Chalkstones and marls	Limestones and marls	Limestones and marls	
Dolomitic limestones and marls			
Limestones and marls			
Marls and limestones			
Dolomitic limestones and marls, clays	Limestones and marls, clays		
Dolomitic limestones and marls, clays with gypsum			
Limestones, ophiolitic series and marls, clays			
Marls, clays and limestones with gypsum and anhydride			

<table>
<tr><th>LEVEL 1</th><th>LEVEL 2</th><th>LEVEL 3</th><th>LEVEL 4</th></tr>
<tr><td>Limestones, claystones, sandstones, conglomerates and marls, sands</td><td rowspan="2">Limestones, claystones and marls</td><td rowspan="9">Limestones and marls</td><td rowspan="13">Calcareous rocks and fine sediments</td></tr>
<tr><td>Marls and claystones, limestones</td></tr>
<tr><td>Limestones, calcarenites, sandstones and marls</td><td rowspan="7">Limestones, sandstones and marls</td></tr>
<tr><td>Limestones, sandstones and marls</td></tr>
<tr><td>Limestones, sandstones, siltstones and marls</td></tr>
<tr><td>Limestones, shales, sandstones and marls</td></tr>
<tr><td>Limestones, siltstones, sandstones and marls, clays</td></tr>
<tr><td>Marls and limestones, sandstones</td></tr>
<tr><td>Marls, clays, sands and limestones, sandstones</td></tr>
<tr><td>Clays, sands and marlstones, pyroclastic rocks with gypsum</td><td>Marlstones, pyroclastic rocks and clays, sands</td><td rowspan="3">Marlstones and clays</td></tr>
<tr><td>Marlstones, sandstones, conglomerates with lignites and clays</td><td rowspan="2">Marlstones, sandstones and clays</td></tr>
<tr><td>Marlstones, sandstones, limestones and clays</td></tr>
<tr><td>Marlstones, sandstones and marls, clays</td><td>Marlstones, sandstones and marls, clays</td><td>Marlstones and marls</td></tr>
<tr><td>Silts, clays, sands, gravels and conglomerates</td><td>Conglomerates and sands, silts</td><td rowspan="4">Conglomerates and sands</td><td rowspan="15">Clastic rocks and coarse sediments</td></tr>
<tr><td>Conglomerates, sandstones, limestones and sands, clays</td><td>Conglomerates, sandstones and sands, clays</td></tr>
<tr><td>Conglomerates (calcareous), sandstones and sands, clays, gravels</td><td rowspan="2">Conglomerates, sandstones and sands, gravels</td></tr>
<tr><td>Conglomerates, sandstones and gravels, sands</td></tr>
<tr><td>Calcarenites and sands</td><td rowspan="5">Sandstones and sands</td><td rowspan="11">Sandstones and sands</td></tr>
<tr><td>Gravels, sands, clays, marls and sandstones, conglomerates, limestones</td></tr>
<tr><td>Pyroclastic rocks and sands, clays</td></tr>
<tr><td>Sands and sandstones</td></tr>
<tr><td>Sandstones, shales and silts</td></tr>
<tr><td>Sands, clays and sandstones</td><td rowspan="3">Sandstones and sands, clays</td></tr>
<tr><td>Sands, silts, clays and sandstones</td></tr>
<tr><td>Siltstones, sandstones and sands, clays</td></tr>
<tr><td>Sands, clays and sandstones, conglomerates</td><td>Sandstones, conglomerates and sands, clays</td></tr>
<tr><td>Sands, clays and sandstones, limestones</td><td rowspan="2">Sandstones, limestones and sands, clays</td></tr>
<tr><td>Sands, clays, marls and sandstones, phosphorites, lignites</td></tr>
</table>

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4
Clays and claystones, marlstones	Claystones and clays	Claystones and clays	Clastic rocks and fine sediments
Clays and shales (combustible)			
Clays and claystones, sandstones, conglomerates	Claystones, sandstones and clays		
Clays, sands, gravels, marls and claystones, sandstones, conglomerates			
Claystones, sandstones, limestones and clays			
Claystones, sandstones, siltstones and clays			
Conglomerates, sandstones, claystones and clays	Conglomerates, sandstones and clays	Conglomerates and clays	
Conglomerates, limestones, sandstones and marls, clays	Conglomerates, sandstones and clays, marls		
Conglomerates, sandstones and marls, clays			
Conglomerates, sandstones and marls, clays with gypsum			
Clays, silts and sandstones, marlstones	Sandstones and clays	Sandstones and clays	
Sandstones, limestones and clays			
Sandstones, shales (combustible) and clays			
Sandstones, siltstones, conglomerates and clays			
Clays, marls and sandstones	Sandstones and clays, marls		
Clays, marls and sandstones, conglomerates			
Clays, marls and sandstones, siltstones, limestones			
Clays, marls and sandstones, siltstones, limestones with gypsum			
Sandstones and clays, marls			
Clays, sands and sandstones	Sandstones and clays, sands		
Clays, sands and sandstones with gypsum			
Clays, sands and siltstones, sandstones			
Clays, sands, gravels and sandstones with gypsum			
Clays, sands, marls and sandstones, shales			
Marls and sandstones	Sandstones and marls	Sandstones and marls	
Marls, sands, clays and sandstones	Sandstones and marls, sands		
Marls, clays and sandstones, conglomerates, limestones with gypsum	Sandstones, conglomerates and marls		
Sandstones, shales, conglomerates, limestones and marls			
Marls and sandstones, limestones with gypsum	Sandstones, limestones and marls		
Marls and sandstones, limestones, claystones			

Level 5: Consolidated materials

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4
Limestones	Limestones	Limestones	Calcareous rocks
Dolomitic limestones			
Travertines			
Dolomitic limestones, plutonic rocks			
Gypsum, anhydrite, dolomitic limestones			
Limestones (jointed, karstified)	Limestones (jointed, karstified)		
Dolomitic limestones (jointed, karstified)			
Chalkstones, limestones (jointed, karstified)			
Limestones, marlstones	Limestones, marlstones		
Dolomitic limestones, marlstones, claystones			
Limestones, marlstones, sandstones, conglomerates			
Limestones, marlstones, schists			
Limestones, claystones, sandstones, conglomerates	Limestones, sandstones		
Limestones, sandstones			
Limestones, cherts, sandstones, shales			
Limestones, sandstones, claystones			
Limestones, shales	Limestones, shales		
Dolomitic limestones, shales, sandstones			
Limestones, claystones, shales			
Limestones, shales, sandstones			
Marlstones, claystones with gypsum and salt	Marlstones, claystones	Marlstones	
Marlstones, claystones, shales, phyllites			
Marlstones, sandstones	Marlstones, sandstones		
Conglomerates	Conglomerates	Conglomerates	Siliciclastic rocks
Conglomerates, limestones, sandstones, marlstones			
Conglomerates, quartzites, sandstones, shales, dolomitic limestones	Conglomerates, sandstones		
Conglomerates, sandstones, cherts, shales, dolomitic limestones, ophiolitic series			

