Resolving the Richat enigma: Doming and hydrothermal karstification above an alkaline complex

Guillaume Matton  
Michel Jébrak  
James K.W. Lee

Abstract

The Richat structure (Sahara, Mauritania) appears as a large dome at least 40 km in diameter within a Late Proterozoic to Ordovician sequence. Erosion has created circular cuestas represented by three nested rings dipping outward from the structure. The center of the structure consists of a limestone-dolomite shelf that encloses a kilometer-scale siliceous breccia and is intruded by basaltic ring dikes, kimberlitic intrusions, and alkaline volcanic rocks. Several hypotheses have been presented to explain the spectacular Richat structure and breccia, but their origin remains enigmatic. The breccia body is lenticular in shape and irregularly thick at its extremities to only a few meters. The breccia was created during karst dissolution and collapse. Internal sediments fill the centimeter- to meter-scale cavities. Alkaline enrichment and the presence of Cretaceous automorphous neoformed K-feldspar demonstrate the hydrothermal origin of these internal sediments and their contemporaneity with magmatism. A model is proposed in which doming and the production of hydrothermal fluids were instrumental in creating a favorable setting for dissolution. The circular Richat structure and its breccia core thus represent the superficial expression of a Cretaceous alkaline complex with an exceptionally well preserved hydrothermal karst infilling at its summit.

Keywords: karst, hydrothermal, breccia, silicification, Africa.

Introduction

The Richat structure is one of the most spectacular terrestrial features visible from space. Ever since the first Gemini missions, its nested circular shape more than 40 km in diameter has become a landmark for space crews (NASA/GFSC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team, 2000). The Richat structure is located in the Mauritanian part of the Sahara Desert, within the Proterozoic Taoudenni Basin that is bounded by the Man and Reguibat basements of Archean age (Monod and Pomerol, 1973).

Early workers cited the crater-like shape and the high-relief center with its kilometer-scale breccia as evidence of a meteorite impact (e.g., Cailleux et al., 1964). Other researchers have explained the structure as the result of basement adjustments, which acted like a cylindrical piston causing vertical telescopic movements (Destombes and Plote, 1962). Magmatic evidence and dolomud deformation of the structure have also been used to support a granitic plutonic hypothesis related to lithospheric doming (Dietz et al., 1969; Boussarouque, 1975).

The origin of the Richat structure and its breccia therefore remains enigmatic. Our field observations, breccia analyses, and petrological studies, combined with new geophysical and geochemical data, allow us to address the problem from a new perspective. We demonstrate that the Richat structure and its breccia core are the superficial expression of an alkaline complex with an exceptionally well preserved hydrothermal karst infilling at its summit.

Geologic Setting

The Taoudenni Basin of Proterozoic to Carboniferous age is one of the major structural units of the West African craton and covers ~2,000,000 km² (Trompette, 1973; Bronner, 1992; Fig. 1). The stratigraphy of the basin begins with a Late Proterozoic (1100–1000 Ma) sequence consisting of sandstone, mudstone, dolomite, and dolomitic limestone. Overlying an angular unconformity, the Proterozoic (650 Ma) to Cambrian–Ordovician sequence is composed of alternating layers of limestone, dolomitic limestone, sandstone, chert, and mudstone. The highest units range in age from Late Ordovician to Carboniferous, and are mostly sandstone with intercalations of mudstone and limestone. Stromatolites have been observed in late Precambrian and Cambrian–Ordovician units.

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Fracture networks oriented slightly elliptical shape and is located at the intersection of two regional structural features, with a slight differentiation from pyroxenite to leucogabbro.

(2) Extensional en echelon carbonatite dikes and less common sills occur in the southern and western part of the structure. They are ~300 m long, 2–4 m wide, and oriented N15°–N20°. Dikes are mainly composed of dolomite and ankerite and show beforite affinities (Woolley et al., 1984). Enclaves of underlying sediments, such as sandstone and shale, are abundant. The dikes are silicified and partially ankeritized.

(3) Extrusive and intrusive alkaline rocks crosscut the inner basaltic ring dike in the central part of the structure. Collectively, they form a circular plug and a small volcano-sedimentary basin that crop out SSW and NNE of the breccia, respectively. The former occurrence, previously described as “analcimolite” by Boussaroque (1975), was attributed to the sodic alteration of sediments, but is interpreted here as a hydrothermally altered diatreme pipe. The small volcano-sedimentary basin contains conglomeratic and tuffaceous rocks that dip toward the center of the dome, suggesting that it represents the remnant of a maar system.

