

Polygonal jointing in sandstones from Eastern Paraguay

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Abstract: *POLYGONAL JOINTING IN SANDSTONES FROM EASTERN PARAGUAY* Columnar joints, resembling those in igneous rocks, are present in quartz sandstones of various formations (Mesozoic to Cenozoic) in Eastern Paraguay. New data concerning the field relationships and the geochemical characteristics constrain the processes responsible for the generation of columnar fracture patterns in sedimentary rocks. The columns are mostly normal to bedding and occur at several different stratigraphic levels. The host rocks are cut by volcanic necks or plugs, acting as heat sources and the development of columnar jointing may be controlled by the presence of magmatic rocks. Alternatively, thermal waters, circulating through fractures and favorable sedimentary layers, are responsible for the replacement of the sandstones by opal. As a result of the strain originated by the contraction of opal, a system of joints was developed. It is also possible that the local tectonic stresses have been developed and contributed to the fragmentation processes.

Resumen: *FRACTURACIÓN POLIGONAL EN ARENISCAS DEL ORIENTE DE PARAGUAY.* La disyunción columnar, similar a esas formadas en rocas ígneas, son comunes en areniscas cuarzosas en formaciones Mesozoicas y Cenozoicas del oriente de Paraguay. Nuevos datos vinculantes a sus relaciones de campo y a sus características geoquímicas refuerzan los procesos responsables en la generación de las fracturas poligonales en estas rocas sedimentarias. Las columnas son principalmente normales a los estratos y ocurren en diferentes niveles estratigráficos. La roca de caja es cortada por cuellos y conductos volcánicos, los que actúan como fuentes de transmisión de calor controlando así el desarrollo de la disyunción columnar en las rocas sedimentarias que se encuentran en sus cercanías. De manera complementaria, la percolación de aguas termales a través de las fracturas y contactos entre las capas sedimentarias, favorecen el reemplazamiento de las areniscas por ópalo. Como resultado del esfuerzo originado por la contracción del ópalo, se desarrolla un sistema de empalmes conjugados con diseño poligonal. Es posible también considerar que el desarrollo de centros de tensión localizados contribuyan al desarrollo del proceso de fragmentación.

Key Words: Polygonal jointing. Sandstones. Paraguay.

Palabras clave: Areniscas. Fracturación poligonal. Paraguay.

Introduction

Joints form in solid, hard rock that is stretched such that its brittle strength is exceeded (the point at which it breaks). When it happens the rock fractures along a plane parallel to the maximum principal stress and perpendicular to the minimum principal stress (the direction in which the rock is being stretched). This leads to the development of a single subparallel joint set.

Velázquez *et al.* (2008) described the columnar sandstones of Areguá (Cenozoic Cerro Patiño Formation, Eastern Paraguay) and suggested that this morphology was caused by the dynamic interactions among dyke intrusions, quartz dissolution and cooling induced fractures.

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However, there are other localities in Eastern Paraguay which according to Miraglia (1965) are also characterized by the presence of polygonal joints such as Luque, Limpio, Piquete Cué, Mariano Roque Alonso, Benjamín Aceval, San Lorenzo, Itauguá, José Fassardi, Colonia Independencia (Ybyturuzú), Villa Hayes, Piribebuy zone (Cordillera de los Altos), Cerro Memby (Colonia Independencia area). On the other hand, in the Triassic sandstones of the Ñemby hill, which constitutes the major outcrop of ankaratrites in Eastern Paraguay (Comin-Chiaramonti *et al.*, 1996), the columnar morphology is absent. Notably, the small-scale (cm to m) polygonal systems, widely developed on the well exposed outcrops of the Areguá sandstones, are similar to those described by Kocurek and Hunter (1986) and Kocurek (1988) in the Jurassic Navajo eolian sandstones from southern Utah and northern Arizona. The eolian sandstones are relatively porous and vary in texture from isotropic/massive to slightly anisotropic perpendicular to cross bedding. Individual cracks form consistently perpendicular to outcrop surfaces regardless of slope or aspect.

Cracks extend inward several decimeters to meters from weathering surfaces and are absent on fresh surfaces exposed by exfoliation and rock falls, indicating that the crack systems are weathering features. Crack systems with well organized 4- to 8-sided polygons form in areas with massive sandstone (from soft-sediment deformation and burrowing) and along some bed-parallel outcrop surfaces, reflecting generation of near-surface, uniform tensile stress. Rectangular crack systems form on steeper outcrop surfaces with bedding anisotropy. Individual high-angle cracks curve to maintain orthogonality to tangential cross beds and locally terminate against bed-parallel cracks. Different polygonal sizes and nested patterns may be controlled by the age and thickness of the weathering "layer". Many outcrop surfaces with polygonal patterns also display small-scale (cm to m) domal relief, interpreted to reflect enhanced weathering along and near cracks. Cracks combined with surface-parallel exfoliation results in local spalling of thin polygonal patches. The Navajo Sandstone crack examples are well developed in the desert regime where there are large temperature and moisture fluctuations that influence weathering.

In this picture, the columnar outcrops from Eastern Paraguay may be interpreted as originated by weathering features that are predominantly controlled by tensile stresses dictated by original host rock properties (lamination or bedding anisotropies vs. massive isotropic character; cf. Kocurek and Hunter, 1986; Kocurek, 1988).

On the other hand, the orthogonal disposition of the columns in central and northern regions of the Eastern Paraguay may be indicative of the fact that the large igneous bodies found associated represent the main heat source to develop the stresses.

