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# PALEOPROTEROZOIC BANDED IRON FORMATION OF THE QUADRILÁTERO FERRÍFERO

## BRAZIL

*Aerial view of Pico do Itabirito formed by a compacted hematite monolith surrounded by an open pit iron ore mine in BIF.*

**ONE OF THE MOST IMPORTANT RECORDS OF PALEOPROTEROZOIC BIF ON EARTH AND PLACE OF FERRUGINOUS CAVES.**

The Banded Iron Formation (BIF) in the Quadrilatero Ferrifero is a Lake Superior-type iron deposit formed at the beginning of the Great Oxygenation Event.
During the Cenozoic the wetter climate favored weathering that enriched iron minerals, which produced economically significant iron ore bodies.

Duricrust is formed by iron oxide and hydroxide (ferricrete) close to the top of weathering profiles in the BIF. These capstone deposits, named regionally as canga, are resistant to erosion and are host to small caves that are the first to have been described in detail in ferruginous rocks (Auler *et al.*, 2014; Simmons, 1963).

# SITE 013

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|---|---|
| GEOLOGICAL PERIOD | Paleoproterozoic |
| LOCATION | State of Minas Gerais, Brazil.<br>20° 14' 25" S<br>043° 52' 01" W |
| MAIN GEOLOGICAL INTEREST | Stratigraphy and sedimentology<br>Geomorphology and active geological processes |

*Outcrop of folded metamorphic BIF in Serra da Piedade Protected Area*

## Geological Description

The most conspicuous Banded Iron Formation in Quadrilátero Ferrífero, together with marbles, dolomites and hematitic and dolomitic phyllites, constitute the Caué Formation of the Supergroup Minas. These rocks are Paleoproterozoic in age, up to 350 m thick, 2.42-2.58 GA, and deposited in a shallow marine ocean (Spier *et al.*, 2003). They are capped by dolomitic BIF and dolomites of the Gandarela Formation, which exhibit biogenetic structures such as stromatolities and algal mats. These rocks have been deformed in two Proterozoic orogenies.

The Cenozoic climate favored weathering, which leached silicious and carbonate minerals of the the BIF and enriched iron minerals. This porcess has produced bodies of iron ore thaty have up to 75% FeO. These deposits are of global significance. Iron mines in the region produced more than 3.0 billion tons of iron in the last 20 years. The weathering profile is the oldest and most continuous known (Spier *et al.*, 2006). The leaching at the tip of the BIF produced duricrust, which is formed by iron oxide and hydroxide (ferricrete). The Duricrust prevents erosion and is regionally called canga.

## Scientific research and tradition

The BIF oucrops were landmarks for European and African populations in the region since the 18th century, and decribed by scientists in the 19th century. These deposits have been the subject of geochemical and tectonic investigations, as well as studies on the genesis of duricrusts and related cave formation.


*Reconstitution of Pico do Itabirito, drawn on current photography. Designed based on 19th century paintings and on Rosiere et al (2009)*



**REFERENCES**

13. Paleoproterozoic Banded Iron Formation of the Quadrilátero Ferrífero

Auler, A. et al. (2014) 'Hypogene Cave Patterns in Iron Ore Caves: Convergence of Forms or Processes', in Hypogene Cave Morphologies. Alexander Klimchouk; Ira D. Sasowsky; John Mylroie; Scott A. Engel; Annette Summers Engel. Lewisburg: Karst Waters Institute, pp. 15–19.

Rosière, C. et al. (2005) 'Pico de Itabira, MG Marco estrutural, histórico e geográfico do Quadrilátero Ferrífero', in Sítios Geológicos e Paleontológicos do Brasil. Winge, M. et al. Brasília: CPRM, pp. 193–202.

Simmons, G.C. (1963) 'Canga caves in the Quadrilátero Ferrífero, Minas Gerais, Brazil', The National Speleological Society Bulletin, 25, pp. 66–92.

