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https://doi.org/10.1590/2317-4889202220210022
BJGEO Brazilian Journal of Geology

Three-dimensional geological modeling of the Itataia Phosphate-Uranium Deposit (Ceará, Brazil)

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Abstract
The Itataia phosphate-uranium deposit is located in the northwest segment of the Borborema Province in the Ceará Central Domain. The ore mineral is uranium-enriched microcrystalline collophanite apatite that occurs in massive bodies and lenses, stockworks, as well as hydrothermal and karst breccias associated with marble, calc-silicate rocks and gneisses of the Itataia Group. The deformational history of the deposit includes ductile structures developed in the final stages of thrust tectonics linked to the Brasilian orogeny and later brittle phases related to extensional tectonics, which influenced phosphorus and uranium remobilization and the formation of ore bodies. The main uranium anomaly coincides with the upper part of the Serrote da Igreja hill, bordered to the north by an E-W trending subvertical fault scarp that controls a wide valley. Geometric modeling of the geological data of the deposit provides a three-dimensional view of the geometry of ore bodies, distribution of host rock and faults that propagate beneath the surface and control mineralization, as well as the upper and lower limits of surface weathering. The three-dimensional geometric model using the GoCAD software served as a powerful tool for the analysis of the geology of the Itataia deposit, highlighting the geometry of rocks and ore bodies and the processes involved in the genesis of phosphate-uranium mineralization.

KEYWORDS: geological modeling; phosphate-uranium ores; Itataia deposit.

INTRODUCTION

The Itataia phosphate-uranium deposit is located in north central Ceará in northeastern Brazil, about 200 km from the state capital, Fortaleza. Geologically, the deposit lies in the Ceará Central Domain (CC), in the northwestern segment of the Borborema Province and the northeastern portion of the South American Platform (Almeida *et al.* 1981) (Fig. 1).

The Itataia deposit was discovered in 1976 by INB (Brazilian Nuclear Industries) in a carborne radiometric survey in north central Ceará. The calculated ore reserve indicated a total of 80,000 tons of uranium with a grade of 0.19% U_3O_8 and 8.9 Mt of phosphate ore with an average grade of 26.35% P_2O_5 (Nuclebrás 1984).

The phosphate was long considered a barrier to the exploration of the Itataia deposit, which recently became economically viable with the creation of a consortium between the Brazilian Nuclear Industries (INB) and the Galvani fertilizer company. Plans for the coming years include the construction of an industrial complex to produce 810,000 metric tons of phosphate fertilizer, 240,000 metric tons of animal feed and 1,600 metric tons of uranium concentrate.

The collection of subsurface information generated during prospection includes 243 drillholes (56,872 m) in and around the deposit, 166 of which are located in the area of the uranium-phosphate ore body, in the elevated portion of the deposit (Nuclebrás 1984). Some of this information (from 124 drillholes and three underground galleries — G1, G2 and G3) was used to generate the 3D models presented here, which allow for a better understanding of the geological and geomorphological setting of the Itataia metasedimentary sequence and its associated ores. The 3D models were generated in the GoCAD environment by lateral interpolation of geological data from drillholes and correlation with surface data.

Different genetic models have been proposed as the primary source of uranium in the Itataia deposit:

- a primary/syngenetic continental source subsequently deposited into localized depressions in a shallow marine platform environment (Favali and Leal 1982, Saad *et al.* 1984, Mendonça *et al.* 1985, Castro 2001, Castro *et al.* 2005a);
- a magmatic-hydrothermal origin, related to episyenites formed from fertile post- orogenic granites (Fyfe 1978, Campos *et al.* 1979, Angeiras *et al.* 1981, Angeiras 1988, Castro 2005, Castro *et al.* 2005b).

More recent studies emphasize the importance of magma hot springs related to the opening of the South Atlantic in

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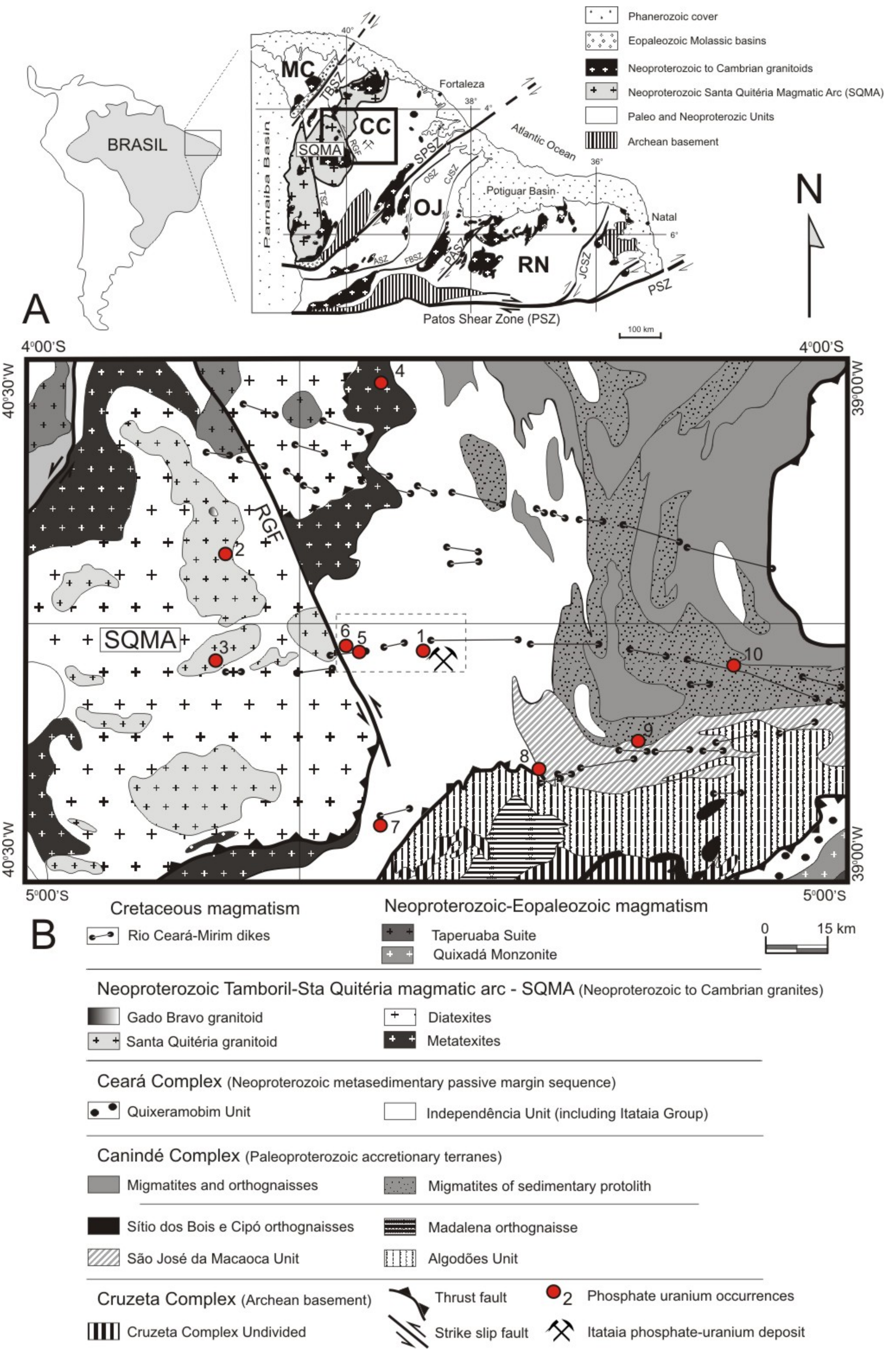


MC: Médio Coreaú; CC: Ceará Central; OJ: Orós Jaguaribe; RN: Rio Grande do Norte.

Source: (A) adapted from Brito Neves *et al.* (2000) and Cavalcante *et al.* (2003); (B) compiled and modified from Cavalcante *et al.* (2003), Torres *et al.* (2008), Cavalcanti and Bessa (2011) and Veríssimo *et al.* (2016).

