Appui à la Gestion des Eaux Souterraines dans le Bassin du Niger

Geological map of the Niger Basin and Expected aquifer productivity map

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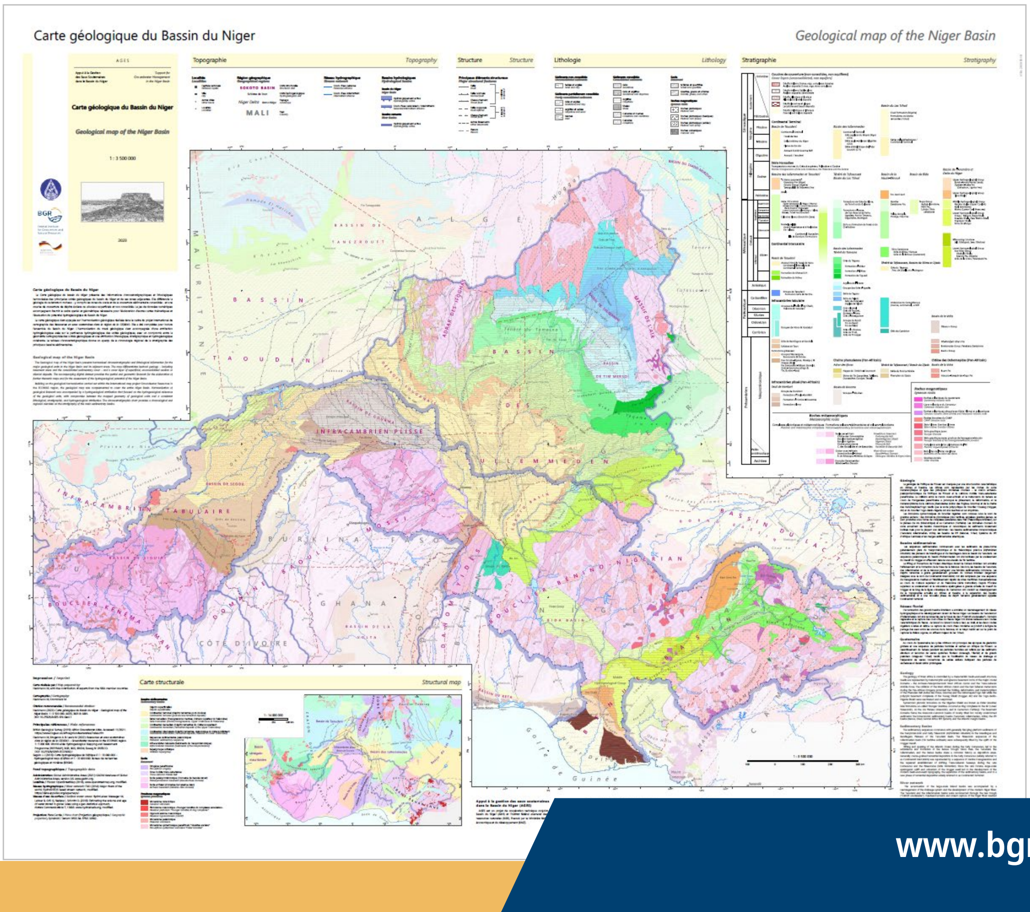
Federal Institute for Geosciences and Natural Resources



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Front page image: Geological map of the Niger Basin, © BGR

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1 Abstract

The ***Geological map of the Niger Basin*** presents harmonised chronostratigraphic and lithological information for the major geological units in the Niger Basin and its adjacent areas. The map differentiates bedrock geology – including basement areas and the consolidated sedimentary cover – and a cover layer of superficial, unconsolidated aeolian or alluvial deposits. The accompanying digital dataset provides the spatial and geometric linework for the elaboration of further thematic maps and for the assessments of the hydrogeological potential of the Niger Basin.

Building on the geological harmonization carried out within the international map project *Groundwater Resources in the ECOWAS region*, the geological map was complemented to cover the entire Niger Basin. Harmonisation of geological linework was accompanied by a geological attribution focusing on the hydrogeological relevance of the geological units, with compromise between the mapped geometry of geological units and a consistent lithological, stratigraphic, and hydrogeological attribution. The chronostratigraphic chart provides a chronological and regional overview on the stratigraphy of the main sedimentary basins.

The ***Expected aquifer productivity map of the Niger Basin*** presents information on the extent and the expected aquifer productivity of hydrogeological units in the Niger Basin and its adjacent areas. The map builds upon and expands the data set produced by the international mapping initiative for the map *Groundwater Resources in the ECOWAS region* covering here the entire Niger Basin and its adjacent areas.

The depicted hydrogeological units are lithostratigraphic strata with comparable hydrogeological characteristics and do not mirror directly the extent of aquifers. The linework and geometry of these hydrogeological units correspond to the lithochronostratigraphic units delimited on the *Geological map of the Niger Basin*. The spatial harmonisation and geological and hydrogeological attribution focused on the relevance of the respective unit, with compromise between the unit geometry and a consistent classification of geological, lithological, and hydrogeological attributes.

2 Introduction

2.1 Technical cooperation: Support for groundwater management in the Niger Basin

Support for Groundwater Management in the Niger Basin (AGES after its French acronym for *Appui à la gestion des eaux souterraines dans le Bassin du Niger*) is a technical cooperation project jointly conducted by the Niger Basin Authority (NBA) and the German Federal Institute for Geosciences and Natural Resources (BGR) financed by the Federal Ministry for Economic Cooperation and Development (BMZ). The project aims to provide the Niger Basin Authority, decision makers, and the public with hydrogeological baseline information and management tools to implement effective groundwater management strategies to safeguard the sustainable exploitation of groundwater resources thus ensuring lasting socio-economic benefits.

2.2 Objective

A **sustainable management** is the precondition for the long-term exploitation of groundwater resources. The poorly known groundwater resources of the sedimentary basins of West Africa may offer considerable potential to support further social and economic prosperity in the Niger Basin. However, sustainable management of groundwater resources faces numerous challenges: most importantly the **lack of effective national and regional groundwater monitoring strategies** associated with **weak national institutions** to channel and control the rising demand of rapidly growing and urbanising populations, agricultural expansion, and industrial growth and to effectively tackle hazards and challenges – notably groundwater pollution, environmental degradation, climate dynamics, and global change.

For the elaboration of groundwater monitoring strategies and hydrogeological assessment on both the national and regional level in the Niger Basin no comprehensive data set or map do exist. With the here presented maps, the technical cooperation project *Support for Groundwater Management in the Niger Basin* aims to make available **reviewed and processed baseline data for hydrogeological analyses** within the Niger Basin. The mapping initiative is part of a groundwater inventory survey to take stock of the present state of groundwater resources in the Niger River Basin.

Basic geological **data is widely available** from national map series and regional mapping projects; specific geological information from the grey literature (institutional reports, academic thesis) and research papers. Small-scale overview maps exist on continental-scales but are thematically restricted to chronostratigraphic units which are not appropriate for applied hydrogeological assessments due to the lack of essential lithological and stratigraphical information.

Research on groundwater in the Niger Basin builds strongly on the comprehensive hydrogeological assessments carried out by the *Observatoire du Sahara et du Sahel* (OSS) an its ongoing studies of the Taoudeni/Tanezrouft and Iullemmeden aquifer systems (GICRESAIT and ITTAS projects). The *Bureau de Recherches Géologiques et Minières* (BRGM) has a long-standing tradition of hydrogeological mapping in West Africa that materialized in the *Hydrogeological Map of Africa* (Seguin 2016). The *British Geological Survey* (BGS) engaged in the compilation and redaction of the *Africa African Groundwater Atlas*, an online resource providing hydrogeological and geological information and spatial data on groundwater on national scales (British Geological Survey 2019a). Recently, an **international mapping initiative – *"Groundwater Resources in the ECOWAS region"*** – led by UNESCO and AMCOW brought together BRGM, BGS, BGR, IGRAC and African partners ECOWAS and NBA to develop a hydrogeological map of the ECOWAS region.

Building on the harmonization work carried out within the mapping initiative for the ECOWAS region, AGES set out to elaborate comprehensive, harmonised hydrogeological and geological base maps for the regional assessment of groundwater covering the entire Niger Basin and its adjacent areas at an intermediate scale of 1 : 3 500 000. The mapping approach stands out by providing both printed maps and a spatial dataset of reviewed and processed thematic information. Geological information from maps and supplementary studies was reviewed and condensed into an attribute table with a variety of hydrogeological attributes ranging from the classical chronostratigraphic and stratigraphic denomination to lithology, aquifer productivity, occurrence of karst and many more.

Printed maps are produced for single thematic features. The first map - ***Geological map of the Niger Basin*** – delimits the major stratigraphic units and their corresponding lithology. It harmonises available stratigraphic information on regional and national scales with a broad lithological classification. A chronostratigraphic chart provides a regional geological overview. This map provides the geological foundation for subsequent hydrogeological and thematic maps. The stratigraphic units delimited on this map provide the spatial foundation and the basic (hydro-) geological units for subsequent hydrogeological and thematic maps.

A second map –***Expected aquifer productivity of the Niger Basin*** – presents information on the extent and the expected aquifer productivity of hydrogeological units in the Niger Basin and its adjacent areas. The **hydrogeological units** correspond to geological strata with comparable hydrogeological characteristics and mirror the litho-chronostratigraphic units delimited on the *Geological map of the Niger Basin*.

A **spatial dataset** with shapefiles of the spatial is made available for the Niger Basin Authority, its member countries, and the general public. The **technical report** presents the mapping approach, the methodological framework, and the data sources. The report discusses regional challenges and key assumptions relevant for the harmonization process. Supplementary themes shown on the maps – like hydrological basins and aquifer systems – are presented and their data sources explained.

Further details and explanations regarding the methodology of the main dataset of the principal base map – *Groundwater resources of the ECOWAS region* – and the challenges related to this literature-based and expert knowledge-driven mapping approach can be found in the respective Technical Note (Heckmann et al. 2022b)

3 The Niger Basin

3.1 Geology

The .geology of West Africa is controlled by a characteristic basin-and-swell structure. Swells are represented by metamorphic and igneous basement rocks of the major crustal domains – the **Archean-Paleoproterozoic West African craton** forming the Guinean rise to the west and the Pan-African Trans-Saharan Mobile Zone and its reworked basement complexes to the east. The collision of the West African craton and the East Saharan metacraton during the **Pan-African Orogeny** resulted in the Trans-Saharan Mobile Belt. Along the crustal suture zone – represented by the Pharusian Belt to the north (Adrar des Iforas, Gourma) and the Dahomeyan/Togo Belt to the south – sedimentary, volcanic, and basement rocks were deformed, folded, and metamorphosed. Further to the east, the Trans-Saharan Mobile Belt comprises polycylic basement complexes of the Tuareg Shield (Hoggar, Air) and the Togo-Benin-Nigeria Shield, which were reactivated and overprinted during the Pan-African Orogeny. Syntectonic plutonic intrusions on the Nigerian Shield are known as Older Granites; later intrusions, so-called Younger Granites, occurred as ring complexes in the Air (Lower Palaeozoic), on the Jos Plateau (Mesozoic), and in Cameroun (Tertiary).

These basement domains frame the Mesozoic-Cenozoic basins of locally tilted but mostly undeformed sediments: the intracratonic sedimentary basins (Taoudeni, Iullemmeden, Volta), the rift basins (Benue, Chad, Central Africa Rift System), and the Atlantic margin basins. The **sedimentary sequences** of the Taoudeni and Iullemmeden basins date back to the Precambrian and the Palaeozoic. Earliest sediments of the southern Taoudeni basin are the generally flat-lying platform sediments of the Neoproterozoic and Early Palaeozoic (*Inframbrien tabulaire*) in the Mandingue and Bandiagara Plateaus. The Palaeozoic sequences of the Iullemmeden basin were tilted by the uplift of the Hoggar massif and crop out in the Tin Seririne subbasin. Along the Liptako and the Benin-Nigerian Shield, Mesozoic and Cenozoic sediments cover and overlay the basement rocks. Only the structural Kandi Basin exposes older sediments of the Ordovician and Silurian glaciation that plunge below the Mesozoic-Cenozoic cover.

Since the Early Cretaceous and up to the Miocene, the three basins share a common history as deposition areas. Generally coarse-grained terrestrial deposition in the Early Cretaceous (widely referred to as *Continental Intercalaire*) was superseded in the Late Cretaceous and the Palaeocene by repeated marine transgressions (*Série Hamadien*). Repeatedly, a Trans-Saharan Seaway established involving early on the eastern later the western basins. Since the Late Eocene, large-scale epeirogenic uplift and volcanism of the Hoggar hot spot led to the development of the modern basin-and-swell topography of West Africa, the separation of the modern sedimentary basins (Chardon et al. 2016) and established a new phase of terrestrial deposition widely referred to as *Continental Terminal*.

The Quaternary evolution of the Niger Basin is characterized orbital cycles that triggered global glaciation episodes and variations of monsoon strength and moisture advection leading to a sequence of humid and dry periods in West Africa. The Greening of the Sahara during humid periods is reflected by the alluvial and lacustrine sediments of extensive river systems (Azawagh, Tilemsi) and large palaeolakes (Lake Mega Chad) while prolonged dry periods and desiccation led to the fossilization of the drainage network and the expansion of extensive aeolian sand covers.

3.2 Hydrology

The Niger River, *Egerou n-igereou* – the river of rivers – is the lifeline for the riparian population in the West African interior. From its source in the Fouta Djallon Massif in the humid highlands of Guinean and of the Ivory Coast at an altitude of about 800 m it travels 4 200 km to the Niger Delta in the Guinean Golf. The river brings reliable floodwater to the vast floodplain of the Niger Inland Delta, the breadbasket of Mali. As a losing stream, he travels the fringes of the Sahara Desert between Timbuctoo and Niamey. Its ancient left-bank tributaries – the wadi network of the Vallée du Tilemsi, the Dallol Basso (Azawagh), and Dallol Maouri (Vallée du Tadiss) are endorheic under the current climatic conditions and limit the extent of the hydrologically active Niger River Basin (ca. 1.4 million km²) to a fraction of its potential extensive catchment area (ca. 2.2 million km²). Its major tributary, the Benue, drains the highlands of Nigeria and Cameroon.

The accentuation of the large-scale inland basins during the Hoggar hot spot swell triggered the rearrangement of the drainage system and the development of the modern Niger River that re-established of the hydrological links between the basins. The two inland basins Taoudeni/Tanezrouft and Iullemmeden are assumed to have been endorheic basins similar to the modern Lake Chad Basin. During the Cenozoic, headward erosion of the Lower Niger River has breached the topographic swells and captured formerly endorheic streams that nourished terminal lakes in the internal drainage basins of the Iullemmeden and the Taoudeni/Araouane/Tanezrouft.

Stream capture resulted in the characteristic river bends – the Great or Large Bend at Gao, Mali, and two minor Nigerian bends at Jelwa and Jebba. Probably in the Late Miocene or the Oligocene, headward erosion of the Lower Niger River breached the basement complex separating the Bida and the Sokoto basin. The Taoudeni basin might have remained an autonomous endorheic basin characterized by terminal lakes (Lake Araouane, Lake Azawagh) until the final capture by the Middle Niger River in the Late Holocene (Bonne 2014). Today, the Niger River connects the two basins through the Gao trough – geographically called “Détroit soudanaise” – an up to 3000 m deep Cretaceous graben system and part of a large-scale structure extending along the margin of the Liptako basement down to the Bida and Benue basin.

3.3 Hydrogeology

The Niger River connects surface and groundwater resources of the major sedimentary basins in West Africa. The Niger River Basin encompasses several large aquifer systems and its numerous aquifers. In the Taoudeni Basin, the Niger River recharges the southern fringes of the **Taoudeni/Tanezrouf aquifer system**, in the Iullemmeden Basin it drains the semi-fossil groundwaters of the Continental Terminal, the upper strata of the **Iullemmeden Aquifer System**, while interlinking with the complex aquifer systems of the Bida, Benue, and Anambra basins in Nigeria.

A hydrogeological unit may host a single or various groundwater bodies, so-called aquifers. **Aquifer systems** are composed of connected aquifers and aquitards constituting “communicating vessels”. They are bounded by non-water-bearing strata, generally solid basement, but also impermeable aquifuges, or in regions of limited recharge by essentially dry hydrogeological units. The extents of the main aquifer systems mirror, in general, the extent of their sedimentary (sub-) basins. Consequently, the geometry of the main aquifer systems in the present dataset follows the linework of the corresponding hydrogeological units.

Each of the sedimentary basins host major aquifer systems – each of these comprising a variety of aquifers and/or aquifer suits. The most important ones listed here:

- **Taoudeni/Tanezrouft Aquifer System**
  - Taoudeni/Tanezrouft Aquifer System sensu strictu (Mesozoic-Cenozoic)
    - Continental Terminal
    - Continental Intercalaire
  - Taoudeni/Tanezrouft Aquifer System sensu latu (Palaeozoic)
  - Infracambrien tabulaire
  - Infracambrien plissé
- **Iullemmeden Aquifer System**
  - Continental Terminal
    - Continental Terminal I
    - Continental Terminal II
    - Continental Terminal III
  - Continental Intercalaire (incl. Grès de Tégama, Continental Hamadien)
  - Mesozoic-Palaeozoic aquifer systems
  - Kandi basin aquifer system
- **Nigerian aquifer systems of the Benue, Anambra and Bida basins**
  - Middle Niger (Bida Basin)
  - Anambra Basin (Lower and Middle Hydrogeological Groups)
  - Mesozoic aquifer systems of the Upper Benue Trough (incl. Kerri-Kerri Fm)
  - coastal aquifers of the Niger Delta (Upper Hydrogeological Group)

3.4 Aquifer systems and river basins

A hydrogeological unit may host a single or various groundwater bodies, so-called aquifers. **Aquifer systems** are composed of connected aquifers and aquitards constituting “communicating vessels”. They are bounded by non-water-bearing strata, generally solid basement, but also impermeable aquifuges, or in regions of limited recharge by essentially dry hydrogeological units. The extents of the main aquifer systems mirror, in general, the extent of their sedimentary (sub-) basins. Consequently, the geometry of the main aquifer systems in the present dataset follows the linework of the corresponding hydrogeological units.

Hydrological basins are the catchment or drainage areas of major rivers. On the map, they are subdivided into hydrologically active areas with permanent surface runoff contributing to the perennial stream network and passive areas where intermittent runoff is ephemeral and/or endorheic.

The groundwater flow pattern rarely mirror surface hydrological conditions and the **limits of an aquifer system and do not necessarily correspond to the watershed boundaries** of a river basin. Surface hydrological conditions defining the watershed of the river basin do not necessarily mirror the surface extent of aquifers or aquifer systems. Aquifer systems may extend far beyond the hydrological surface catchment and in arid areas particularly beyond the currently hydrologically active catchment. As a surface stream, the Niger River traverses impermeable geological strata that separate different aquifer system. Despite being part of the hydrological watershed of the Niger Basin, the aquifer systems of the Niger Basin extend beyond its surface catchment – and particularly beyond the currently hydrologically active catchment. Conversely, despite being part of the Niger River Basin, the underlying groundwater may belong to another aquifer system.

An example are the headwaters of the Mayo Kébbi, a tributary of the Benue River, draining the Toubouri depression – the ancient outlet of the palaeolake Megachad. Groundwater flow westwards towards the Benue Basin is, however, impeded by impervious granitic Precambrian basement (Gauthiot Falls). The aquifers hosted in the Cretaceous and Quaternary sediments of the Chadian Mayo Kebbi region thus pertain to the aquifer system of the endorheic Lake Chad Basin, although its surface waters drain to the Atlantic Ocean.

The Mayo Kébbi is also an example of modern **stream capture** at the water divide between the Benue and the Lake Chad Basin. The Mayo Kebbi is on the verge of capturing the Logone a major tributary of the Lake Chad by seasonally reactivating the ancient outlet of the paleolake Megachad. During high water, the Lower Logone overflows the sediment-obstructed ancient lake outlet at Dana (near Bongor) and the shallow swell at Eré into the Loka stream diverting floodwater of the Logone into the lakes Fianga, Tikem, and N'Gara in the Toubouri depression. Conversely, during the dry season, it is the groundwater of the Mayo Kebbi region that contributes to sustain the discharge of the Lower Logone River (Biscaldi 1970d). In the near future, the capture of the Logone River will enlarge the Niger-Benue watershed and accelerate the desiccation of the Lake Chad basin.

4 Geological map of the Niger Basin

4.1 Summary

The *Geological map of the Niger Basin* presents harmonized geological, chronostratigraphic and lithological information for the major geological units in the Niger Basin and its adjacent areas. It provides **basic spatial geometries for further thematic maps** and **assessments of the hydrogeological potential of the Niger Basin**.

Map elaboration encompassed thematic and spatial harmonization of generally mid-scale (1 : 250 000 – 1 :1 000 000) regional, national and local maps. The work builds upon the data set produced by the international mapping initiative for the *Groundwater Resources in the ECOWAS region* (Heckmann et al. 2022b, 2022a). The present map expands on this fundamental data set to include the Niger Basin portions of Chad and Cameroon and shows the entire Niger Basin and its adjacent areas.

The map (Fig. 1) differentiates bedrock geology, chronostratigraphic units, lithology, and superficial unconsolidated deposits. Spatial harmonisation and the accompanying hydrogeological attribution focused on the hydrogeological relevance of the geological units, with compromise between the mapped geometry of geological units and a consistent classification of hydrogeological attributes and lithological attribution. The general legend is complimented by a chronostratigraphic chart (Fig. 2) that juxtaposes stratigraphic units from different regions

Building on readily available maps and data, this lithological and stratigraphic map highlights the rich potential for integrating and harmonising existing geological information to improve the mapping in the Niger Basin.