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4
Sandstones, phyllites, quartzites	Sandstones	Sandstones	Siliciclastic rocks
Sandstones			
Diatomaceous rocks			
Sandstones, claystones	Sandstones, claystones		
Siltstones, claystones, sandstones			
Sandstones, claystones, lignites			
Sandstones, claystones, marlstones, limestones with gypsum			
Sandstones, conglomerates	Sandstones, conglomerates		
Sandstones, conglomerates, shales, quartzites			
Sandstones, conglomerates, claystones, shales, marlstones			
Sandstones, limestones, shales, lignites	Sandstones, limestones		
Sandstones, marlstones	Sandstones, marlstones		
Sandstones, marlstones, limestones, volcanic rocks (basic)			
Sandstones, shales	Sandstones, shales		
Sandstones, shales, limestones			
Sandstones, shales, conglomerates, phyllites, volcanic rocks (basic)			
Sandstones, siltstones, claystones, limestones	Sandstones, siltstones		
Sandstones, siltstones, claystones			
Sandstones, siltstones, claystones with gypsum			
Shales	Shales	Shales	
Shales, limestones	Shales, limestones		
Shales, phyllites, schists, sandstones	Shales, phyllites		
Shales, quartzites, volcanic rocks	Shales, quartzites		
Shales, quartzites, sandstones			
Shales, quartzites, sandstones, phyllites, schists			
Shales, sandstones, limestones	Shales, sandstones		
Shales, sandstones			
Shales, sandstones, conglomerates			
Shales, sandstones, cherts, volcanic rocks			

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4
Plutonic rocks (acid to intermediate)	Plutonic rocks (acid)	Plutonic rocks	Magmatic rocks
Plutonic rocks (acid to intermediate, gneissic)			
Plutonic rocks			
Plutonic rocks (ultrabasic)	Plutonic rocks (basic)		
Plutonic rocks (basic)			
Volcanic rocks (jointed)	Volcanic rocks	Volcanic rocks	
Volcanic rocks			
Volcanic rocks, shales, sandstones, conglomerates, claystones, limestones			
Volcanic rocks, sandstones, shales, dolomitic limestones			
Volcanic rocks (acid)	Volcanic rocks (acid)		
Volcanic rocks (acid to intermediate)			
Volcanic rocks (basic)	Volcanic rocks (basic)		
Volcanic rocks (basic), ophiolitic series			
Volcanic rocks (basic to intermediate)			
Pyroclastic rocks	Volcanic rocks, pyroclastic rocks		
Volcanic rocks, pyroclastic rocks			
Pyroclastic rocks, volcanic rocks, marlstones			
Volcanic rocks (acid), pyroclastic rocks, sandstones, shales			
Gneisses, mica schists, amphibolites	Gneisses, mica schists	Gneisses	Metamorphic rocks
Gneisses, mica schists, migmatites			
Gneisses, plutonic rocks (acid)	Gneisses, plutonic rocks		
Marbles	Marbles	Marbles	
Marbles, schists, quartzites	Marbles, schists		
Phyllites, gneisses, shales, sandstones, volcanic rocks	Phyllites, gneisses	Phyllites	
Phyllites, schists, quartzites	Phyllites, schists		
Quartzites, shales	Quartzites	Quartzites	
Quartzites			
Quartzites, conglomerates, sandstones, shales (jointed)			
Quartzites, conglomerates, phyllites, shales			
Quartzites, sandstones, shales, volcanic rocks	Quartzites, sandstones		
Quartzites, sandstones, shales, limestones			
Quartzites, sandstones, shales			
Quartzites, sandstones, phyllites			
Quartzites, sandstones			
Schists, gneisses	Schists, gneisses	Schists	
Serpentinites, ophiolitic series	Serpentinites		

V Cross-sections

The following pages list the most relevant geological cross sections of the study area. For a comprehensive overview, see Tab. 10.

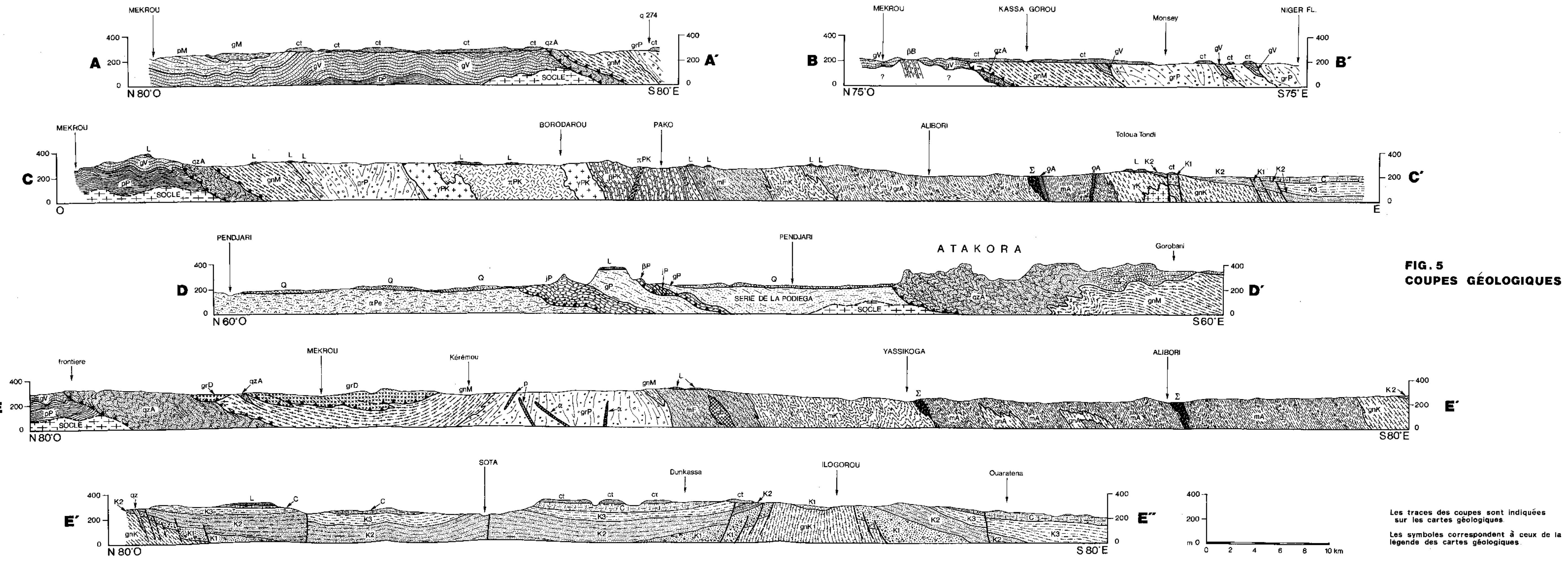


Fig. 36: Cross section of the northern Kandi Basin from the Notice explicative de la Carte Géologique à 1/200.000. Feuilles: Karimama, Porga, Kandi, Malanville *(Istituto ricerche Breda & OBEMINS 1989)*