Figure 1. (A) Crustal blocks and simplified geological map of the northern Borborema Province. (B) Simplified geological map of part of the Ceará Central domain, with the location of the Itataia deposit and other phosphate-uranium occurrences: (1) Itataia Deposit; (2) Aquiri Farm; (3) Serrotes Baixos; (4) Taperuaba; (5) Itataia East 1; (6) Itataia West 2; (7) Aguas Belas; (8) Madalena, (9) Manitoba Farm; (10) Pedra Preta Farm.

the formation of the Itatiaia deposit (Cavalcanti and Bessa 2011, Cavalcanti *et al*. 2013, Santos *et al*. 2014, Cavalcanti *et al*. 2018). Petrographic studies and detailed isotopic analysis (oxygen, carbon, and strontium) performed by Veríssimo *et al*. (2016) confirm the epigenetic and post-deformational character of mineralized fluids and suggest a multiphase mineralization process for the Itataia deposit. These authors highlight at least two major mineralizing events in Itataia: an initial high temperature event connected with a sodium metasomatism-related uranium episode, taking place in the Borborema Province and its African counterpart; and a second, low temperature stage, consisting of a multiphase cataclastic/hydrothermal event limited by the fault and paleokarst zones, with the latter involving the mixing of hydrothermal and meteoric fluids combined with decreasing temperature and salinity.

The purpose of this article is not solely limited to presenting procedures and steps applied in the construction of a three-dimensional model for the Itataia deposit, but also to contribute to analyzing the geology of the deposit, structural controls of the ore bodies, and the processes involved in the genesis of the deposit and the phosphate-uranium mineralization.

GEOLOGICAL SETTING

The study area is located in the Borborema Province (PB), defined as part of the Neoproterozoic Western Gondwana collage, which was formed in the collision of an complex orogenic system between the São Luís — West Africa and São Francisco- Congo cratons (Van Schmus *et al*. 1995, Santos 1996, Brito Neves *et al*. 1999, 2000). This province is subdivided into the following subprovinces or domains: Médio Coreaú (MC), Ceará Central (CC), Orós-Jaguaribe (OJ) and Rio Grande do Norte (RN) by large transcurrent shear zones: Transbrasiliano (TBSZ), Senador Pompeu (SPSZ), Portalegre (PASZ) and Patos (PSZ) (Brito Neves *et al*. 2000, Medeiros 2004) (Fig. 1A).

The Ceará Central Domain (CC) encompasses a number of phosphate-uranium occurrences, including the Itataia deposit, which is divided as follows:

- Archean basement represented by the Cruzeta Complex (Oliveira and Cavalcante 1993);
- Paleoproterozoic accretionary terranes, including the Canindé Complex (Torres *et al*. 2008), São José da Macaoca and Algodões units, Sítio dos Bois and Cipó orthogneisses and the Madalena Suite (Cavalcante *et al*. 2003);
- the Neoproterozoic metasedimentary passive margin sequence, represented by the Ceará Complex, including the Quixeramobim and Independência Units (Castro 2005, Arthaud 2007, Arthaud *et al*. 2008, Arthaud *et al*. 2015);
- the Neoproterozoic Tamboril-Santa Quiteria magmatic arc;
- Neoproterozoic to Cambrian granites;
- Eopaleozoic molassic basins associated with Brasiliano strike-slip shear zones;
- Cretaceous magmatism, represented by the Rio Ceará-Mirim dykes (Figs. 1A and 1B).

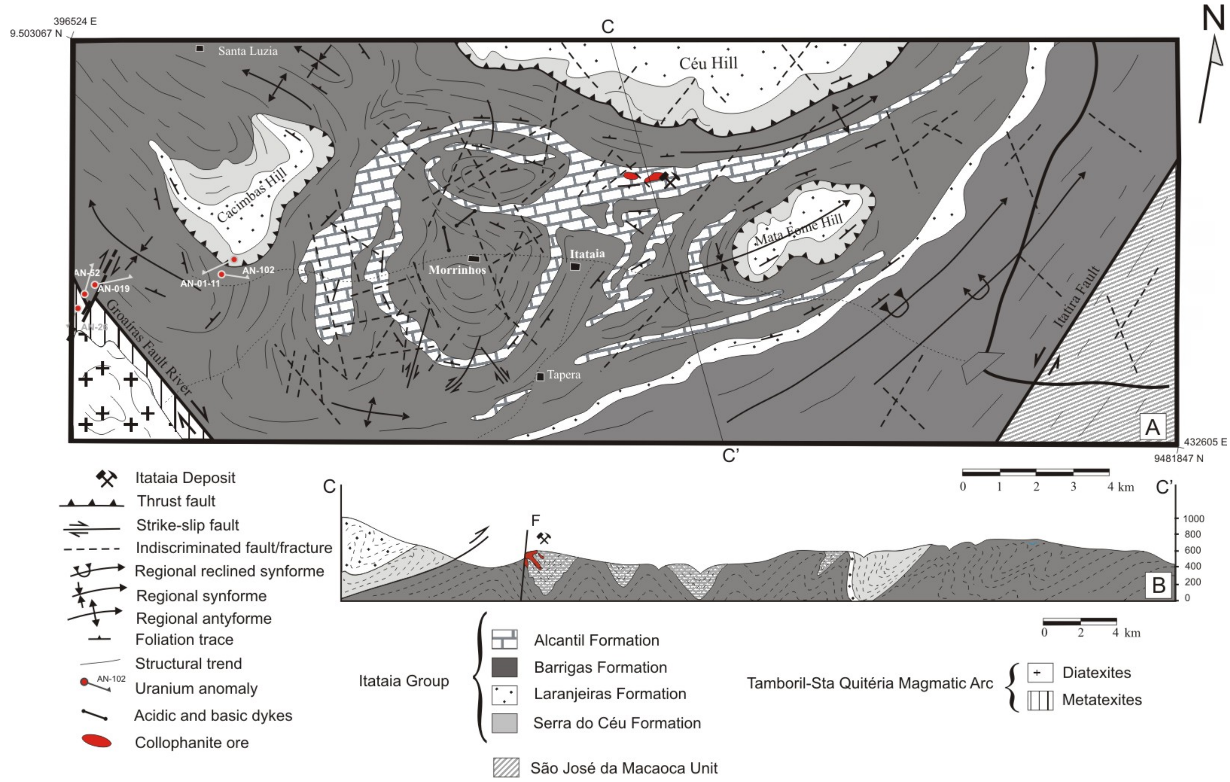
The Itataia phosphate-uranium deposit is hosted by Neoproterozoic supracrustal quartz-carbonate-rocks (Santos 2003, Castro 2005, Castro *et al.* 2005b, Arthaud 2007) surrounding the Santa Quitéria Magmatic Arc (SQMA) (Fetter 1999). These rocks are located within the Itataia Group and, in conjunction with the Independence unit and the Ceará complex, are part of the Ceará Central Domain (CC) as defined by Arthaud *et al*. (1998, 2015).

The Itataia Group is dominated by medium to high-grade metamorphosed sedimentary rocks that were strongly deformed during the Pan-African/Brasiliano orogeny. The first contractional phase in the study area indicates a S-SW nappe and thrust development in the Itataia Group (Garcia and Arthaud 2004, Arthaud 2007, Santos *et al*. 2008, Arthaud *et al*. 2015). Recent SHRIMP U-PB zircon ages (0.63 Ga) of paragneisses in the Ceara Group (Arthaud 2007, Arthaud *et al*. 2015) and Sm-Nd isochron ages (0.62 Ga) of paragneisses from the Barrigas Formation (Santos *et al*. 2003) are interpreted to be an indication of the metamorphism time in the Itataia Group.

The rocks at the base of the Itataia Group are arranged together within the Serra do Céu Formation, where the most common lithotypes are garnet- and sillimanite-bearing migmatites that usually display granitic pegmatitic veins, amphibolitic gneisses and, less often, fine-grained leucrocratic gneisses with alkali feldspar, quartz, garnet, with mica and tourmaline (Mendonça *et al*. 1982). Placed stratigraphically above this unit are the paragneisses of the Barrigas Formation, thrusted by quartzites of the Laranjeiras Formation, leading to alternating tectonic gneisses and quartzites in some instances. The upper portion of the Itataia Group consists of metapsamitic rocks of the Barrigas Formation and marble lenses of the Alcantil Formation (Fig. 2).