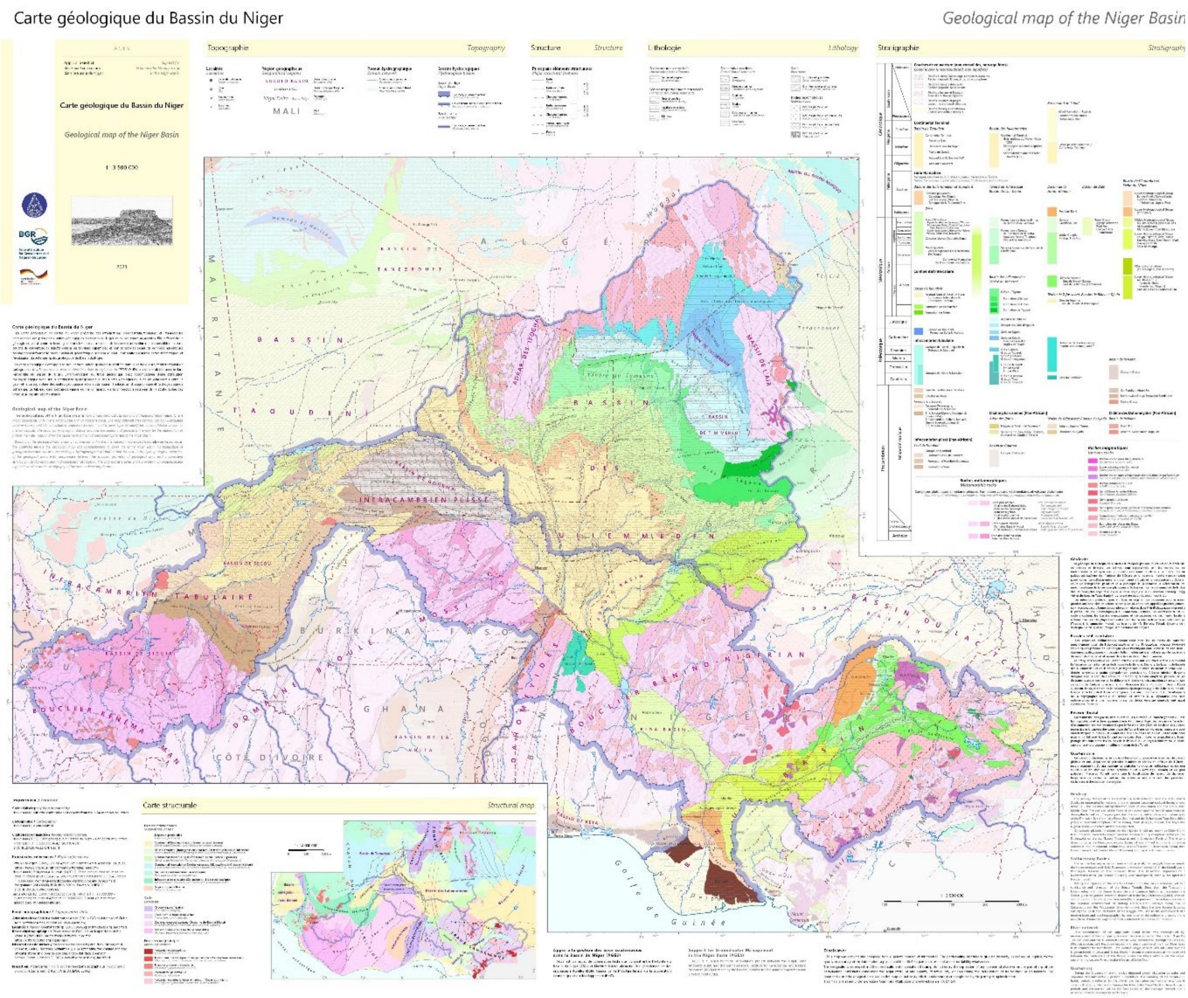

Fig. 1: The *Geological map of the Niger Basin.*

4.2 Materials and methods

The *Geological map of the Niger Basin* builds on the publicly available data set published as *Ressources en eaux souterraines dans la région de la CEDEAO – Groundwater resources in the ECOWAS region, 1 : 5 000 000* (Fig. 1, DOI: 10.25928/GWR-ECOWAS.1) and has been extended to include the hydrological basin of the Niger River and to cover relevant adjacent parts of Chad, Cameroun, Algeria, and Mauretania.

This report covers the extension of the map. More details on the elaboration of the aforementioned hydrogeological mapping initiative can be found in the corresponding technical note (Heckmann et al. 2022b).

4.2.1 Base maps

Geometric linework and thematic attribution is based on six principal maps (in bold) of a similar scales between 1 : 5 000 000 and 1 : 1 000 000. Complementary maps were consulted to resolve geometric and thematic mismatches particularly along national boundaries. The most relevant maps and datasets are listed in the Annex. For Chad, this include detailed maps with scales between 1 : 250 000 and 1 : 500 000.

Guinea, Côte d'Ivoire, Mali, Burkina Faso, Benin, Niger, Nigeria

***Ressources en eaux souterraines dans la région de la CEDEAO – Groundwater resources in the ECOWAS region,* 1 : 5 000 000** (Heckmann et al. 2022a)

Cameroon

For Cameroon, the 1 : 1 000 000 map *Geological Map of Nigeria* (Dessauvagie 1974) was consulted. It is based on the linework of the geological map series *Carte géologique de reconnaissance de la République Fédérale du Cameroun* (1 : 500 000) with the map sheets listed below covering the Niger Basin:

***Geological Map of Nigeria*. 1:1 000 000.** (Dessauvagie 1974)

Carte géologique de reconnaissance de la République Fédérale du Cameroun (1 : 500 000)

- *Garoua Ouest* (Dumort & Péronne 1966),
- *Garoua Est* (Schwoerer 1962),
- *Maroua* (Dumort & Péronne 1966),
- *Wum-Banyo* (Péronne 1969),
- *Douala-Est* (Weeksteen 1957),
- *Douala-Ouest* (Dumort 1968).

This map series is also the basis for the geometric linework of a further small-scale overview maps of Cameroun. Although they provide in detail differing thematic generalisation of the unit geology.

Carte géologique de la République unie du Cameroun - Geological map of the united Republic of Cameroon, 1 : 1 000 000 (Direction des mines et de la géologie 1980)

Géologie et ressources minérales du Camerou, 1 : 1 000 000 (Toteu et al. 2008)

Chad

For Chad, no single geological map of the boundary region to Nigeria and Cameroun is available. The consulted maps cover different parts of the southern Lake Chad Basin and show differing legend themes, generally with a strong focus on Quaternary stratigraphy (cf. .(Torrent 1965; Pias 1967; Biscaldi 1970a). Drawing particularly on the work of Bosch & Rueckl (2020) for the Lake Chad Basin Commission, a synthesis of the above-mentioned maps was elaborated.

***Esquisse géologique des formations tertiaires et quaternaires du Tchad (au Sud du 16e parallèle)*. 1:1 000 000. Feuille Est & Ouest,** (Pias 1967)

Unpublished digital data set of the *Groundwater Vulnerability to Pollution Map of the Lower Chari-Logone River Basin* (Bosch 2022) harmonizing geological and hydrogeological information of the original national maps:

- *Carte hydrogéologique de la plaine du Tchad. Nappe phréatique*. 1:2 00 000, Feuille N°1 – Nord, Feuille N°2 - Centre, Feuille N°3 - Sud, BRGM. (Biscaldi 1970a, 1970b, 1970c)
- *Hydrologic Map. Sheet 16. Ngala & Sheet 28. Gulumba*. 1:250 000 (SATTEC & SATMAP 1992b, 1992a)

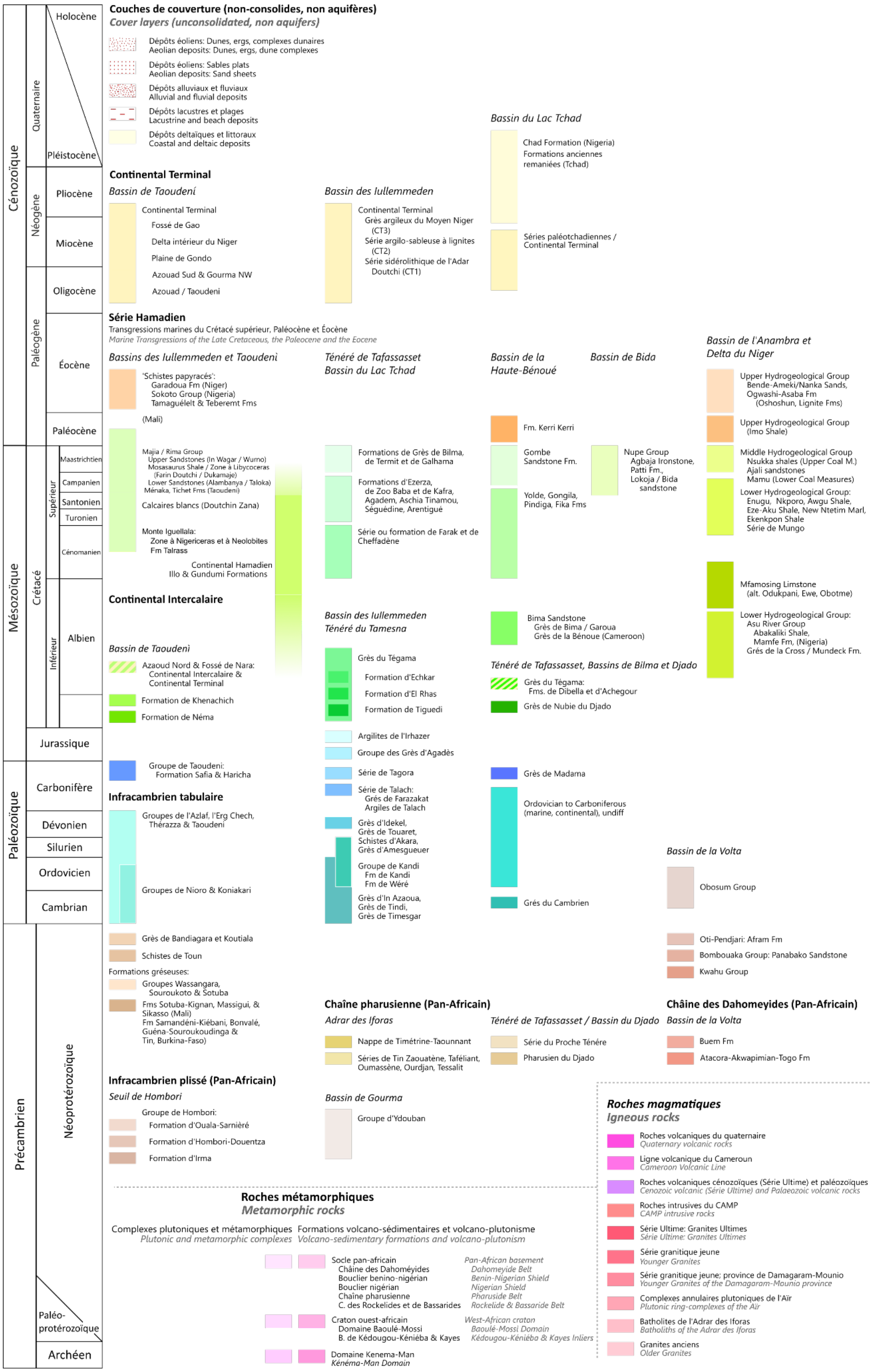

Fig. 2: Stratigraphic chart of the Niger Basin and its adjacent regions

Carte hydrogéologique de reconnaissance. Moundou. 1:500 000, BRGM (Torrent 1965)

Carte Geologique du Mayo Kebbi. from Guide Investisseur Minier – Mining Investor Guide. PNUD – UNDP CHD/91/007 (cited in Oyamta et al. 2013)

Nigeria

Dessauvagie's *Geological Map of Nigeria* covers beside of Nigeria all of north and substantial parts of south Cameroun providing already a transboundary geological overview facilitating the harmonisation process. Its thematic generalisation of the basement units is on a level comparable to the target map *Ressources en eaux souterraines dans la région de la CEDEAO* (Heckmann et al. 2022a).

***Geological Map of Nigeria*. 1:1 000 000.** (Dessauvagie 1974)

Geological Map of Nigeria. 1:1 000 000. Reprint 2011 (NGSA 2006)

Algeria

Republique du Niger. Carte Géologique (Greigert & Pougnet 1966)

Mauretanie

Africa Groundwater Atlas Country hydrogeological Maps Mauretania (British Geological Survey 2019b)

4.2.2 Methodology

Map harmonization does not create new information but presents existing information in a different – harmonized or unified –way facilitating the analysis and evaluation of the combined data set, which would not be possible with the individual original data sets. Harmonization naturally involves the loss of the original detailed information and the restriction on a tiny subset of available data. Further, during the harmonization process existing data is reinterpreted and despite the objective to minimize misinterpretation and mismatches between maps, these can never be ruled out.

The unification of thematic information from maps and data sets of different scale, with different classification and requires 1) thematic harmonisation including the elaboration of a common classification and a synoptic legend and 2) spatial harmonisation including the merging of corresponding units, the straightening or the splitting and creation of new spatial units guided by supplementary information and finally generalization and smoothing of unit boundaries.

All working stages require **expert decisions and manual modifications** of tables, charts or of the spatial extent of the respective thematic units. Only few parts of the process, mainly subordinated working steps like merging of legend classes can be automatized in a Geographic Information System. **Expert knowledge** is particularly required for the thematic harmonisation here foremost the juxtaposition of thematic units and the development of a common legend but also for the selection and formulation of attributes and nomenclature. Knowledge-based decision and manual comparison of geometries are equally indispensable for the creation of new spatial features, generalisation, and smoothing of rugged unit boundaries.

Rarely straightforward, map harmonization is an iterative process between thematic and geometric harmonization. The harmonization process is strongly dependent on the editor's knowledge and arbitrary judgement, thus requiring the contribution of an expert team and external validation.

I. Thematic harmonization (correlation, aggregation, attribution)

Based on the original map units, a comprehensive chrono- and lithostratigraphic framework is developed by correlating identical and/or similar stratigraphic units and assigning a common denomination and a suit of common attributes.

i. **Synoptic stratigraphic chart**.
Juxtaposition of the original stratigraphic units in a synoptic stratigraphic chart (Tab. 1).

ii. Aggregation and classification into a common legend

Comparison of stratigraphic position, thematic (geological/hydrogeological) attributes and identification of corresponding identical units. Aggregation on a common level and condensing into a unified general legend

iii. Nomenclature
Assignment of a common denomination for the entire stratigraphic unit

iv. Attribution
Assignment of associated hydrogeological attributes and population of the attribute table

II. Spatial harmonization and generalisation

Data sets of the original base maps were digitised and were available as shapefiles. Spatial harmonization was performed using the Geographic Information System QGIS (QGIS Development Team 2018). Given heterogeneous base maps, a large number of geometric adjustments was necessary to produce a consistent and harmonized dataset.

i. Digitisation of base maps
Relevant base maps were digitised and topologically corrected

ii. Geometric Harmonization
During geometric harmonization the original shape and extent of spatial features are modified to match the specifications defined by the unified general legend. following the knowledge-based expert decisions

Geometric harmonisation is conducted without a final attribute table as attributes are omitted during geoprocessing.

a. Union
Entire shapefiles with corresponding attribute fields are merged using the QGIS tool *Union*. *Union* is recommended over *Merge* (*Fusionner*) as it will split and create new features where the input features overlap.

b. **Merging**.
Spatial features corresponding to the same stratigraphic unit are merged

- *Merge (Regrouper*) transforms single parts to multipart features with a single attribute table entry for all instances of the same category. Merging can be done for combination of attributes to avoid the loos of attribute information.
- For manual manipulation the reverse tool *Multipart to single part* splits multipart features into spatially independent single features.
- *Merge selected features* (*Advanced Digitizing toolbar*) allows merging of manually selected features and selection of the attributes to be adopted

c. Splitting of features
Spatial features covering two or more different stratigraphic units are split

- *Split features* (*Advanced digitizing toolbar*) allows to split features following a manual outline or in combination with tracing (Topology toolbar) following boundaries of existing features. The separated features are attributed according to their new stratigraphic unit or merged with a feature of its new unit.

iii. Generalisation
For the target scale small features and minor or unrepresentative features are partly automatically or manually omitted and subsumed under and aggregated with dominant features

Spatial mismatch occur between map sheets and along national boundaries. The geometric linework was generalised drawing on expert-knowledge and a variety of thematic maps (c.f. Annexe 8.1).

iv. Smoothing
Prominent irregularities were smoothed manually. To preserve most features of the original geometries, a generally smoothing was not applied. The unit geometries were not brought to a

common scale and the final linework still shows a non-uniform ductus reflecting the scale and level of detail of the original maps.

v. **Topology**

Automated topological corrections were performed with the QGIS tools

- Topology Checker
- Check Validity
- Check Geometries
- vclean (GRASS tool)

Despite automatization tools and technically accurate data sets, manual correction was necessary to provide a topologically correct data set.

vi. **Attribute table**

In a final step the attribute table elaborated during the thematic harmonisation process is appended.

Tab. 1: Classification of sedimentary units in the Cameroon-Chad-Nigeria border region and general assignment of geological units between the consulted maps.

Carte géologique du Bassin du Niger - Geological map of the Niger Basin			Geological Map of Nigeria. 1:1.000.000 (Dessauvagie, 1974)		Esquisse géologique des formations tertiaires et quaternaires du Tchad (au Sud du 16e parallèle) (Pias, 1967)				Carte Hydrogeologique de la Plaine du Tchad (Biscaldi, 1970)			
ID	Geology	Géologie	ID	Géologie	ID	Strat.	Trans.	Géologie	ID	Géologie	Strat.	Valeur d'Aquifère
Qe	Aeolian deposits: Dunes, ergs, dune com plexes	Dépôts éoliens: Dunes, ergs, complexes dunaires	Qc	Quaternaire indifférencié, dunes anciens, ergs anciens								
									d1	Dunes anciennes remaniées : remanniement du a1-2 (feuille nord)	Q. ancien	Bonne
Ql	Alluvial and lacustrine deposits of modern Lake Chad	Dépôts alluviaux et lacustres du Lac Tchad actuels										
Qa4	Modern alluvial sediments: Mandara alluvial complex	Sédiments alluviaux actuels: Complexe alluvial de Mandara (4éme Transgression)										
Qa4	Modern alluvial sediments: Série alluviale subactuelle à actuelle (4éme Transgression)	Sédiments alluviaux actuels: Série alluviale subactuelle à actuelle (4éme Transgression)		~ Alluvium, river deposits	IV a	Formations Quaternaires récentes	IV éme Transgression	Série alluviale subactuelle à actuelle (3° delta du Chari triangle Fort-Lamy - Hadjer el Hamis - Suéram "Cameroun")	a4	Alluvions des cours d´eau		Bonne
				~ Alluvium, river deposits								
				~ Alluvions								
Qb4, N	Ngelewa ridge (290m, ~3ka)	Cordon sableux périlacustre - Ngelewa ridge (4éme Transgression, 290m, ~3ka)	Qb	Beach ridge deposits	IV b			Cordon sableux nord	a3(c1)	Cordon perilacustre stade 300-290m	Quaternaire récentes	Bonne
Ql3	Lacustrine sediments of the Late Holocene: Série lacustre (3éme Transgression, 2° delta du Chari) - Logone floodplain	Sédiments lacustres de l'Holocène tardif: Série lacustre (3éme Transgression, 2° delta du Chari) - Plaine du Tchad	Qc	Chad Formation					I3	Série argileuse récentes (stade lacustre 320m)		Mauvaise
Qa3	Alluvial sediments of the Holocene: Série sableuse récente (3éme Transgression, 2° delta du Chari)	Sédiments alluviaux du Holocene: Série sableuse récente (3éme Transgression, 2° delta du Chari)			III d		III éme Transgression	Accolements sableux aux massifs de l´est				
Qb3, B	Bama ridge (329m, ~5ka)	Cordon sableux périlacustre - Bama ridge (3éme Transgression, 2° delta du Chari. 329m, ~5ka)	Qb	Beach ridge deposits	III c			Cordon sableux sud: Bongor-Koro Toro	a3(c2)	Cordon périlacustre stade 320m (feuille sud)		Bonne
Ql3	Lacustrine sediments of the Holocene: Série lacustre argileuse récente (3éme Transgression, 2° delta du Chari)	Sédiments lacustres du Holocene: Série lacustre argileuse récente (3éme Transgression, 2° delta du Chari)			E (IIIb+IVa)			Juxtaposition	a3	Alluvions récentes (bourrelets de berge des cours d´eau et sables de la région de Zymando)		Bonne à exellente
					III b			Série lacustre argileuse récente				
Qa3	Alluvial sediments of the Holocene: Série sableuse récente (3éme Transgression, 2° delta du Chari)	Sédiments alluviaux du Holocene: Série sableuse récente (3éme Transgression, 2° delta du Chari)			III a			Série sableuse récente (2° delta du Chari: triangle Dourbali - Hadjer el Hamis - Am Djemena)				
Qal2	Série fluvio-lacustre argilo-sableuse: Quaternary alluvial and lacustrine sediments of the Quaternary - 2nd Transgression (Pias, 1968)	Sédiments alluviaux et lacustres du Quaternaire: Série fluvio-lacustre argilo-sableuse: (2éme Transgression)			II b		II éme Transgression	Série fluvio-lacustre argilo-sableuse des "regs"				
					II a			Série fluvio-lacustre argilo-sableuse à nodules calcaires	I2	Série sablo-argileuse á nodules calcaires	Quaternaire ancien	Généralement mauvaise
CF	Chad Formation	Formations anciennes remaniées (Chad Formation)	Qc	Chad Formation	E (IIIb+IVa)	Formation continentales terminales et quaternaires anciennes à moyennes	I éme Transgression	Juxtaposition				
					D (II a + III a)			Juxtaposition	a1-2(d1)	Alluvions anciennes plus ou moins remaniées		Généralement bonne
					I e			Sud du 13° parallèle (1° delta du Chari: Milou - Bongor - Mandélia - Bokoro) - Séries anciennes remaniées				
					C (I d + III b + IV a)			Juxtaposition				
					B (I d + III b + IV a)			Juxtaposition				
					I d			Nord du 13° parallèle - Séries anciennes remaniées				
CT	Continental Terminal	Séries paléotchadiennes (Continental Terminal)			A (1 + II a + II b)			Juxtapositions Hälfte CF-FAR-Id				
					I c			Surface ferrallitiques - ancienne (antérieure à la surface cuiasses) - plus récentes				
					I b			Cuirasses ferrugineuses anciennes (par places cuirasses subactuelles à actuelles au sud du 10° parallèle)				
					I a			Surface bauxitique résiduelle de Koro				
CT-BF, Be	Benin Formation (Continental Terminal)	Benin Formation (Continental Terminal)	TQb	Benin Formation								
			TQm	Mpundu Formation (Mio-Pliocéne)								
Ci-Bi	Bima sandstone (Cameroun: Grès de Garoua, Grès de la Bénoue)	Grès de Bima (Cameroun: Grès de Garoua, Grès de la Bénoue)	Kgb	Grés de Garoua / Grés de la Bénoue / Grès de Bima	3			Formations crètacées (arkosos, grès, marnes, calcaires…)				
PzCT	Undiff. Palaeozoic and Cenozoic sandstones	Grés paléozoiques et continentaux terminaux indifférenciés			2			Grés paléozoiques et continentaux terminaux indifférensiés				
E-Bo	Série de Bonangando		Tb	Série de Bonangando								
P-Dz	Série de Dizangué		Tdi	Série de Dizangué								
C-Lb	Série de Logbatjek		Klo	Série de Logbatjek								
C-Mb	Série de la Mbéré		Kmr	Série de la Mbéré								
Cm-LHG-Mf	Mfamosing (alt. Odukpani, Ewe, Obotme) Limestone	Calcaires de Mfamosing (alt. Odukpani, Ewe, Obotme)	Ko	Odukpani Formation								
Cm-LHG	Lower hydrogeological group: Ekenkpon Shale, New Ntetim Marl, Eze-Aku Shale, Awgu Shale, Nkporo Shale, Enugu Shale (Nigeria), Série de Mungo (Cameroon)		Kmu	Série de Mungo								
			Knk	Nkporo Shale								
Cm-LHG-AR	Lower Hydrogeological Group: Asu River Group incl. Abakaliki Shale, Mamfe Fm (Nigeria), Grés de la Cross incl. Mundeck Fm (Cameroon)		Kas	Asu River Group, incl. Abakaliki Shale, Mamfe Formation								
			Kc	Grés de la Cross incl. Mundeck Formation								
Ci-AFK	Grés d' Amakoussou et Grès de Figuil	Grés d' Amakoussou et Grès de Figuil	Kam	Grés d' Amakoussou								
Ci-AFK	Grés de Kontcha	Grés de Kontcha	Kko	Grés de Kontcha								
Ci-AFK	Metasandstones	Metasandstones	ms	Metasandstone [Sandstone, closly ass. With volcanics of uncertain Palaeozoic ? Age]								