Geological background

Eastern Paraguay lies in an intercratonic region which includes the westernmost side of the Brazilian Paraná Basin (PB). The latter represents an undeformed basin at the western Gondwana part with sedimentation beginning in the Ordovician, tapped by Early Cretaceous tholeiitic flood basalts of the Serra Geral Formation (Zalán *et al.*, 1990; Rogers *et al.*, 1995) and followed by younger sedimentation (Fig. 1). From stratigraphic evidences and starting from Mesozoic times, almost five main alkaline magmatic events have occurred in Eastern Paraguay (Comin-Chiaramonti *et al.*, 2007a, b; Gomes *et al.*, 2013), other than the Early Cretaceous tholeiitic magmatism (main peak 133-134 Ma, Thiede and Vasconcelos, 2008). Three of the alkaline events include rocks of sodic affinity, corresponding geographically to the provinces of

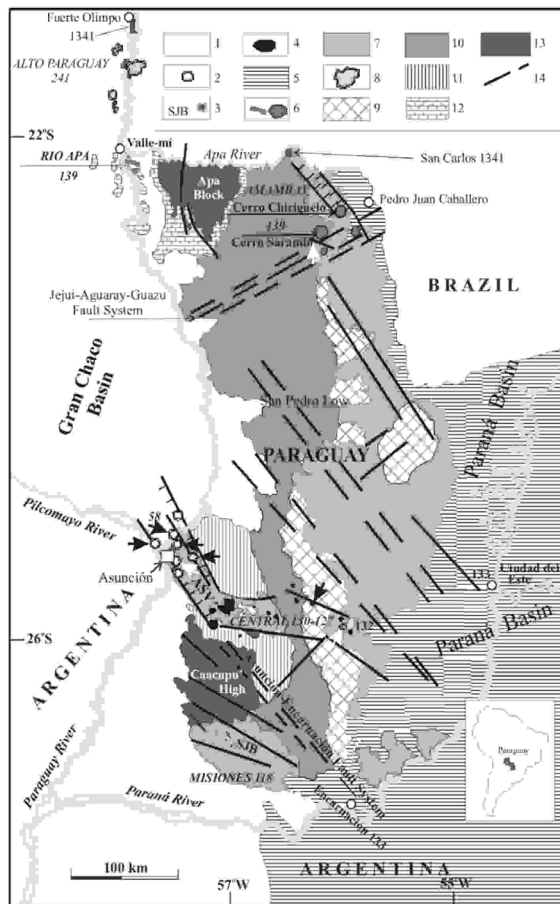


Figure 1. - Simplified geological map of the Eastern Paraguay (after Comin-Chiaromonti *et al.*, 1997, 1999 and unpublished geological maps). **1:** Neogene and Paleogene sedimentary cover **2:** Paleogene sodic alkaline rocks, Asunción Province; **3:** Late Early Cretaceous sodic alkaline rocks (Misiones Province, SJB); **4:** Early Cretaceous potassic alkaline rocks (post-tholeiites, Central Province); **5:** Early Cretaceous tholeiites of the Paraná Basin; **6:** Early Cretaceous potassic alkaline rocks (pre-tholeiites, Rio Apa and Amambay Provinces); **7:** Jurassic-Cretaceous sedimentary rocks (Misiones Formation); **8:** Permo-Triassic alkaline rocks (Alto Paraguay Province); **9:** Permian sedimentary rocks (Independencia Group); **10:** Permo-Carboniferous sedimentary rocks (Coronel Oviedo Group); **11:** Ordovician-Silurian sedimentary rocks (Caacupé and Itacurubí Groups); **12:** Cambro-Ordovician platform carbonates (Itacupumí Group); **13:** Archean and Neoproterozoic crystalline basement: high- to low-grade metasedimentary rocks, metarhyolites and granitic intrusions; **14:** major tectonic lineaments and faults. The numbers of the main provinces are referred to the best geochronological results listed in Comin-Chiaromonti *et al.*, (2007a, b). Red arrows indicate the localities where sandstones with columnar joints are found / **Figura 1** Mapa geológico simplificado del Paraguay Oriental (Comin-Chiaromonti *et al.*, 1997, 1999 y mapas geológicos inéditos). **1.** Cobertura sedimentaria Neógena y Paleógena. **2.** Rocas sodicas alcalinas de la Provincia Asunción. **3.** Rocas alcalinas potásicas del Cretácico temprano Provincia Misiones, SJB). **4.** Rocas potásicas alcalinas del Cretácico temprano (post- toleitas, Provincia Central). **5.** Toleitas del Cretácico temprano de la Cuenca de Paraná. **6.** Rocas potásicas alcalinas (pre-toleitas, Provincias de Rio Apa y Amambay). **7.** Rocas sedimentarias del Jurásico – Cretácico (Formación Misiones). **8.** Rocas alcalinas Permo-Triásicas (Provincia Alto Paraguay). **9.** Rocas sedimentarias Pérmicas (Grupo Independencia). **10.** Rocas sedimentarias Permo-Carboníferas (Grupo Coronel Oviedo). **11.** Rocas sedimentarias del Ordovícico y Silúrico (Grupos Caacupé e Itacurubí). **12.** Carbonatos de plataforma del Cambro-Ordovícico (Grupo Itacupumí). **13.** Rocas del basamento cristalino, metasedimentitas de alto a bajo grado, metariolitas e intrusiones graníticas. **14.** Lineamientos y fallas mayores. El número de las principales provincias se refieren a los datos geocronológicos de Comin-Chiaromonti *et al.*, (2007a, b). Flechas rojas indican las localidades donde se localizan las areniscas columnares.