Spier, C.A., de Oliveira, S.M.B. and Rosière, C.A. (2003) 'Geology and geochemistry of the Águas Claras and Pico Iron Mines, Quadrilátero Ferrífero, Minas Gerais, Brazil', Mineralium Deposita, 38(6), pp. 751–774. Available at: https://doi.org/10.1007/s00126-003-0371-2.

Spier, C.A., Vasconcelos, P.M. and Oliviera, S.M.B. (2006) '40Ar/39Ar geochronological constraints on the evolution of lateritic iron deposits in the Quadrilátero Ferrífero, Minas Gerais, Brazil', Chemical Geology, 234(1), pp. 79–104. Available at: https://doi.org/10.1016/j.chemgeo.2006.04.006.

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# THE SUGAR LOAF MONOLITH OF RIO DE JANEIRO
## BRAZIL

UNESCO World Heritage Site

*It is the ideal lookout for a stunning 360-degree view, giving the place invaluable educational importance for understanding landscape evolution (Alexandre Macieira / Riotur)*

**ONE OF THE MOST ICONIC ROCK MONOLITHS IN THE WORLD IN AN URBAN LANDSCAPE.**

Although more than 50 mountains are named "Sugar Loaf" (New Webster's Dictionary and Thesaurus. Lexicon Publications, Danbury, Connecticut, 1993), the Sugar Loaf monolith is the world reference for this type of landform. The top of this outstanding pinnacle, easily reached by cable car, is the ideal lookout for the unique geomorphology of Rio de Janeiro (Silva and Ramos 2002) and the Serra do Mar range more to the north. It is also a cultural landmark because it has been a symbol of Brazil and of Rio de Janeiro in paintings and reports since the colonial period (Castro *et al.*, 2021). It is part of a UNESCO World Heritage Site.

# SITE 079

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|---|---|
| GEOLOGICAL PERIOD | Neoproterozoic / Ediacaran |
| LOCATION | Rio de Janeiro City, Rio de Janeiro State, Brazil. 22° 56' 59" S 043° 09' 23" W |
| MAIN GEOLOGICAL INTEREST | Geomorphology and active geological processes<br>Tectonics |

*The type example of near-conical granite domes or bornhardts. Although accessible by difficult climbing routes, the summit is easily reachable by cable car.*

## Geological Description

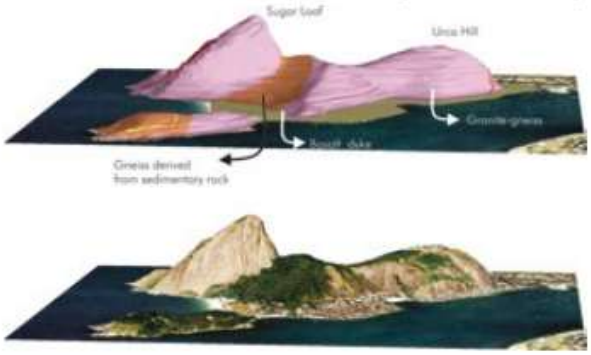
The Sugar Loaf (Pão de Açúcar, in Portuguese) is an outstanding 396 m high near-conical gneiss monolith located at the entrance of the Guanabara Bay, in Rio de Janeiro, SE Brazil.

The Sugar Loaf is composed of an augen gneiss referred in local literature as the "Phacoid Gneiss" (from the Greek word for lens shaped). This gneiss is the product of metamorphism and deformation of a K-feldspar granite during the main collisional phase of the Ribeira orogenic belt at ca. 560 Ma (Ediacaran Period). Several isoclinal folds can be seen in the northern, southern and western sub-vertical faces (Valeriano *et al.*, 2012).

Considering the geomorphological evolution of Sugar Loaf, the role of chemical alteration under the rainy tropical climate is evident. The metasedimentary gneiss was preferentially weathered and eroded, leaving the fresher augen gneiss making up the higher local relief. Steep ENE vertical fractures that affected the area during the Paleogene also control erosive processes that formed the sub-vertical south and north walls. At the southern wall a rock pillar, still attached to the main body, is a remnant of rockfall processes that shaped the monolith. Around the bottom of this pillar, an impressive boulder deposit represents debris from past rockfall events (Valeriano and Magalhães, 1984).