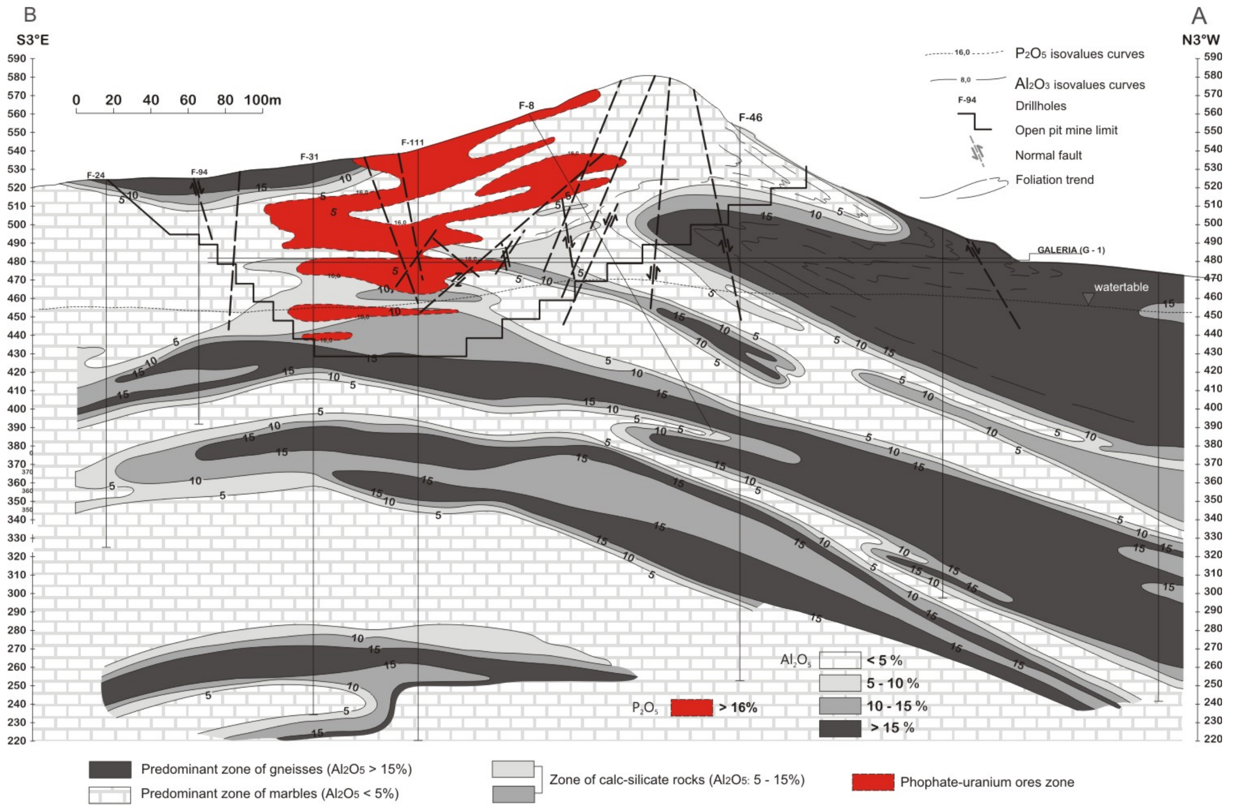
The marbles of the Alcantil Formation are the main host rock of the mineralization. They are usually calcitic, white to gray in color, and may exhibit minerals such as graphite, pyroxene, scapolite, amphibole, and phlogopite. They are typically more than 50 m thick and, in cases of successive tight folding, may reach up to 500m thick. In addition to marbles, gneisses and calc-silicate rocks also host the uranium-phosphate mineralization (Mendonça *et al*. 1982, 1985). Based on the relationship between folding and failure, Veríssimo *et al.* (2016) suggest that the architecture of the mineralization area was established by the end of the Brasiliano orogeny, with the thrusts and nappes of the pelitic unit (Fm Barrigas) in the Itataia Group over the chemical sequence (Alcantil Formation), generating south-trending isoclinal folds. Geometrically, the location of the main ore body coincides with the hinge zone of isoclinal decametric folds, where ductile and brittle planes acted as channels for fluid percolation (Fig. 3).

The largest uranium anomaly coincides with the top of the Serrote da Igreja hill, roughly E-W trending, bordered to the north by an extensional fault scarp. The surface map (Fig. 4A) and underground gallery G3 (Fig. 4B) show the influence of brittle tectonics accompanied by brecciation and karstification in the phosphate-uranium mineralized zone. Towards the center of this zone and along its borders are marble and calc-silicate outcrops with collophanite filling the schistosity



Source: (A) (adapted from Mendonça *et al.* (1985), Santos (2003) and Pires (2012); (B) compiled from Veríssimo *et al.* (2016).

Figure 2. (A) Geological map and location of the Itataia phosphate-uranium deposit. (B) Geological cross-section of the Itataia neoproterozic supracrustal Group.

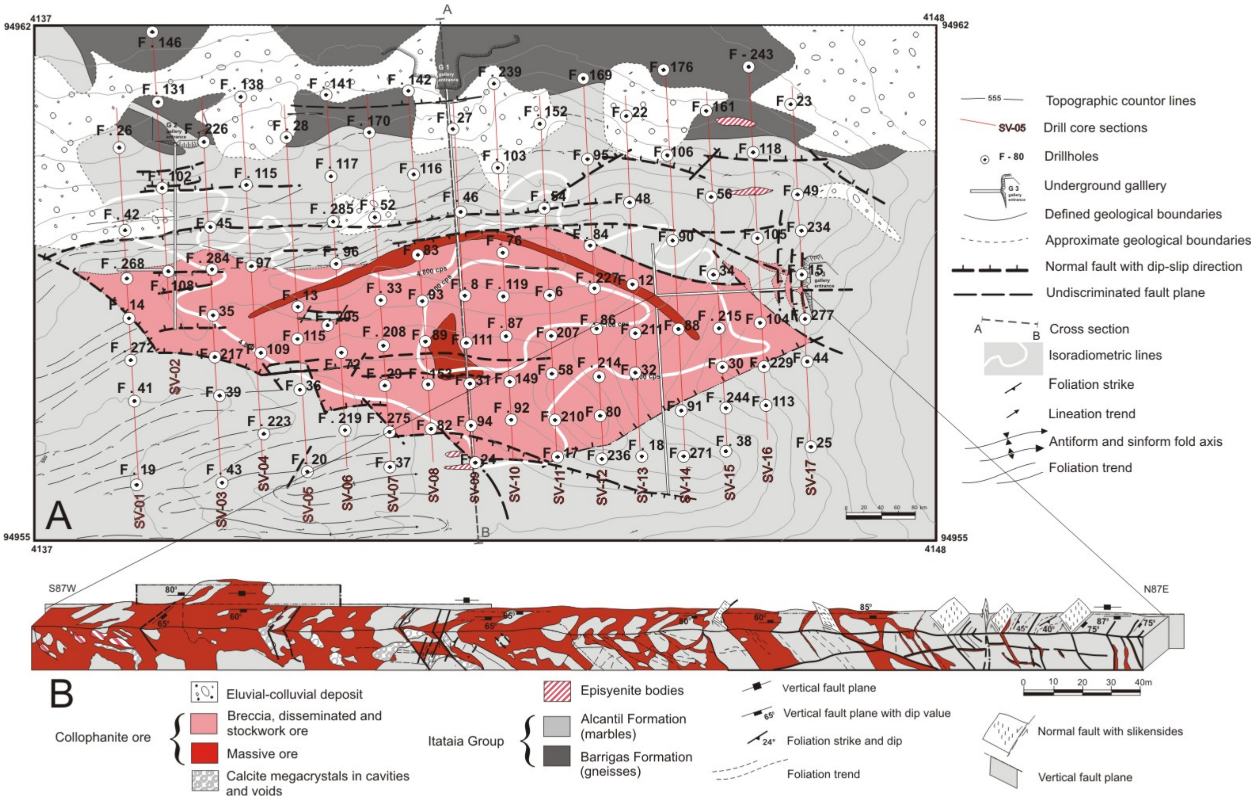


Source: modified from Nuclebrás (1984), Alcântara and Silva (2003) and Veríssimo *et al.* (2016).