4.3 Challenges for harmonisation and ambiguities

This chapter highlights major challenges in the harmonisation of the stratigraphic units and outlines relevant stratigraphic correlations between the original maps as well as stratigraphic assignments and ambiguities.

4.3.1 Sedimentary cover

Cretaceous sedimentary units

Cretaceous sediments occur in Nigeria, in small locations in Cameroon and to a lesser extend in Chad. Geological units are derived from the *Geological Map of Nigeria* (Dessauvagie 1974), the *Geological Map of Nigeria (NGSA 2006)*, and the map *Ressources en eaux souterraines dans la région de la CEDEAO*.

Along the Calabar Flank, the Albian –Cenomanian Mfamosing Limestone [Ko], also known as Odukpani, Ewe, or Obotme Limestone (Oti & Koch 1990), is correlated with the Asu River Group in Nigeria. Together with the Campanian Nkporo Shales [Knk] and the Cameroonian Serie de Mungo [Kmu] they correspond to the Lower Hydrogeological Group (Lower Cretaceous). The Asu River Group outcropping along the Abakaliki High is correlated due to direct continuation in Cameroon with the Grès de la Cross and/or the Mundeck Formation. Two Asu River Group inliers within these correlated units on the maps of Dessauvagie, however, indicate a possible mismatch.

The Upper Benue Valley is characterized by the Early Cretaceous Bima sandstone. It is overlain by the Yolde formation described as passage or transition beds (100-300 m) between the continental sandstones and the marine deposits of the Pindiga formation (ca 200 m) consisting essentially of blue-grey calcareous clay (Bessong 2012). On Nigerian maps, the geometries of the Bima sandstone and the overlying Yolde-Gongila-Pindiga-Fika Formations differ strongly; the proposed linework is arbitrary. The lateral equivalent of the upper Bima sandstone in Cameroon is the Grès de Garoua – also known as Grès de la Bénoué or locally as Grés de Muri (Falconer 2011).

Cenozoic and quaternary sedimentary units

The seminal work of Pias (1967) provides a detailed subdivision of alluvial geomorphic activity into phases of Lake Chad transgression and Chari delta formation. These have been adopted but slightly generalized. The Cenozoic sequence of terrestrial sediments in the Lake Chad Basin starts with the coarse sandstones of the ***Séries paléotchadiennes*** of Eocene to Miocene age. Also denominated as *Formations continentales terminales*, the *Séries paléotchadiennes* is the equivalent of the well-known *Continental Terminal*. Outcrops are found along the rim of the basement areas while it is covered by younger sediments in the central part of the Lake Chad Basin. Characteristic for the *Séries paléotchadiennes* is the development of several planation surfaces and corresponding iron-rich ferricretes (*cuirasses*): Pias (1967) distinguishes on his map *Esquisse géologique des formations tertiaires et quaternaires du Tchad (au Sud du 16e parallèle)* the following planation surfaces indicating sediments of the *Séries paléotchadiennes* or the Continental Terminal (from bottom to top):

- *1a* *Surface bauxitique résiduelle* de Koro [on top of the uppermost *Série paléotchadienne*]
- *1b* *Cuirasses ferrugineuses anciennes* (par places cuirasses subactuelles à actuelles au sud du 10° parallèle)
- 1c *Surface cuirassée générale* composed of an ancient (*ancienne antérieure à la surface cuirassée, altitude 420-500 m*) and a second more recent (*plus récente*) surface that gives way to the modern surface.

While the observation of surface processes such as planation and erosion, weathering, and soil formation processes, often allows to infer the underlying geology, these processes also cut across and levelled Tertiary and Cretaceous sediments and basement units. Particularly the legend unit 1b includes both outcrops of Cenozoic sediments, Cretaceous sandstone, and basement.

The surfaces of the *Séries paléotchadiennes* are widely eroded and only locally preserved as inselbergs. Denudation of these planation surfaces and reworking of the eroded *Séries paléotchadiennes* provided material for the ***Séries anciennes remaniées***. Pias (1967) geographically differentiates two sub-units of the *Séries anciennes remaniées*:

1d *Nord du 13° parallèle*

1e *Sud du 13° parallèle* (*1° delta du Chari*: Milou - Bongor - Mandélia - Bokoro)

Geomorphologically, they form a uniform depositional surface characterizing the central part of the southern Lake Chad Basin which developed during a first set of marine transgressions related to a Miocene-Pliocene Mega-Lake Chad (Pias 1968). Pedogenesis is not pronounced and only initial stages of lessivation are observed. The *Séries anciennes remaniées* differ from the *Séries paléotchadiennes* by the lack of ferricrete development (*cuirasse*) and surface planation. Following its deposition, aeolian reworking and longitudinal (NE-SW) dune formation (e.g. *1er erg*) reflect the southernmost extension of dune formation down to the 10th parallel in northern Cameroon and Nigeria.

The *Séries anciennes remaniées* are the lateral equivalent to the well-known Nigerian **Chad Formation** - although no comprehensive review and no comparison between the geomorphological-inspired Chadian nomenclature of Pias (1958, 1967, 1968) and the borehole-based three-fold stratigraphy of the Nigerian Chad Formation are available. The chronostratigraphic but also the spatial misfits between the two national stratigraphical terms call for a transboundary study of the Neogene deposits and their hydrogeological linkages and hampers a straightforward spatial and thematic harmonisation.

Quaternary sediments

The extension of the detailed Chadian classification of Neogene and Quaternary sediments and related phases of geomorphic activity and/or lake transgressions into Nigeria is challenging, arbitrary, and has not been pursued. For the Chadian plain, the detailed differentiation by Pias (1967, 1968) was adopted although this might have resulted in a locally more detailed coverage of the Chadian section compared to a simple generic alluvial cover for the adjacent territories of Nigeria where they are less prominent. Subdivision of aeolian deposits – as proposed by (Pias 1968) – was abandoned as there is probably no hydrogeological relevance.

4.3.2 Basement

To comply with the simplified basement legend of the map *Ressources en eaux souterraines dans la région de la CEDEAO*, a very simple reclassification of the complex basement units shown on the original maps of the map series *Carte géologique de reconnaissance de la République Fédérale du Cameroun* (1 : 500 000) was necessary (cf. Tab. 7). Further the similarly generalized basement classification of the Nigerian map *Geological Map of Nigeria* (Dessauvagie 1974) did not allow to extent the spatial differentiation available for Cameroon to Nigeria. The extensive basement region along the border of Cameroon and Nigeria could not be further differentiated resulting in the persistence of geological limits mirroring national map boundaries. The following units were differentiated:

Tab. 2: Aggregation of Cameroun-specific basement units for the Lithological and stratigraphic Map of the Niger Basin

Lithological and stratigraphic Map of the Niger Basin	**Cameroon-specific basement units** (as displayed on different source maps
Ng-v	Cenozoic volcanic rocks of the Cameroon Volcanic Line
PCe-v	Undifferentiated volcanic rocks of the Cenozoic and Palaeozoic (Série Ultime)
Ce-Gr	Granitoids of the **Série Ultime**. Sub-volcanic ring complexes, granitic, intermediate, and basic plutonic intrusions of the 3rd Pan-African cycle. Subsequent to the Formation de Mangbeï)
nP-oGr	• **Older Granites of the 1st and 2nd cycle** (Neoproterozoic, Pan-African). • Undifferentiated group of ▪ “Anciennes” – pre- and syn-tectonic plutonic intrusions (640-625 M) and “Récentes” – generally calc-alkaline post-tectonic granitoids (625-550 M) separated by the emplacement of the Serie de Poli • Paleoproterozoic gneisses and orthogneiss along the Central Cameroon shear zone (CCSZ) and the Tcholliré-Banyo shear zone (TBSZ) as shown on Cameroun-wide maps (Toteu et al. 2008; Kwékam et al. 2013; Caxito et al. 2020; Ntieche et al. 2021)

pA-vs	• Metasedimentary Sinassi-Mayo Kebbi unit • Série de Poli (Neoproterozoic): low to medium grade volcano-sedimentary schists of the Groupe de Tago, Groupe de Douva, Groupe de Sélou • Formation de Mangbeï (Palaeozoic): Metabasites associated to volcano-sedimentary schists of the Balché graben including sandstone, conglomerate, andesite, rhyolite
pA-cpx	**Complexe de base**: Undifferentiated complex of Precambrian gneisses including remobilized Paleoproterozoic migmatitic gneisses, undifferentiated Neoproterozoic medium to high grade gneisses, and Pan-African gneisses

5 Expected aquifer productivity map of the Niger Basin

5.1 Summary

The map *Expected aquifer productivity of the Niger Basin* presents harmonized **quantitative estimates of expected borehole yields** for properly sited and constructed boreholes in the respective hydrostratigraphic units. The hydrogeological units are derived from the lithostratigraphic units of the base map *Geological map of the Niger Basin*. The attribution followed an in-depth literature review for the corresponding spatial units and a classification of expected yields into the most likely range of borehole yields expected for the given hydrogeological unit. The map builds and extends the data set elaborated by the international mapping initiative for the map *Groundwater Resources in the ECOWAS region* (Heckmann et al. 2022a) to include the Niger Basin portions of Chad and Cameroon and covers the entire Niger Basin and its adjacent areas.

The classification scheme of the expected aquifer productivity is a two-dimensional legend that combines the classification of aquifer flow type (colour), with an independently derived estimate of expected borehole yield (lightness). The map differentiates fractured flow in basement (brown), mixed porous and fractured flow in the sedimentary basins (green), porous flow in unconsolidated sediments (blue), and karst regime for carbonate rocks (violet). Regions with a moderate to high expected aquifer productivity are the shallow aquifers within poorly consolidated often Quaternary sediments (particularly locally restricted alluvial deposits), the partly consolidated Cainozoic sedimentary basins, and the spatially limited karst aquifers. For the supply of rural populations most important are the extensive areas of basement aquifers and the consolidated sediments of the Palaeozoic and Neoproterozoic.

The map *Expected aquifer productivity of the Niger Basin* highlights the potential for integrating and harmonising existing hydrogeological information to improve regional groundwater mapping in the Niger Basin.

5.2 Materials and methods

The map *Expected aquifer productivity of the Niger Basin* builds upon and expands the data set produced by the international mapping initiative for the ***Ressources en eaux souterraines dans la région de la CEDEAO – Groundwater resources in the ECOWAS region, 1 : 5 000 000*** (Heckmann et al. 2022a) to include the Niger Basin portions of Chad and Cameroon. For a more detailed discussion of aquifer productivity parameters, the attribution process, the elaboration of the data set, and the aforementioned hydrogeological mapping initiative, the reader is referred to the corresponding Technical Note (Heckmann et al. 2022b). The following paragraphs synthesize the detailed information provided in this Technical Note.

5.2.1 Hydrogeological attribution

The lithostratigraphic units delimited for the *Geological map of the Niger Basin* were attributed with the predominant aquifer flow type and the expected yield. Information on aquifer flow type and borehole yield was compiled from an in-depth review of the relevant groundwater literature and allowed a comprehensive and consistent attribution at the regional scale. The **aquifer flow type** class is directly linked to the lithological description of the hydrostratigraphic unit (attribute: lithology) of the data set of the *Geological map of the Niger Basin*. **Borehole yield** was chosen over more robust hydrogeological parameters such as transmissivity or hydraulic conductivity due to its wide availability in reports and literature for most of the hydrogeological units. Borehole yield – also called flow or pumping rate – is influenced not only by the aquifer productivity (ability of an aquifer to provide water) but also by site location and technical characteristics including the borehole geometry, construction, and the installed pumping capacity. Nevertheless, borehole yield has been shown to be a reasonable quantitative proxy for transmissivity (Graham et al. 2009), and it is the most relevant parameter of interest for borehole owners, communities, contractors, planning agencies, and decision makers.

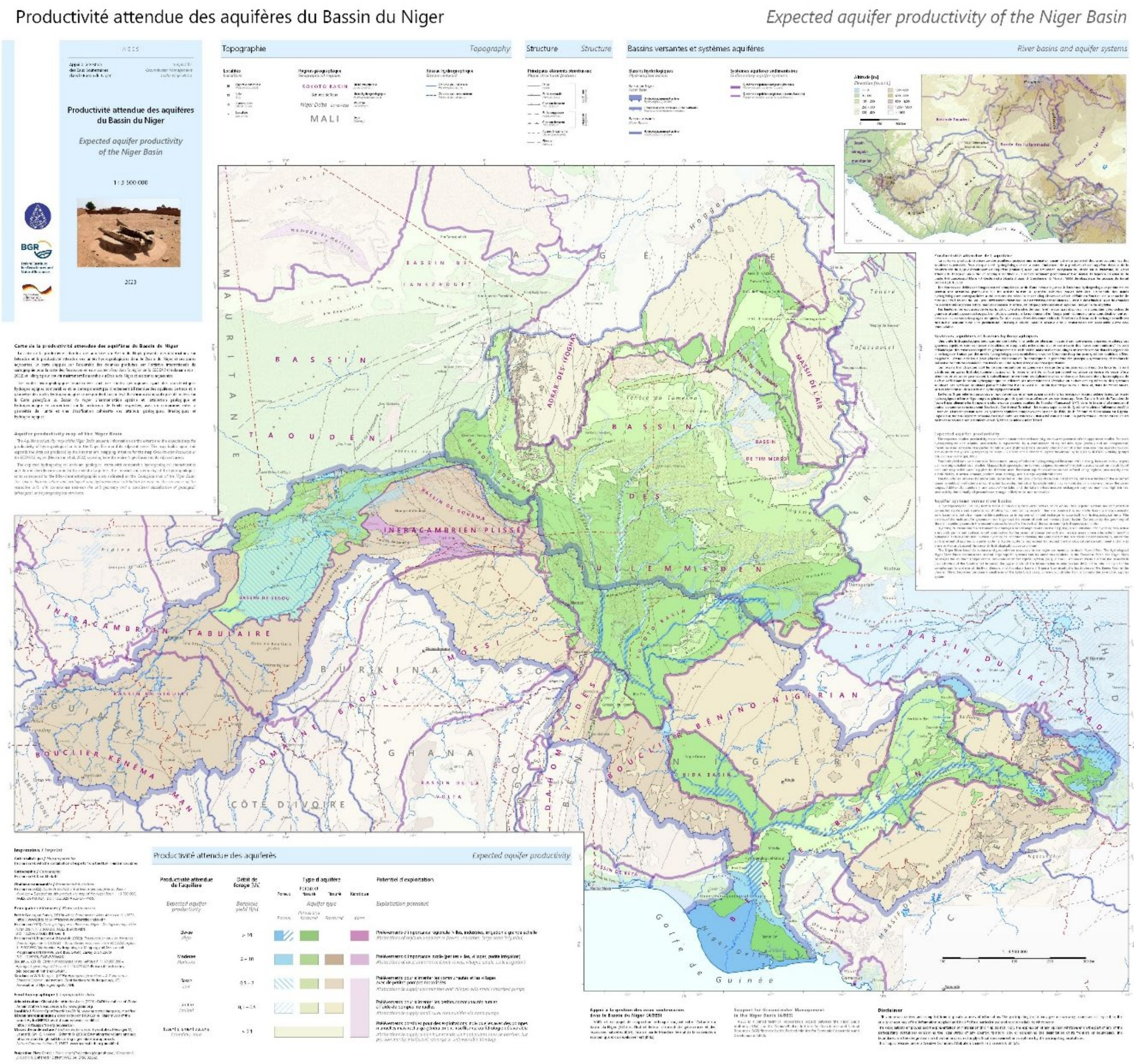

Fig. 3: Expected aquifer productivity map of the Niger Basin

5.2.2 Classification

The expected aquifer productivity is presented by a **two-dimensional classification scheme** that combines different aquifer flow type classes (colour) and the independently derived estimate of the expected borehole yield (lightness). This classification scheme was explicitly developed for the here presented *Expected aquifer productivity of the Niger Basin* and the *Groundwater Resources in the ECOWAS region*. It evolved from the widely applied and well-known aquifer productivity classification scheme proposed by the *International Legend for Hydrogeological Maps* developed by IAH/IAHS/UNESCO working groups (UNESCO et al. 1970; Struckmeier et al. 1983) and published as *Standard Legend for Hydrogeological Maps* (Struckmeier & Margat 1995). The new classification expands on the formerly **qualitative** approach of **potential aquifer productivity** to include a **quantitative estimate of expected borehole yield** that reflects the most likely range of borehole yields to be expected for a given hydrogeological unit.

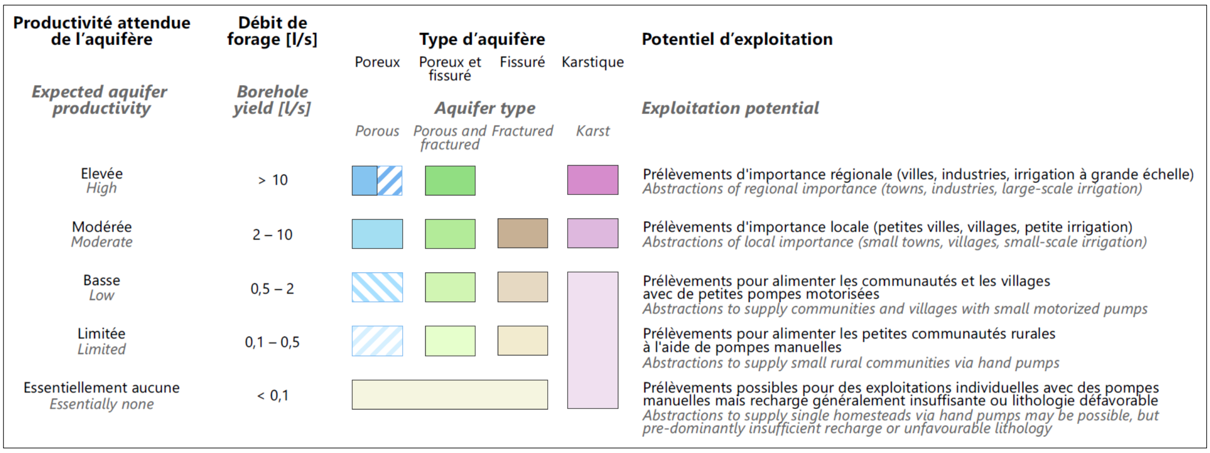

Fig. 4: Expected aquifer productivity classification scheme

The legend differentiates:

Aquifer flow type by colour on the x- axis:

- **Blue**: Unconsolidated sediments of porous aquifers with **intergranular groundwater flow**;
- **Green:** Partly consolidated, sedimentary rocks spanning the continuum from weakly consolidated Neogene sediments to partly metamorphosed Precambrian metasedimentary rocks, with an unspecified **combination of intergranular and fractured groundwater flow**;
- **Brown:** Strongly consolidated crystalline basement rocks, including metamorphic, plutonic, and volcanic rocks, all with only **fractured groundwater flow**;
- **Violet:** Consolidated carbonate rocks formed predominantly of limestone or dolomite, for which significant **karst features** have been reported.