Alto Paraguay (241.5 ± 1.3 Ma), Misiones (118.3 ± 1.6 Ma) and Asunción (58.7 ± 2.4 Ma), whereas two involve rocks of potassic affinity associated with the Apa and Amambay Provinces, both of similar age (138.9 ± 0.7), and with the Central Province (ASU, 126.4 ± 0.4 Ma).

The thermal history, using apatite fission track analyses (AFTA), reveals that at least two main episodes have been identified in sedimentary and igneous/metamorphic samples ranging in age from Late Ordovician to Early Cretaceous (Hegarty *et al.*, 1996). AFTA data from Asunción-Sapucaí-Villarrica graben (ASU) show evidence for rapid cooling beginning some time between 90 and 80 Ma (cooling from about 110°C , similar to the results from Brazilian and Uruguayan coasts), followed by a Tertiary heating/cooling episode (about 60 Ma, $70\text{--}80^\circ\text{C}$). Late Cretaceous cooling may be involved several kilometers of differential uplift and erosion, and would played an important role on the control of the geomorphology and drainage patterns in the region (*cf.* figure 1).

Notably, among the sandstones of the Eastern Paraguay, columnar joints are present, generally not far from magmatic bodies (*cf.* red arrows of figure 1), but the major lot of alkaline outcrops do not show columnar joints (*cf.* figure 1).

Notably, columnar joints in sandstones of Eastern Paraguay are usually found not so far from magmatic bodies, as indicated by the red arrows in figure 1, however, mostly of the major alkaline outcrops do not show the columnar features.

The polygonal joints

Some localities showing polygonal joints are the following (*cf.* red arrows of figure 1): Areguá (Lat. $25^\circ 19'S$, Long. $57^\circ 24'W$), José Fassardi (Lat. $25^\circ 59'S$, Lon. $56^\circ 08'W$), Luque (Lat. $25^\circ 16'S$, Long. $57^\circ 30'W$), Limpio (Lat. $25^\circ 12'S$, Long. $57^\circ 40'W$), Benjamín Aceval (Lat. $25^\circ 3'S$, Long. $57^\circ 30'W$), San Lorenzo (Lat. $25^\circ 2'S$, Long. $57^\circ 30'W$), Mbocayaty (Lat. $26^\circ 0'S$, Long. $56^\circ 50'W$), Colonia Independencia (Lat. $25^\circ 13'S$, Long. $56^\circ 12'W$) and Cerro Memby (Lat. $22^\circ 50'S$, Long. $56^\circ 10'W$). All these localities are in: <http://www.geologiadelparaguay.com/Areniscas-Columnares.htm>.

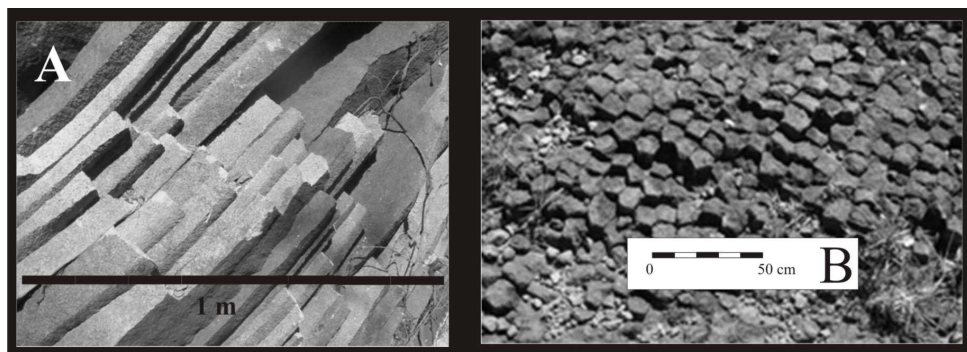


Figure 2. A. Columnar morphology of the quartz-sandstones from Areguá. B. Oblique view of the columns of A; to be noted the presence of rectangular, pentagonal, hexagonal and octagonal forms./ **Figura 2.** A. Morfología columnar de las areniscas cuarzosas de Areguá. B. Vista oblicua de las columnas de A; se aprecian formas rectangulares, pentagonales, hexagonales y octogonales.

The polygonal joints were developed in quartz sandstone from different geological units: the Jurassic Misiones Formation, Permian Independencia Group and Silurian Caacupé Group (s. lato). Averaged chemical analyses for some sandstones are reported in Table 1. In general, the polygonal joints are found near to the contact zone with magmatic bodies. Some examples are shown in figures 2, 4 and 5.

Columnar joints at Cerro Patiño

The most spectacular example of columnar joints in Eastern Paraguay is represented by the Cerro Patiño hill (figure 2; see also Velázquez *et al.*, 2008), a monadnock of Silurian sandstones (Caacupé Group; cf. Comin-Chiaramonti and Gomes, 1996) in the Misiones Formation (figure 1; chemical analysis 3 in Table 1). The Cerro Patiño hill is intruded by a plug of Na-ankartrites (K/Ar age 38.8 ± 2.0 Ma; Comin-Chiaramonti and Gomes, 1996), bearing crustal xenoliths, up to 25 cm across, and rare mantle xenoliths, up to 2 cm in diameter, spinel-peridotites facies (Comin-Chiaramonti *et al.*, 1991; Comin-Chiaramonti and Gomes, 1996).