Figure 3. Cross-section through the phosphate-uranium mineralized zone of the Itataia deposit. Structural and chemical data were used to compile a schematic geological cross-section to assign mineralization to the hinge zone of isoclinal folds and brittle tectonic, with foliation planes dipping to the north.

and fractures/faults planes, exhibiting typical stockwork-type features and brecciated zones containing scattered marble blocks enveloped in a red colophanite film with spathic calcite megacrystals (Fig. 4B).

At least two main stages were involved in the Itataia ore genesis. The first is a high-temperature stage, characterized by albitization, quartz leaching (episyenitization), hematitization and sodium amphibole formation. This stage is



Source: (A) modified from Nuclebrás (1984). (B) adapted from Veríssimo *et al.* (2016).

Figure 4. (A) Geological map illustrating the drill core sections applied to 3D modeling of the Itataia deposit. The N3W – S3E trending sections crosscut the main uranium anomaly, coinciding with the main phosphate-uranium ore body. The A-B line corresponds to the cross-section of Figure 4. (B) Detailed geological and structural map of gallery G-3 crossing the mineralized zone, illustrating the collophanite ore-brittle tectonic relation.

most likely part of a Na-metasomatic uranium mineralization episode that occurred in PB and its African counterpart as a result of fluid-rock interaction with magmatic/hydrothermal fluids, soon after or during the late Pan-African/Brasiliano orogeny, from the end of the Neoproterozoic to the early Paleozoic periods (Cambro-Ordovician) (Castro *et al.* 2005b, Veríssimo *et al.* 2016). The second stage is characterized by several mineralizing events, involving a multiphase cataclastic/hydrothermal event of fluid flux/input on fracture/fault and paleokarst zones, which requires a better definition. The only age available for this stage (ca. 91 Ma) was obtained by apatite fission-track (AFT) in collophanite (e.g., Netto *et al.* 1991). This thermochronological record is compatible with regional AFT studies carried out in the Borborema Plateau recorded a late Cretaceous cooling event beginning between 100-90 Ma that affected the entire Borborema Province and has been interpreted as the result of continental uplift and erosion (Hegarty *et al.* 2004, Morais Neto *et al.* 2008, 2009).

Table 1 describes the different stages and mineralizing events of uranium and phosphorus proposed by Veríssimo *et al.* (2016) for the Itataia deposit.

For greater detail on the genesis of the Itataia deposit, see Angeiras *et al.* (1978), Haddad and Leonardos (1980), Haddad (1981), Favali and Leal (1982), Saad *et al.* (1984), Mendonça *et al.* (1985), Angeiras (1988), Castro (2001), Santos (2003), Castro (2005), Castro *et al.* (2005a, 2005b), Cuney (2010), Cavalcanti and Bessa (2011), Cavalcanti *et al.* (2013, 2018), Santos *et al.* (2014) and Veríssimo *et al.* (2010, 2016).

THREE-DIMENSIONAL MODELLING

Methodology

The methodology used to model the Itataia deposit consisted of four different stages:

- analysis and interpretation of the data obtained from INB (topographic maps, geological cross-sections, drill logs, lithochemical and composite data);
- field activity and redescription of drill core samples in order to analyze, differentiate and laterally interpolate the main lithostratigraphic units and minerals present;
- digitalization of the topographic data (contour lines) to compile digital surface and subsurface models of the deposit;
- construction of surfaces and objects based on lateral interpolation of the points and lines (curves) and 3D modelling.

Considering that the data obtained from INB can be dated back to the late 70s and early 80s, each geological cross-section used for modelling was reinterpreted based on a detailed analysis of drill core samples stored in warehouses near the INB office and accommodation facilities in Itataia. All sixteen vertical cross-sections were reviewed and reinterpreted before final modeling.

Preliminary digitalization of the data was performed in the Geotechnical Engineering and Prospection Laboratory of the Universidade Federal do Ceará (UFC), using the AutoCAD software. Three-dimensional modeling was then carried out using the GoCAD software version 2.07 at the Geomodelling Laboratory of the Universidade Estadual Paulista "Júlio de Mesquita Filho" (UNESP), run by then-coordinator Prof. Dr. Hans Dirk Ebert.

Table 1. Proposed genetic model for the mineralization U-P events and ore genesis of Itataia deposit (Veríssimo *et al.* 2016).

Mineralization U - P events	Mineralogy and related processes in the host rocks	Typology of phosphorous-uraniferous ores
Phosphate deposition in coastal environment formed by delta and lagoons in the presence of organic matter, with calcareous mud, psammites pelites and chemical sediments. Shallow marine platform.	Primary phosphate	Sedimentar phosphate deposits (phosphorite)
Metamorphism, deformation and granitogenesis tardi to post Brasiliano/Pan-African orogeny	Phosphate formation and recrystallization in metamorphic conditions	
Event 1 Hydrothermal/metasomatic high temperature peralcaline to alkaline fluid circulation of magmatic origin along open spaces (schistosity, extensional zones and fault planes)	- Albite from calcic plagioclase, arfvedsonite and fe-eckermannite from tremolita-actinolita - Fluorapatite (Ap1) from igneous and sedimentary apatite; - Widespread epissienitization process (metassomatism with quartz lixiviation, Na, Fe and Ti supply and Ca, Mg remotion, precipitation of coffinite) - Formation of vugs and larger cavities in structural traps (schistosity, extensional zones and fault planes)	Episyenites, uranium and phosphate phases in vugs, voids and structural traps
Event 2 Low temperature heated meteoric waters mixed with a hydrothermal fluid	Fluorapatite (Ap2) with fibro-radious and collophorm habit large calcite crystals and drusy calcite (generation I), autigenic quartz, chorite and zeolite karstification in hypogenic conditions	Stockwork and veins of collophanite ore Carbonate and carbonaceous mineralized breccias
Event 3 Supergene phreatic phase (likely meteoric waters) and vadose phase (meteoric waters)	Fluorapatite and hydroxyapatite (Ap3) with botryoidal habit drusy and microcristaline calcite (generation II) clay minerals and likely others such as calcium and aluminous phosphates	Massive collophanite ore

GoCAD (Geological Object CAD) is a computer program developed by the Computer Science Department of the Ecole Nationale Supérieure de Geologie de Nancy (ENSGN), France, with integrated applications that offer advanced visualization, 3D modeling interpretation and geoanalysis capabilities. It consists of a set of modules that are continuously updated by different research groups, which are funded by an international consortium of companies and universities. In Brazil, these include UNESP, Petrobras and the Alberto Luiz Coimbra Institute for Graduate Studies in Engineering — COPPE/UFRJ. The software's main capability is integrating isolated information (geophysical data, information on production, structural and stratigraphic test wells, etc.) into a single 3D model.

The techniques used to construct the 3D model of the Itataia deposit were adapted from those described by Pflug and Harbaugh (1992), Ebert *et al.* (1994, 1999) and Veríssimo *et al.* (2000). Each plane represented by a line in the geological cross-section was digitalized in AutoCAD in an independent layer and then exported in .dxf format and inserted into GoCAD as curves. The layers of the sections were distributed and organized as follows: the name of the layer or contact surface, followed by the number of the layer and finally, the number of the geological cross-section it belongs to. For example, the different collophanite layers were renamed as follows: colophanite1-GS01 (first collophanite body in the first section), colophanite1 — GMS02 (first collophanite body in the second section) and so on. In this example, the nomenclature identifies the same geological layer but in different sections laterally interpolated. After the nomenclature for each line in the cross-sections was established, different colors were assigned to each layer to make the lines easier to visualize during lateral correlation. More than 470 layers were defined during this stage and then exported to the GoCAD 3D modeling software.

Lateral interpolation of the different curves associated with the geological cross-sections led to the creation of 3D surfaces that can depict a contact surface (top or bottom of the layer), lens, fault, or closed body.

More than 50 surfaces that represent the same lithotype were rendered in the same color, allowing for differentiation and better visualization of the 3D model.

Digital Elevation Model of the Itataia Region and Deposit

The map used to depict the surface topography of the region was compiled by INB-NUCLEBRÁS in the 1980s, with contour lines every 10 meters. Within this large topographic area (4.5 km long and 2.5 km wide), a smaller section was selected, where the largest phosphate-uranium ore body and the majority of the geological features on the Itataia deposit can be found.