Expected borehole yield by lightness on the y-axis:

- **> 10 l/s:** Abstractions of regional importance (can supply large towns, large industries, large-scale irrigation);
- **2 - 10 l/s:** Abstractions that can supply small towns, villages, small-scale irrigation;
- **0.5 - 2 l/s:** Abstractions that can supply village-sized communities via small motorised pumps;
- **0.1 - 0.5 l/s:** Abstractions that can supply small communities via hand pumps;
- **< 0.1 l/s:** Abstractions that may be able to supply small numbers of households via hand pumps.

The borehole yield classes include more resolution for lower yields (< 2 l/s) than higher yields. This is deliberate, in response to the importance of decentralised groundwater supply in this region, which means most water demand is for relatively small supplies, such as for villages or small communities. The higher resolution for lower yields is also driven by the available information in the hydrogeological literature. Although very high borehole yields (> 10 l/s) in individual aquifers are highlighted frequently in the literature, there is little evidence for their representativeness, as other data often indicates that the average yield range of the respective hydrogeological unit is much lower. The aquifer productivity map therefore aims to provide a suitable level of resolution in low-yielding aquifers, but in doing so it may underestimates the productivity of high-yielding aquifers.

The selected aquifer productivity classes have been guided by WASH classifications, in particular those of Olley (2008) and Baumann (2000). They differ from similar classification approaches by MacDonald et al. (2012, 6 classes), Krásný (1993, 6 classes) and Bäumle et al. (2007, 4 classes), and from approaches by European geological surveys that focus on high yielding boreholes for centralised water supplies.

5.3 Challenges

A major challenge is the **lack of reliable and consistently collected quantitative aquifer properties data**. Literature data of our meta-survey is biased by the availability and the selection of the reviewed literature. Heterogeneous in quality, quantity, and coverage, the final classification of aquifer productivity strongly relied on expert decisions to assess and weight the available aquifer properties data and assign the yield and aquifer productivity classes.

While **borehole yield** might be the most useful parameter in terms of its applied use, it is not the most appropriate parameter to describe the hydrogeological environment. In data-poor aquifers, the availability of borehole yields and the lack of reliable hydrogeological parameters such as transmissivity, hydraulic conductivity, or specific capacity justify the use of borehole yield as a **proxy for aquifer productivity**.

The downside of overview maps is the need for **generalisation** and classification that ignores the **inherent (hydro-) geological heterogeneity** and requires generalising the often wide range of existing yields for a given unit, which inevitably leads to a loss of information on the yield distribution. The class boundaries of the aquifer productivity legend therefore are, therefore, not absolute, but are estimates of the dominant range of yields of properly-sited and well-constructed boreholes. Individual borehole yields may vary substantially above or below the given ranges.

Caution is required assessing the **potential of aquifers in arid areas**, where recharge is very low. Here aquifers may have a high intrinsic (potential) productivity, but the lack of recharge means that in shallow aquifers there is little or **no groundwater available**. Any groundwater storage in deeper aquifers is likely to be non-renewable.

5.4 Description of expected aquifer productivity classes

This chapter is an excerpt from the Technical Note accompanying the map *Groundwater resources in the ECOWAS region* (Heckmann et al. 2022b).

High productivity aquifers (> 10 l/s): **abstractions of regional importance that can supply large towns, large industries, large-scale irrigation**

High productivity aquifers allow groundwater abstractions of regional importance that can supply large towns, large industries or large-scale irrigation projects. Borehole yields of > 10 l/s are common. These are often unconsolidated, sedimentary aquifers with intergranular flow, high permeability, and high storage capacity, and are generally continuous and extensive over a large area. High productivity aquifers in the ECOWAS region include:

- unconsolidated sediments of Quaternary age, such as alluvial and coastal sediments;
- partly consolidated sediments of the coastal Continental Terminal;

Moderate productivity aquifers (2 - 10 l/s): **abstractions that can supply small towns, villages, small-scale irrigation**

Moderate productivity aquifers allow groundwater abstractions that can supply small towns, villages, and small-scale irrigation. Borehole yields of between 2 - 10 l/s are common.

Moderate productivity aquifers can be of any lithology, and groundwater flow may be intergranular, fractured or mixed. Most extensive in the ECOWAS region are partly consolidated sedimentary hydrogeological units with a mixture of intergranular and fractured groundwater flow, they are usually continuous and extend over large areas. They are often heterogeneous in lithology and aquifer properties, characterised by mixed sandstones, siltstones, and mudstones, with occasional thick, extensive high permeability sandstone beds forming zones of moderate to high productivity, alternating with clay-rich, low-permeability beds forming zones of low to limited productivity. They are often, therefore, only moderately productive on average when classed over their whole mapped extent. Examples of moderately productive aquifers in the ECOWAS region include:

- Chad Formation and Continental Terminal of the intracratonic Iullemmeden and Taoudéni basins;
- Cretaceous sandstones (Continental Hamadien, Bima and Nupe Sandstones);
- Neoproterozoic sandstones (Anyaboni Sandstone, Pita Formation);
- Limestone aquifers (Formation d'Irma/Group de Hombori, Formation de Safia and Haricha).

Low productivity aquifers (0.5 - 2 l/s): abstractions that can supply village-sized communities via motorised pumps

Low productivity aquifers allow groundwater abstractions that can supply village-sized communities via small motorised pumps. Borehole yields of up to 2 l/s are common. The most common low productivity aquifers in the ECOWAS region are basement, consolidated sedimentary and metasedimentary hydrogeological units, with fractured flow, but they also include some hydrogeological units with mixed groundwater flow, as well as unconsolidated alluvial deposits in the cover layer. These aquifers are typically highly heterogeneous, discontinuous and spatially restricted. Covering large areas of the basement, this class is one of the most prevalent in the ECOWAS region. Examples of low productivity aquifers in the ECOWAS region are:

- unconsolidated alluvial aquifers of limited extent, with intergranular flow, in the Adar-Doutchi area;
- mixed intergranular/fractured flow aquifers such as Menaka and Trichet Formations, Groupe de Majia, Grès de Tégama, Kerri Kerri Sandstone, Gongila, Pindiga & Fika Formations;
- fractured aquifers such as the Bandiagara & Koutiala Sandstones in Mali, Dunkro & Densubon Sandstones in the Volta Basin, the Groupe d'Youban, and the Asu River Group;
- extensive fractured basement aquifers.

Limited aquifer productivity (0.1 - 0.5 l/s): abstractions that can supply small communities via hand pumps

Aquifers with limited productivity allow small abstractions that can supply small communities via hand pumps. Yields of between 0.1 and 0.5 l/s are common. These aquifers are generally local and discontinuous, with low permeability and groundwater storage capacity. Much of the metamorphic and plutonic basement rocks of the West African Cratons are of limited aquifer productivity. Sedimentary aquifers of limited productivity are typically fine-grained, such as mudstone or shale. In the arid areas of the Sahara desert, expected aquifer productivity is limited by low precipitation and consequently insufficient recharge to replenish available aquifer storage, so that even sedimentary aquifers with favourable hydrogeological properties can have limited aquifer productivity. Examples of the limited aquifer productivity class in the ECOWAS region are:

- mixed intergranular/fractured flow aquifers such as the Formation de Khnachich (Mali), Formation de Farak (Niger), or the Lower Hydrogeological Group (Nigeria);
- fractured aquifers such as the Groupes de l'Azlaf & l'Erg Chech (Mali);
- extensive areas of fractured basement aquifers.

Essentially no groundwater (very limited aquifer productivity): (< 0.1 l/s):
abstractions that may be able to provide small numbers of households via hand pumps (rocks with very little groundwater, either due to lithology (very low transmissivity and storage) or to insufficient recharge)

Groundwater sources even for small domestic water supplies are difficult to find and cannot be guaranteed everywhere. However, these aquifers may provide significant local supplies in areas with few other water resources. These are mainly clay-dominated sedimentary rocks with very low groundwater storage capability, but may include all other rock types. In the arid areas of the Sahara desert, expected aquifer productivity is also limited by low precipitation and consequently insufficient recharge to replenish available aquifer storage. Here, otherwise limited or low productivity aquifers, particularly of the basement but also including sedimentary and metasedimentary rocks, are all likely to contain essentially no groundwater resources. Similarly, unconsolidated aeolian and lacustrine sediments in areas of restricted recharge do not contain any significant groundwater resources, and so these units are included in the cover layer. Examples of very limited productivity aquifers in the ECOWAS region include:

- the Argilites de l'Irhazer (Niger), Plaine de Gondo (Mali).

6 Dataset & GIS layers

The digital version of the maps is made available as a series of shapefiles for use in a Geographic Information System (GIS). Each shapefile has an associated attribute table with a consistent description of relevant geological and hydrogeological parameters. The dataset comprises five GIS layers – a master layer providing the geometry and the attributes of the stratigraphic units (*Uniteshydrogeologiques*) and four thematic layers.

- **AGES_BassinNiger_UnitesHydrogeologiques:** Field: *UID_unit*
  Geological base layer showing individual lithochronostratigraphic and hydrostratigraphic units.
  The accompanying attribute table provides relevant geological and hydrogeological parameters. The base layer lists regional unit variants that at the given scale of analysis are not differentiated by other parameters but which, due to their spatial distance, should be assessed separately (e.g. Continental Terminal of Tchad, Niger, and Mali).

Simplified thematic layers have been prepared for four key parameters shown on the printed map. These are available in the accompanying dataset:

- **AGES_BassinNiger_Stratigraphie:** Fields: *ID_strat, Unit_fr, Unit_en*
  Major lithochronostratigraphic / hydrostratigraphic units (Section 6.1.3)
- **AGES_BassinNiger_Lithologie:** Field: *Lithologie*
  Generalised lithological classes of stratigraphic units (Section 6.1.5)
- **AGES_BassinNiger_ProductiviteAquifer:** Field: *Aq_prod*
  Expected aquifer productivity of hydrostratigraphic unit (described in detail in sections 5 & 6.1.9)
- **AGES_BassinNiger_CoverLayer:** Field: *ID_cov_BN*
  Cover layers and superficial deposits including local alluvial aquifers and non aquifers (Section 6.1.2)

The dataset of the two maps is the same. It can be accessed via:

Geological map of the Niger Basin:	DOI: 10.25928/AGES-BN-Geol.1
Expected aquifer productivity of the Niger Basin:	DOI: 10.25928/AGES-BN-Prod.1

For a more comprehensive overview please refer to the Technical report of the map *Ressources en eaux souterraines dans la région de la CEDEAO – Groundwater resources in the ECOWAS region* (Heckmann et al. 2022).

6.1 Unique thematic unit code (UID_unit)

Unique unit identifier is based on the stratigraphic code (ID_strat). Suffixes are added to differentiate regional unit variants separated to allow for regional distinction. The regional variants may or may not have different hydrogeological parameters. This identifier field is used to join the attribute table.

6.2 Cover layer code (ID_cov_BN)

The cover identifier discerns the most important sedimentary covers – with or without local aquifers - overlying the regionally most important aquifer or stratigraphic layer.

6.3 Stratigraphic code (ID_strat) and stratigraphic unit (Unit_fr/Unit_en)

The stratigraphic unit describes the predominant and uppermost geological strata that hosts the uppermost and thus generally phreatic aquifer. The stratigraphic identifier is a simplified version of the unique unit identifier (UID_unit) without any regional differentiation. It is directly linked to the stratigraphic unit.

Units have been selected for representativeness on the map and include, depending on their spatial relevance and the available geological background information, Groups, Formations, Members, and/or facies names. In the process of generalisation, many minor stratigraphic units have been combined under the most dominant unit. As far as possible, they are named using established regional stratigraphic nomenclature; alternative names and local variants may exist.

The identifier is composed of a chronostratigraphic prefix (e.g.: Q: Quaternary, nP: Neoproterozoic) or regionally accepted abbreviations (e.g.: Ci: Continental Intercalaire, Cm: Cretaceous marine, CH: Continental Hamadien, CT: Continental Terminal) and an abbreviation of the stratigraphic unit (e.g.: -T: Grès de Tégama, -YGPF: Yolde, Gongila, Pindiga, Fika Formations). Regional variants of stratigraphic units occurring in more than one basin are indicated by a suffix separated by a comma (CT, AzS: Continental Terminal – Azaoud Sud).

6.4 Chronostratigraphy [CS_era, CS_system, CS_series, CS_stage]

Chronostratigraphic information is provided on the geochronological/chronostratigraphic levels of erathem/era, system/period and, if available, series/epoch and stage/age.

6.5 Lithology [Lithology]

Lithologies were classed into 18 generalized lithological classes (Tab. 2). Two unconsolidated classes – sand and clay – are restricted to the cover layer. On the printed map acid and basic igneous rocks are not differentiated.

6.6 Aquifer flow type [Aq_type]

The dominant aquifer flow type characterises the hydraulic properties of an aquifer and is a relevant parameter for successful groundwater prospection. The two flow type categories of the *Standard Legend for Hydrogeological Maps* (Struckmeier & Margat 1995) – intergranular (porous) and fractured – were amended with two additional categories, a mixed intergranular and fractured regime, and a specific karst flow regime (Tab. 2). The aquifer flow type regimes roughly correspond to the consolidation type, but some deviations occur. Aquifer flow type, together with lithology and expected aquifer productivity, is portrayed on the published map.

Tab. 3: Lithological classes, rock consolidation type, and aquifer flow regimes

Lithology	Consolidation	Aquifer flow type	N° of units [dataset]
Cover layer			
Sand	unconsolidated	intergranular (porous)	12
Clay			7
Hydrogeological unit base layer			
Sand and clay	unconsolidated	intergranular (porous)	9
Sandstone and clay	partly consolidated	intergranular / fractured	47
Marl			7
Claystone and sand			9
Sandstone	consolidated, (meta-)sedimentary	fractured	22
Sandstone and claystone			4
Claystone			9
Shale			3
Limestone and marlstone			2
Limestone		fractured (karst)	5
Schist and quartzite	consolidated, metamorphic rocks	fractured	19
Granite, gneiss, and schist			15
Volcanic rock	consolidated, igneous rocks		4
Plutonic rock			3
Plutonic rock (acid)			1
Plutonic rock (basic)			4

6.7 Expected yield [Yield]

Average yield values gathered from literature using the approach described in Section 5.

6.8 Expected aquifer productivity [Aq_prod]

Expected aquifer productivity defined as a combination of aquifer flow type and expected borehole yield regionalised using the approach described in Section 5.

In addition, karst features are reported for the Mfamosing Limestone Formation, Calabar Flank, Nigeria (Reijers, 1998). However, the Mfamosing Limestone is not included as a mapped unit due to its limited size. A complex lithology including intercalated karstified limestone does not justify the characterisation of an extended lithostratigraphic unit as karstified carbonates. Such is the case for the Calcaires blancs of the Majia Group in Niger (Greigert 1966), the Rima and Sokoto Groups in Nigeria (Anderson & Ogilbee 1973; Kogbe 1981; JICA 1990), or the Terrecht I & II (Menaka Formation) in Mali (O'Leary et al. 2019). These are flagged as containing carbonates in the accompanying attribute table. Outside of the above-mentioned regions, the thickness and extent of karstified limestones are probably not sufficient for the development or the reporting of any significant karst features.

6.9 Carbonate rocks [Carb_rock]

Calcareous rocks may occur in virtually all rock types. Probably due to limited thicknesses and extents, or to the difficulty in assessing the proportion of calcareous material, lithological descriptions rarely provide sufficient information to judge their significance. Where information is available, significant amounts of calcareous (marls, etc.) or carbonate rocks (significant occurrence of limestone) are flagged in the attribute table (Tab. 3). The classification is a tentative first approximation and requires reviewing on a case-by-case basis.

Despite its high relevance for hydrogeological assessments, reports of carbonate karst are rare in the West African geological literature. Given a considerable number of studies on sandstone karst in Northern Niger (Busche & Sponholz 1992; Sponholtz 1994; Vicat & Willems 1998; Willems et al. 2002; Wray & Sauro 2017), overall environmental conditions must have been suitable for the development of karst and a wider spread of carbonate karst should be expected. Documented carbonate karst features with sufficient extent to be shown as karstic aquifers on the map are reported for the

- Formation d'Irma, Mali (DNHE 1990);
- Calcaires à Stromatolites du Hank, Groupe d'El Mreïti, Mali (DNHE 1990);
- Formation Safia & Haricha, Mali (DNHE 1990);
- Calcaires du Paléocèene (Intermediary Aquifer System), Senegal (Myers et al. 1984; Travi et al. 2017; DGPRE 2018; Madioune et al. 2020).

Tab. 4: Carbonate rocks

Typology of carbonate rocks	Description	**N° of units** [dataset]
No data	assumptions about the occurrence of carbonate rocks not possible	56
Basement	carbonate rock classification not applicable	44
No mention of calcareous strata	occurrence of major calcareous strata unlikely	39
Likely occurrence of calcareous strata	occurrence of minor calcareous strata likely	11
Calcareous rocks	includes calcareous strata (e.g. marls, calcareous sandstones or minor occurrence of limestone)	23
Carbonate rocks	substantial occurrences of carbonate rocks (limestone, dolomite), no reports of karst features	12
Carbonate rocks, karst	karstified carbonate rocks with documented occurrence of relevant karst features	5

6.10 Consolidation type [Consoldtn]

Consolidation refers to the consolidation status of the sediment or rock. Four consolidation levels are differentiated (Tab. 2): unconsolidated rocks, partly consolidated rocks, consolidated sedimentary and metasedimentary rocks, and consolidated metamorphic and igneous rocks (basement rocks).

6.11 Environment [Envirnmnt]

Type of depositional or rock formation environment (sedimentary, metasedimentary, igneous rocks or basement/mobile belt) and, where relevant, environmental conditions (continental, marine, volcanic). Units of the basement or mobile belts are differentiated according to the geological time period of the dominant metamorphic overprint (Archean, Eburnean, Birimian, Pan-African) and the predominance of either plutonic and metamorphic complexes or (meta-) volcano-sedimentary sequences.(Tab. 4).

Tab. 5: Depositional or rock formation environment and main orogenic event.

Depositional environment / Geological domain	N° of units [dataset]
Sedimentary	
Sedimentary, aeolian	4
Sedimentary, alluvial	10
Sedimentary, lacustrine	8
Sedimentary, coastal	5
Sedimentary, continental	53
Sedimentary, continental & marine	11
Sedimentary, marine & continental	13
Sedimentary, marine	19
Metasedimentary	
Metasedimentary, continental	2
Metasedimentary, continental & marine	1
Metasedimentary, continental & marine, volcanic	1
Metasedimentary, marine & continental	1
Metasedimentary, marine	6
Basement	
Archean basement (plutonic and metamorphic complexes)	1
Archean basement, (meta)volcano-sedimentary	1
Eburnean basement (plutonic and metamorphic complexes)	6
Birimian terranes, (meta)volcano-sedimentary, deep water basins	6
Pan-African basement (plutonic and metamorphic complexes)	7
Pan-African Mobile Belt, (meta)volcano-sedimentary	10
Pan-African terranes, (meta)volcano-sedimentary	7
Igneous rocks	
Extrusive/volcanic (felsic)	1
Extrusive/volcanic (mafic)	3
Intrusive/plutonic rocks (felsic)	2
Intrusive/plutonic rocks (mafic)	5
Intrusive/plutonic rocks (undifferentiated)	1

6.12 West African stratigraphic and structural groups [Group_fr / Group_en]

This classification of stratigraphic groups in West Africa builds on that proposed by Kilian (1931) (Tab. 5) and combines elements of various existing classifications. This approach may be useful when addressing the complex geology of the region, and, therefore, it is released as an attribute with the digital map. It is proposed as a working classification to further discussion and review by experts on the geology of West Africa (Tab. 6).

The stratigraphic group in West Africa classes the geological units in a high level hierarchy according to depositional environment, chronostratigraphy, and rock type (degree of metamorphism, igneous rocks, and basement). Conventional stratigraphic designations broadly follow the stratigraphic intervals proposed by Kilian (1931; see also Swezey 2009) differentiating marine (*Couverture* or *Série*) and continental (*Continental*) sequences of the broader Saharan region. While widely adopted (e.g. *Continental Terminal* has been adopted throughout West Africa for the coastal continental deposits), the classification developed for the Hoggar area approaches its limits in other regions such as Nigeria, Mali, or Guinea – particularly where the implied link between chronostratigraphic interval and lithology fails due to facies changes or an entirely different sedimentary environment. In Niger, continental deposition along the shores of the Upper Cretaceous Trans-Saharan seaway early on required the introduction of the *Continental Hamadien* concurrent with the eponymous marine *Série hamadienne*.

For Mali, the established differentiation between *Infracambrien plissé* and *Infracambrien tabulaire* is adopted to discriminate between Upper Neoproterozoic to Cambrian sedimentary strata that have – or have not – undergone folding and weak metamorphism. A classification that perhaps could be extended to the Cambrian to Devonian strata of Guinea.

Basement rocks are classed as cratonic shields, igneous rocks, and Pan-African mobile belts (Trans-Saharan Belt). The Pan-African mobile belts consist of Neoproterozoic volcano-sedimentary sequences that have undergone locally varying degrees of metamorphism and folding during the Pan-African orogeny. The mobile belts are differentiated from the metamorphic complexes of the Paleoproterozoic cratonic shields that have experienced reworking and metamorphism during multiple orogenies. Igneous, intrusive and extrusive, rocks are separated into intrusive "Older Granites" (Neoproterozoic), CAMP intrusives, "Younger Granites" (Mesozoic) and Cenozoic and Quaternary volcanic rocks.