The SEM images show that the quartz grains are mostly completely corroded and have been laterly replaced by microcrystalline quartz and by colloidal silica (opal or chalcedony; figure 3).

The dissolution temperatures may be determined by means of Al content in quartz, following the equation of Dennen and Blackburn (1970): $T(^{\circ}\text{C}) = 3.6 \text{ Al}_{\text{Quartz}}(\text{ppm}) + 33.0$.

Aluminium concentration in quartz was determined by X-ray fluorescence analytical procedure (Leoni and Rivalenti, 1974 and quoted references). The quartz from Areguá sandstones contain up to 10-12 ppm of Al, which corresponds to temperature of 69-72°C; on the other hand, the sandstones at the contact with the Cerro Patino plug (where the polygonal joints are absent; Comin-Chiaramonti and Gomes, 1996) contain up to 29-55 ppm of Al, which corresponds to temperatures of 137- 231 °C. These data support the hypothesis proposed by Arribas and LaTorre (1982) as follows: thermal waters, circulating through fractures and favorable sedimentary layers, could have caused the replacement of the sandstones by opal. As a result of the strain originated by the contraction of opal, a system of joints was developed. Yet, it is also possible that the tectonic stresses developed in the Ypacaray neighborhood may have contributed to the fragmentation processes.

The temperatures of 69-72°C are also confirmed by the isotopic composition of oxygen (Hervig *et al.*, 1995; Marchand *et al.* 2002 and therein references for analytical methods and temperature calibration). Infact the $\text{O}18\text{‰}$ of authigenic quartz and of pore water are $+19.1 \pm 0.4\text{‰}$ and $-6.8 \pm 0.5\text{‰}$, indicating temperatures around 70°C (Marchand *et al.*, 2002). Notably the temperatures and ages of heating/cooling episode affecting the area (about 60-30 Ma, 70-80°C) correspond to those suggested by Heggarty *et al.* (1996).

Columnar joints at Mbocayaty

Continental sediments of the Independencia Group (Permian; figure 4; cf. figure 1) occur near the Mbocayaty elliptic stock (1.5 km², 0.2 km³; cf. Comin-Chiaramonti *et al.*, 1996a) made of K-alkaline essexitic gabbros and essexites (127.8 ± 7.2 Ma; post-tholeiitic: cf. Comin-Chiaramonti *et al.*, 2007 a,b); effusive K-trachybasalts are also present

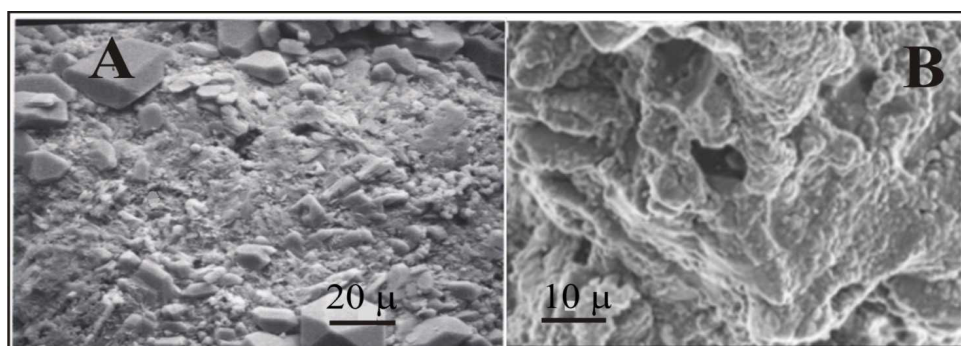


Figure 3. A: SEM images showing partially corroded quartz and overgrowth of silica micrograins. **B:** silica aggregates of botryoidal shape, a characteristic feature of colloidal silica of low crystallinity / **Figura 3. A.** Imágenes MEB mostrando cuarzo parcialmente corroído y sobrecrecimiento de los microgranos de sílice. **B.** Agregado de sílice con morfología botroidal.

Wt%	1; N=4	3399-P	2; N=7	263-I	3; N=5	PS49-I
SiO ₂	94.21 (0.25)	42.52	88.27 (4.95)	51.66	89.26 (2.07)	54.99
TiO ₂	0.06 (0.01)	2.32	0.20 (0.03)	1.76	0.26 (0.01)	1.89
Al ₂ O ₃	2.78 (0.71)	14.40	4.93 (2.17)	13.89	1.67 (0.17)	11.76
Fe ₂ O ₃	2.12 (0.10)	10.80	1.35 (0.17)	7.87	3.98 (1.27)	8.73
MnO	0.01 (0.01)	0.17	0.12 (0.01)	0.11	0.05 (0.01)	0.15
MgO	0.04 (0.02)	9.77	0.01 (0.01)	6.37	0.16 (0.11)	3.06
CaO	0.02 (0.01)	11.71	1.20 (0.12)	5.25	1.25 (0.16)	6.24
Na ₂ O	0.50 (0.10)	5.00	0.41 (0.18)	2.04	0.38 (0.13)	2.74
K ₂ O	0.03 (0.03)	0.67	0.26 (0.05)	8.13	0.27 (0.03)	7.39
P ₂ O ₅	0.01 (0.01)	0.87	0.08 (0.01)	0.59	0.09 (0.01)	0.76
LOI	3.00 (0.50<)	1.87	3.25 (0.44)	2.17	2.77 (0.28)	1.10
Sum	99.80	100.10	100.08	99.84	100.14	98.78
ppm						
Rb	0.4 (0.2)	22	8.2 (4.3)	162	7.4 (3.9)	146
Sr	32 (9)	1016	158 (12)	1618	222 (15)	2258
Zr	12.1 (0.9)	152	38.9 (2.1)	382	41.4 (2.3)	423
Y	1.2 (1.0)	25	4.1 (0.8)	19	5.5 (1.3)	32
Nb	4.5 (0.7)	86	7.8 (0.6)	48	8.6 (0.7)	59
Ba	99 (11.0)	1090	287 (5)	1995	412 (11.0)	4856
La	4.6 (2.1)	81	10.2 (2.3)	91	8.7 (4.1)	194
Ce	7.7 (2.2)	145	19.9 (2.1)	178	15.8 (4.4)	379
Nd	2.5 (1.7)	49	10.7 (0.9)	73	17.1 (1.8=)	154
Cl	6 (1)	n.d.	6 (1)	n.d.	5 (1)	n.d.
Fl	120 8 (26)	n.d.	133 (21)	n.d.	166 (13)	n.d.