For both areas and the DEMs, contour lines were digitalized using the PLINE command in AutoCAD, then transferred from CAD to GoCAD as point sets containing the X, Y and Z files (coordinates and altitudes). The respective DEMs of the Itataia region and the deposit are shown in Figures 5 and 6. It is important to underscore the regional E-W trend of the set of small mountains, hills and straight valleys that

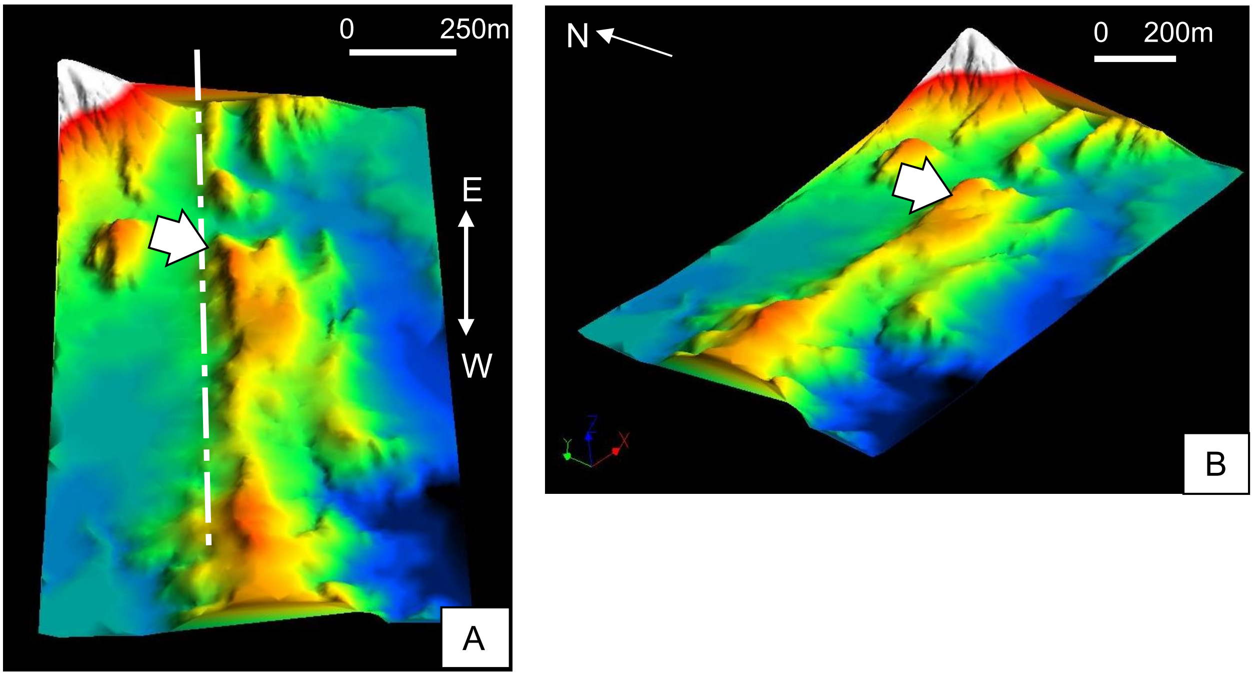


Figure 5. (A and B) Digital elevation models of the Itataia region, Ceará (CE), Brazil. The arrow indicates the location of the main ore body and uranium-phosphate anomaly in the Itataia deposit.

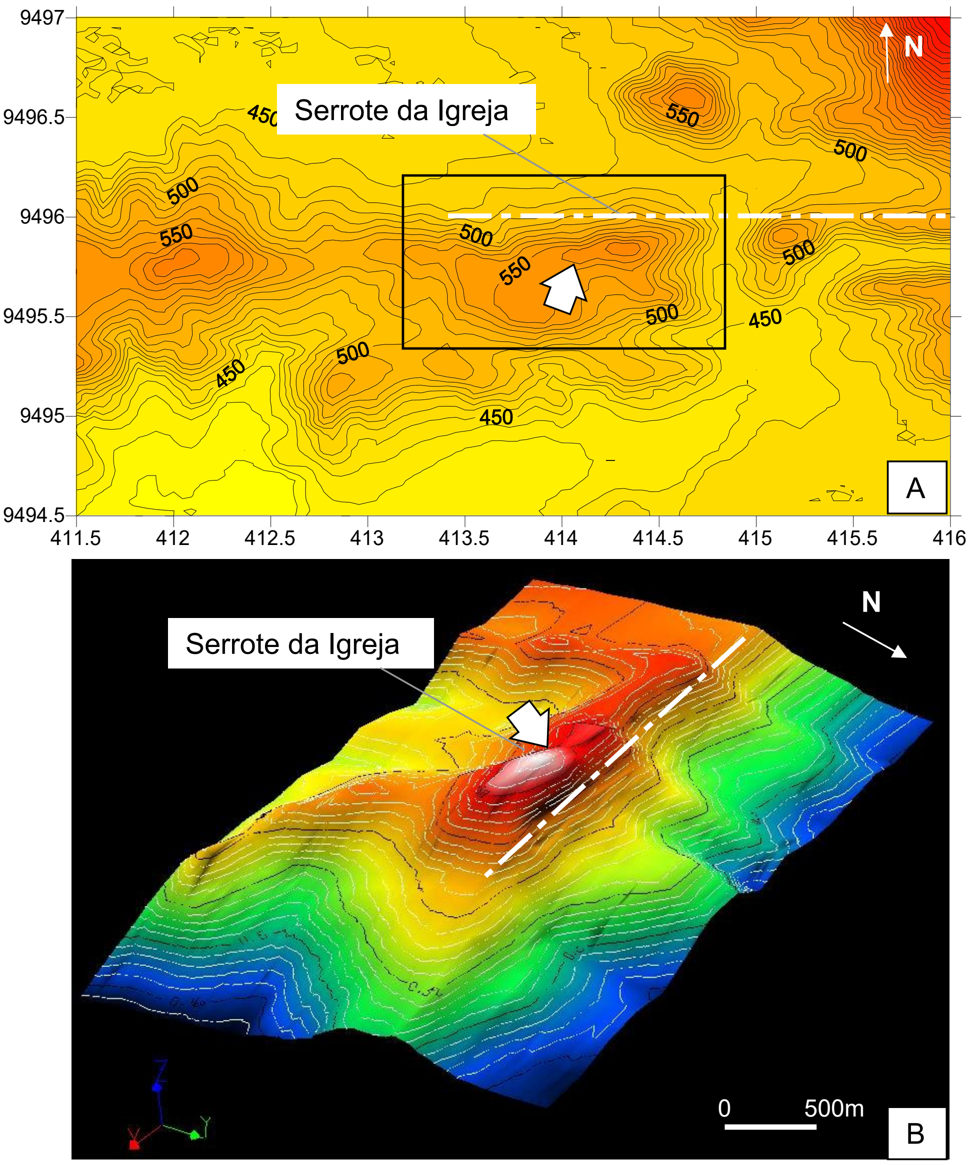


Figure 6. (A and B) Countor regional map and local Digital Elevation Model of Serrote da Igreja. The white dotted line indicates the approximate position of the fault scarp bordering the ore occurrence.

form a heavily structured relief where the largest ore anomaly is located, in the northern segment of Serrote da Igreja, bordered by an extensional fault scarp.

3D Model of the Itataia Deposit

The subsurface geological information included sixteen N3W – S3E trending geological cross-sections containing 124 drillholes (Fig. 4A). Sixteen other intermediate sections parallel to the main sections were constructed to smooth the surfaces and define the lenses and layers (Fig. 7).

Due to the large amount of information and in order to visualize the features/objects (layers, ore, lenses, contact surfaces) in the model in the correct scale, data were filtered to differentiate between representative and non-representative features in terms of thickness and lateral continuity. In general, surfaces with at least one dimension shorter than 10 m were excluded, except for small bodies.

Based on the parameters previously described, the most significant lithotypes in terms of volume were identified to be included in the model. Important, albeit thin, layers located very closely were grouped together to allow for better 3D visualization. The criteria established during reinterpretation of the drill core samples made it possible to simplify the subsurface data for representation in the 3D model.