Tab. 6: Marine and continental stratigraphic intervals following Kilian (1931)

<table>
<tr><th colspan="2">Marine environment (predominantly)</th><th>Continental environment (predominantly)</th><th>Stratigraphic interval</th><th>Examples</th></tr>
<tr><td colspan="2"></td><td>Quaternary continental sediments</td><td>Pleistocene to Holocene (Quaternary)</td><td>Coastal sediments</td></tr>
<tr><td colspan="2"></td><td>Continental Terminal (CT)</td><td>Cenozoic i.e Paleogene (Eocene) to recent</td><td>Continental Terminal, Kerri-Kerri</td></tr>
<tr><td colspan="2">Série Hamadienne
(Cm, E)</td><td>Continental Hamadienne (CH)</td><td>Upper Cretaceous (Cenomanian) to Lower Paleocene (Danian)
later including Eocene marine strata (E)</td><td>Rima Group, Calcaires blancs, Schistes papyracées/
Continental Hamadien</td></tr>
<tr><td colspan="2"></td><td>Continental Intercalaire (Ci)</td><td>Upper Carboniferous (Moscovian) to Upper Cretaceous (Cenomanian)</td><td>Grés de Tégama, Nubian sandstone</td></tr>
<tr><td rowspan="3">Palaeozoic sedimentary sequences</td><td>Série post-Tassilienne</td><td></td><td>Upper Devonian (Frasnian, Famennian) to
Middle Carboniferous (Visean, Namurian)</td><td>Série de Tagora/Talach</td></tr>
<tr><td>Couverture Tassilienne</td><td></td><td>Ordovician, Silurian (Gothlandian) to Lower Devonian</td><td>Kandi Group</td></tr>
<tr><td></td><td>Continental de base</td><td></td><td>Grès de Timesgar, Grès du Cambrian</td></tr>
</table>

Tab. 7: Major stratigraphic groups in West Africa

West African stratigraphic group			Predominant depositional environment
Sedimentary basins (Classification of Kilian, 1931)			
	Quaternary continental sediments (Neogene to Quaternary, unconsolidated deposits)		sedimentary, aeolian/ alluvial/ lacustrine/ coastal
	Continental Terminal (Post-Eocene, terrestrial deposits)		sedimentary, continental
	Continental Hamadien (Terrestrial deposits of the Upper Cretaceous)		sedimentary, continental
	Série hamadienne (Marine transgressions of the Upper Cretaceous/Paleocene)		sedimentary, marine (to continental)
	Continental Intercalaire (Terrestrial deposits of the Mesozoic/Lower Cretaceous)		sedimentary, continental (to marine)
	Undifferentiated Continental Intercalaire, Série Hamadien, Continental Terminal and recent deposits		sedimentary
	Palaezoic sedimentary sequences	Série post-Tassilienne (Transgression marine du Dévonien supérieur et Carbonifère)	sedimentary, marine (to continental)
	Palaezoic sedimentary sequences	Couverture Tassilienne (Transgression marine du Ordovicien-Silurien)	sedimentary, marine (to continental)
	Palaezoic sedimentary sequences	Continental de base (pre-Ordovician continental strata)	sedimentary, continental (to marine)
Sedimentary basins - Metasediments			
	Pan-African orogeny	Infracambrien tabulaire	metasedimentary, continental - marine
	Pan-African orogeny	Infracambrien plissé (Pan-African)	metasedimentary, marine
	Pan-African orogeny	Supergroup 1 (Hodh)	metasedimentary, marine
	Pan-African orogeny	Youkounkoun Group	metasedimentary, cont. & marine, volcanic
	Pan-African orogeny	Pan-African orogeny: Rockelide & Bassaride belts	(meta-) volcano-sedimentary
	Pan-African orogeny	Pan-African orogeny: Pharusian Belt	(meta-) volcano-sedimentary
	Pan-African orogeny	Pan-African orogeny: Dahomeyan Belt	(meta-) volcano-sedimentary
Basement			
	Trans-Saharan Belt	Pan-African orogeny: Touareg Shield	plutonic & metamorphic complexes & (meta-) volcano-sedimentary terranes
	Trans-Saharan Belt	Pan-African orogeny Dahomeyan Belt	plutonic & metamorphic complexes & (meta-) volcano-sedimentary terranes
	Trans-Saharan Belt	Pan-African orogeny: Benin-Nigerian Shield	plutonic & metamorphic complexes & (meta-) volcano-sedimentary terranes
	West-African Craton	Palaeoproterozoic (Eburnean) basement: Baoulé-Mossi Domain	plutonic & metamorphic complexes & (meta-) volcano-sedimentary Birimian terranes
	West-African Craton	Archean basement: Kénéma-Man domain	plutonic & metamorphic complexes & (meta-) volcano-sedimentary sequences
Igneous rocks			
	Extrusive rocks	Quaternary & Cenozoic volcanics	extrusive/volcanic (mafic)
	Intrusive rocks	Mesozoic hypovolcanism (CAMP intrusives)	intrusive/plutonic rocks (mafic)
	Intrusive rocks	Mesozoic plutonism "Younger Granites & Ring Complexes"	intrusive/plutonic rocks (felsic)
	Intrusive rocks	Pan-African intrusives: Plutonic ring-complexes of the Aïr, Batholiths of the Adrar des Iforas, Older Granites (syn- & post-tectonic pan-African granitoids)	intrusive/plutonic rocks (mafic/felsic)

6.13 References [Sources]

This field lists the most relevant references for the geological and hydrogeological characterisation of the map units. In addition, references are listed in the respective parameter fields.

7 Topographic themes

7.1 Stream network and water bodies

The linework for the stream network was assembled by AGES drawing on a variety of data sources – most importantly on internal data from the Niger Basin Authority, and on the stream network developed by Open Street Map (OpenStreetMap contributors 2022).

Lakes and open surface water bodies and the Lake Chad highstand (ca. 1960) were adapted and modified from HydroLAKES (Messager et al. 2016).

7.2 Lineaments

Lineaments were harmonized from data sets provided by the Niger Basin Authority and a lineament data set developed during the Projet Réseau SIG Afrique for the *Carte hydrogéologique de l'Afrique à 1:10 M* (Lescuyer 2005; Seguin 2016). The data sets were harmonized; thematic duplicates were omitted. The data set was thinned out to only show a restricted subset of the main structural features.

7.3 Hydrological basins

Hydrological basins, and in particular the outline of the Niger Basin, follows the delineation proposed by HydroBASINS level 04 (Lehner & Grill 2013) based on a 15 arc-second grid resolution. HydroBASINS builds on the HydroSHEDS v1 database (Lehner et al. 2008) derived primarily from the SRTM (Shuttle Radar Topography Mission) digital elevation model at a resolution of 3 arc-seconds. Most other current basin products build on the HydroSHEDS v1 or HydroBASINS data sets. These include the shapefiles currently provided by FAO/Geonetwork but also the *Major River Basins 2020 edition* of the Global Runoff Data Center (GRDC) a refined version of the HydroBASINS restricted to the major river basins. The geometries of the basin were smoothed to allow for an easy linework.

Differentiation into hydrologically active and passive (endorheic) parts of the basin followed an original proposition of the Niger Basin Authority and has not been validated independently. Runoff within the hydrologically active part might be intermittent but contributes seasonally to the perennial stream network. Runoff in the hydrologically passive part is intermittent and endorheic, and do not contribute to the active stream network.

On the present map, the Niger Basin encompasses not only the traditional hydrological drainage basin – but follows the conventional limits of the Niger Basin including the Niger Delta complex in Nigeria. The published version is partly smoothed and adjusted to the map scale of 1:3 500 000.

7.4 Aquifer systems

The outline of large aquifer systems builds upon the geometric extent of sedimentary (sub-) basins as delimited by the present map and draws on the proposition of *Transboundary Aquifers of the World – Update 2021* (IGRAC - International Groundwater Resources Assessment Centre 2021). Higher order hydrogeological units in Mali were separated based on the *Synthèse Hydrogéologique du Mali* (DNHE 1990). All linework has been adjusted to correspond to the stratigraphic units of the geological map. The published version is partly smoothed and adjusted to the map scale of 1:3 500 000.

8 Perspectives

The *Geological map of the Niger Basin* and the map *Expected aquifer productivity of the Niger Basin* are first Niger Basin-wide approximations to describe the geological and hydrogeological setting in a comprehensive and harmonised way. Ideally, the maps will serve as a basis for basin-wide hydrogeological assessments and general groundwater potential estimations. The **small-scale base maps** and the harmonisation processes warrant to not use the map for assessments on scales larger than 1 500 000 – although locally a more detailed geometry is suggested and provided by the shapefiles.

To support the Niger Basin Authority and its member states with **large-scale maps** and data sets adequate to address applied regional questions such as transboundary groundwater exploitation, large-scale river-aquifer interaction, or groundwater potential mapping for planning activities, a Niger Basin-wide mapping effort on a scale of 1 : 100 000 – 1 : 250 000 should be envisaged. **Local studies** for the siting of groundwater wells, groundwater vulnerability studies, local river-aquifer interactions require detailed groundwater mapping at scales between 1 : 5 000 and 1 : 25 000.

Ongoing groundwater research at institutions and universities has treasured up a wealth of new information superseding the baseline information provided by the here consulted freely available maps and reports many of them dating back to the mid-20th century. **National expertise from the member states is required to review, correct, validate, and refine the proposed data set**.

Subsequent mapping efforts should be designed as **conjoint projects between the Niger Basin Authority and the responsible national institutions** (e.g. ministries of water and/or geology) and should draw on the knowledge, the analytical skills, and the personal resources offered by **universities and academic institutions**.

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10 Annex

10.1 Consulted Maps

10.1.1 Westafrica

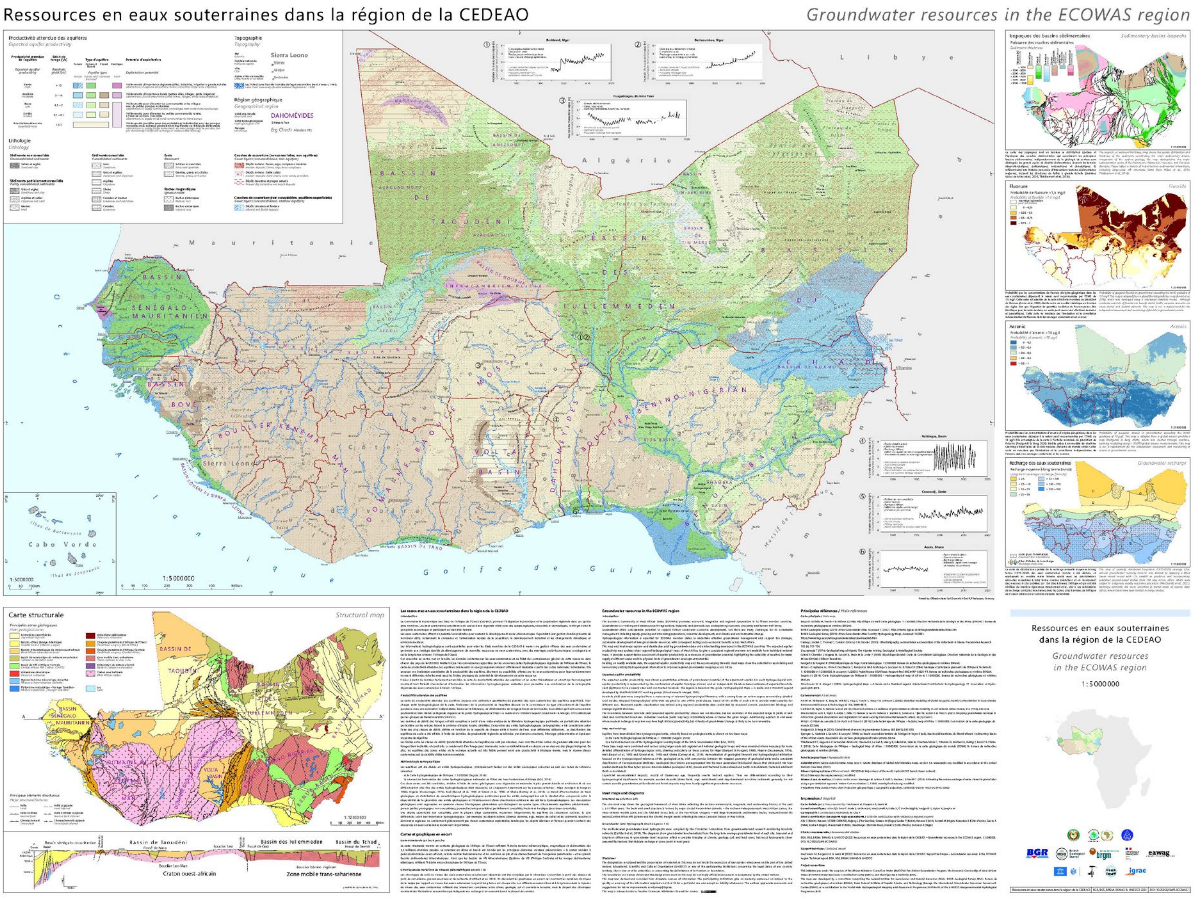
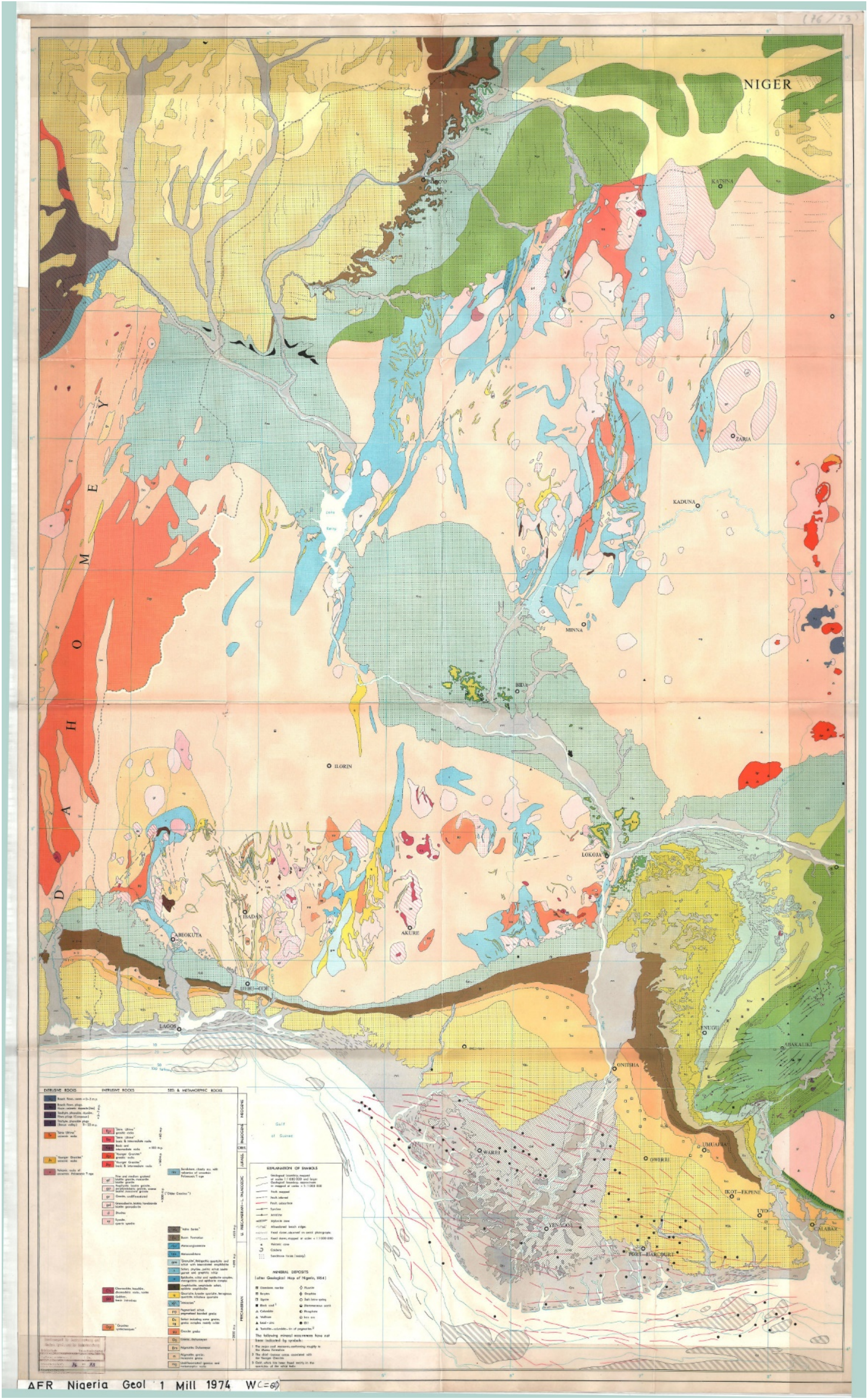


Fig. 5: Ressources en eaux souterraines dans la région de la CEDEAO – Groundwater resources in the ECOWAS region, *1 : 5 000 000 (Heckmann et al. 2022a)*

10.1.2 Nigeria



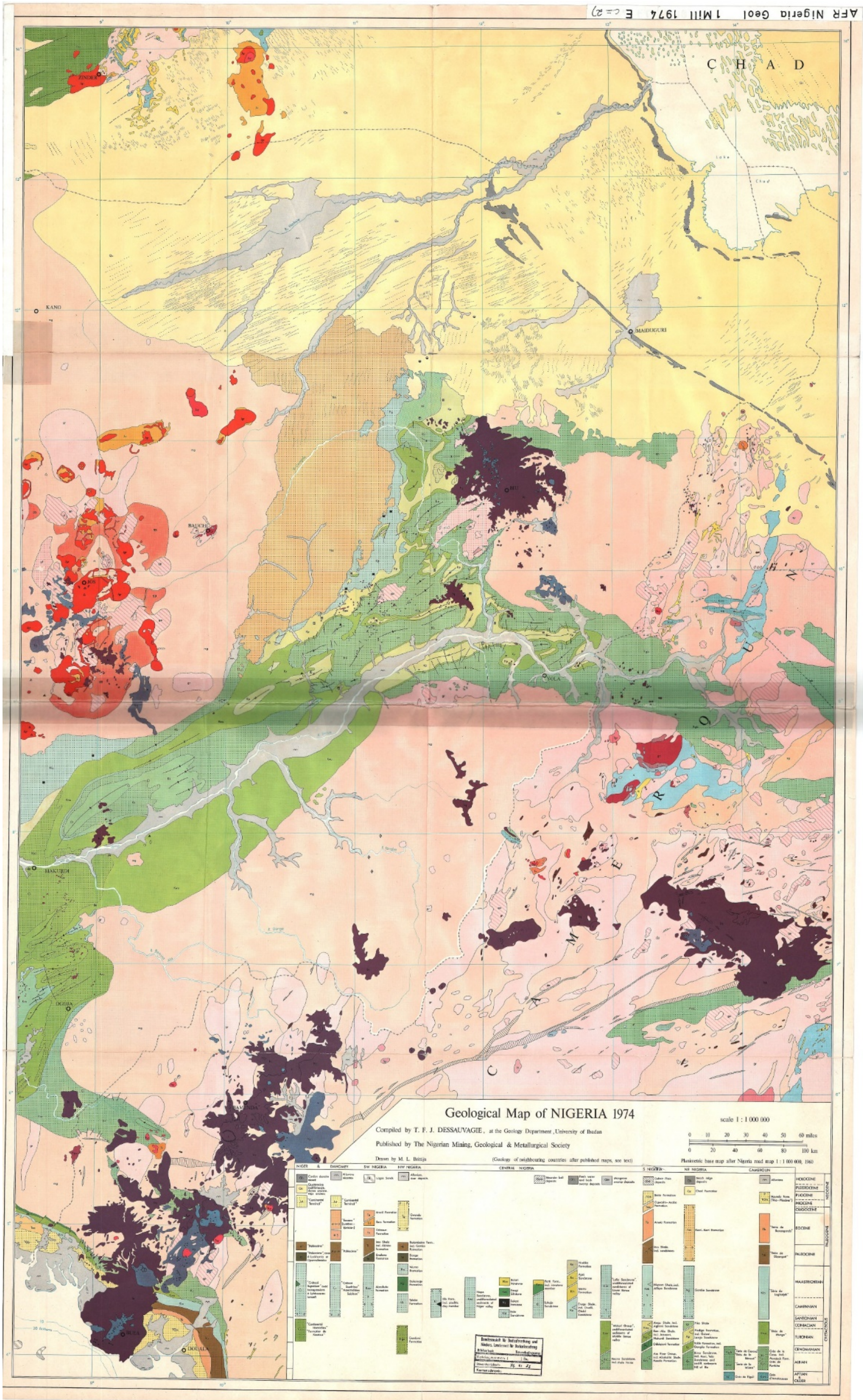


Fig. 6: Dessauvagie TFJ (1974): Geological Map of Nigeria. 1:1.000.000. The Nigerian Mining, Geological & Metallurgical Society.