## Scientific research and tradition

The Sugar Loaf is represented in maps as early as the 16th century when Europeans arrived in Brazil. One of the earliest map is from Jean de Léry (The singularities of the Antarctic France, 1572), where it was named "Pot de Beurre" by the French sailors, serving as the main reference for the entrance of the Guanabara Bay and Rio de Janeiro. In his famous voyage aboard the Beagle, Charles Darwin also pointed out the imposing presence of Sugar Loaf when he left Rio de Janeiro on the 8th of July 1832 (Chancellor and Wyhe, 2009).




*Chemical alteration has preferentially weathered and eroded away the biotite-rich metasedimentary gneiss (forested area), leaving the fresher augen-gneiss making up the higher local relief.*



**REFERENCES**

79. The Sugar Loaf monolith of Rio de Janeiro Castro, N. et al. (2021) 'A heritage stone of Rio de Janeiro (Brazil): the Facoidal gneiss', Episodes, 44(1), pp. 59–74. Available at: https://doi.org/10.18814/EPIIUGS/2020/0200S13. Chancellor, G. and Wyhe, J. van (eds) (2009) Charles Darwin's Notebooks from the Voyage of the Beagle. Illustrated edition. Cambridge: Cambridge University Press. Available at: http://darwin-online.org.uk/content/frameset?itemID=EH88202330&viewtype=text&pageseq=1. Da Silva, L.C. et al. (2003) 'Zircon U-Pb Shrimp dating of the Serra Dos Órgäos and Rio De Janeiro Gneissic Granitic Suites: Implications for the (560 Ma) Brasiliano/Pan-African collage', Revista Brasileira De Geosiencias, 33(2), pp. 237–244. Silva, L.C.D. and Ramos, A.J.A. (2002) 'Pão de Açúcar, RJ – Cartão Postal Geológico do Brasil', in Sítios Geológicos e Paleontológicos do Brasil. Schobbenhaus C., Campos D.A., Queiroz E.T., Winge M., Berbert-Born M. (eds). Brasília:

DNPM/CPRM, Comissão Brasileira de Sítios Geológicos e Paleobiológicos (SIGEP), pp. 263–268. Available at: http://sigep.cprm.gov.br/sitios.htm. Valeriano, C. de M. et al. (2012) Geologia e recursos minerais da folha Baía de Guanabara SF.23-Z-B-IV, estado do Rio de Janeiro, escala 1:100.000. 1. ed. Belo Horizonte. CPRM-Serviço Geológico do Brasil / UERJ- Universidade do Estado do Rio de Janeiro. Available at: http://rigeo.cprm.gov.br/jspui/handle/doc/11375. Valeriano, C. de M. and Magalhães, A.C. (1984) 'Geologia estrutural de area do Pão de Açucar e adjacências, Rio de Janeiro, Brasil', Anais da Academia Brasileira de Ciências, 56(3), pp. 295–304.

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# DOMO DE ARAGUAINHA IMPACT STRUCTURE

## BRAZIL

View of the central uplift of Araguainha Dome. The hills comprise Furnas sandstone and impact breccia. The scene in the background is close to 9 km across. (Photo: J. Sanchez).

**THE LARGEST (~40 KM) AND BEST EXPOSED IMPACT STRUCTURE IN SOUTH AMERICA WITH EXAMPLES OF IMPACTITES AND SHOCK DEFORMATION FEATURES.**

The structure boasts spectacular scenery and is easily accessible. A diversity of impact lithologies, such as polymictic impact breccia and impact melt rocks, together with abundant shock deformation features such as shatter cones and a variety of microscopic shock deformation features, make the Araguainha Dome a fantastic natural laboratory to understand impact cratering and planetary processes. It has even been suggested that this impact could have been involved, directly or indirectly, with the major mass extinctions at the Permian-Triassic boundary. Textbook examples of impactites and shock deformation features make Araguainha an ideal location for developing geotourism, geoheritage and geoconservation-related, as well as educational, activities.

