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Permo-carboniferous paleoclimate of the Congo Basin: Evidence from lithostratigraphy, clay mineralogy, and stable isotope geochemistry

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ABSTRACT

Approximately 1000 m of strata in the Upper Paleozoic Lukuga Formation in the Dekese core in the central Congo Basin provide lithostratigraphic, mineralogical, and isotopic evidence for substantial climatic variation within a long-lived lacustrine basin. Lithostratigraphic indicators of cold climate include polymictic strata (dropstone deposits) and coupled laminations of fine clay-size material and coarse silt (glacial varves). Dropstones are concentrated in three stratigraphic zones in the lower ~425 m of the Lukuga Formation, and varved strata occur in two broad stratigraphic zones in the lower ~700 m of the formation. These sedimentological indicators suggest that the lower ~2/3 of the Lukuga Formation was strongly influenced by frigid conditions and glacial-like processes. The clay-size fraction of 97 samples is dominated by detrital minerals, including quartz, feldspar, chlorite, illite, and poorly ordered expansible 2:1 phyllosilicates. Based on variation in the mineralogy of these samples, the Lukuga Formation is divisible into three Clay Mineral Zones (CMZs), numbered in ascending stratigraphic order. CMZ 1 and CMZ 3 include several horizons of expansible 2:1 phyllosilicates that represent warmer/wetter intervals. Intervening CMZ 2 is a long (~500 m) zone of chlorite and illite with no expansible phyllosilicates and is interpreted as a continuous cold/frigid interval.

There are numerous calcite-cemented layers, including spar-filled veins that cross depositional bedding and represent postburial alteration, radiaxial fibrous cements that displace detrital grains, and micrite that crystallized near the time of deposition. Eighty-two stable isotope analyses of micrite yield $\delta^{13}C$ values that range from −44.6‰ to −4.1‰ and $\delta^{18}O$ values that range from −20.0‰ to 5.0‰ (VPDB). The carbon isotope data likely reflect a range of local carbon sources derived from bacterial activity and are unrelated to paleoclimatic conditions. In contrast, stratigraphic patterns in the oxygen isotope data suggest five or six intervals of frigid conditions conducive to glacial processes.

1. Introduction

Over the past two decades, mounting sedimentological, mineralogical, geochemical, and chronologic evidence from various parts of Gondwana indicates that Permo-Carboniferous paleoclimate fluctuated between frigid (~0–8 °C), mesic (~8–15 °C), and possibly hyperthermic (>22 °C), temperature regimes (e.g., Fielding et al., 2008; Isbell et al., 2003; Scheffler et al., 2006; Tabor et al., 2011). Recent studies delineate a complex paleoclimatic history between the Late Pennsylvanian (Gzhelian) and Middle Permian (Guadalupian) that includes several 10^6 yr cycles, alternating between large-scale glaciation events and periods with little to no continental ice (e.g., Fielding et al., 2008; Isbell et al., 2003; Montañez and Poulsen, 2013; Montañez et al., 2007). Although these studies have been critically important in resolving the timing and magnitude of the Gondwanan glaciation, they are based entirely on marine and mixed marine–terrestrial successions. To date, relatively little is known about the evolution of Late Pennsylvanian–Middle Permian paleoclimate in continental Gondwanan environments. This lack of knowledge is especially acute in Sub-Saharan Africa, despite its vast record of Late Paleozoic glaciation (e.g., Frakes et al., 1992; Visser, 1997).

This study presents lithostratigraphic, petrographic, mineralogical, and stable isotope data from a continuous sequence of Upper Carboniferous–Lower Permian lacustrine strata in the Lukuga Formation, central Democratic Republic of Congo (DRC). The stratigraphic distribution of different sedimentary climate indicators within the Lukuga Formation delineates a long-term climatic shift from relatively cold to warm conditions through the entire Permo-Carboniferous succession. Clay mineralogy reveals a more complex pattern of paleoclimatic change, comprising at least two large-scale oscillations between relatively cold and warm conditions. The $\delta^{18}O$ values of early burial, calcite cements define three to six climate cycles. The lack of agreement among the details of the paleoclimatic interpretations based on these different proxies is somewhat perplexing and may reflect different levels of climate sensitivity. Nevertheless, these various paleoclimate proxies from the Lukuga Formation, considered in conjunction with data from other basins,

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provide a basis to potentially delineate Gondwanan paleoclimate evolution, and its relation to glacial ice dynamics.