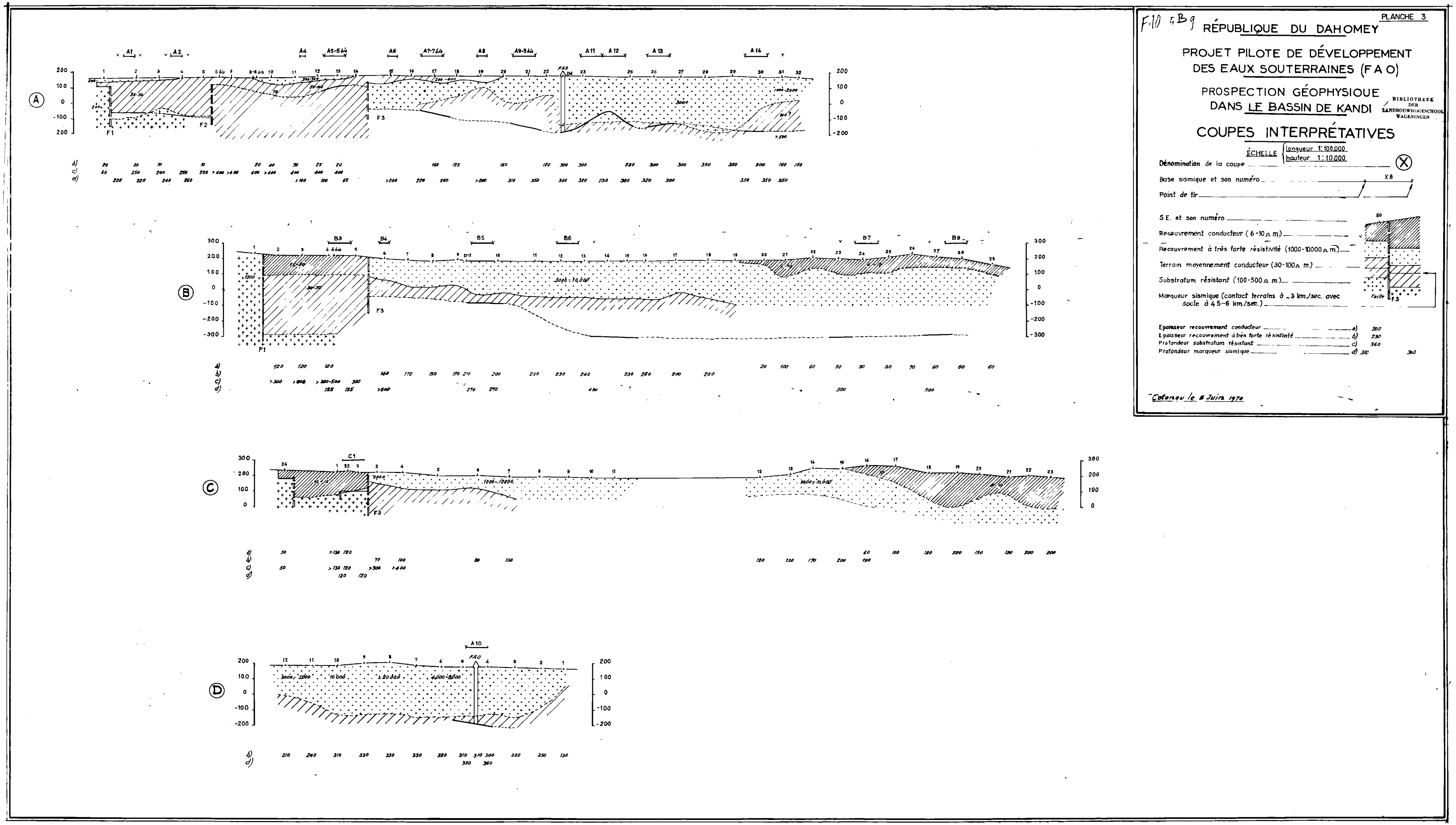


Fig. 37: *Interpreted geophysical cross section of the northern Kandi Basin from the Porjet pilote de développememt des eaux souterraines, FAO (Bouzid 1971)*

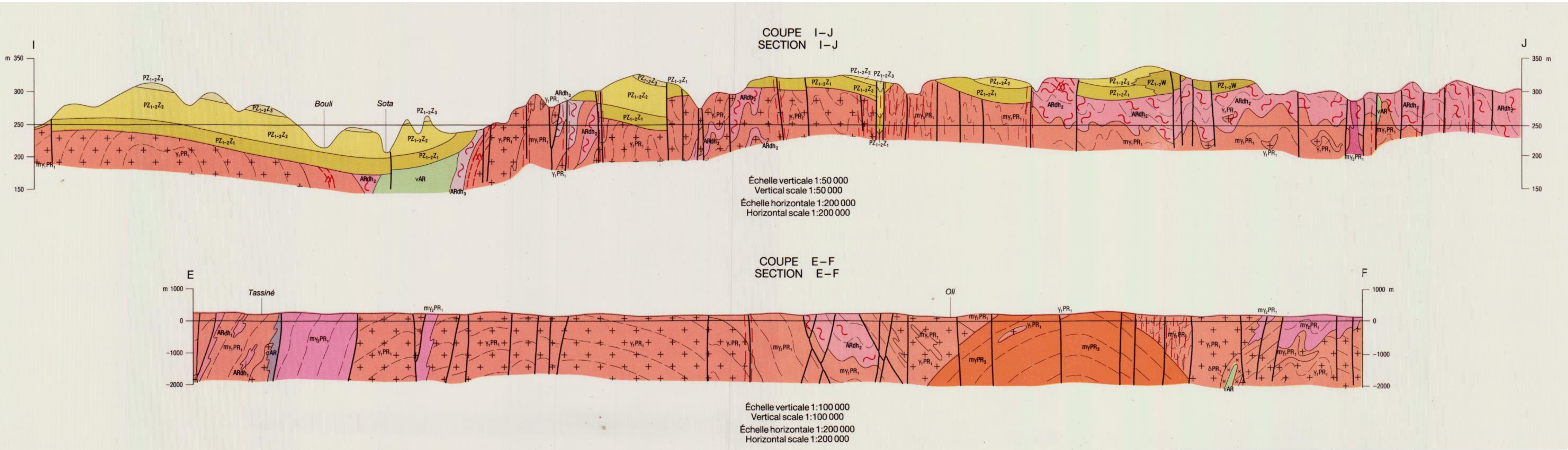


Fig. 38: Cross section of the southern Kandi Basin from the Carte de Géologie et des Minéraux utiles, Dunkassa, 1:200 000 of (Technoexport 1995b)