Table 1. Representative chemical analyses of sandstones and associated magmatic rocks from Eastern Paraguay (in parentheses sws, standard deviation): **1**, Caacupé Group, 3399, P, ankaratritic plug (39 Ma); **2**, Independencia Group, 263, essexitic intrusion (128 Ma); **3**, Misiones Formation, PS 49, syenodioritic intrusion (139 Ma). Data sources: Comin-Chiaramonti *et al.*, 1996, a, b; Comin-Chiaramonti *et al.*, 2014. Sandstone analyses (this work): 1, Cerro Patiño; 2, Mbocayaty; 3, Memby. / **Tabla 1.** Análisis químicos representativos de las areniscas y las rocas magmáticas asociadas del Paraguay Oriental (en paréntesis SWS, desviación estándar). **1.** Grupo Caacupé, 3399, P, plug acararítico (39 Ma). **2.** Grupo Independencia, 263, intrusión essexítica (128 Ma). **3.** Formación Misiones, PS 49, intrusión sienodiorítica (139 Ma). Fuente: Comin-Chiaramonti *et al.*, 1996, a, b; Comin-Chiaramonti *et al.*, 2014. Análisis sobre areniscas (este trabajo): 1, Cerro Patiño; 2, Mbocayaty; 3, Memby.

(Comin-Chiaramonti and Gomes, 1996). The sediments are quartz sandstones with a composition similar to those of Areguà (cf. Table 1), but the Al content in the quartz is higher

(109 ppm), which corresponds to a temperature of about 425°C, according to Dennen and Blackburn (1970).

As matter of fact, the relatively high temperatures can promote dehydration reactions during uplift or burial and may cause a volume decrease and the formation of polygonal dehydration fractures in rock (analogous to mudcrack; cf. Chan *et al.*, 2008).

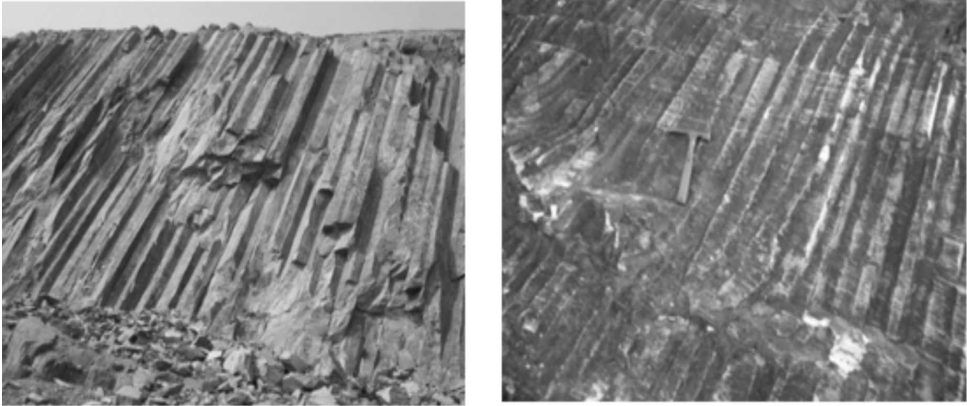


Figure 4. Columnar morphology of the quartz-sandstones from Mbocayaty / **Figura 4.** Morfología columnar de las areniscas cuarzosas de Mbocayaty.



Figure 5. Quartz sandstones of the Memby hill / **Figura 5.** Areniscas cuarzosas de la colina Memby.

Cerro Memby

Cerro Memby is a towering, mound of quartz sandstones with crimson cliffs and thick vegetation on the top. It stands out, visible for miles in the grassy land of shallow valleys and low trees (figure 5). The area is represented by Ordovician-Silurian sediments (figure 1), where the Memby hill crops out near to the Cerro Sarambi complex: the latter is a near circular structure, about 8.5 km in diameter, composed mainly of an inner pyroxenite body that is transected by trachyte and phonolite dykes, as well as thin carbonatite veins. Radial fenitic and trachytic dykes occur cutting the up-domed country rock ridges at the southern rim of the complex (Gomes *et al.*, 1996, 2011 and therein references). On the whole the rock-types have K-alkaline affinity and an age of 139.3 ± 0.5 Ma (pre-tholeiitic; Comin-Chiaramonti *et al.* 2007a,b). Al content in quartz from the sandstones is not available, but the most probable formation of the columnar joints is similar to that relative to the Mbocayaty columnar joints.

