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

Guillaume Matton
Michel Jébrak — Department of Earth and Atmospheric Sciences, University of Quebec at Montreal, 201 President Kennedy Avenue, Montreal, Quebec H3C 3P8, Canada
James K.W. Lee — Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario K7L 3N6, Canada

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 thins 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 domal deformation of the structure have also been used to support a granitic plutonic hypothesis related to lithospheric doming (Dietz et al., 1969; Boussaroque, 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 km^2 (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.

The Richat structure is a large structural dome located within the Late Proterozoic to Ordovician part of the Taoudenni Basin. Erosion has created circular cuestas that appear as three nested rings dipping outward at 10°–20° (Fig. 2).

MAGMATISM

Four types of magmatic rocks crosscut the Richat dome (Fig. 1). These magmatic rocks are restricted to the structure and are not found in the region beyond the dome.

(1) Basalt occurs as subvertical dikes that appear continuous on recent magnetic surveys (T. Abdival, 2005, personal commun.) and are interpreted here as two ring dikes almost centered on the circular structure. The external ring dike is ~50 m wide and the internal one is

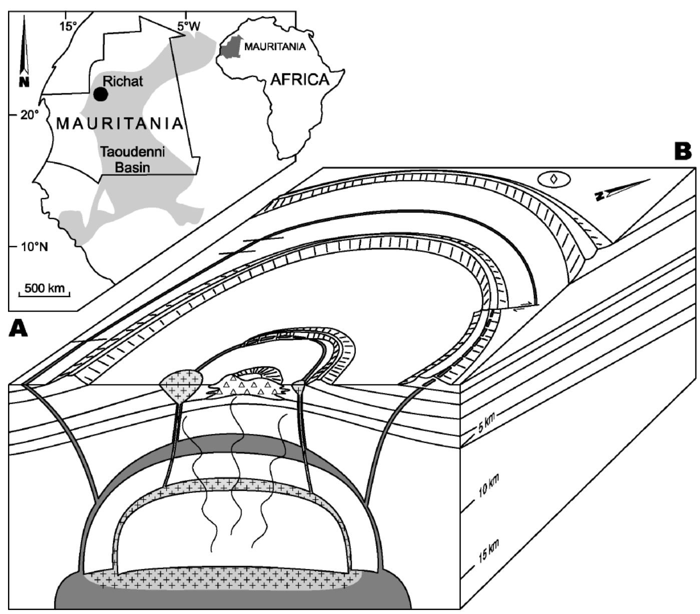

Figure 1. A: Location map for Richat dome. Taoudenni Basin is shaded. B: Block diagram displaying distribution of magmatic phases: basaltic (gray), felsic (crosses), and kimberlitic (triangles). External basaltic ring dike is displaced by NNE-SSW fault system in northeastern part of structure and is crosscut by carbonatite dikes in southern and western sectors (oblique slashes). Circular plug and small volcano-sedimentary basin outcrop respectively to SSW and NNE of breccia. Wavy lines indicate possible flow of hydrothermal fluids.

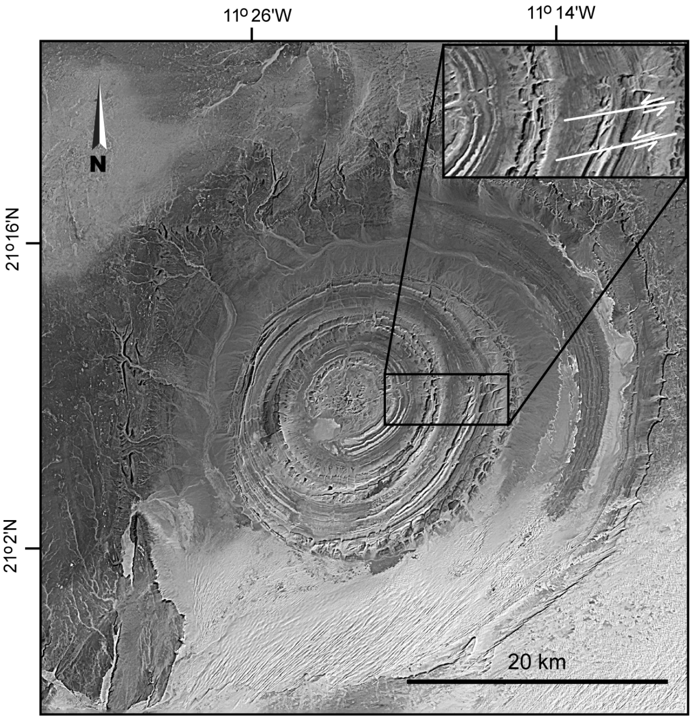

Figure 2. Modified satellite image of Richat structure after NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team, 2000. ENE-WSW faults display sinistral movement as shown by offset of external cuesta.