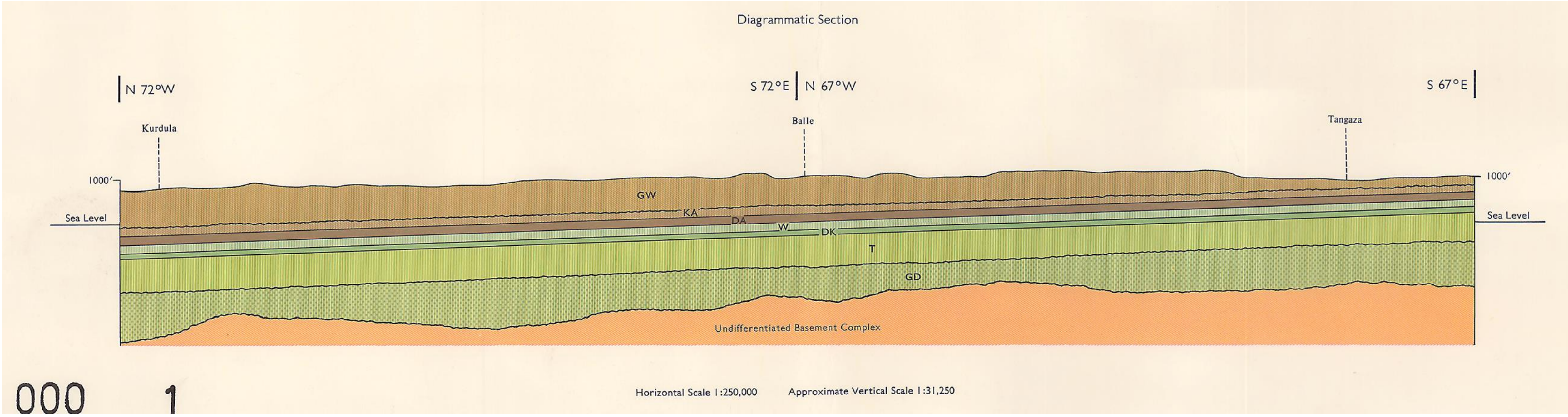


Fig. 39: *Cross section of the Sokoto Basin from the Geological Survey of Nigeria map series 1:250 000: Sheet 1-Tangaza (D.O.S. 1966a)*

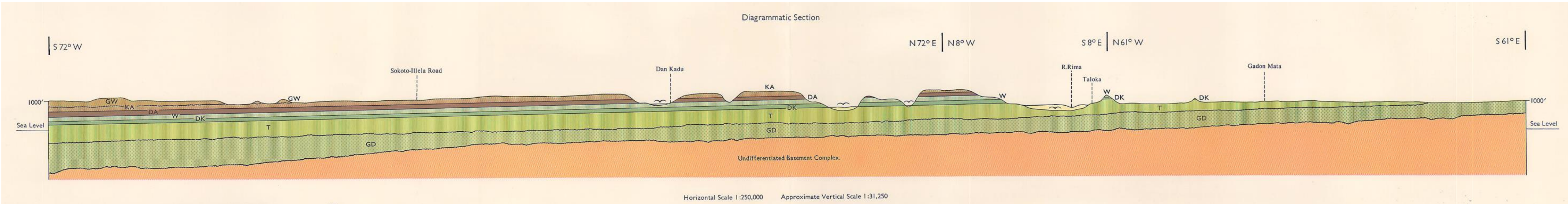


Fig. 40: *Cross section of the Sokoto Basin from the Geological Survey of Nigeria map series 1:250 000: Sheet 2-Sokoto (D.O.S. 1965a)*

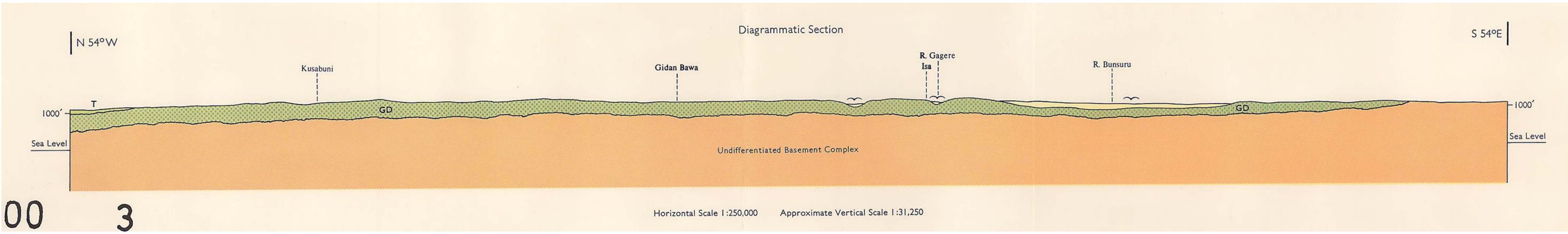


Fig. 41: *Cross section of the Sokoto Basin from the Geological Survey of Nigeria map series 1:250 000: Sheet 3-Shinkafe (D.O.S. 1965b)*

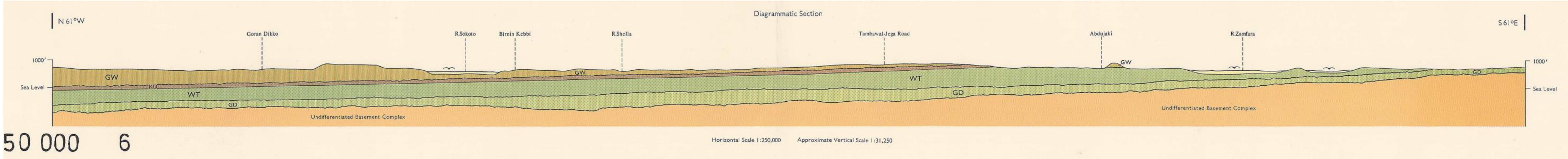


Fig. 42: *Cross section of the Sokoto Basin from the Geological Survey of Nigeria map series 1:250 000: Sheet 6 Birnin Kebbi (D.O.S. 1965c)*