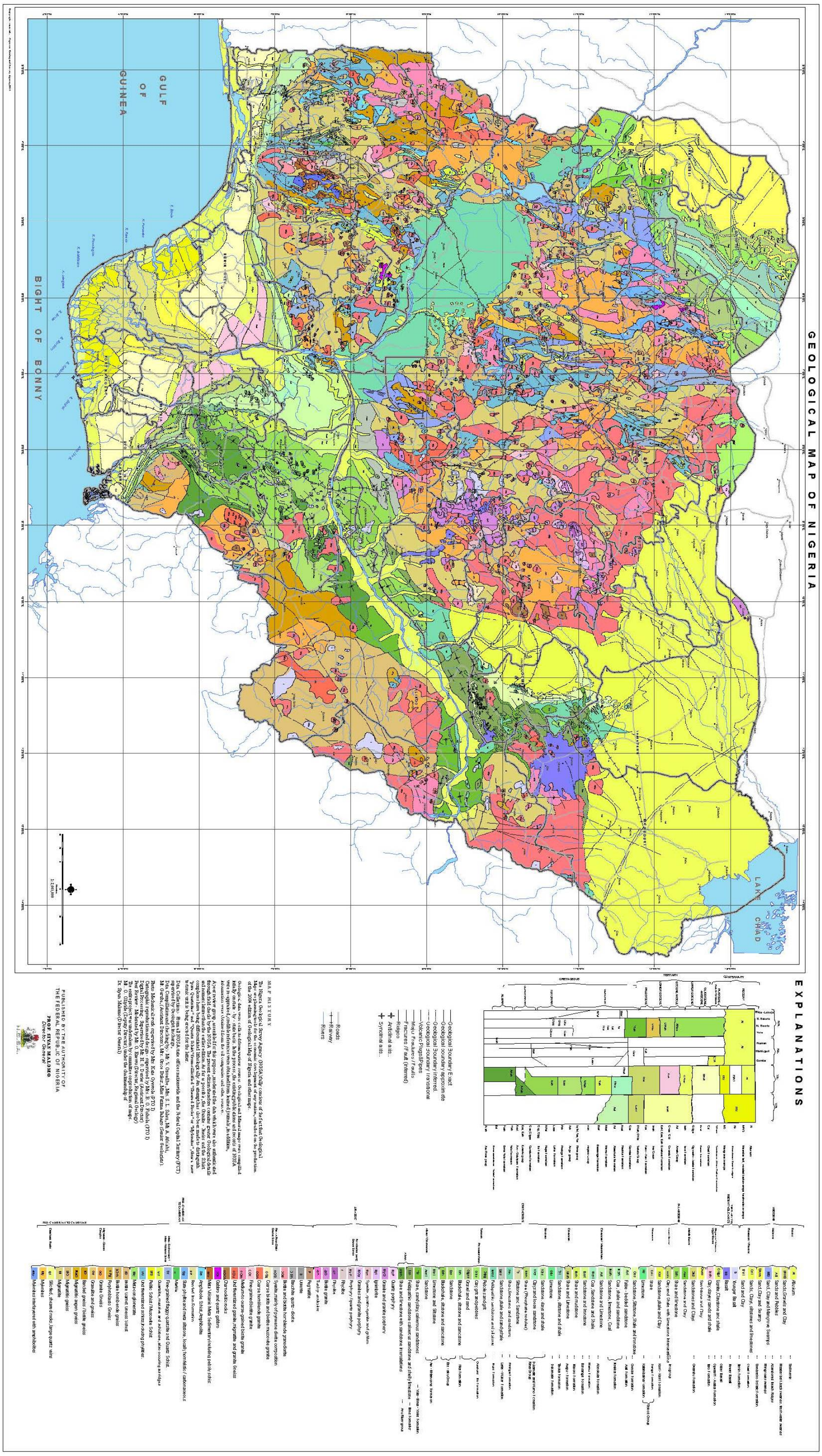


Fig. 7: *NGSA (2006): Geological Map of Nigeria. 1:1 000 000. Reprint 2011.*

10.1.3 Cameroon

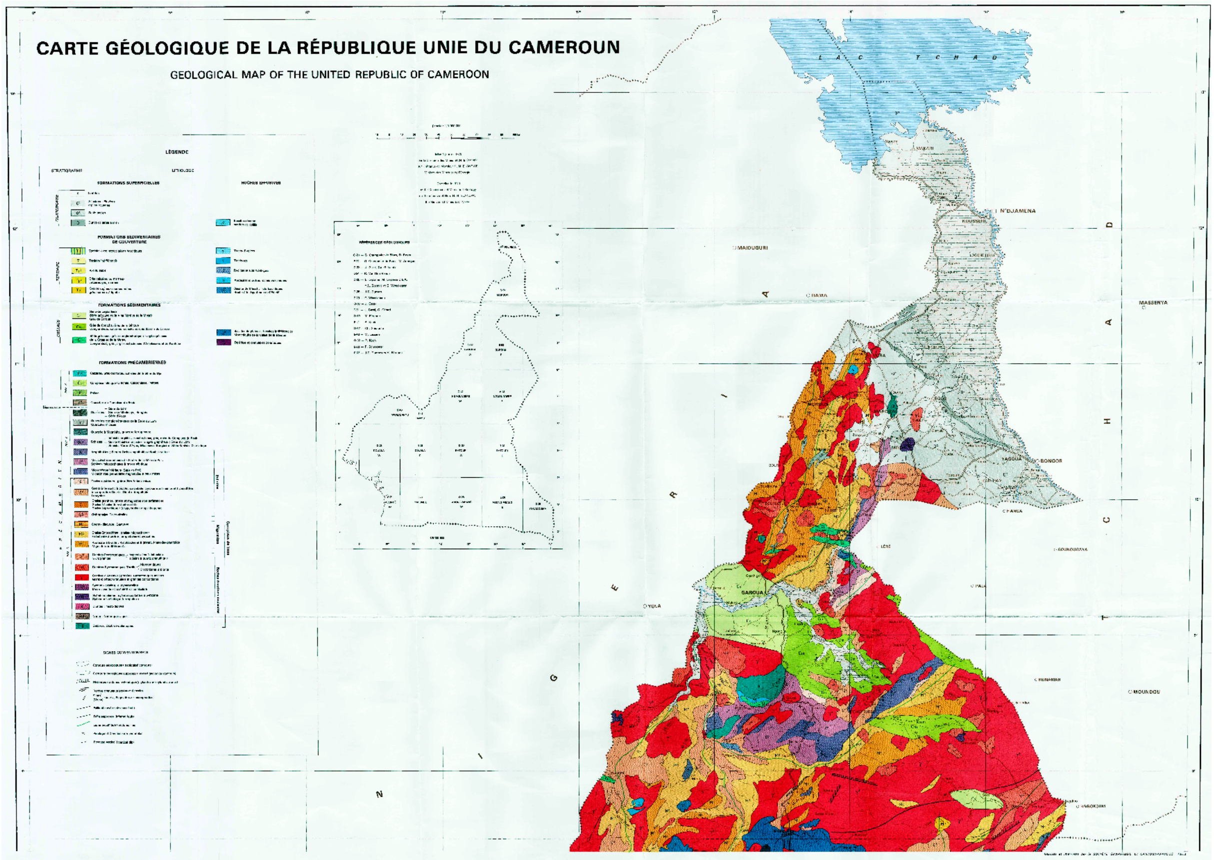


Fig. 8: Carte géologique de la République unie du Cameroun - Geological map of the united Republic of Cameroon, 1 : 1 000 000 (Direction des mines et de la géologie 1980)

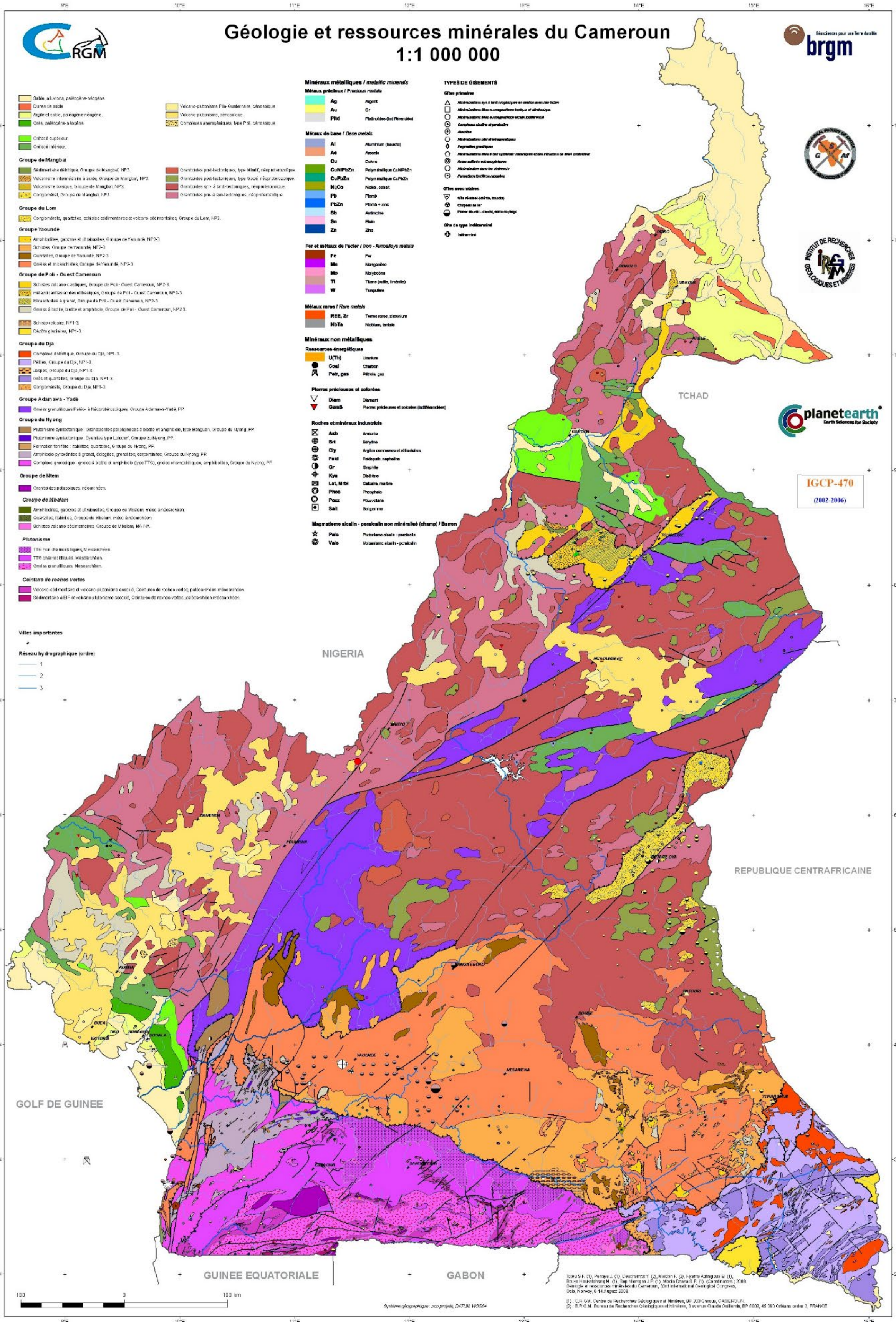


Fig. 9: Géologie et ressources minérales du Cameroun. *1:1 000 000. 33rd International Geological Congress, Oslo, Norway, 6-14 August 2008, CRGM & BRGM, Yaoundé. (Toteu et al. 2008)*

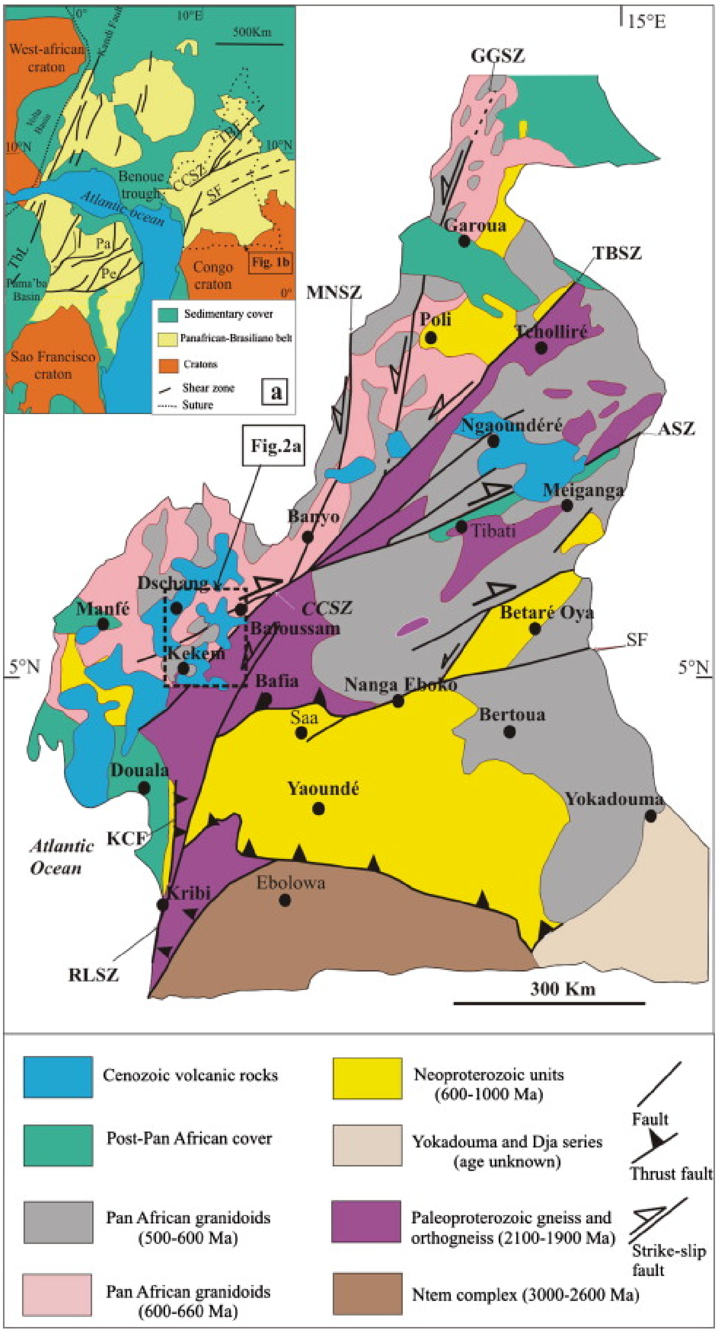


Fig. 10: *The Pan-African Kekem gabbro-norite (West-Cameroon), U–Pb zircon age, geochemistry and Sr–Nd isotopes: Geodynamical implication for the evolution of the Central African fold belt.* Journal of African Earth Sciences *84 pp. 70–88. (Kwékam et al. 2013)*

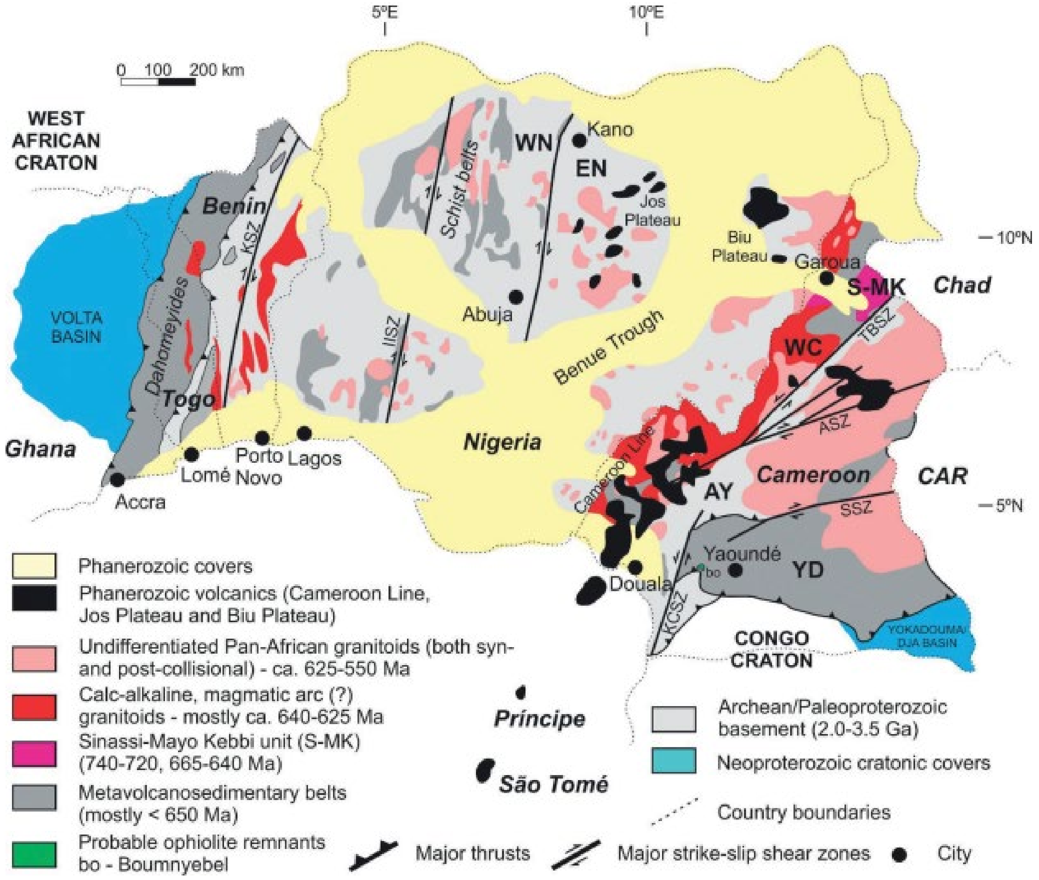


Fig. 11: Toward an integrated model of geological evolution for NE Brazil-NW Africa: The Borborema Province and its connections to the Trans-Saharan (Benino-Nigerian and Tuareg shields) and Central African orogens. Sociedade Brasileira de Geologia., Brazilian Journal of Geology *50. (Caxito et al. 2020)*

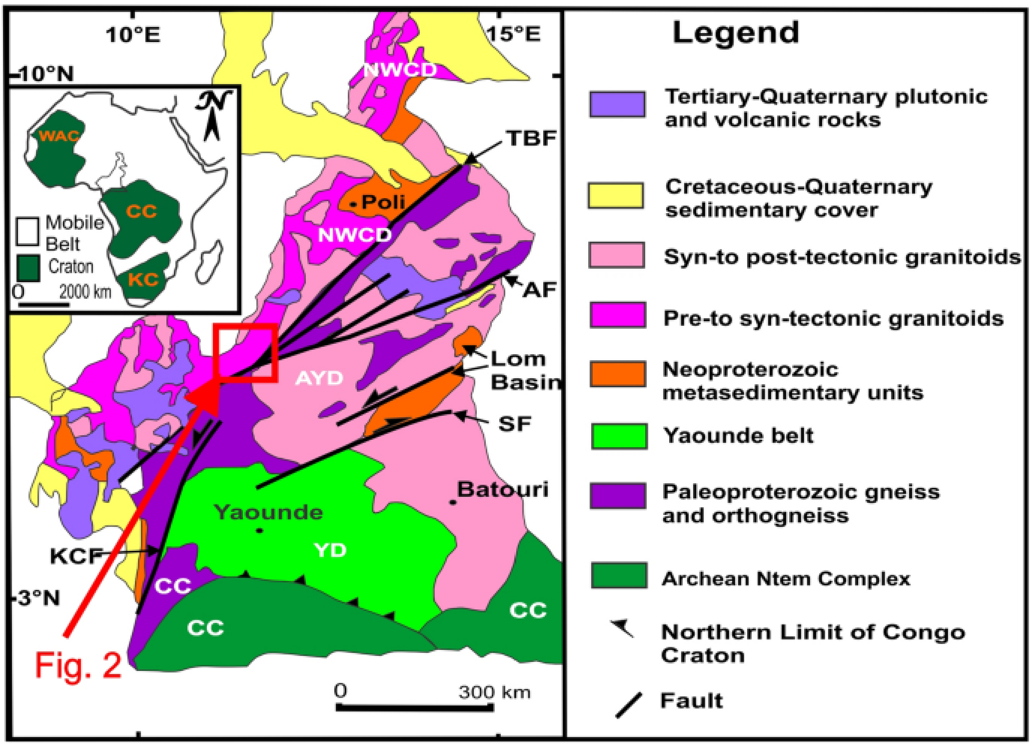


Fig. 12: Geological map of Cameroon (Ntieche et al. 2021)

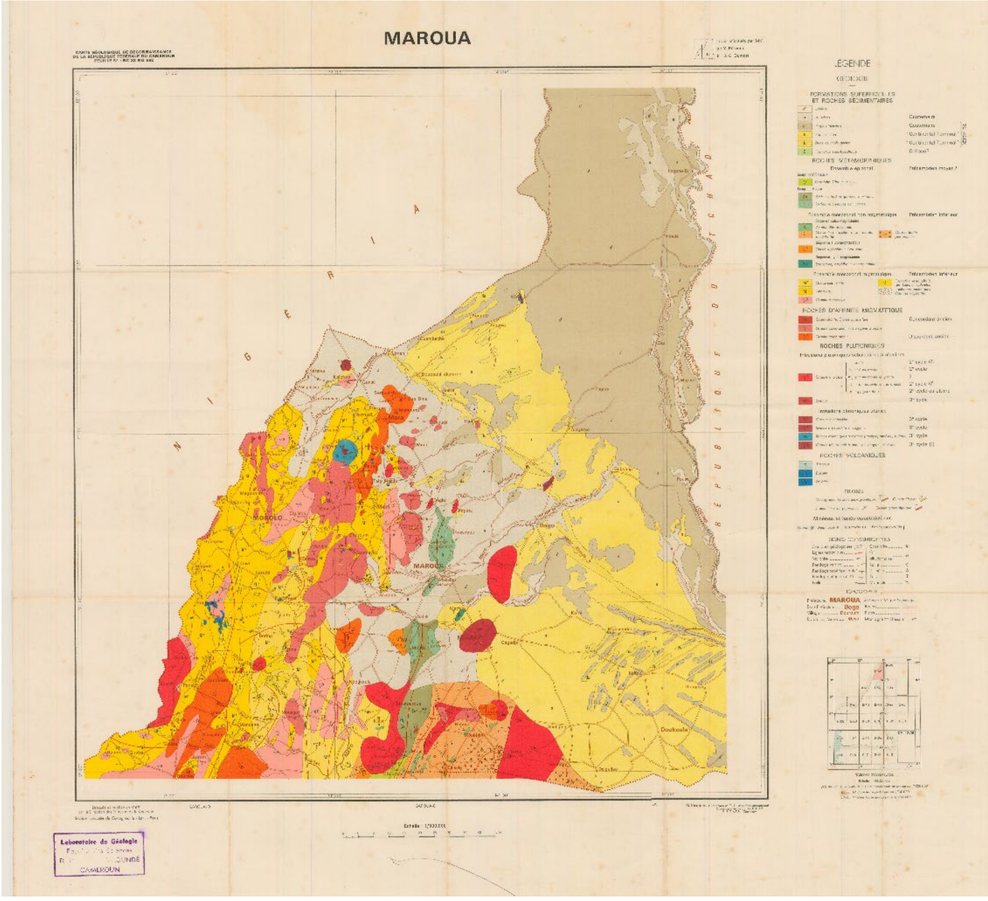


Fig. 13: Dumort C & Péronne Y (1966): Carte géologique de reconnaissance de la République Fédérale du Cameroun. NC-33 E-62. Maroua. *1:500 000, Direction des Mines et de la Géologie, Yaoundé.*