~20 m wide: they are located ~7–8 km and ~3 km, respectively, from the center of the structure. The rocks represent microgranular to pegmatitic facies of tholeiitic basaltic magma, 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 beforsite 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 kimberlitic 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.

STRUCTURAL FEATURES

Satellite observations have shown that the Richat structure has a slightly elliptical shape and is located at the intersection of two regional fracture networks oriented ~N-S and E-W (N70°–N90°; Netto et al., 1992). The N-S fractures are related to the Pan-African event (600 Ma; Poupeau et al., 1996), whereas the E-W fractures are younger, crosscutting Pan-African structures (Bayer and Lesquer, 1978). As suggested by Bonin (1995), the noncircular shape of the structure could be the result of symmetrical magmatic doming overprinted by a regional stress field with a major strain oriented NW-SE, suggesting emplacement in a transtensional environment. The Richat structure postdates the Pan-African event, but appears to predate the E-W regional event.

The fractures measured in the Richat structure can be classified into two sets of brittle faults trending subparallel to regional fractures. The NNE-SSW faults in the western part of the structure display dextral movements as well as minor vertical offsets. The dextral component of these faults is demonstrated by the displacement of the external ring dike (Fig. 1) and by the en echelon pattern of the N15°–N20° carbonatite dikes. The ENE-WSW faults display sinistral movement, clearly shown by the offset of the external cuesta in satellite photos (Fig. 2). These geometric relationships imply a late, regional-scale, NE-SW–oriented horizontal main stress in a conjugated pattern. Stress inversion related to doming could explain the apparent misfit between the main stress orientations suggested by the structure shape (NW-SE) and the brittle faults (NE-SW).

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 polymictic and include white to dark gray cherty material, quartz-rich sandstone, diagenetic chert nodules, and silicified stromatolitic 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

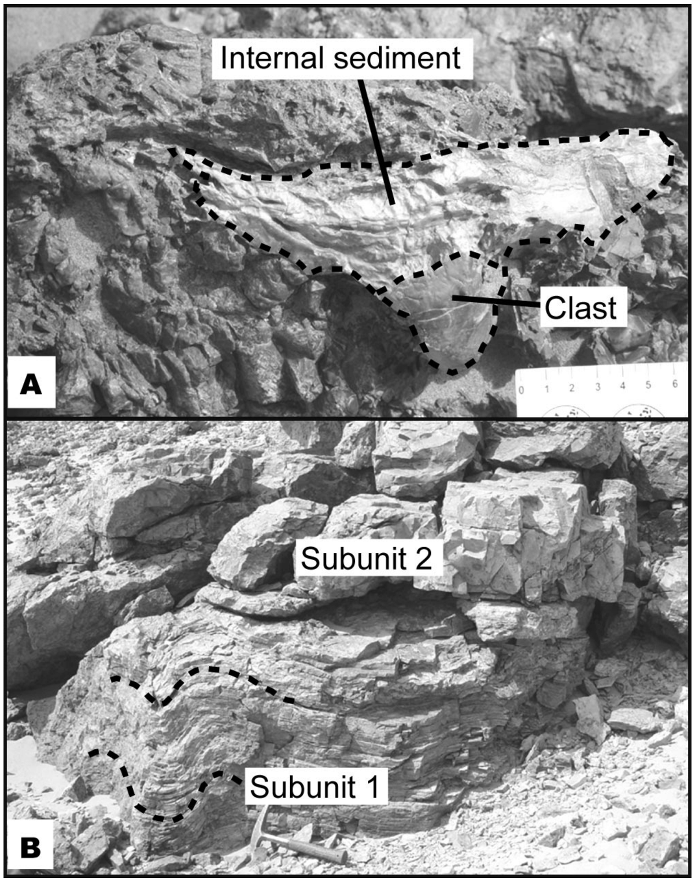

Figure 3. A: Small cavity filled by internal sediment. Limits of internal sediment, cavity, and clasts are outlined by dashes. Fragments are common in sediments that fill breccia cavities. B: Large cavity filled by internal sediment: subunit 1 is banded and displays slump structures (dashes); subunit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