The lithotypes defined were collophanite, breccia ore, indiscriminate altered ores, pegmatitic vacuolar rocks (episyenites), calc-silicate rocks, gneisses and marbles. The first four are uranium-phosphate ores in the Itataia deposit, briefly described below:

- Collophanite: Represents the main type of ore in the Itataia deposit, is fine-grained, reddish brown with a botryoidal texture and occurs as massive bodies filling vugs and fractures covered in concentric layers of collophane. Quartz, graphite, calcite and albite crystals are common, the last partially altered to kaolinite (Fig. 8A). There is microscopic evidence of fibroradial crystals of apatite forming spherulites with black and red inclusions, prismatic crystals and cryptocrystalline apatite typically containing albite and quartz filling vugs and fractures (Fig. 8B);
- Karst breccia ore: consisting of clasts of marble, collophanite, fine feldspatic and calc-silicate rock cemented by calcite and concentric layers of botryoidal collophane. The galleries and drillholes that cross the mineralized zone contain fault breccia consisting of angular clasts of marble and collophanite with calcite megacrystals up to 10 cm wide, crystallized in vugs generated by karstification (Figs 8C and 8D). The presence of botryoidal collophanite and young calcite phases in vugs produced by megacrystal dissolution suggests the existence of more than one karstification phase and karst breccia. Among the breccia ores are uranium-rich carbonaceous breccias consisting of clasts of feldspatic rocks, marble, calc-silicate rocks and collophanite in a dark grey to black matrix containing graphite and organic matter. Due to their small size and localized occurrence, these bodies were grouped with the karst breccias in the 3D model;
- Episyenites: granular rocks with a coarse to pegmatitic texture, pinkish to reddish, occurring as metric discordant veins crosscutting the gneisses and marbles of the Itataia Group (Fig. 8E). Uranium mineralized apatite (collophane) is found filling fractures and voids formed by quartz leaching in albite and crystal interstices, ranging from white to reddish due to the of iron (Fig 8F);
- Indiscriminate weathered ores: encompasses all the *weathered* ores containing clay or carbonaceous material that could not be classified as one of the above-mentioned ore types. The term

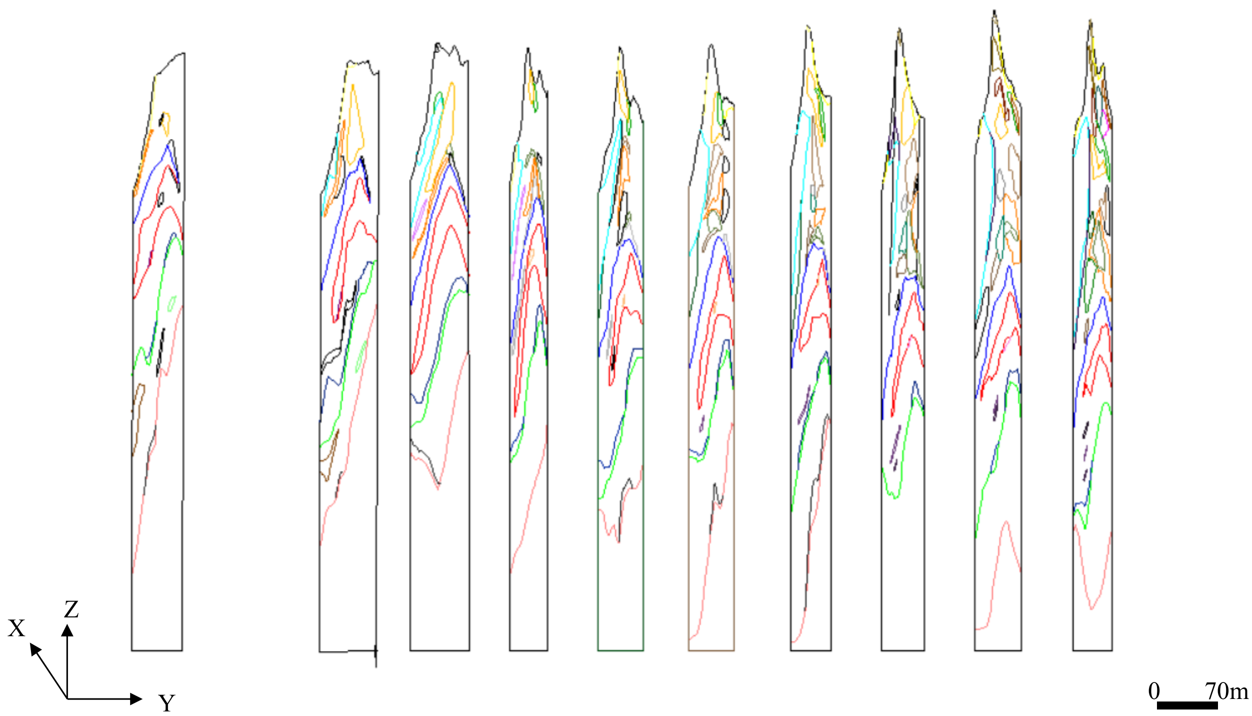
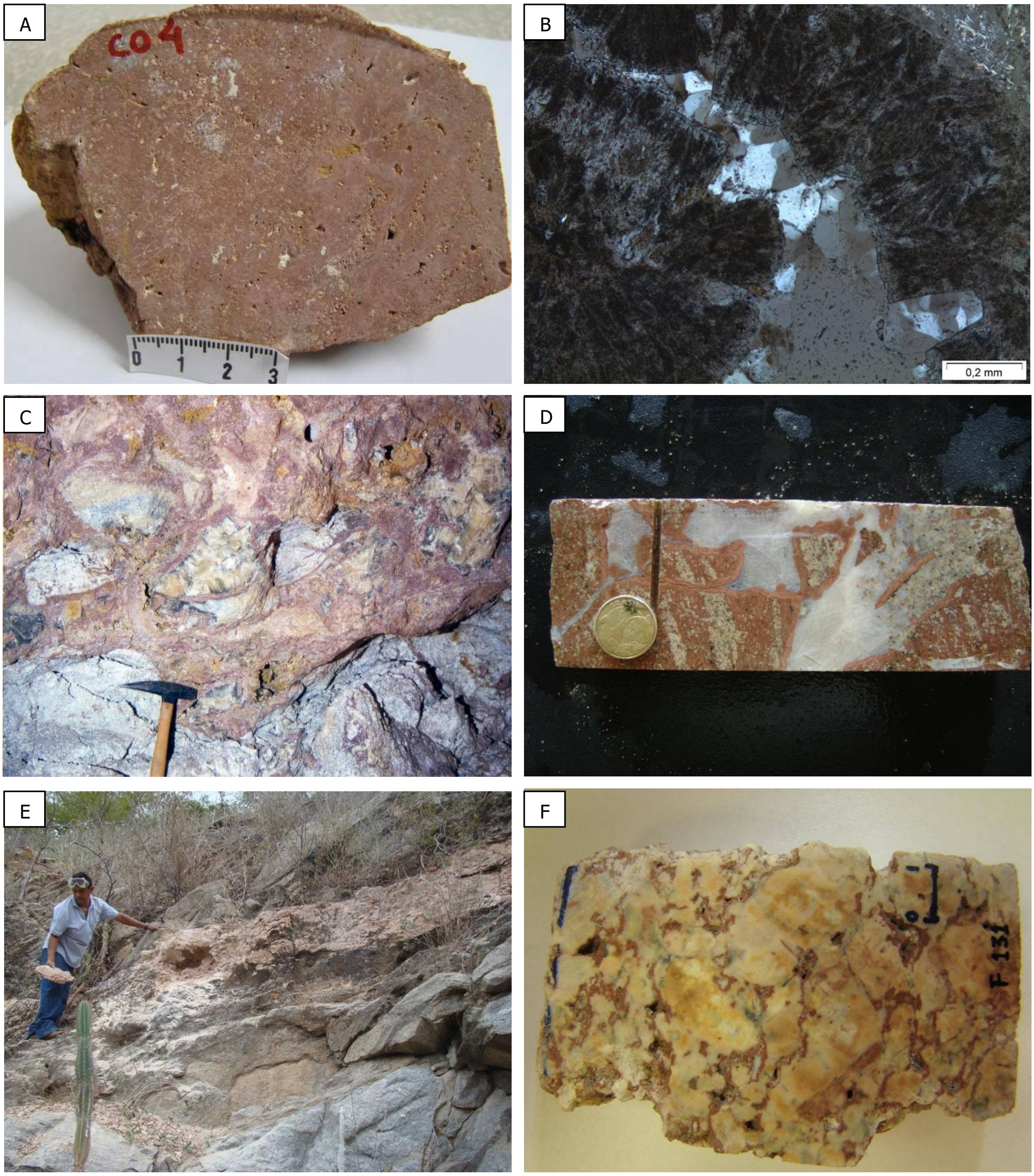


Figure 7. Vertical cross-sections used to build the three-dimensional model of the deposit. In total there were sixteen main sections and the same number of intermediate sections. The latter were constructed to smooth the surfaces and define the lenses and layers in the main sections. For illustration purposes, only ten of the sixteen main sections used in the model are shown.