(4) Kimberlitic rocks in the form of plugs and sills were recognized in the northern part of the circular structure. Aeromagnetic surveys do not reveal any notable anomalies except for the kimerlitic intrusions and the two magnetic rings formed by the basaltic dikes, yet the presence of carbonatite and analcime-bearing rocks shows that an alkaline complex is located at depth. Fission-track dating of apatite in the carbonatite yielded a mid-Cretaceous age (99 ± 5 Ma; Poupeau et al., 1996), thus implying a similar age for the Richat structure.

BRECCIA

The center of the Richat structure is occupied by a breccia body ~3 km in diameter and at least 40 m thick. The breccia defines a lenticular shape that thins at its extremities to only a few meters. This thinning is irregular and creates a finger-like shape.

The breccia body is located within the Proterozoic series between partially dolomitized limestone and an overlying sandstone sequence. The breccia is composed of four types of material: coarse fragments, cement, and two types of internal sediment. Matrix-supported textures are dominant, but fragment-supported textures appear locally.

Breccia fragments are polymeric and include white to dark gray cherty material, quartz-rich sandstone, diagenetic chert nodules, and silicifiedstromatolitic limestone. Stromatolite-bearing fragments are restricted to the upper part of the unit. Locally restricted transport distances (usually centimeter to meter scale) characterize the fragments displaced inside the breccia. Units show downward dismantling by simple normal faulting, which can usually be reconstructed to their original position. Vugs between breccia fragments range from millimeters to several meters in size and are filled by microcrystalline quartz cement (±calcite, ±ankerite) and internal sediments.

Fragments display various shapes, from angular to rounded. Angular fragment edges are sharp, whereas rounded fragment borders are irregular, corroded, and may show reaction rims and dissolution textures such as embayments and cusps. Fragment shapes were quantified using the boundary fractal analysis method of Bérubé and Jébrak (1999), which measures the complexity of a fragment boundary. Strongly corroded fragments are characterized by large fractal dimensions (Fd), whereas weakly corroded fragments reveal small Fds. A bimodal distribution of the fractal values was observed; one group had an average Fd value of 1.12 (subrounded fragments), and the other had an average value of 1.04 (angular fragments).

The breccia body is intensely silicified. Thin sections reveal that most of the fragments have been replaced by microcrystalline quartz, although rare carbonate remnants are observed. Field examinations of the dolomitized and pyritized limestone at the base of the breccia unit reveal vertical veins as wide as several centimeters containing microcrystalline quartz and marked by silicified selvages as much as several centimeters thick. The veins define two sets of fractures oriented N90° and N153° and may represent the basal conduits for silicification through the breccia.

The silicification event was contemporaneous with the main breccia event but also continued afterward, as evidenced by the fact that both fragments and the internal sediments are extensively silicified, and
that microcrystalline quartz cement fills the breccia cavities and intergranular spaces. Furthermore, fragments are found within internal sediments in the breccia as clasts dropped downward from the overlying unit (Fig. 3A). The microcrystalline quartz cement is consistently equi-crystalline. Such a texture suggests that nucleation sites were evenly distributed and that the level of silica supersaturation in the fluid was high (Sibley and Gregg, 1987).

Figure 3. A: Small cavity filled by internal sediment. Limits of internal sediment, cavity, and clasts are outlined by dashes. Fragments are common in sediments that fill breccia cavities. B: Large cavity filled by internal sediment: subunit 1 is banded and displays slump structures (dashes); subunit 2 is massive and homogeneous. Both subunits are composed of quartz and K-feldspar. Hammer for scale.

INTERNAL SEDIMENTS

The degree of sediment infilling of any cavity varies depending on the vertical position of the cavity in the system (Sass-Gustkiewicz, 1996). At Richat, two types of internal sediments can be distinguished and display distinct spatial distributions: pink quartzitic sandstone is mainly observed in the upper levels of the breccia where it partially fills cavities, and gray laminated sediments dominate the lower levels where they create a more extensive infilling.

Pink sandstone is partially silicified and composed of quartz grains with a minor clay component, cemented by quartz; grains are sub-rounded to rounded and vary from 0.2 to 1 mm. The finely laminated gray sediments fill cavities of all sizes, the largest being ~3 m high and >7 m wide in the core of the breccia body. Sediment layers are usually horizontal, but some meter-scale folds have been observed and are interpreted as slump features along cavity margins.

Two distinct subunits were observed in the large central cavity as alternating layers <1 m thick (Fig. 3B). (1) The first subunit is banded sediment composed of millimeter-scale microsequences of quartz and K-feldspar. Quartz-dominated basal sequences appear pale gray, where-as K-feldspar-dominated upper sequences are light beige. The K-feldspar content increases upsequence from 40% to 85%. A dynamic depositional environment in the cavity is indicated by slumps and syn-sedimentary faults. (2) The second subunit occurs as massive, homogeneous layers containing almost equal proportions of quartz and K-feldspar.