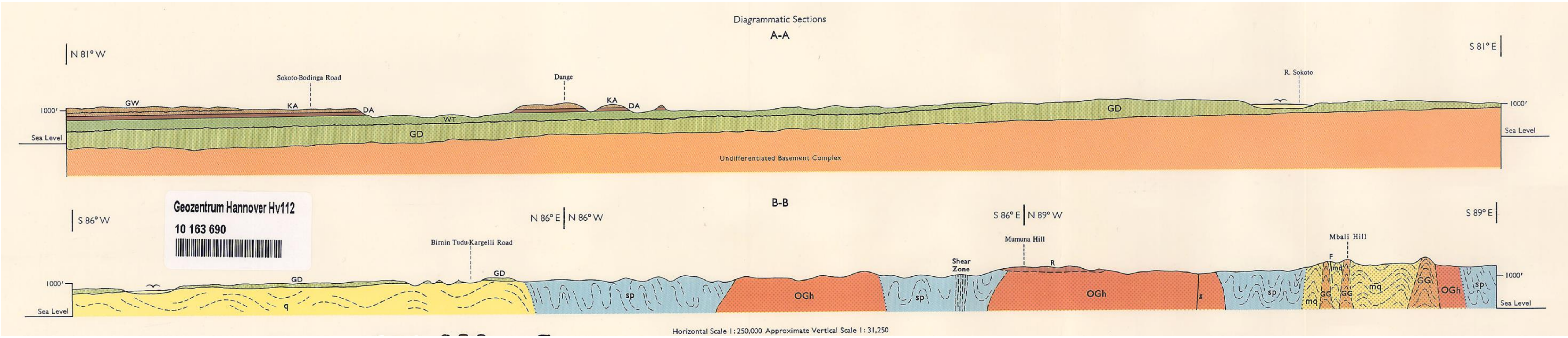


Fig. 43: *Cross section of the Sokoto Basin from the Geological Survey of Nigeria map series 1:250 000: Sheet 7-Gummi (D.O.S. 1966b)*