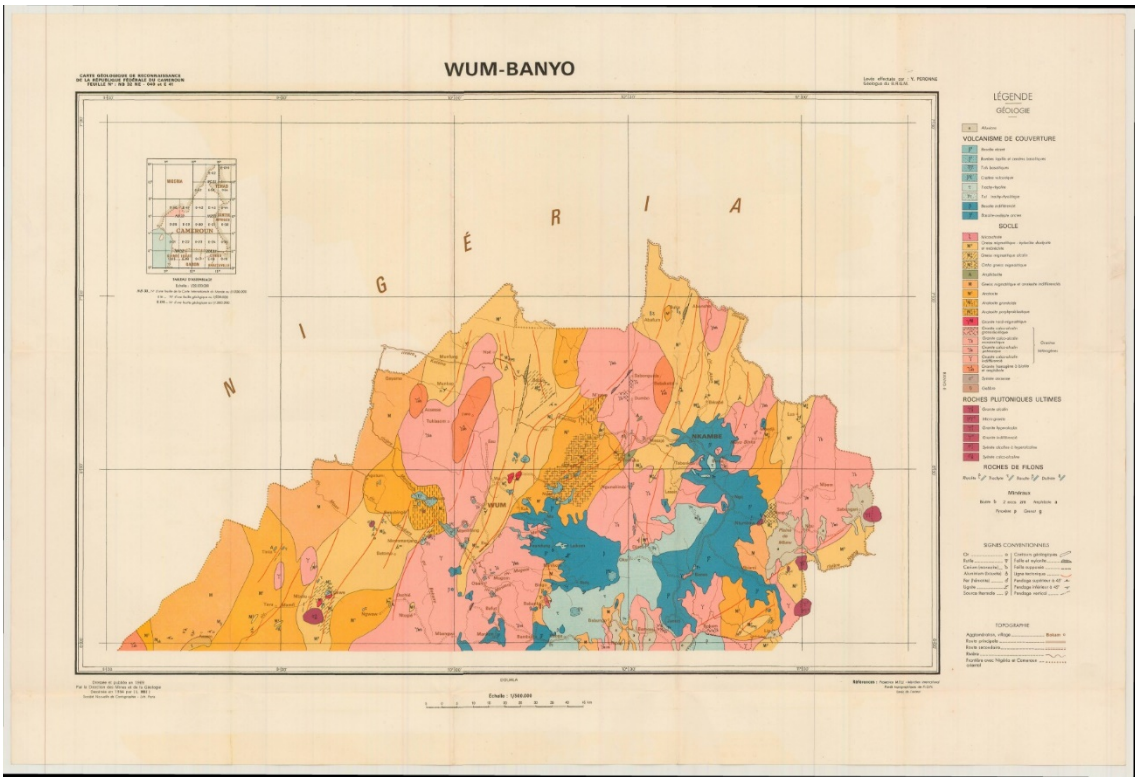


Fig. 14: Péronne Y (1969): Carte géologique de reconnaissance de la République Fédérale du Cameroun. NB-32 NE40 & E41. Wum-Banyo. *1:500 000, Direction des Mines et de la Géologie, Yaoundé.*

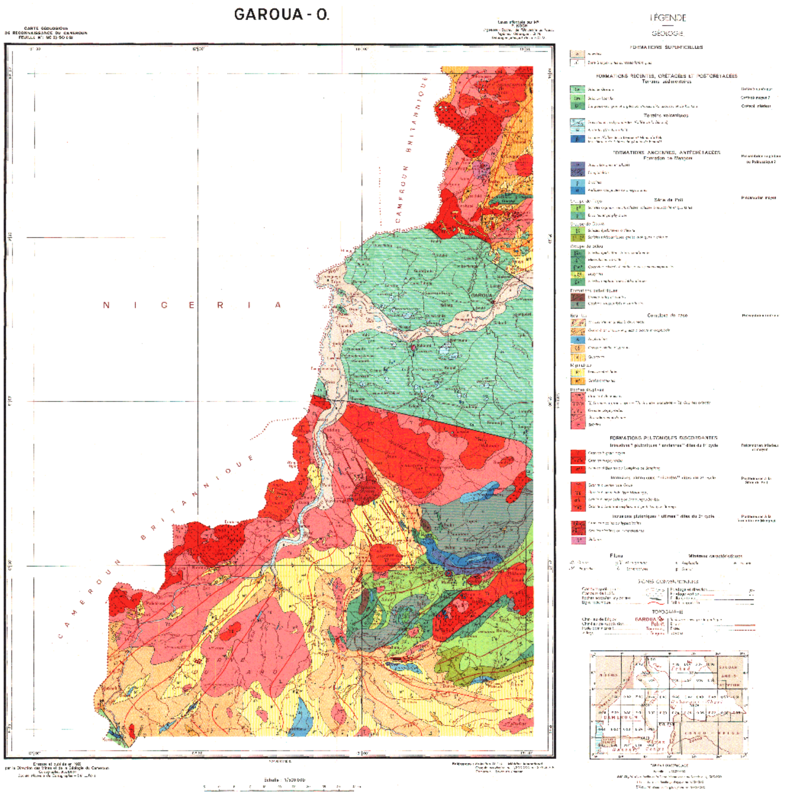


Fig. 15: Koch P (1959): Carte géologique de reconnaissance de la République Fédérale du Cameroun. NC-33 SO O-52. Garoua-Ouest. *1:500 000, Direction des Mines et de la Géologie, Yaoundé.*

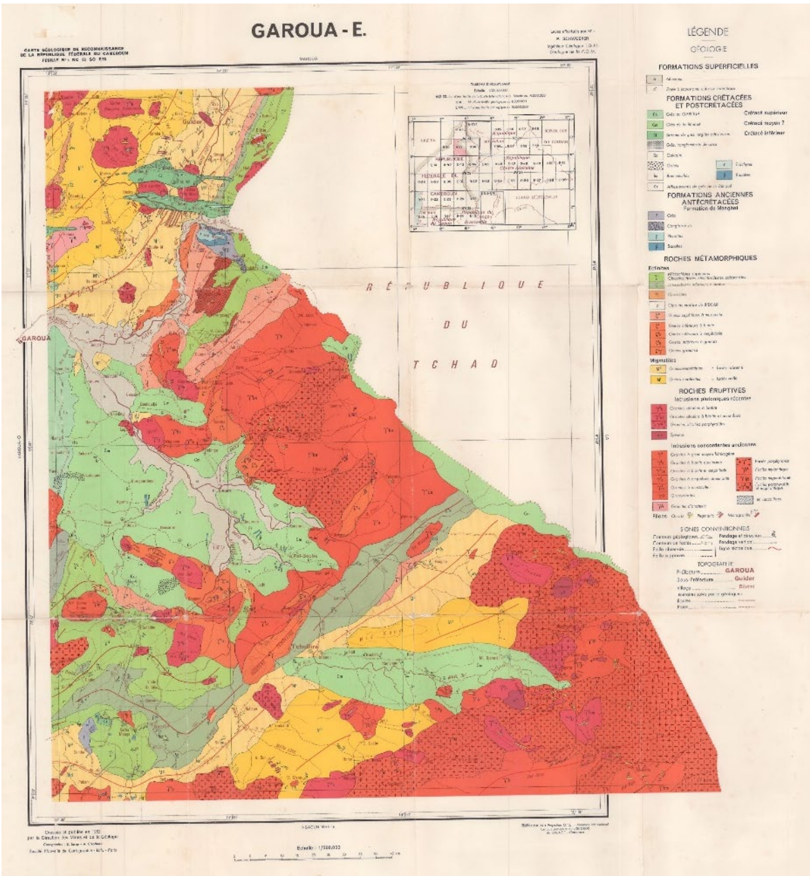


Fig. 16: Schwoerer P (1962): Carte géologique de reconnaissance de la République Fédérale du Cameroun. NC-33 SO E-53. Garoua-Est. *1:500 000, Direction des Mines et de la Géologie, Yaoundé.*

10.1.4 Tchad

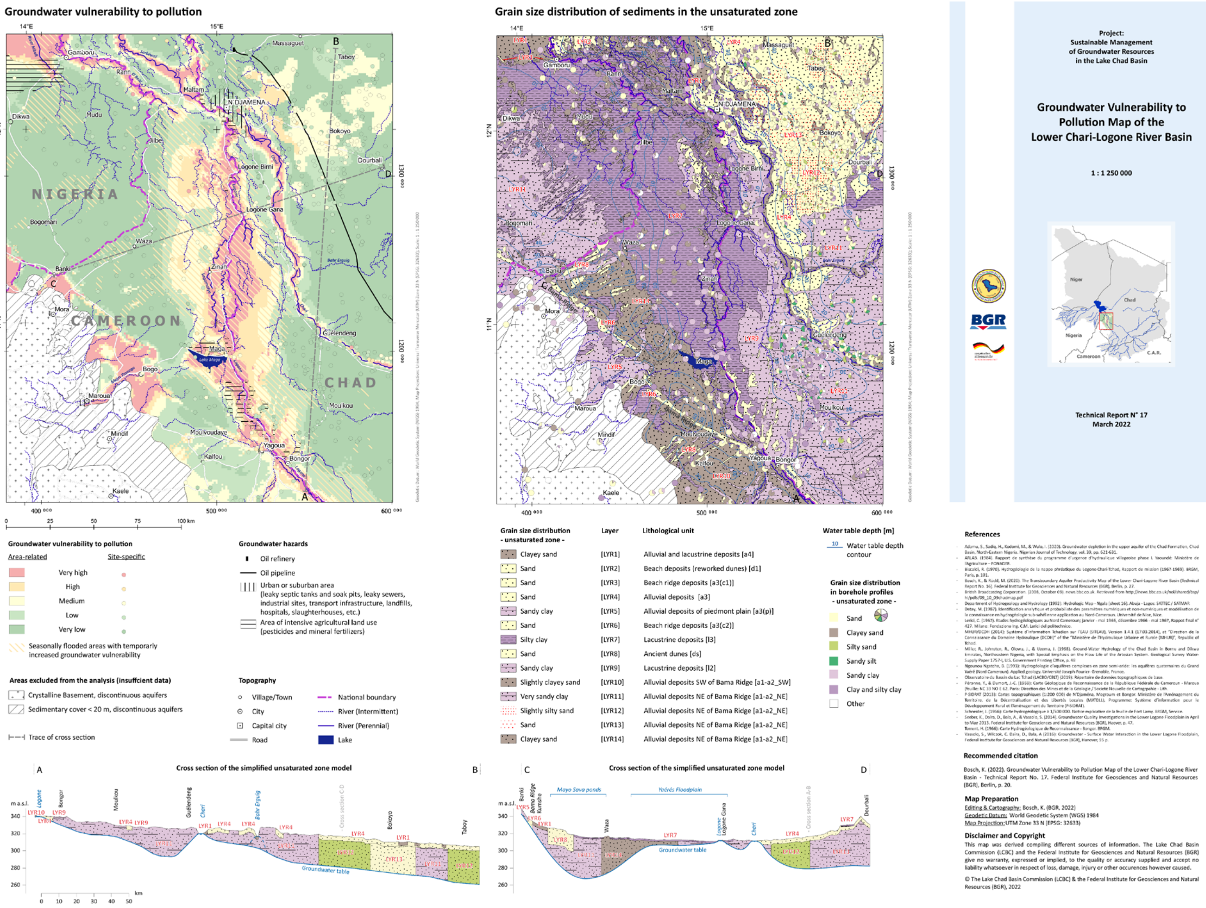
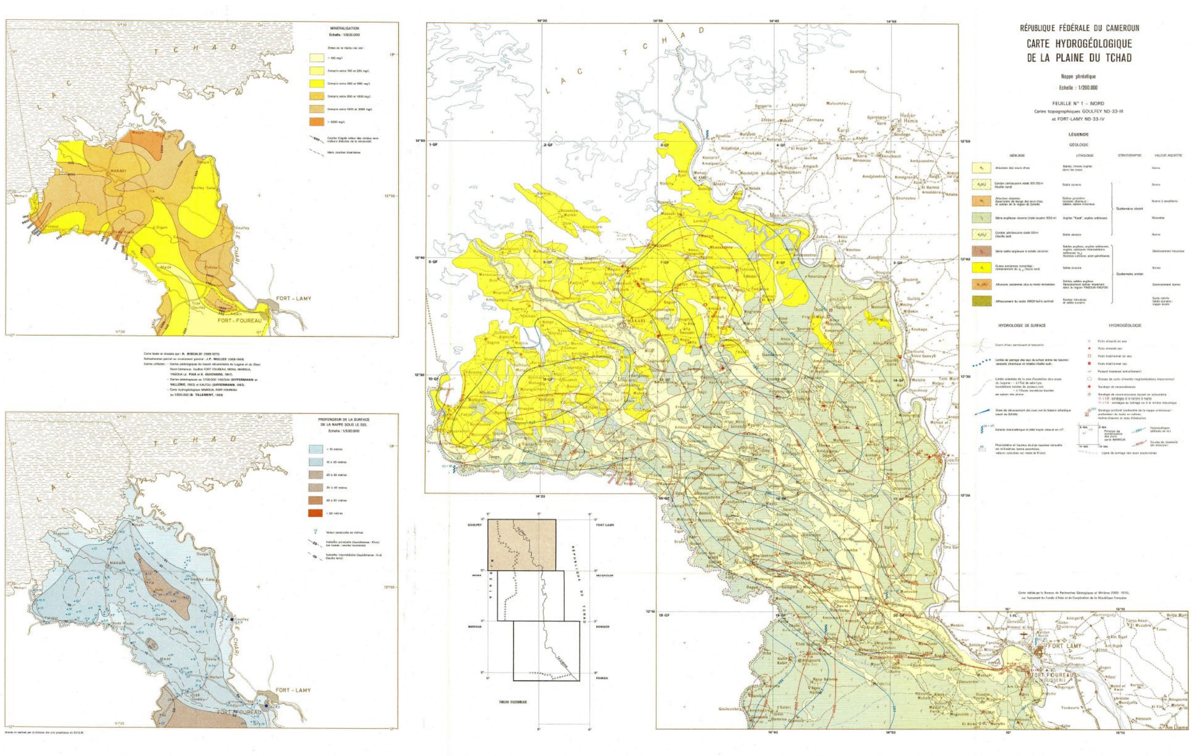
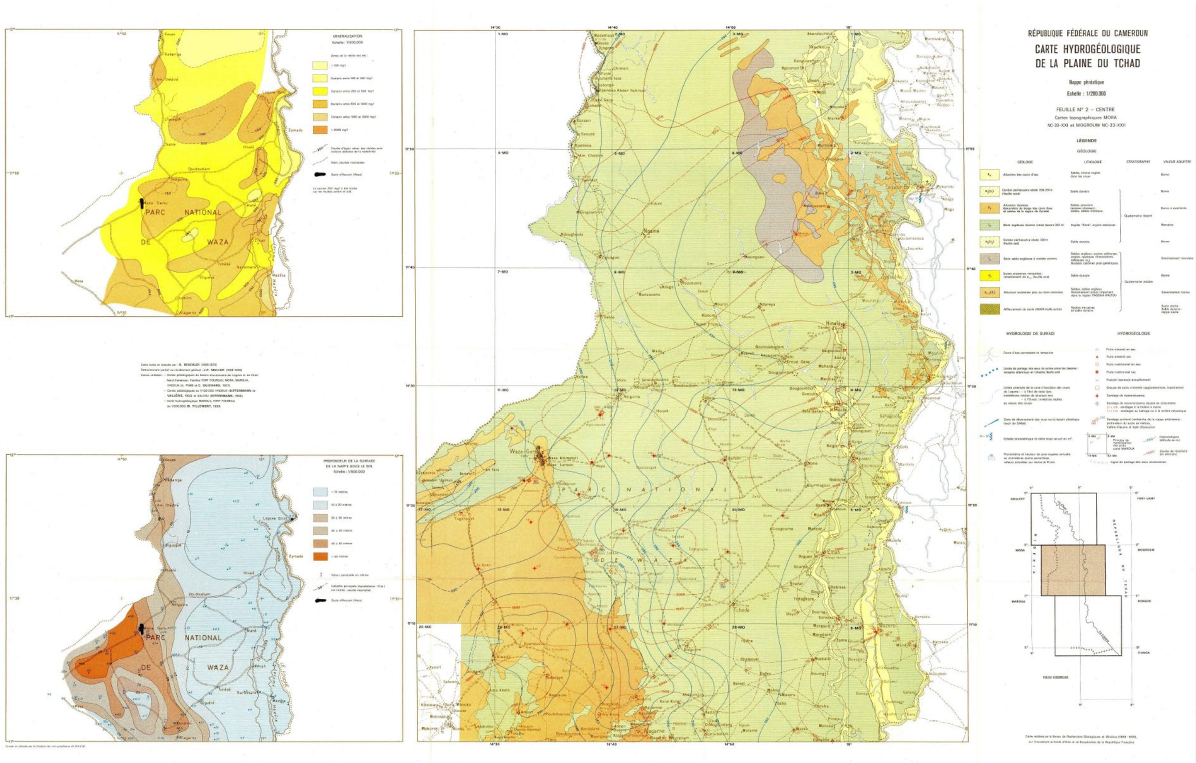


Fig. 17: Groundwater Vulnerability to Pollution Map of the Lower Chari-Logone River Basin *(Bosch 2022) harmonizing geological and hydrogeological information of the original national maps*





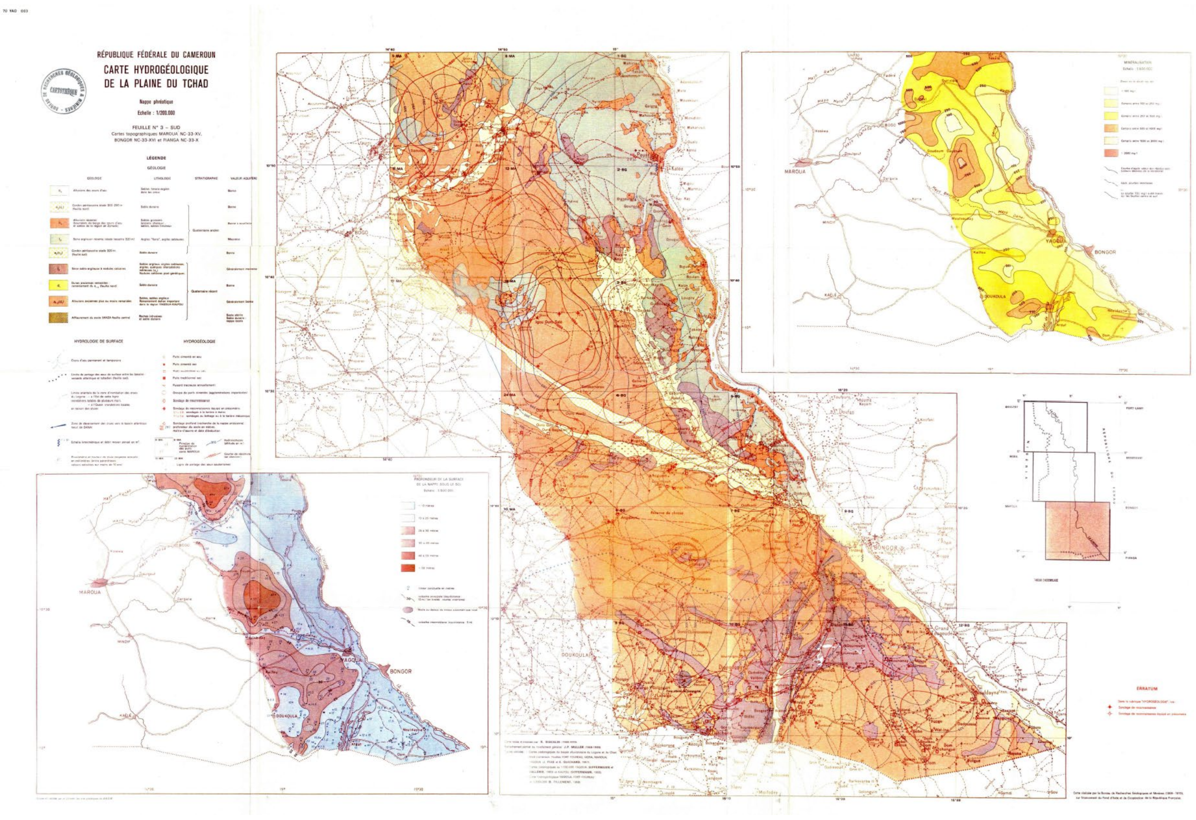


Fig. 18: Carte hydrogéologique de la plaine du Tchad. Nappe phréatique*. 1:2 00 000, Feuille N°1 – Nord, Feuille N°2 - Centre, Feuille N°3 - Sud, BRGM. (Biscaldi 1970a, 1970b, 1970c)*