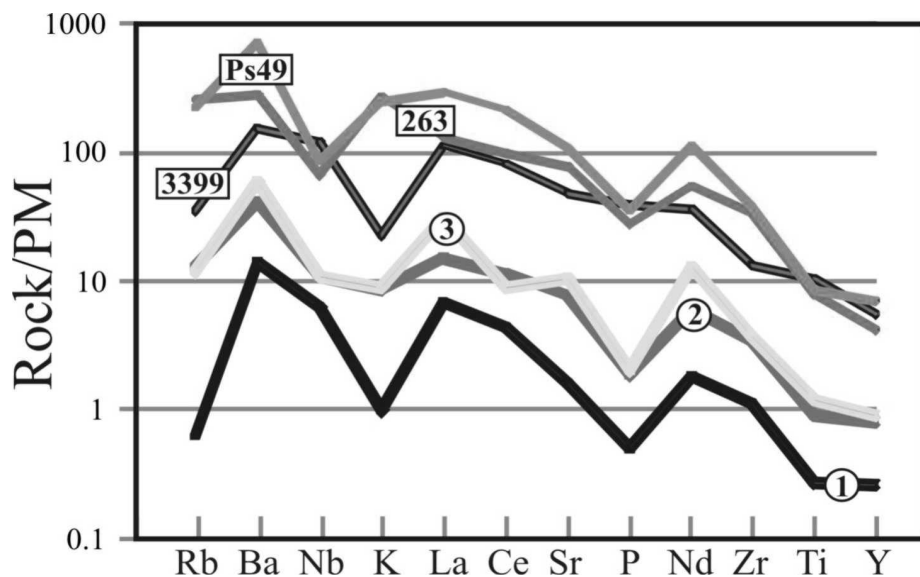


Figure 6. Incompatible elements of the quartz sandstones and associated magmatic rocks from Eastern Paraguay, normalized to the Primitive Mantle (PM of Sun and MacDonough 1989). Curves 1, 2 and 3: Cerro Patiño, Mbocayaty and Memby occurrences, respectively. Numbers as in Table 1. / **Figura 6.** Elementos incompatibles de las areniscas cuarzosas asociadas a rocas magmáticas del Paraguay Oriental, normalizadas al manto primitivo (PM de Sun y MacDonough 1989). Curvas 1, 2 y 3: Cerro Patiño, Mbocayaty y Memby. Los números se refieren a la Tabla 1.

To be noted that the incompatible elements relative to the Mbocayaty and Memby quartz sandstones are about ten times more concentrated in respect to those from Cerro Patiño (following the normalization to the PM of Sun and Mac Donough; *cf.* figure 6). The geochemical differences may be due to 1) the different compositions of the magmatic rocks (*cf.* Table 1), 2) the higher temperatures reached in the Mbocayaty (and may be in Memby), favoring the recrystallization of quartz (425°C), a more efficient hydrothermal circulation with consequent diffusion and concentration of incompatible elements.

Discussion and concluding remarks

When cracks form in a thin contracting layer, they sequentially break the layer into smaller and smaller pieces. A rectilinear crack pattern encodes information about the order of crack formation, as later cracks tend to intersect with earlier cracks at right angles. In a hexagonal pattern, in contrast, the angles between all cracks at a vertex are near 120° . Hexagonal crack patterns are typically seen when a crack network opens and heals repeatedly, in a thin layer, or advances by many intermittent steps into a thick layer. Here, it is shown how both types of pattern can arise from identical forces, and how a rectilinear crack pattern can evolve towards a hexagonal one. Such an evolution is expected when cracks undergo many opening cycles, where the cracks in any cycle are guided by the positions of cracks in the previous cycle but when they can slightly vary their position and order of opening. The general features of this evolution are outlined and compared with a review of the specific patterns of contraction cracks in dried mud, polygonal terrain and columnar joints. The physical-mathematical approaches (forces, separation tensors, relaxations) are developed in Hirota *et al.* (1998, 2000) and in Iben and O'Brien (2006).

As matter of fact, e.g., small-scale (cm to m) crack systems are widely developed on outcrops of the Jurassic Navajo Sandstone in southern Utah and northern Arizona (Chan *et al.*, 2008). The eolian sandstone is relatively porous and varies from isotropic/massive to slightly anisotropic perpendicular to cross bedding. Individual cracks form consistently perpendicular to outcrop surfaces regardless of slope or aspect. Cracks only extend inward several centimeters to decimeters from weathering surfaces and are absent on fresh surfaces exposed by exfoliation and rock falls, indicating that the crack systems are weathering features. Crack systems with well organized 5- to 6-sided polygons form in areas with massive sandstone (from soft-sediment deformation and burrowing) and along some bed-parallel outcrop surfaces, reflecting generation of near-surface, uniform tensile stress. Rectangular crack systems form on steeper outcrop surfaces with bedding anisotropy. Individual high-angle cracks curve to maintain orthogonality to tangential cross beds and locally terminate against bed-parallel cracks. Different polygonal sizes and nested patterns may be controlled by the age and thickness of the weathering "layer". Many outcrop surfaces with polygonal patterns also display small-scale (cm to m) domal relief, interpreted to reflect enhanced weathering along and near cracks. Cracks combined with surface-parallel exfoliation results in local spalling of thin polygonal patches. The Navajo Sandstone crack examples are well developed in the desert regime where there are large temperature and moisture fluctuations that influence weathering (*cf.* figure 2 of Chan *et al.*, 2008).