2. Geological background

2.1. Tectonics

The Congo Basin covers approximately 1.2 million km^2 in central Africa and contains up to 9 km of sedimentary strata (Kadima et al., 2011). Sedimentary deposits overlying the Archean to Paleoproterozoic crystalline basement range in age from Neoproterozoic to Recent (Kadima et al., 2011) and are bounded to the east and west by the Mitumbe (Kibaran fold belt) and Mayombe (West Congolian fold belt) mountain ranges. The Carboniferous and Permian strata in this sedimentary sequence comprise glacio-lacustrine deposits of the Lukuga Formation, which correlate with the Dwyka and Ecca groups of the Karoo Basin in South Africa (Catuneanu et al., 2005; Kadima et al., 2011).

2.2. Lukuga formation

The Congo Basin migrated northward, from 65°S to 40°N, between the Early Carboniferous (~340 Ma) and Late Permian (~250 Ma). Permo-Carboniferous strata in the Congo Basin and adjacent areas belong to the Lukuga Formation (Cahen and Lepersonne, 1980) and are among the northernmost components of the Karoo Supergroup. Lukuga Formation is known from (1) exposures along the eastern basin margin and (2) a continuous, 1860 m-long, core taken near Dekese, DRC (Fig. 1).

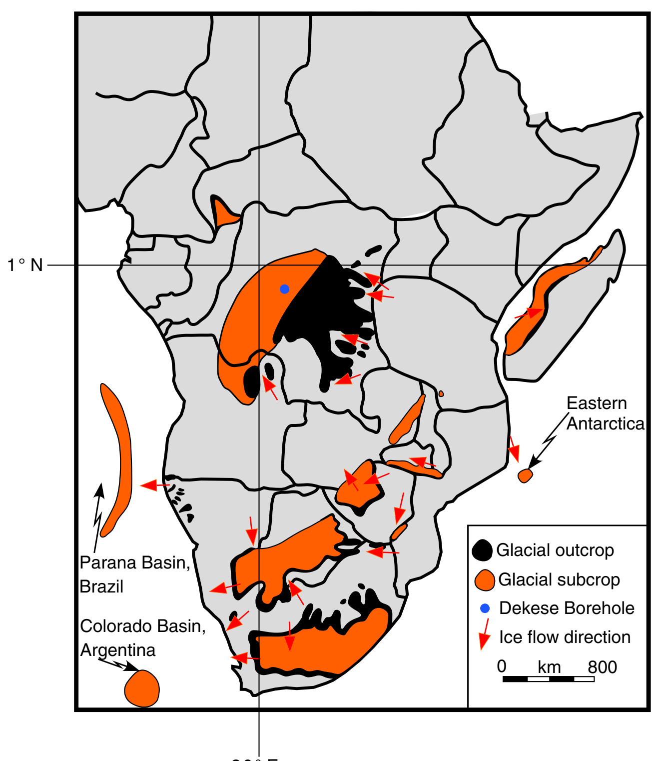

Fig. 1. Map of Africa in its modern continental configuration with the paleogeographic positions of South America, Madagascar, and East Antarctica projected to the west and to the east. The thick dark lines depict current political boundaries in Africa, whereas the thin vertical and horizontal lines approximate 20°E longitude and 1°N latitude. Outcrops of Upper Paleozoic glacial deposits are depicted in black and subsurface extensions of these strata are shown in orange. Red arrows indicate approximate directions of advance of glacial ice in the Late Paleozoic with respect to contemporary sedimentary basins. The blue circle represents the approximate position of the Dekese borehole, which provided the core sampled in this study.