Source: (C and F) compiled from Veríssimo *et al.* (2016).

Figure 8. (A) Surface sample of massive collophanite. (B) Botryoidal collophanite filling voids from quartz crystals in marble from the Alcantil Formation — plane-polarized light. (C and D) Gallery outcrop and drill core sample of karst breccia ore showing collophanite and calcite megacrystals associated with clasts of feldspatic rock, marble and calc-silicate rocks. The clasts are usually enveloped by a layer of reddish collophane film, indicating at least two collophanite ore phases. Feldspar within breccia fragments is yellowish in hand specimens and may exhibit strong turbidity under the microscope, resembling feldspar associated with episyenites. (E) Uranium mineralized pegmatites (episyenites) crosscutting the marbles of the Alcantil Fomation. (F) drill core sample of episyenite showing collophanite filling voids left by quartz leaching.

is a loosely translated from the original term in Portuguese (*minério decomposto indiscriminado*) coined by technicians from Nuclebrás (INB) when describing drill core samples.

TYPES OF GEOLOGICAL SURFACES GENERATED

Four types of surfaces were generated in the Itataia 3D model, based on the geological information obtained from the cross-sections: contact surfaces between lithostratigraphic units (formations), geological bodies, lenses, and faults.

The first type comprises the lower portion of the 3D model, whereby the surfaces correspond to contacts between the dominant lithotypes represented by the gneisses and marbles of the Barrigas and Alcantil Formations, respectively (Figs. 9A and 9B).

Geological bodies are all bodies with significant lateral continuity (more than 4 geological cross-sections), including surface cover, discontinuous bodies of episyenites, gneisses, collophanites, weathered ore bodies and mineralized breccias (Figs. 10, 11, 12 and 13). The episyenite and collophanite bodies are generally concordant to discordant, with tectonic-metamorphic foliation, accompanying the larger surfaces that mark the contacts between lithotypes (gneisses and marbles) (Figs. 11A and 11B).

The geometry of the mineralized breccia bodies and weathered ores is peculiar, corresponding to smaller, generally flat and rectilinear bodies, either in the form of thicker lenses or pockets close to the fault planes (Figs. 12A and 12B).

Lenses are small but genetically important bodies, typically depicted in two, three or four geological cross-sections, at most.

In addition to the surfaces created by lateral interpolation of the points and curves, planes representing the faults observed in the drillholes, galleries and on the surface of the Itataia deposit were constructed based on information from the geological cross-sections. Three lines in the fault surface in three different sections were used to model the faults. These three lines made it possible to delimit the fault plane, showing the slip of the affected layers (Figs. 14 and 15).

Some curved surfaces in the Itataia deposit correspond to normal or gravitational extensional faults, with metric to decametric slips, and predominantly subvertical dips. In the gneisses, slips on both sides of the fault are not accompanied by thickening or curving of the surfaces that border the contacts, bodies or lenses (Fig. 14). On the other hand, the geometry of the weathered ores and breccias is distinctive. The geometry in the breccias is tabular or rectilinear (Fig. 12B), whereas the bodies of weathered ores systematically exhibit greater thickening and curving of the surfaces near the fault planes (Fig. 14). In both cases, the faults are normal and almost vertical.

FINAL MODELING AND GEOLOGICAL INTERPRETATION OF THE DATA

The final integration of the different geological surfaces in GOCAD via lateral interpolation of the curves produced 3D models that enabled data to be analyzed and interpreted in three dimensions, from different angles and perspectives.

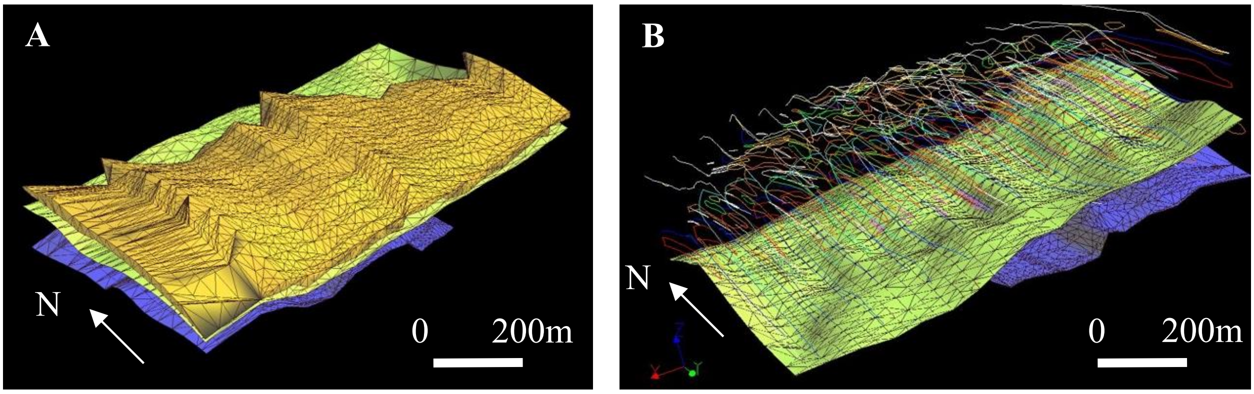


Figure 9. Contact surfaces between the two main types of lithotypes: (A and B) gneisses and marbles from different angles represented by distinct colors.

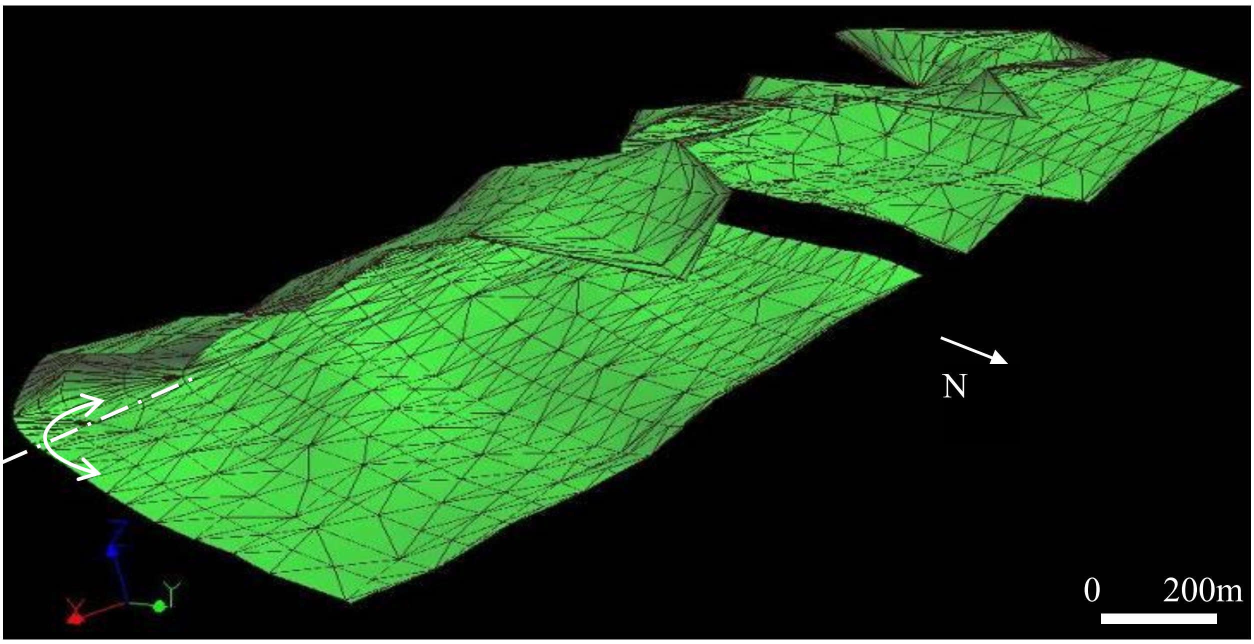


Figure 10. Gneiss body of the Itataia Group with folded surfaces, suggesting successive south-trending layers compatible with the S-SW regional nappe and thrust belt linked with the first contractional phase of the Pan-African/Brasiliano orogeny.