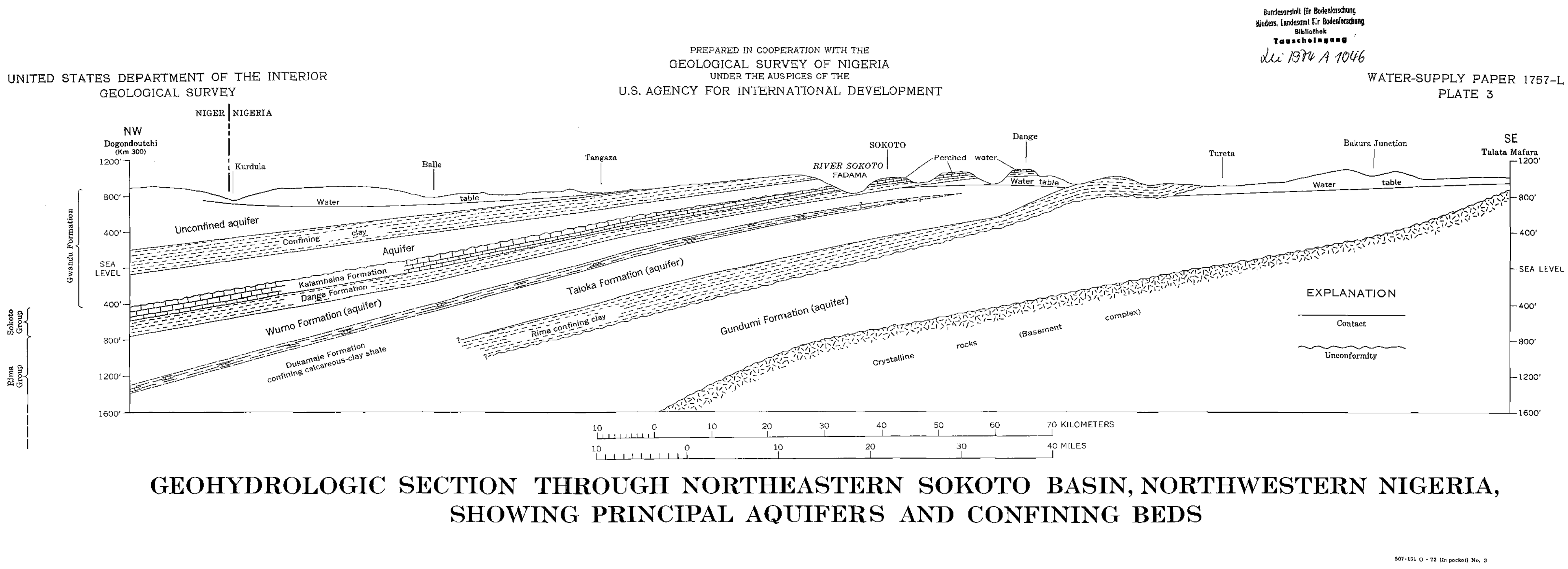


Fig. 44: *Cross-section of the Sokoto Basin from Anderson & Ogilbee (1973)*

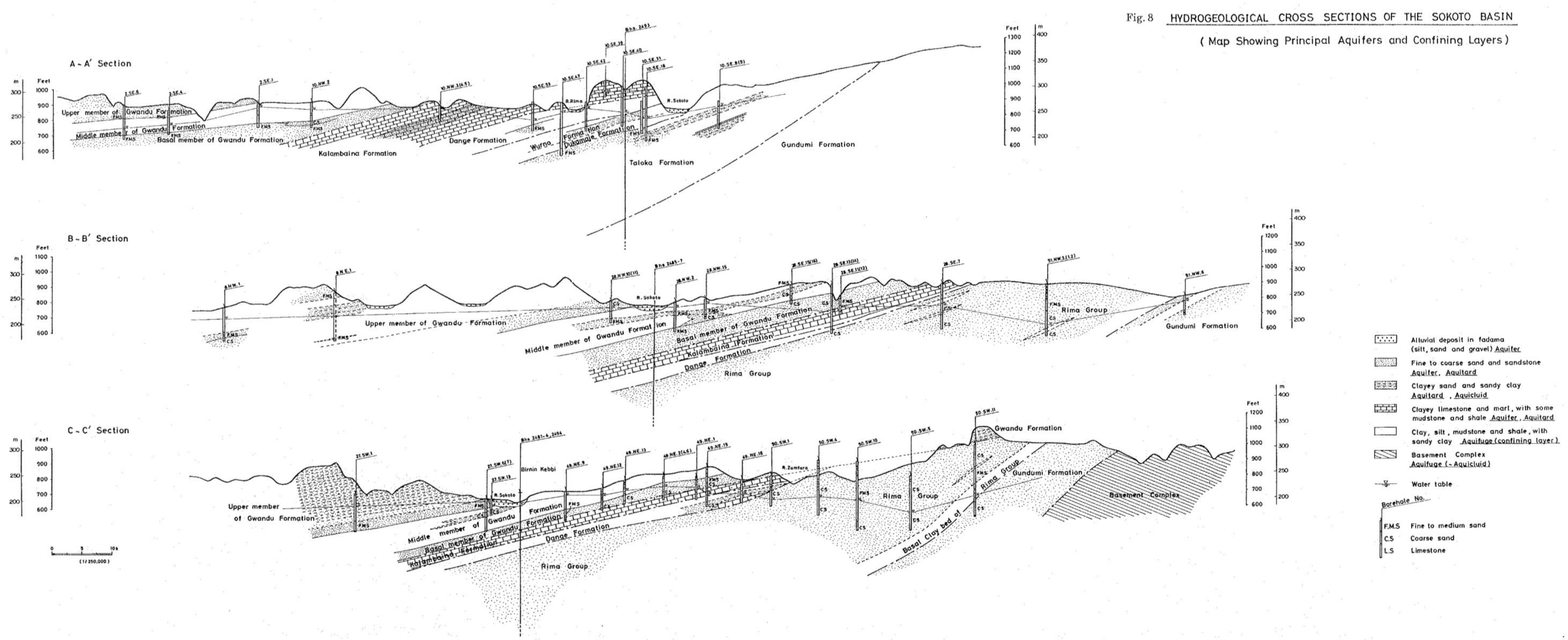


Fig. 45: Cross-sections of the Sokoto Basin elaborated by the Japan International Cooperation Agency (JICA 1990)

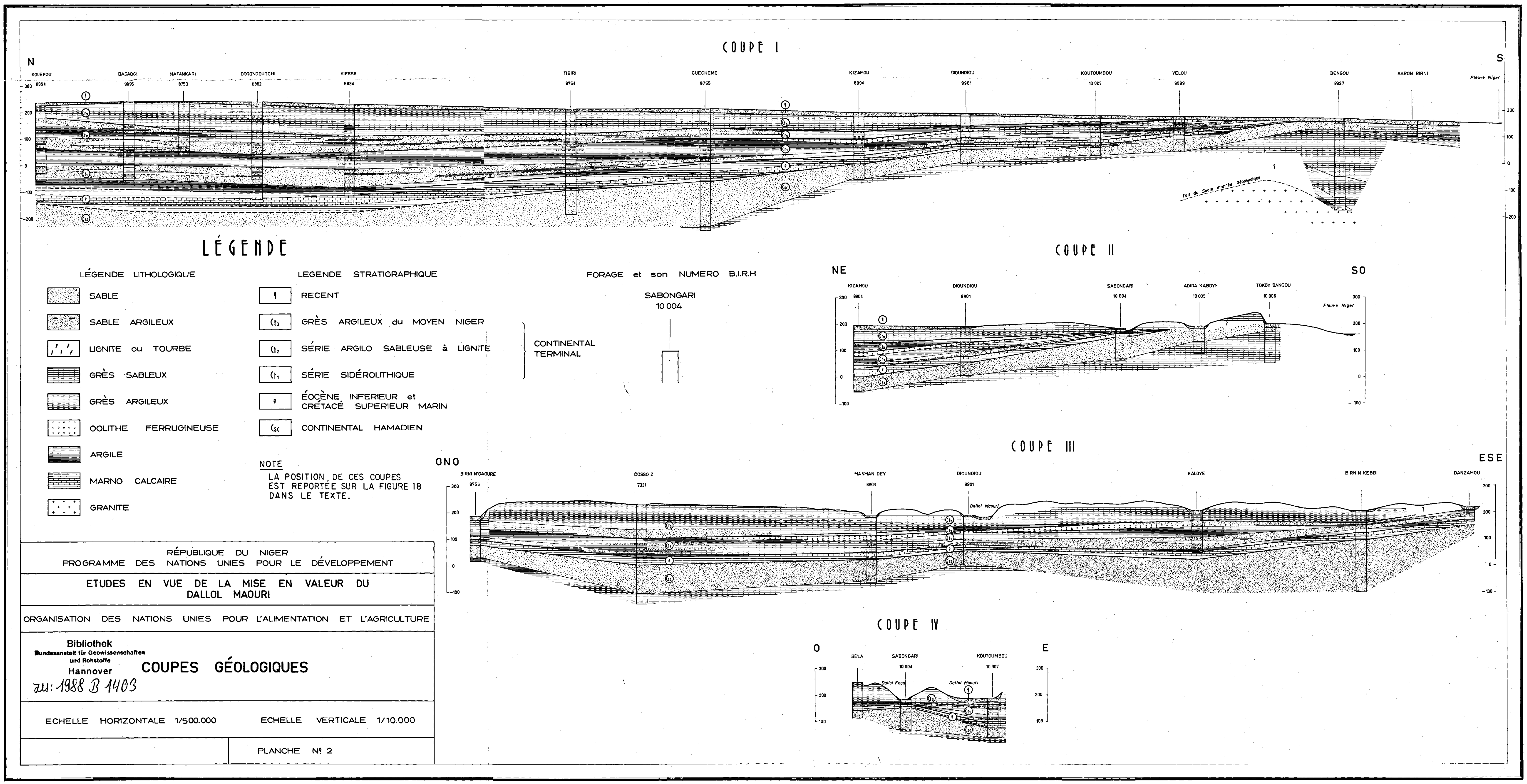


Fig. 46: Cross-sections along the Dallol Maouri, Dosso department of Niger. Planche 2 of the report "Études en vue de la mise en valeur du Dallol Maouri, Niger: Les Eaux Souterraines.(FAO 1970).