In the central Congo Basin, subsurface units of the Lukuga Formation consist of massive diamictites and varved dark-gray shales deposited in a large glacial/periglacial lacustrine system. The Lukuga Formation crops out along the eastern margin of the Congo Basin and in a series of tectonic grabens adjacent to the western edge of Lake Tanganyika (Kadima et al., 2011; Sachse et al., 2012). Lukuga strata exposed in U-shaped, glacial valleys in the eastern Congo Basin are divided into five lithostratigraphic units, numbered in ascending order (Boutakoff, 1948; Cahen and Lepersonne, 1980): (I) conglomerates and sandy polymicts interpreted to be washout tillites; (II) polymictitc argillites interpreted as seasonal, varved, lacustrine deposits with dropstones; (III) dark-colored, pyrite- and kaolinite-rich, mudstones with common vascular-plant fossils; (IV) coal measures; and (V) “transition beds.” Lithostratigraphic units I–III range from 140 to 160 m thick in outcrop, and they are collectively called the Kiralo ya Mungu beds (Catuneanu et al., 2005; Lower Subgroup of Cahen and Lepersonne, 1980). These strata are thought to record a single and contemporaneous deglaciation event at the end of Unit III (Boutakoff, 1948; Cahen and Lepersonne, 1980; Wopfner, 1999).

Subsurface units of the Lukuga Formation in the central Congo Basin have been recovered from three deep boreholes: the Gibson, Mbandaka, and Dekese cores (Kadima et al., 2011). The Dekese core, which is the focus of this study, was collected from the deepest part of the Congo Basin in the 1950’s by the Syndicate pour l’Etude Géologique et Miniere de la Cuvette Congolaise and is currently archived at the Central African Museum in Tervuren, Belgium. Within the core, strata belonging to the Lukuga Formation are over 960 m thick and divided informally into four members (Cahen et al., 1960): Couche G (1677.15–1553.77 m below surface), Couche F (1553.77–860.63 m below surface), Couche E (860.63–753.04 m below surface), and Couche D (714.78–753.04 m below surface). Couche G is an upwards-fining unit of brown-red polymicts grading upward to dominantly reddish-brown sandstone, with or without disseminated granule- to pebble-sized grains. Couche F is dominantly gray to black, finely laminated claystone interbedded with clay-rich to sand-rich polymicts. The laminated claystones are interpreted as glacial varveites, and the polymicts are interpreted as glacial deposits with dropstones. Couche E grades upward from poorly sorted brown to brownish-red clayey sand, with or without pebbles, to yellow-brown, clayey to fine-grained sand. Couche D, the uppermost unit of the Lukuga Formation in the core, is composed of brown-yellow sandy claystones and mudstones. Although the Lukuga Formation in the Dekese core is coeval with outcrops of the Kiralo ya Mungu beds in the eastern Congo Basin, the characteristic “deglaciation” facies composed of organic-rich clays and iron-sulfide minerals is not present in the core (Catuneanu et al., 2005; Wopfner, 1999).

The burial history of the Lukuga Formation in the Dekese core is not well constrained. Based on the distribution of strata in other parts of the Congo Basin (e.g., the Samba core; Cahen et al., 1959), it is possible that a Jurassic and Cretaceous sequence was deposited and then eroded from the Dekese stratigraphic succession. With this possibility in mind, the most conservative estimate for the maximum burial depth of the Lukuga Formation is its current depth of approximately 700–1700 m.

3. Methods

3.1. Sampling

Cuttings from the Lukuga Formation ($n = 114$), between 1680 and 715 m depth in the Dekese core, were collected by the authors (N. Tabor, S. Myers) at the Royal Museum for Central Africa (RMCA) in Tervuren, Belgium. Generalized lithological descriptions were made to complement previous work with this core material (e.g., Cahen et al., 1960). Although all lithologies were sampled for mineralogical analysis, particular attention was given to parts of the stratigraphy with calcareous cements suitable for stable isotope analysis. The presence of calcareous cements was determined by applying 1 drop each of 1 N HCl and