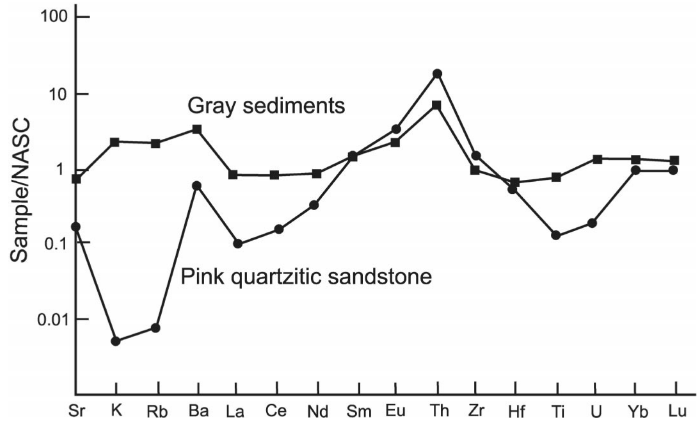

Figure 4. North American shale composite (NASC)–normalized spider diagram for pink quartzitic sandstone and gray sediments. NASC values are from Gromet et al. (1984).

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 equicrystalline. 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).

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 subrounded 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, whereas 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 synsedimentary 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 automorphous 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 $^{40}Ar/^{39}Ar$ 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

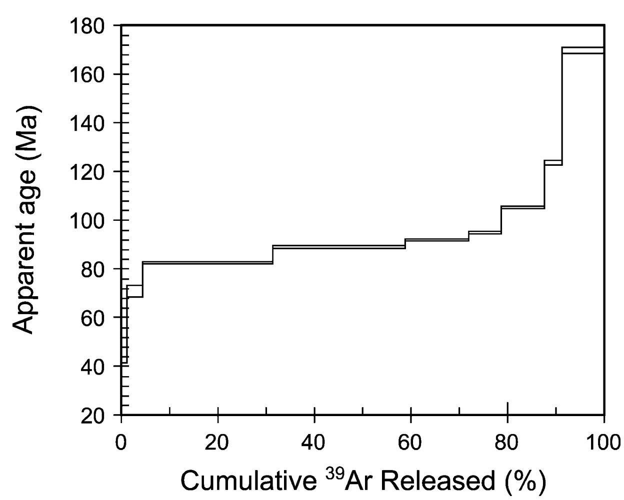

Figure 5. $^{40}Ar/^{39}Ar$ age spectrum of fine-grained K-feldspar (25–50 μm diameter) from gray laminated sediments. Apparent ages increase from 56 Ma in initial step to a range of ages between 80 and 95 Ma over 75% of the ^{39}Ar released to ages older than 100 Ma in final three steps. Integrated (average) age of two duplicate $^{40}Ar/^{39}Ar$ analyses is 98.2 ± 2.6 Ma.

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 siliceous 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 disaggregation 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. Doming 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 temporally coincident, although silicification also continued after brecciation ceased.

The proposed model invokes relatively continuous siliceous hydrothermal flow from the underlying pluton, leading to karst 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.

ACKNOWLEDGMENTS

We thank Ashton Mining for maps and information, Venetia Bodycomb for her revisions of the English text, Ahmedou Ould Mahfoudh for his collaboration in the field, and Doug Archibald for facilitating the $^{40}Ar/^{39}Ar$ analyses. We also thank Stuart F. Simmons, Francisco Gutiérrez, Lee Florea, Michael J. Simms, Alain Tremblay, and Gilbert Prichonnet for their comments and Michelle Laithier for her help with the figures. This work was supported by a Fonds Québécois de la Recherche sur la Nature et les Technologies grant to Matton, a Natural Sciences and Engineering Research Council (NSERC) of Canada Discovery grant to Jébrak, and NSERC Discovery and Major Facilities Access grants to Lee.

REFERENCES CITED

Bayer, M., and Lesquer, A., 1978, Les anomalies gravimétriques de la bordure orientale du craton Ouest-africain: Géométrie d'une suture panafricaine: Bulletin de la Société Géologique de France, v. 7, p. 863–876.