On the other hand, shallow, near-surface magma emplacement into a porous, unlithified sandstone occurred by forceful dike dilation and was accompanied by a localized hydrothermal event. Petrographic fabric, authigenic mineralogy and petrophysical data, grade smoothly through the quartzite contact zone outward into the friable Inmar sandstone (e.g. Summer and Ayalon, 1995). Quartz grain deformation, fracturing and rehealing of grains, and pressure solution constitute overwhelming evidence of a compressive environment adjacent to margins of magmatic rocks, albeit with temperatures and pressures insufficient to fully recrystallize detrital grains. Post emplacement heating together with elastic compressive stress dissipation, lead to fracture healing and pressure solution. The occasional columnar-jointing must be related to thermal contraction of the quartz sandstones during later cooling and resulting model cracks. Around the world highly altered intrusions bordered by indurated sometimes uniformly jointed sediments, may also be the result of forceful magma emplacement and hydrothermal alteration at near-surface levels.

In this pictures, we can see that:

1)- Thermal waters (temperatures around 70°C), circulating through fractures, could have caused a replacement of quartz of the quartz sandstones by opal (chalcedony) in the quartz sandstones, e.g., from Areguá, Luque and Limpio. As a result of the strain originated by contraction during opal formation, a system of joints was developed, giving place to formation of columnar jointing, following a mechanism similar to that postulated by Goeringh and Morris (2005). Moreover, the tectonic stresses, developed in the neighborhood of the Ypacaray Valley (*cf.* Comin-Chiaramonti *et al.*, 2007 a, b) could have contributed to the fracturation processes.

2)- Other columnar joints, resembling those common in igneous rocks, are present in other quartz sandstones from Eastern Paraguay, e.g., Mbocayaty and Cerro Memby (*cf.* figures 4 and 5), associated with large intrusions of K-alkaline rocks. Geochemistry of these quartz sandstones points to hydrothermal system at high temperature with an enrichment of rare earth elements and incompatible elements in respect to the Cerro Patiño (Areguá) quartz sandstones, other than the crystallization of high temperature quartz.

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References

- Arribas, A. and LaTorre, C.O. 1982. El origen de la disyunción columnar en areniscas. Caso de las cuarcarenitas de Areguá (República del Paraguay). *Tecniterrae*, Madrid, 48: 7-18.
- Chan, M.A., Yankee, W.A., Netoff, D.I., Seiler, W.M. and Ford, R.L. 2008. Polygonal cracks in bedrocks of Earth and Mars: implication for weathering. *Science Direct*, Icarus, 194: 65-71.
- Comin-Chiaramonti, P. and Gomes, C.B., (Eds). 1996. Alkaline magmatism in Central-Eastern Paraguay. Relationships with coeval magmatism in Brazil. São Paulo, *Edusp/Fapesp*: 464p.
- Comin-Chiaramonti, P., Civetta, L., Petrini, R., Piccirillo, E.M., Bellieni, G., Censi, P., Bitschene, P., Demarchi, G., De Min, A., Gomes, C.B., Castillo, A.M.C. and Velázquez, J.C. 1991. Tertiary nephelinitic magmatism in Eastern Paraguay: petrology, Sr-Nd isotopes and genetic relationship with associated spinel-peridotite xenoliths. *European Journal of Mineralogy*, 3: 507-525.
- Comin-Chiaramonti, P., Cundari, A., De Graff, J.M., Gomes, C.B. and Piccirillo, E.M. 1999. Early Cretaceous-Tertiary magmatism in Eastern Paraguay (western Paraná basin): geological, geophysical and geochemical relationships. *Journal of Geodynamics*, 28: 375-391.
- Comin-Chiaramonti, P., Cundari, A., Piccirillo, E.M., Gomes, C.B., Castorina, F., Censi, P., DeMin, A., Marzoli, A., Petrini, R. and Speziale, S. 1997. Potassic and sodic igneous rocks from Eastern Paraguay: their origin from the lithospheric mantle and genetic relationships with the associated Paraná flood tholeiites. *Journal of Petrology*, 34: 495-528.
- Comin-Chiaramonti, P., De Min, A., Girardi, V.A.V. and Gomes, C.B. 2014. Carbonatites and primary carbonates in the Rio Apa and Amambay regions, NE Paraguay. *Lithos*, 188: 84-96.
- Comin-Chiaramonti, P., De Min, A. and Gomes, C.B. 1996a. Magmatic rock-types from the Asunción-Sapucaigraben: description of the occurrences and petrographical notes. Appendix I. In: Comin-Chiaramonti, P., Gomes, C.B., Eds., Alkaline magmatism in Central-Eastern Paraguay. Relationships with coeval magmatism in Brazil. São Paulo, *Edusp/Fapesp*: 275-330 pp.