# SITE 100

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| GEOLOGICAL PERIOD | Permian-Triassic boundary |
| LOCATION | States of Mato Grosso and Goiás, central Brazil.<br>16° 48' 00" S<br>052° 59' 00" W |
| MAIN GEOLOGICAL INTEREST | Impact structures and extraterrestrial rocks<br>Stratigraphy and sedimentology |

*Prominent shatter cones in phyllites of the crystalline basement. Pen for scale is 14 cm long. (Photo: A. P. Crósta)*

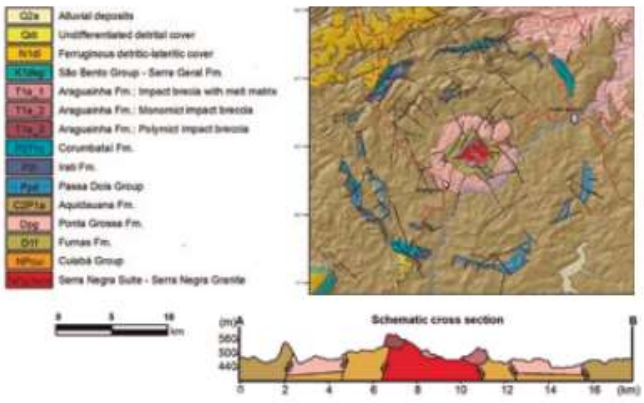
## Geological Description

The Domo de Araguainha (Araguainha Dome) exhibits a large diversity of rock types and impact features exposed in its >1.3 thousand km² area, including Neoproterozoic and Paleozoic crystalline rocks at the center of the structure that are surrounded by Silurian to Permian sedimentary strata of the intracratonic Paraná Basin. The impact structure is cut by the Araguaia River that drains into the Amazon River basin. The structure exhibits an annular, concentric structure with a central uplift where the Neoproterozoic to Cambrian crystalline basement is well exposed. The central uplift is surrounded by sedimentary sequences of the Paraná Basin including, from the base to the top, the Rio Ivaí (Silurian), Paraná (Devonian), Itararé (Carboniferous), and Passa Dois (Permian) groups. The sedimentary strata are arranged in a bull's eye pattern around the central crystalline core, forming a formidable geological scenario. Impactites, namely polymict impact breccia and various types of impact melt rock, occur abundantly in the central portion of the structure.

## Scientific research and tradition

Brazilian and foreign scientific investigations have been conducted at Araguainha since the 1960s, and results have been widely published. Excursions have been conducted as part of international conferences, such as an International Geological Congress, Annual Meeting of the Meteoritical Society, Large Meteorite Impacts and Planetary Evolution VI conference.

*Geological map and cross section for the Araguainha Dome (CPRM/Brazilian Geological Survey); inset: location of the structure in the Paraná Basin (dark grey).*






**REFERENCES**

IX. IMPACT STRUCTURES AND EXTRATERRESTRIAL ROCKS 100.

Domo de Araguainha Impact Structure

Crósta, A.P. et al. (2019) 'Impact cratering: The South American record – Part 1', Geochemistry, 79(1), pp. 1–61. Available at: https:// doi.org/10.1016/j.chemer.2018.06.001. Crósta, A.P., Gaspar, J.C. and Candia, M. (1981) 'Feições de metamorfismo de impacto no Domo de Araguainha', Revista Brasileira de Geociências, 11, pp. 139–146. Available at: https://doi.org/10.5327/ RBG.V11I3.219.

Engelhardt, W.V., Matthäi, S.K. and Walzebuck, J. (1992) 'Araguainha impact crater, Brazil. I. The interior part of the uplift', Meteoritics, 27(4), pp. 442–457. Available at: https://doi.org/10.1111/j.1945-5100.1992.tb00226.x. Hauser, N. et al. (2019) 'Linking shock textures

revealed by BSE, CL, and EBSD with U-Pb data (LA-ICP-MS and SIMS) from zircon from the Araguainha impact structure, Brazil', Meteoritics & Planetary Science, 54(10), pp. 2286–2311. Available at: https://doi.org/10.1111/ maps.13371. Lana, C. et al. (2008) 'Structural evolution of the 40 km wide Araguainha impact structure, central Brazil', Meteoritics & Planetary Science, 43(4), pp. 701–716. Available at: https://doi. org/10.1111/j.1945-5100.2008.tb00679.x.