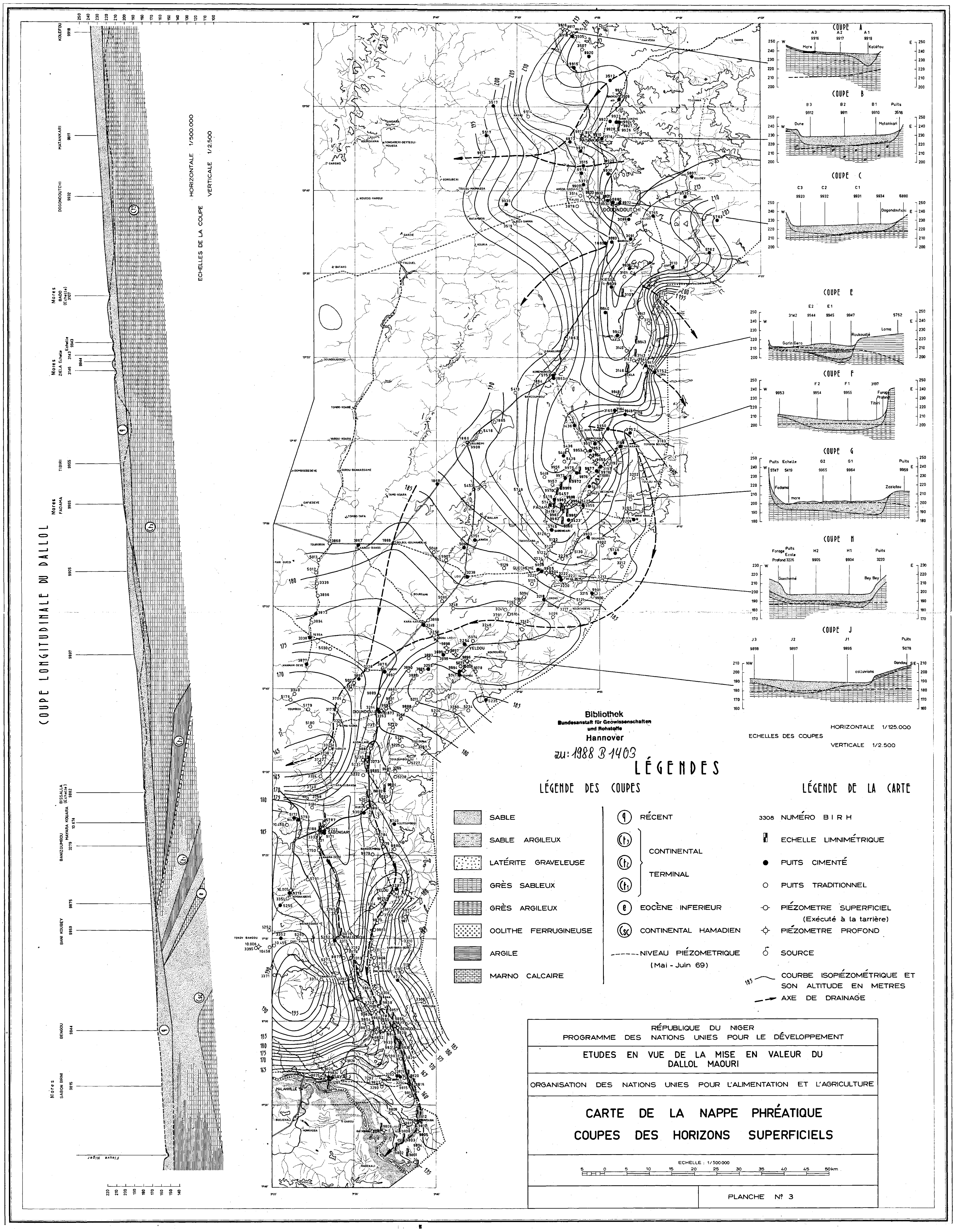


Fig. 47: Cross-sections along the Dallol Maouri in the Dosso department of Niger. Planche 3 of the report "Études en vue de la mise en valeur du Dallol Maouri, Niger: Les Eaux Souterraines.(FAO 1970)

VI Implementation in QGIS

This chapter is dedicated to the implementation of the workflow in the open source geographic information system QGIS. Here, the most important working steps are listed and explained:

VI.I Preparation: Topology (GIS)

For the correct performance of geoprocessing tools topologically correct input layers are necessary. QGIS provides several external plugins to check and correct the geometric topology:

- *Check Geometry Validity*
- *Topology Checker*
- *Check Geometry*
- GRASS algorithms (*v.clean*)

Topological corrections require often both automatic and manual cleaning. Manual editing may involve the use of QGIS tools (*Difference, Dissolve, Intersect*) to clear topological flaws not resolved otherwise. Slivers (small polygons, products of intersection processes) can be eliminated using the QGIS tool *Sliver elimination* after selection of the respective sliver size threshold. Highly inconsistent topologies of single features can be resolved by eliminating and subsequently recreation of features using *Saga GIS uunion* (*uunion*—no duplicate features are created as opposed to the QGIS tool: *Union*) and reattributed using *Join attributes by location* of *polygon centroids*.

Caution:

Topological artefacts may arise after EACH geoprocessing step. Topological correction using QGIS plugins (see above) or manual correction are necessary each time. Uncorrected topological errors may lead to erroneous geoprocessing results.

Particularly the build-in geoprocessing tools of QGIS may produce erroneous results. SAGA tools are more robust but do not conserve original coding (work-around using the coding: *system* for processing) as do (most) of the QGIS tools.

VI.II Spatial harmonization (GIS)

VI.II.I Union of maps

The shapefiles needs to be topologically correct to perform the following tasks!

1. **Create an outline polygon** of the (smaller) shapefile to be inserted in the main (larger) map dataset: Use the QGIS tool: *Dissolve all fields.*
2. **Cut out** the outline of the smaller dataset from the larger dataset and create a void: QGIS tool *Difference* or the more robust *SAGA Difference*
3. **Union** the main dataset with the inset dataset using the SAGA tool: *Uunion* (This tools often produced better results as the QGIS tool *Union*). The resulting attribute table has separated columns for each of the input shapes.

Create a field for the harmonized code:

4. Create a new field in the attribute table to store the harmonized Code: *Add Field*
5. Copy the harmonized codes from the respective original fields into the new single field: *Field Calculator*

VI.II.II Manual adaption of features

Spatial offset of features along the sheet margins or between maps can be manually corrected to obtain a seamless map without map sheet offsets. The QGIS vector editing functions *Node Tool, Merge selected features, Split parts, Reshape Features* allow comprehensive editing.

1. Make sure to A*ctivate Topological Editing*
2. Use the *Node Tool* from *Editing* to change the original outline of your features
3. Use the tool *Reshape objects* from the plugin A*dvanced Editing* to create extensive new outlines of your features.
4. Use the tool *Cut with polygon from another layer* from the plugin *Digitizing Tools* to a) create voids and b) fill these voids with new features that combine the outlines from different original dataset.

➔ **BaseLayer (3467 features)**

Union of overlapping map areas

When merging maps along a common map boundary joining of a general legend to the two original datasets and dissolution following a common code will often sufficient to assign a new unified classification. However, if overlapping maps are to be blended together, numerous small polygons will be created that have to be automatically or manually assign and merged to the larger units.