Optical and scanning electron microscope observations show that the K-feldspar and quartz grains for both subunits are composed of tiny homogeneous crystals (25–50 μm). K-feldspar grains are automorphic and partially replaced by xenomorphic silica. Furthermore, the gray sediments are enriched in alkaline elements in comparison to pink quartzitic sandstone (Fig. 4). Two K-feldspar concentrates from the gray sediments were dated using the 40Ar/39Ar method. Samples were analyzed at Queen’s University, Canada, using an 8 W continuous argon-ion laser coupled with a Mass Analyzer Products 216 noble-gas mass spectrometer. All data were corrected for mass discrimination, extraction-line blanks, and neutron-induced interferences. All ages were calculated using the decay constants recommended by Steiger and Jäger (1977) and are reported with 2σ uncertainties; a representative age spectrum is shown in Figure 5. Minor disturbances in the low- and high-temperature portions of the age spectrum are directly attributed
to $^{39}$Ar recoil artifacts resulting from the fine grain size of the crystals, but the data from both K-feldspar runs yield an integrated mid-Cretaceous age of 98.2 ± 2.6 Ma, which can be directly related to the emplacement of the carbonatites. It is thus proposed that the origin of this sediment is more consistent with chemical precipitation during hydrothermal circulation of a fluid enriched in alkaline elements, whereas the pink quartzitic sandstone is detrital. Microsequences in subunit 1 therefore represent pulses of variable K-feldspar content in siliciclastic fluids.

DISCUSSION

The presence of corrosion textures and reaction rims on fragment boundaries as well as the low level of transportation of the rounded fragments imply a chemical dissolution process rather than physical rounding in the Richat breccia formation. If more material is dissolved than new minerals are formed, cavities will appear and may enhance fluid flow, thus resulting in a positive feedback loop where further dissolution leads to cavity enlargement (Lorilleux et al., 2002). A temporary loss of cohesion of the breccia may occur when the amount of dissolved material becomes very large, inducing gravity control of the fragment organization (Knipe, 1993) and collapse phenomena. Gravitational collapses and normal faults produce mixing of well-rounded and angular fragments and would explain the presence of blocks of the overlying rock units within the breccia and local fragment-supported texture. The collapses occurred in open cavities as rock falls that caused the brittle warping of consolidated layers with concomitant dis-aggregation and the slumping of unconsolidated chemical sediments. The observed bimodal distribution of fragment complexity (Fd) is directly linked to the dissolution-collapse processes. Low Fd values reflect the noncorroded fragments, fallen from the breccia hanging wall, whereas high Fd values represent the fragments corroded by the dissolution event prior to the collapse. Such relations were observed by Lorilleux et al. (2002) in sandstone-hosted breccias surrounding uranium ore in the Athabasca basin (Canada).

A magmatic event is dated as 99 ± 5 Ma by fission tracks in apatite in the carbonatite. A corresponding age of 98.2 ± 2.6 Ma is obtained by $^{40}$Ar/$^{39}$Ar dating of the chemical sediment in the breccia. The hydrothermal episode therefore appears related to the magmatic event. Furthermore, the position of the brecciated and silicified zones at the center of the Richat structure implies a doming-related origin. Domes would have created an intensely fractured and permeable zone, thus favoring fluid infiltration and consequent karstification and silicification. Vertical microcrystalline quartz veins observed at the base of the breccia could reflect the conduits for such fluids. Silicification and brecciation are spatially and temporarily coincident, although silicification also continued after brecciation ceased.

The proposed model invokes relatively continuous siliceous hydrothermal flow from the underlying pluton, leading tokarst formation. The hydrothermal fluids then caused the precipitation of chemical sediments in the lower levels and pervaded the rest of the karst zone, producing widespread silicification and cementation of the remaining voids. The alkaline complex located at depth acted as a heat source for the hydrothermal system.

CONCLUSION

The circular Richat structure appears to be the superficial expression of a buried alkaline complex of Cretaceous age that was affected by cuesta-type erosion. The breccia core is genetically related to plutonic activity, since doming and the production of hydrothermal fluids were instrumental in creating a favorable setting for dissolution. The resulting fluids were also responsible for subsequent silicification and hydrothermal infilling. To the best of our knowledge, karst collapse phenomena at the summit of an alkaline complex are unique, but may be more frequent than previously believed.

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