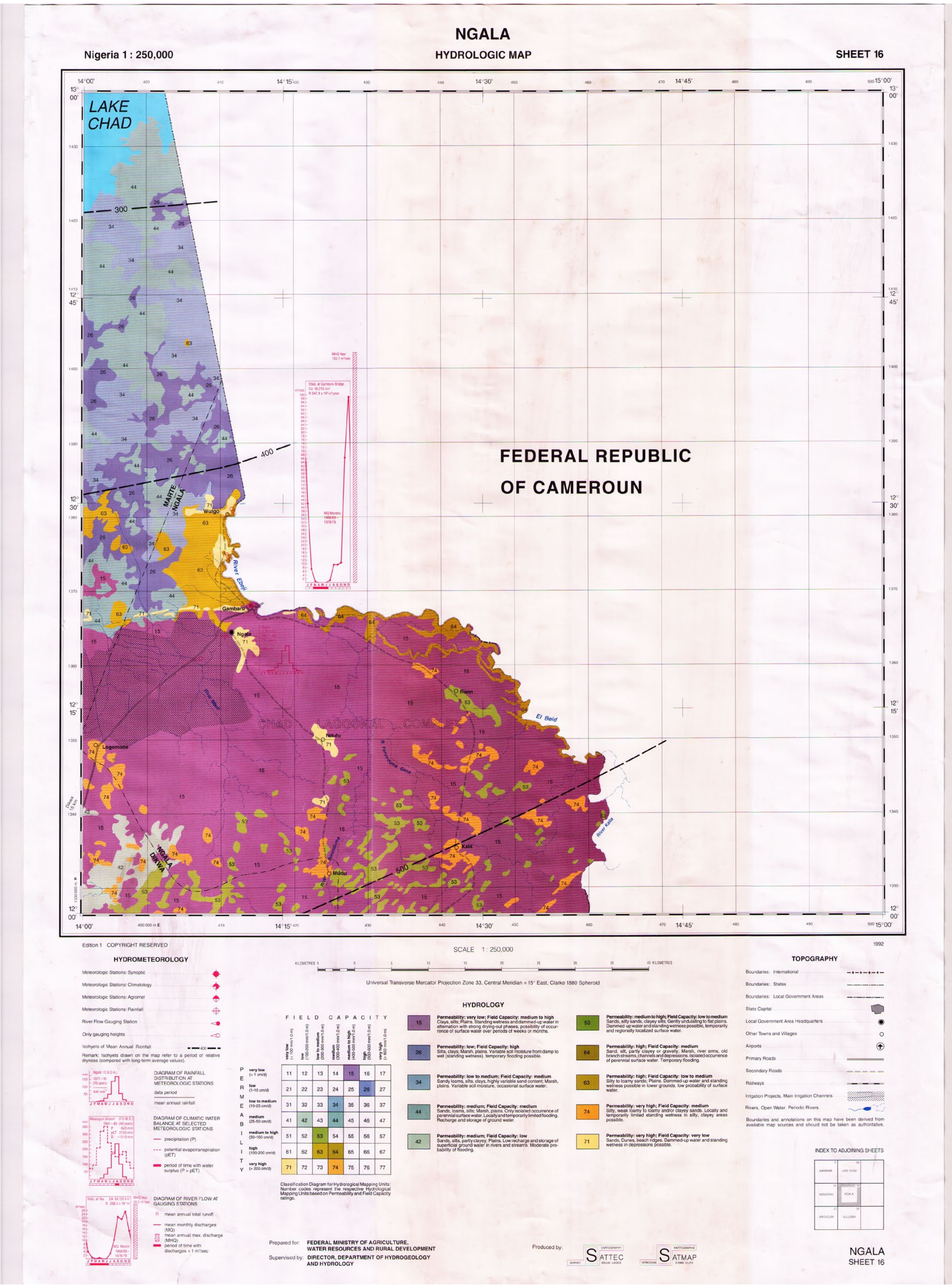


Fig. 19: Hydrologic Map. Sheet 16. Ngala. *1:250 000 (SATTEC & SATMAP 1992a)*

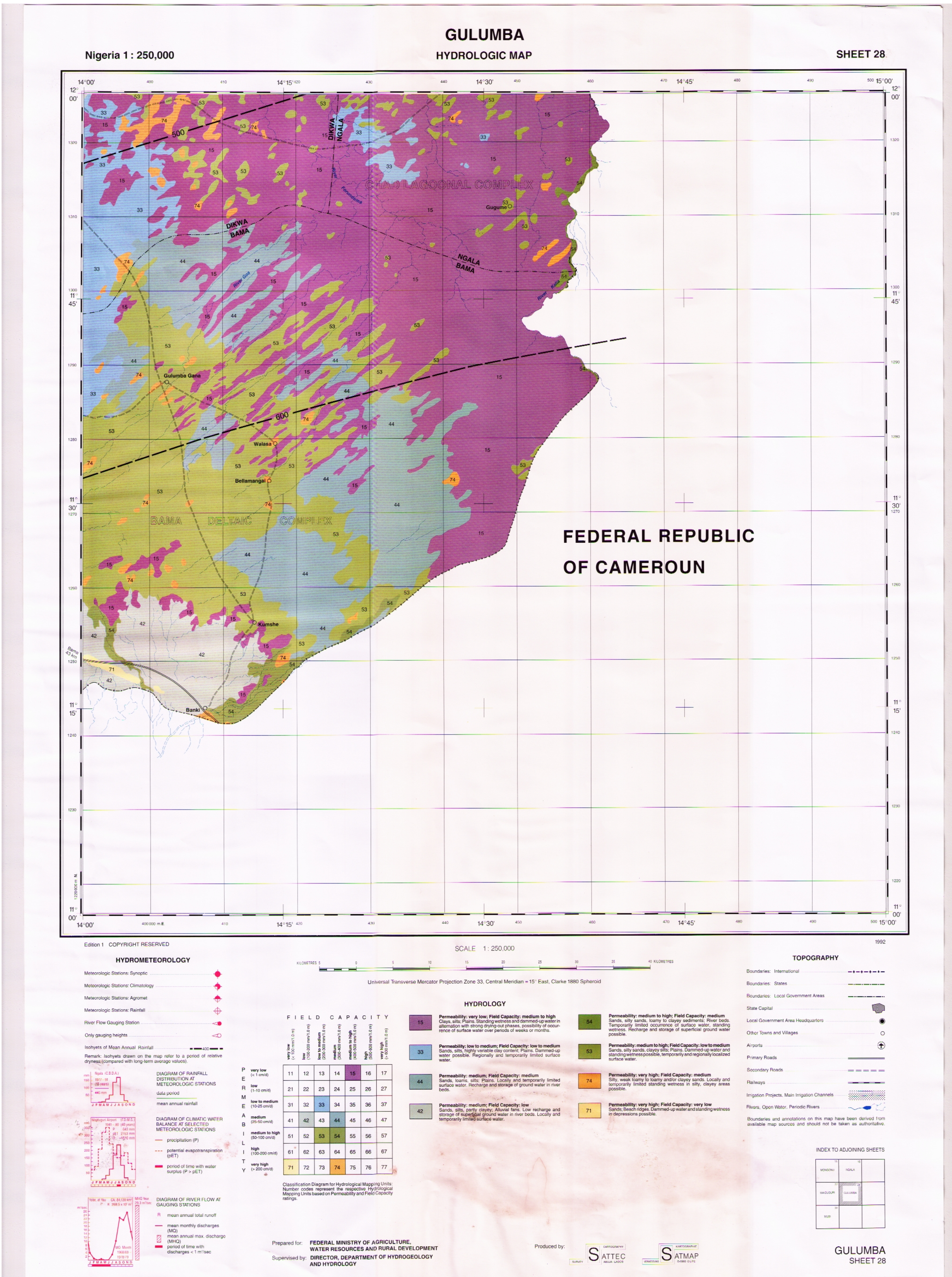


Fig. 20: Hydrologic Map. Sheet 28. Gulumba. *1:250 000 (SATTEC & SATMAP 1992b)*

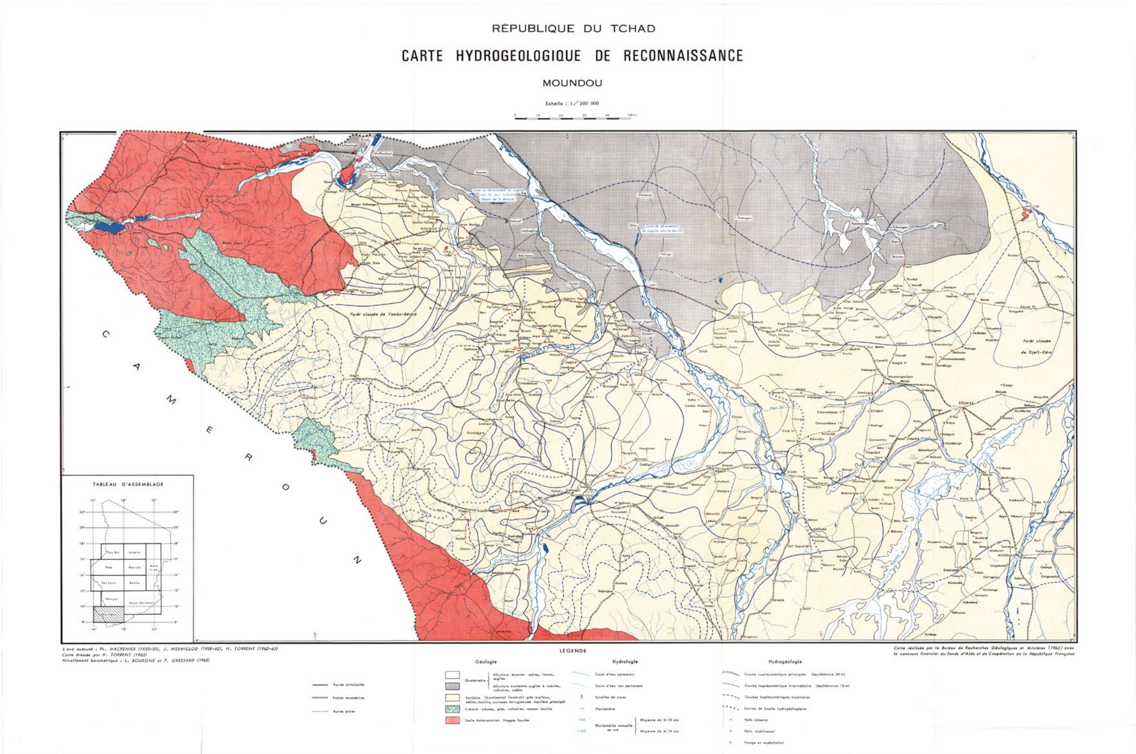


Fig. 21: Carte hydrogéologique de reconnaissance. Moundou. 1:500 000, BRGM (Torrent 1965)

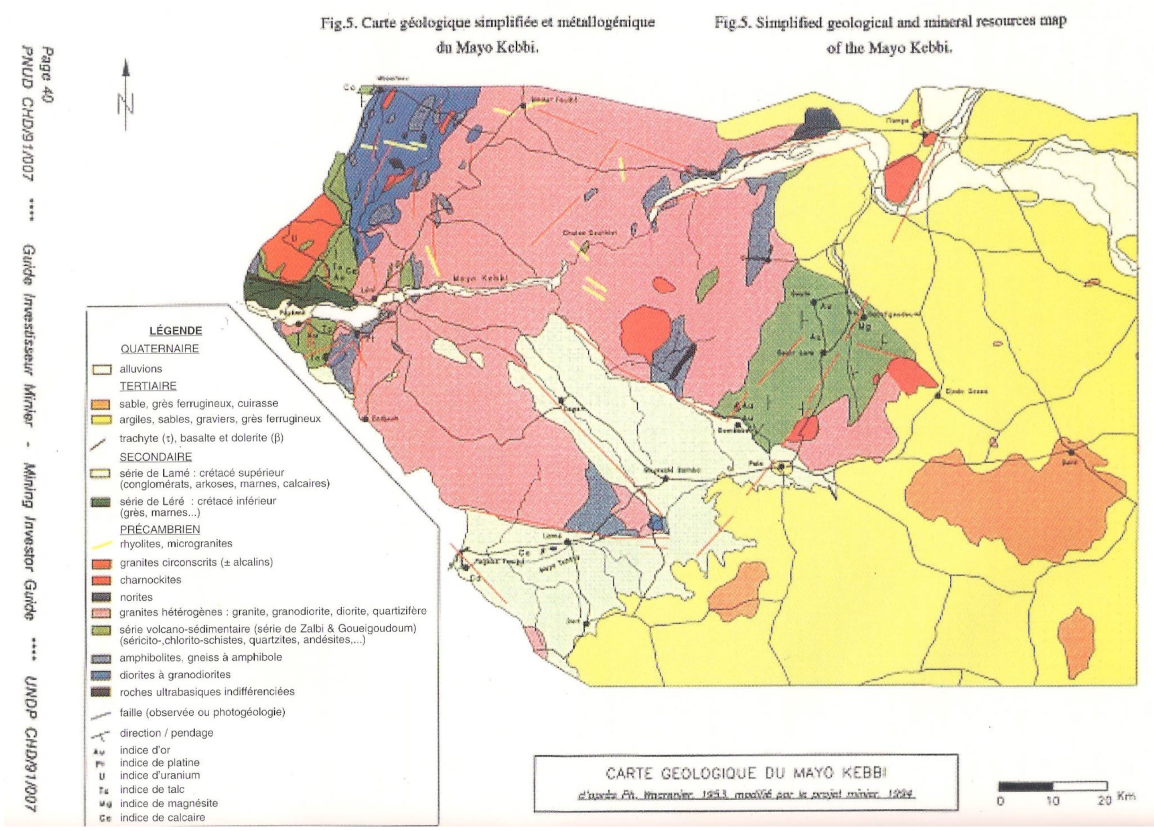


Fig. 22: Carte Geologique du Mayo Kebbi. *Drawn by an unknown author in 1953 (?) and modified for the Guide Investisseur Minier – Mining Investor Guide. PNUD –UNDP CHD/91/007 (cited in Oyamta et al. 2013)*

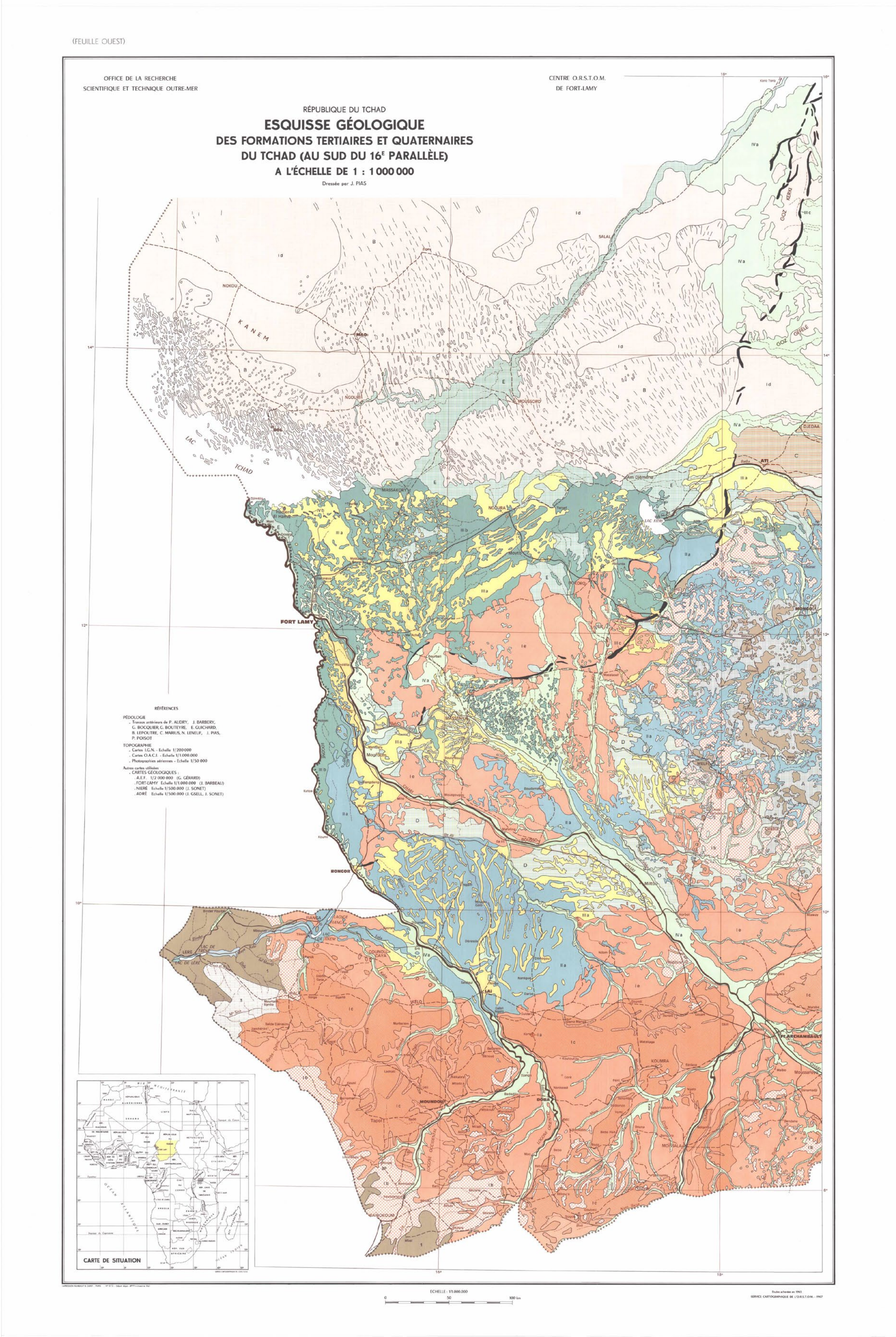


Fig. 23: Esquisse géologique des formations tertiaires et quaternaires du Tchad (au Sud du 16e parallèle). 1:1 000 000. Feuille Ouest, (Pias 1967)

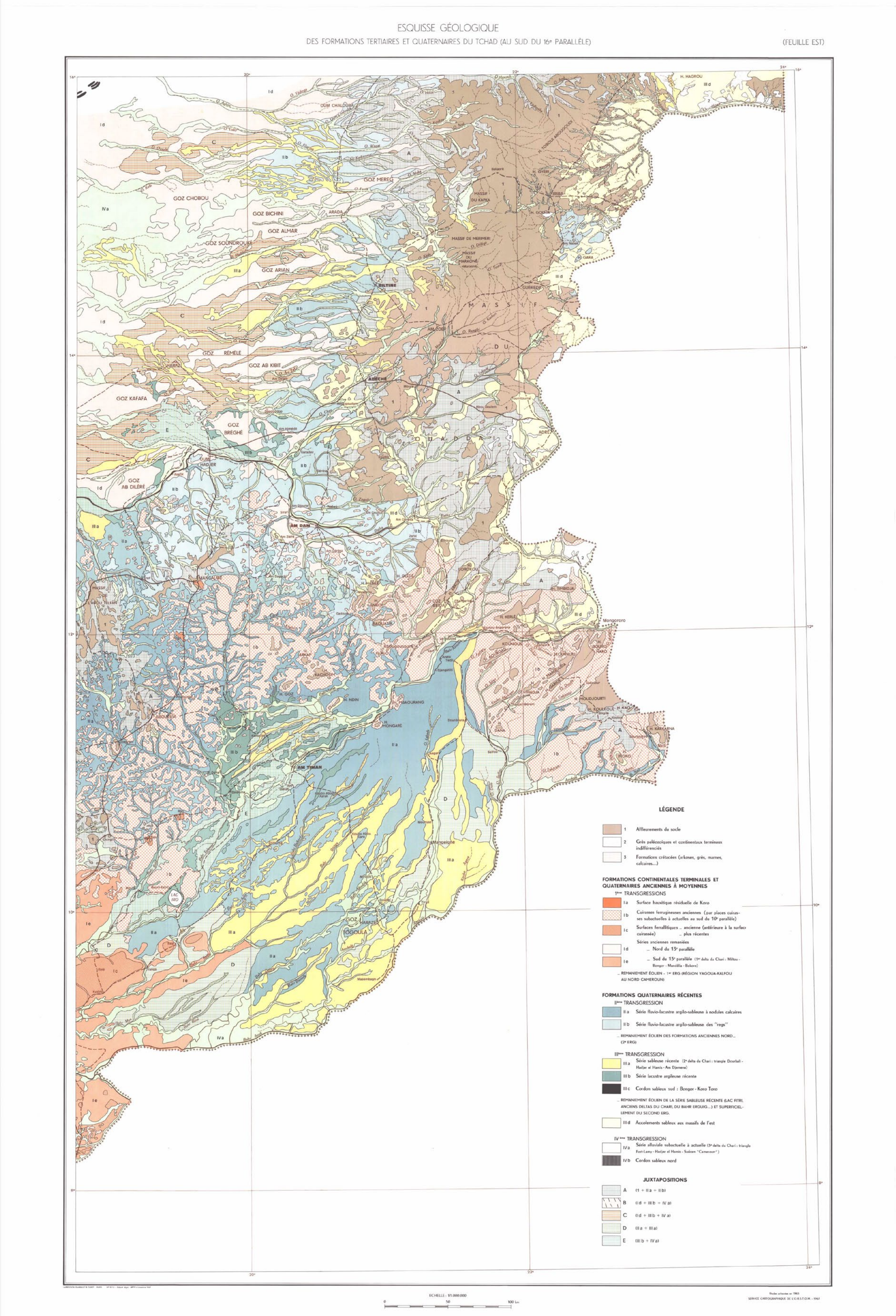


Fig. 24: Esquisse géologique des formations tertiaires et quaternaires du Tchad (au Sud du 16e parallèle). 1:1 000 000. Feuille Est, (Pias 1967)

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