If no automatization mechanism is possible, manual assignment of the new code is necessary. Iterative repetition of the thematic and spatial harmonization steps might be necessary to obtain a final base layer with a single field (here: *Code*) showing the new codes of the new harmonized map. The resulting base layer should contain all data from the original maps, the new harmonized geological code, and additionally comments on harmonization steps and expert decisions.

VI.III Thematic harmonization (table work, GIS)

VI.III.I General legend (table work, e.g. Excel)

1. **Create a general legend** with fields for:
    a. original map codes,
    b. new harmonized common code for each thematic unit,
    c. information on the harmonized/generalized themes,
    d. complementary information on geometric harmonization steps
2. **Export** the general legend as a delimited text file (.csv) using semicolon-separated.
    ➔ **General Legend**

VI.III.II Join of the general legend

Base layer with a single field

The topologically correct base layer contains all information necessary for the new harmonized map. To ease the following steps, only the harmonized field code is necessary. Dissolving after the code field and splitting into single parts merges all neighbouring polygons belonging to the same new unit.

1. **Dissolve** features according to the new code field (*QGIS: Dissolve* or *SAGA: Polygon dissolve (by attribute);* more robust but loss of encoding)
2. Split **multipart features into singlepart features** (*SAGA tool Multipart to singlepart*)
3. The new polygons may show attributes inherited from the original maps. **Delete** all fields of the basis layer except fields necessary for joining the general legend.
    ➔ **BaseLayer_dissolved**

The resulting layer has a single field with the new harmonized code. Based on this code we add the generalized legend containing additional information such as a harmonized and classified lithology or generalized geological denominations.

Join attribute table (general legend) to the original dataset

1. **Add delimited text layer:** Load the prepared general legend as a delimited text file (.csv). Check the box: *No geometry* as the attribute table does not have spatial information.
2. **Join** the general legend as an attribute table (.csv) to the base layer shapefile using a common field (Abbreviation; here: *Code*) and create a dataset with the respective original codes and the new common code.
    Caution: Ensure the **coding** of all layers corresponds to your system (*System*). Using UTF8 might result in loss of special characters when using certain geoprocessing tools (particularly SAGA tools).
3. **Export** as a new shapefile with appended attribute table (*Save as …*)
    ➔ **GeologicalMap (BaseLayer merged with GeneralLegend) (82 classes)**

Boundary-free thematic layers

To create boundary-free thematic layers to display attributes (e.g. lithology or geological formations), it is necessary to dissolve features according to the respective fields:

4. **Dissolve** using the desired field from the joined attribute table to create a boundary-free thematic layer (*QGIS: Dissolve* or *SAGA: Polygon dissolve (by attribute);* more robust but loss of encoding).
   Depending on the tool, the dissolved layer shows only a single field thus requiring once more joining of the attribute table. If the resulting layer has a multipart geometry it will require conversion from multipart to singlepart (*SAGA tool Multipart to singlepart*) for individual treatment and labelling of features.
   ➔ **GeologicalMap_Lithology_IHME3 (16 classes)**
   ➔ **GeologicalMap_Formations (51 classes, Code_GL; 1236 features)**

VI.IV Harmonization of vector layers with identical fields (accessory datasets)

Layers/shapefiles with identical fields can be merged directly:

1. **Assure** that the common fields (same field names) of all layers to be merged are stored in the **same data type** (double, integer, string,…). Use the *QGIS tool Refactor Fields* to change field names and data type.
2. **Merge** (*QGIS tool: Merge vector layers*) the vector layers (point, line, polygon) with the common attributes (e.g. lineaments, minerals, strike and dip, …)
3. **Create a common field** for the legend with the main attributes and classes.
4. **Archive** the original attributes in new fields indicating their source layer (*Refactor fields, Field calculator*)

VI.V Datasets

VI.V.I Geological map

Formations:	Polygon shapefile *Formations* contains 51 chronostratigraphic units The solid geology map excludes drift and superficial deposits. Within the ➔ shapefile *baselayer* two fields indicate the original solid & drift geology (field: Code) and the assigned solid geology (field: *Code_GL*). Cover layers are displayed in a separate shapefile (➔ *CoverLayers*).
Lithology	Polygon shapefile *Lithology* shows the 16 different lithological classes of the third level of the lithological aggregation scheme of the IHME.
CoverLayers	Polygon shapefile *CoverLayers* comprises all units which do not belong to the solid geology, namely Aeolian deposits, shallow of the remnants Continental Terminal in Benin, and lateritic ferricrete plateaus.
BaseLayer	Polygon shapefile *Baselayer* features all original map legend information prior to dissolution and joining with the general legend. Important processing steps and decision are documented for each feature.

VI.V.II Supplementary data

Lineaments	Line shapefile *Lineaments* contains information on observed and inferred (field: *certainty*) lineaments and differentiates four classes (field: *type*): Lineaments (observed), Lineaments (inferred), Lineaments (omitted), and Fissures. Only observed and inferred lineaments are displayed on the harmonized map.
CrossSections:	Line shapefile *CrossSections* contains course of 71 cross sections of West Africa taken from maps and literature. Relevant cross sections of the study area are provided in the appendix.
Strike and Dip:	If available *Strike and Dip* has been recorded in a separate point shapefile.
Fossils	Point shapefile with the location of fossils and trace fossils and the original data sources.
Mineral Resources	Point shapefile with the locations of mineral occurences and the original data sources and if available an estimation of quantity.

VI.V.III Topographic data

Localities	Point shapefile *Localities* provides a selection of localities necessary for topographic orientation including locations of important (hydro-) geological sites/boreholes, and type locations for geological formations.
NationalBoundaries	Line shapefile *NationalBoundaries* shows the international limits between Benin, Niger, and Nigeria derived from the GADM28 database and adjusted to the Niger River (https://gadm.org/).

StreamNetwork — Line shapefile *StreamNetwork* shows the main drainage pathways of the study area differentiating perennial and intermittent watercourses. The shapefile *StreamNetwork* was adjusted using as a baseline internal data of the NBA, OpenStreetMap data (www.openstreetmap.org), and satellite images

VI.VI QGIS styles

The lithological patterns are derived from the standard library of the Federal Geographic Data Committee (FGDC). For accurate display of the digital dataset the the folder */USGS_FGDC* containing the provided scalable vector graphics (SVG) needs to be copied to the preset QGIS path for SVGs:

QGIS 2.x C:/Users/USERNAME/.qgis2/svg/USGS_FGDC/

QGIS 3.x C:/USERNAME/Application Data/QGIS/QGIS3/profiles/default/svg/USGS_FGDC/