Bérubé, D., and Jébrak, M., 1999, High precision boundary fractal analysis for shape characterization: Computers & Geosciences, v. 25, p. 1059–1071.

Bonin, B., 1995, Pétrologie endogène: Paris, Dunod, Collection Géosciences, 336 p.

Boussaroque, J.L., 1975, Étude des analcimolites des Richat (Adrar de Mauritanie) [Ph.D. thèse]: Paris, Université de Paris VI, 105 p.

Bronner, G., 1992, Structure et évolution d'un craton archéen: La dorsale Réguibat occidentale (Mauritanie); tectonique et métallogénie des formations ferrifères: Editions du Bureau de Recherches Géologiques et Minières, 448 p.

Cailleux, A., Guillemaut, A., and Pomerol, C., 1964, Présence de coésite, indice de hautes pressions dans l'accident circulaire des Richat (Adrar Mauritanien): Paris, Académie des Sciences Comptes Rendus, v. 258, p. 5488–5490.

Destombes, J.-P., and Plote, H., 1962, Une structure aberrante dans le Précambrien du Sahara Mauritanien; hypothèse nouvelle sur l'origine du Richat (Adrar Mauritanien): Société Géologique de France Comptes Rendus Sommaires, 7, p. 202–203.

Dietz, R.S., Fudali, R., and Cassidy, W.A., 1969, Richat and Semsityat Domes, Mauritania: Not astroblemes: Geological Society of America Bulletin, v. 80, p. 1367–1372.

Gromet, L.P., Dymek, R.F., Haskin, L.A., and Korotev, R.L., 1984, The North American shale composite: Its compilation, major and trace element characteristics: Geochimica et Cosmochimica Acta, v. 48, p. 2469–2482.

Knipe, R.J., 1993, The influence of fault zone processes and diagenesis on fluid flow, *in* Horbury, A.D., and Robinson, A.G., eds., Diagenesis and basin development: American Association of Petroleum Geologists Studies in Geology, v. 36, p. 135–151.

Lorilleux, G., Jébrak, M., Cuney, M., and Baudemont, D., 2002, Polyphase hydrothermal breccias associated with unconformity-related uranium mineralization (Canada): From fractal analysis to structural significance: Journal of Structural Geology, v. 24, p. 323–338.

Monod, T., and Pomerol, C., 1973, Contributions à l'étude de l'accident circulaire des Richat (Adrar de Mauritanie): Nancy, Sciences de la Terre Mémoires 28, 191 p.

NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team, 2000, Richat Structure, Oudane, Mauritania: ASTER Image acquired October 7, 2000, http://asterweb.jpl.nasa.gov/gallery-detail.asp?name=Richat.

Netto, A.M., Fabre, J., Poupeau, G., and Champemmois, M., 1992, Datations par traces de fissions de la structure circulaire des Richats: Paris, Académie des Sciences Comptes Rendus, v. 314, p. 1179–1186.

Poupeau, G., Fabre, J., Labrin, E., Azdimoussa, A., Netto, A.M., and Monod, T., 1996, Nouvelles datations par traces de fission de la structure circulaire des Richat (Mauritanie): Mémoires du Service Géologique de l'Algérie, v. 8, p. 231–236.

Sass-Gustkiewicz, M., 1996, Internal sediments as a key to understanding the hydrothermal karst origin of the upper Silesian Zn-Pb ore deposits: Society of Economic Geologists Special Publication 4, p. 171–181.

Sibley, D.F., and Gregg, J.M., 1987, Classification of dolomite rock textures: Journal of Sedimentary Petrology, v. 57, p. 967–975.

Steiger, R.H., and Jäger, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359–362.

Trompette, R., 1973, Le Précambrien supérieur et le Paléozoïque inférieur de l'Adrar de Mauritanie: Bordure occidentale du bassin de Taoudenni, Afrique de l'ouest [Ph.D. thèse]: Marseille, Université de Saint Jérôme, 573 p.

Woolley, A.R., Rankin, A.H., Elliott, C.J., Bishot, A.C., and Niblett, D., 1984, Carbonatite dykes from the Richat dome, Mauritania, and the genesis of the dome: Indian Mineralogist, p. 189–207.

Manuscript received 18 January 2005
Revised manuscript received 19 April 2005
Manuscript accepted 22 April 2005

Printed in USA