Tohver, E. et al. (2013) 'Shaking a methane fizz: Seismicity from the Araguainha impact event and the Permian–Triassic global carbon isotope record', Palaeogeography, Palaeoclimatology, Palaeoecology, 387, pp. 66–75. Available at: https://doi.org/10.1016/j. palaeo.2013.07.010.

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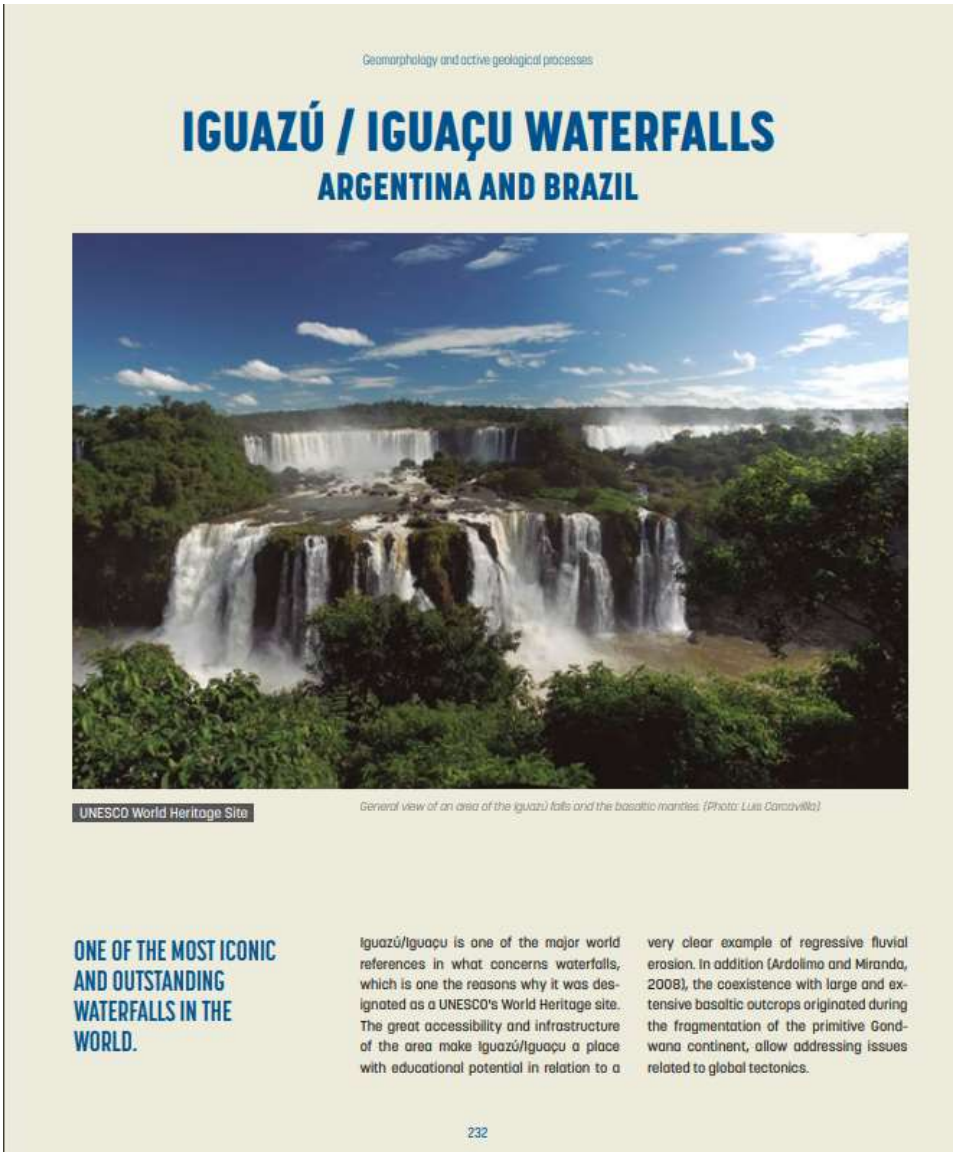