- Comin-Chiaromonti, P., De Min, A. and Marzoli, A. 1996b. Magmatic rock-types from the Asunción-Sapucaigraben: chemical analyses. Appendix II. In: Comin-Chiaromonti, P., Gomes, C.B., Eds., Alkaline magmatism in Central-Eastern Paraguay. Relationships with coeval magmatism in Brazil. São Paulo, *Edusp/Fapesp*: 331-388 pp.
- Comin-Chiaromonti, P., Gomes, C.B., De Min, A., Ernesto, M., Marzoli, A. and Riccomini, C. 2007a. Eastern Paraguay: an overview of the post-Paleozoic magmatism and geodynamic implications. *Rendiconti Lincei, Scienze Fisiche e Naturali*, 9-18: 139-192.
- Comin-Chiaromonti, P., Marzoli, A., Gomes, C.B., Milan, A., Riccomini, C., Mantovani, M.M.S., Renne, P., Tassinari, C.C.G. and Vasconcelos, P.M. 2007b. Origin of Post Paleozoic Magmatism in Eastern Paraguay. In: Foulger G.R., Jurdy, D.M., Eds., *Geological Society of America, Special Paper*, 430: 603-633.
- Dennen, W. and Blackburn, W.H. 1970. Aluminium in quartz as geothermometer. *Contributions to Mineralogy and Petrology*, 27: 332-342.
- Goeringh, L. and Morris, S.W. 2005. Order and disorder in columnar joints: *Europhysics Letters*, 69: 739-745.
- Gomes, C.B., Comin-Chiaromonti, P. and Velázquez, V.F. 2013. A synthesis of the alkaline magmatism of Eastern Paraguay. *Brazilian Journal of Geology*, 43: 745-761.
- Gomes, C.B., Comin-Chiaromonti, P., Velázquez, V.F. and Orué, D. 1996. Alkaline magmatism in Paraguay: a review. In: Comin-Chiaromonti, P., Gomes, C.B., Eds., Alkaline magmatism in Central-Eastern Paraguay. Relationships with coeval magmatism in Brazil. São Paulo, *Edusp/Fapesp*, 31-56 pp.
- Gomes, C.B., Velázquez, V.F., Azzone, R.G. and Paula, G.S. 2011. Alkaline magmatism in the Amambay area, NE Paraguay: the Cerro Sarambí complex. *Journal of South American Earth Sciences*, 32: 75-95.
- Hegarty, K.A., Duddy, I.R. and Green, R.E. 1996. The thermal history in around the Paraná Basin using apatite fission track analysis. Implications for hydrocarbon occurrences and basin formation. In: Comin-Chiaromonti, P., Gomes, C.B., Eds., Alkaline magmatism in central-eastern Paraguay. Relationships with coeval magmatism in Brazil. São Paulo, *Edusp/Fapesp*, 67-83 pp.
- Hervig, R.L., Williams, L.B., Kirkland, I.K. and Longstaffe, J. 1995. Oxygen isotope microanalyses of diagenetic quartz: possible low temperature occlusion of pores. *Geochimica et Cosmochimica Acta*, 59: 2537-2543.
- Hirota, K., Tanque, Y. and Kanako T. 1998. Generation of crack patterns with a physical model. *The Visual Computer*, 3: 126-137.
- Hirota, K., Tanque, Y. and Kanako T. 2000. Simulation of three-dimensional cracks. *The Visual Computer*, 16: 371-378.
- Iben, H.N. and O'Brien, J.F. 2006. Generating surface crack patterns. In: Cani, M.P., O'Brien, J.F., Eds., Symposium on computer animation. *The Eurographics Association*, 177-185 pp.
- Kocurek, G. 1988. First-order and super bounding surfaces in eolian sequences. Bounding surfaces revisited. *Sedimentary Geology*, 56: 193-206.
- Kocurek, G. and Hunter, R.E. 1986. Origin of polygonal fractures in sand, uppermost Navajo and Page Sandstones, Page, Arizona. *Journal of Sedimentary Petrology*, 56: 895-904.
- Leoni, L. and Rivalenti, G. 1974. An evaluation of the temperature and volatile pressure during the crystallization of granitic rocks. *Atti della Società Toscana di Scienze Naturali, Memorie, Serie A*, 81: 379-386.
- Marchand, A.M.E., Macanlay, C.I., Haszeldine, R.S. and Fallick, A.E. 2002. Pore water evolution in sandstones: constraints from oxygen isotope microanalyses of quartz cement. *Chemical Geology*, 191: 285-304.
- Miraglia, L. 1965. Volcanismo postplioceno del Paraguay. *Revista de la Sociedad Científica del Paraguay*, 7: 1-51.
- Rogers, J.J.W., Unrug, R., Sultan, M. 1995. Tectonic assembly of Gondwana. *Journal of Geodynamics*, 19: 1-34.
- Summer, N.S. and Ayalon, A. 1995. Intrusions into unconsolidated sandstones and the development of quartzite contact zone. *Journal of Structural Geology*, 17: 997-1010.
- Sun, S-S and McDonough, W.F. 1989. Chemical and isotopic systematics of oceanic basalts. In: Saunders, A.D., Norry M.J., Eds., Magmatism in the ocean basins. *Geological Society of America, Special Paper*, 42: 313-345.
- Thiede, D.S. and Vasconcelos, P.M. 2008. Paraná flood basalts rapid extrusion hypothesis supported by 40Ar/39Ar results. *44th Brazilian Geological Congress*, Curitiba, Províncias Magmáticas, magmatismo básico-ultrabásico, p. 563.
- Velázquez, V.F., Giannini, P.C.F., Riccomini, C., Sallun, A.E.M., Hachiro, J. and Gomes, C.B. 2008. The columnar joints in the Patiño Formation sandstones, Eastern Paraguay: a dynamic interaction between dyke intrusion, quartz dissolution and cooling-induced fractures. *Episodes*, 31: 302-308.
- Zalán, P.V., Wolff, S., Astolfi, M.A., Santos, V.L., Conceição, J.C., Appi Neto, E.V.S., Cerqueira, J.R. and Marques, A. 1990. The Paraná basin, Brazil. In: Leighton, M.W., D.R. Kolata, D.R., Oltz, D.F., Eidel, J.J.I., Eds., *American Association of Petroleum Geology, Memoir*, 51: 681-703.

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