Geomorphology and active geological processes

# IGUAZÚ / IGUAÇU WATERFALLS

## ARGENTINA AND BRAZIL

UNESCO World Heritage Site

*General view of an area of the Iguazú falls and the basaltic rapides. (Photo: Luis Carcavilla)*

**ONE OF THE MOST ICONIC AND OUTSTANDING WATERFALLS IN THE WORLD.**

Iguazú/Iguaçu is one of the major world references in what concerns waterfalls, which is one the reasons why it was designated as a UNESCO's World Heritage site. The great accessibility and infrastructure of the area make Iguazú/Iguaçu a place with educational potential in relation to a very clear example of regressive fluvial erosion. In addition (Ardolimo and Miranda, 2008), the coexistence with large and extensive basaltic outcrops originated during the fragmentation of the primitive Gondwana continent, allow addressing issues related to global tectonics.

# SITE 085

| | |
|---|---|
| GEOLOGICAL PERIOD | Quaternary / Holocene |
| LOCATION | Argentina: Puerto Iguazú / Misiones Province<br>Brazil: Foz do Iguaçu / Paraná. 25° 41' 44" S 054° 26' 13" W |
| MAIN GEOLOGICAL INTEREST | Geomorphology and active geological processes<br>Volcanology |

*Garganta del Diablo (Devil's throat). (Photo: Luis Carcavilla)*

## Geological Description

The Iguazú/Iguaçu waterfalls constitute a set of 275 falls with an average height of 75 meters distributed along a front of almost 2,700 meters. These discharge an average of 1,800,000 l/s into the narrow and deep canyon of the Iguazú river (Salamuni *et al.*, 1998). The "Garganta del Diablo" (Devil's Throat), the most important fall, is the culmination of this canyon that begins in the Paraná river, on the border between Argentina, Brazil and Paraguay, 18 km downstream from the falls. Fissural basaltic volcanic rocks that spread over the surface some 125 to 115 Ma ago (Lower Cretaceous) dominate the region (Ardolino and Miranda, 2008). These lava flows covered an area of 1,200,000 km² and accumulated thicknesses of up to 1,500 meters, constituting the largest basaltic lava flow recorded on the planet's continental crust. Its origin is synchronous with the fragmentation of Gondwana, for which these rocks are also recognized in the western sector of Africa, an intercontinental group known as the Paraná-Etendeka volcanic province (Llambías, 2023). In South America, these lavas are known as the Serra Geral Formation. The region is a high, flat plateau that is crossed and incised by several rivers. The channel of some of them, like part of the Paraná and the final section of the Iguazu are probably structurally controlled (Ardolino and Miranda, 2008).

*Iguazú/Iguaçu waterfalls are a very clear example of an active geological process of regressive fluvial erosion*

## Scientific research and tradition

Since the waterfalls are located on the border between Argentina and Brazil and constitute the most imposing feature within the homonymous National Parks, there is profuse international research on active geomorphological processes, petrological and volcanological aspects, as well as numerous publications that contemplate biotic factors.




**REFERENCES**

Ardolino, A.A. and Miranda, F. (2008) 'Las Cataratas del Iguazú. El agua grande', Instituto de Geología y Recursos Minerales. Servicio Geológico Minero Argentino, Anales, 46(1), pp. 377–388.

Llambías, E.J. (2003) Geología de los cuerpos ígneos. 2a. ed. Buenos Aires: Asociación Geológica Argentina (Instituto Superior de Correlación Geológica: serie correlación geológica, nro. 15).

Salamuni, R. et al. (1998) 'Cataratas de fama mundial', in C. Schobbenhaus et al. (eds) Sítios geológicos e paleontológicos do Brasil: volume I. Brasília: DNPM/CPRM, Comissão Brasileira de

Sítios Geológicos e Paleobiológicos (SIGEP). Available at: http://rigeo.cprm.gov.br/jspui/handle/doc/19865.

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