In the case of the Itataia deposit, this approach raised important aspects related to the geometry of bodies and contact surfaces at depth, as well as the spatial distribution of ores and their relationship with host rocks, fault planes and topography.

The importance of supergene processes in collophane genesis in Itataia is cited in several studies on the deposit (e.g., Angeiras *et al.* 1981, Favali and Leal 1982, Mendonça *et al.* 1985, Angeiras 1988, Castro *et al.* 2005a, Cavalcanti *et al.* 2013, 2018, Veríssimo *et al.* 2016). The depth of around 130m below the topographic surface suggested by researchers can be clearly observed in the 3D models in Figure 16, representing the lower limit of supergene enrichment and the generation of enriched ores in Itataia. This is also evident in Figure 3, where the lower limit of the phosphate contour lines, corresponding to the highest P_2O_5 concentrations (> 16%), is located above the altitude of 440 m.

Another interesting aspect is the structural control in collophanites and other ore types described in the drillholes, such as mineralized breccia and weathered ores.

In addition to topographic control, collophanites exhibit concordant to discordant behavior with host rocks. This is evident in the geometry of the collophanite bodies and lenses, which roughly accompanies the geometry of marble and calc-silicate rocks (see Fig. 11B). On the other hand, the ore bodies show a defined E-W trend, evident in the digital surface (Figs. 5 and 6) and subsurface models (Fig. 16).

In the northern border of the main Itataia ore body is a fault scarp consisting of a subvertical E-W trending primary fault that dips to the north, and secondary faults with dips typically above 60º to the north or south, forming a set of high and low blocks. Intense karstification and brecciation processes as well as the largest phosphate and uranium anomalies are associated with these fractures. The digital elevation models demonstrate the importance and regional expression of the E-W trend of structures, influencing the alignment of the ridges, slopes of the mountains and linearity of the valleys between the mountains (Figs. 5 and 6).

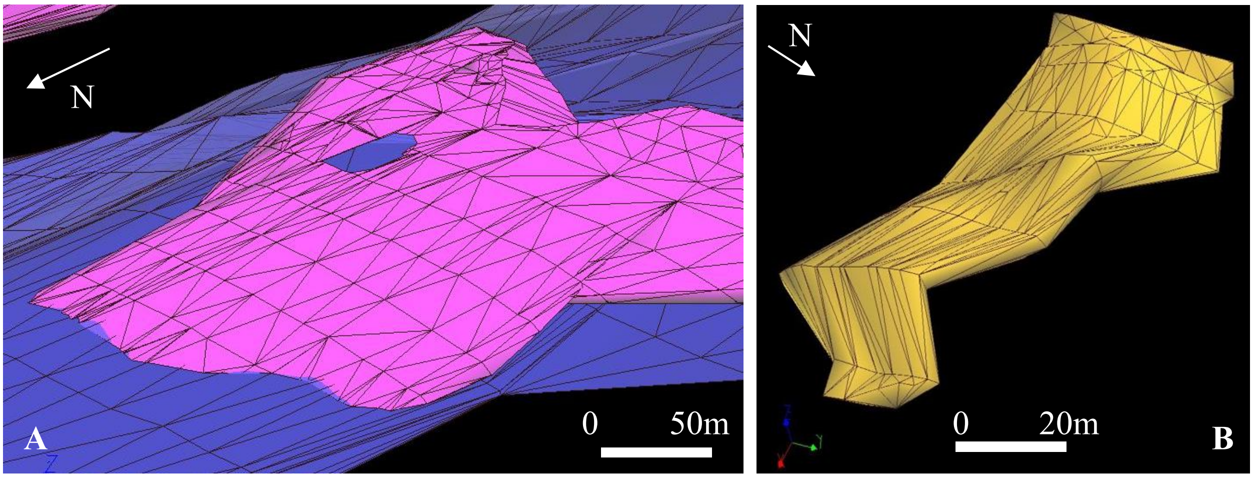


Figure 11. Geological bodies. (A) Body of albitite feldspatic rock (episyenite) (pink) cut by the gneiss layer (blue) using a GoCAD cut tool. (B) Elongated, medium-thick (around 10-20 m) collophanite body with undulating features suggesting folding or concordance with the foliation planes of the host rocks.

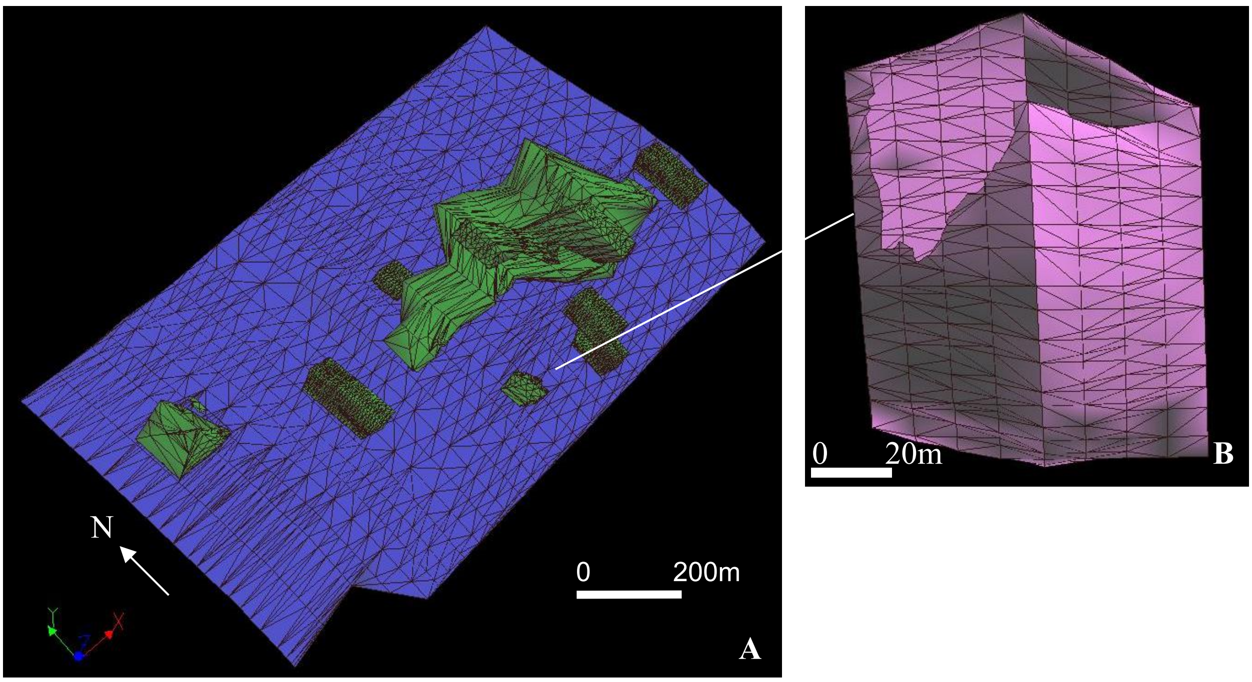


Figure 12. (A) Spatial distribution of the mineralized breccia bodies and weathered ores (green) gneiss/marble contact surface (blue). (B) Detail of the tabular-shaped mineralized breccia (pink).

The 3D subsurface model in Figure 17 illustrates the arrangement of ores in comparison to the northern border of mineralization and the fault scarp, indicated by the plane surrounded by a dotted white line. The southern border of the model is roughly the limit of phosphate-uranium ore occurrence in the Itataia deposit.

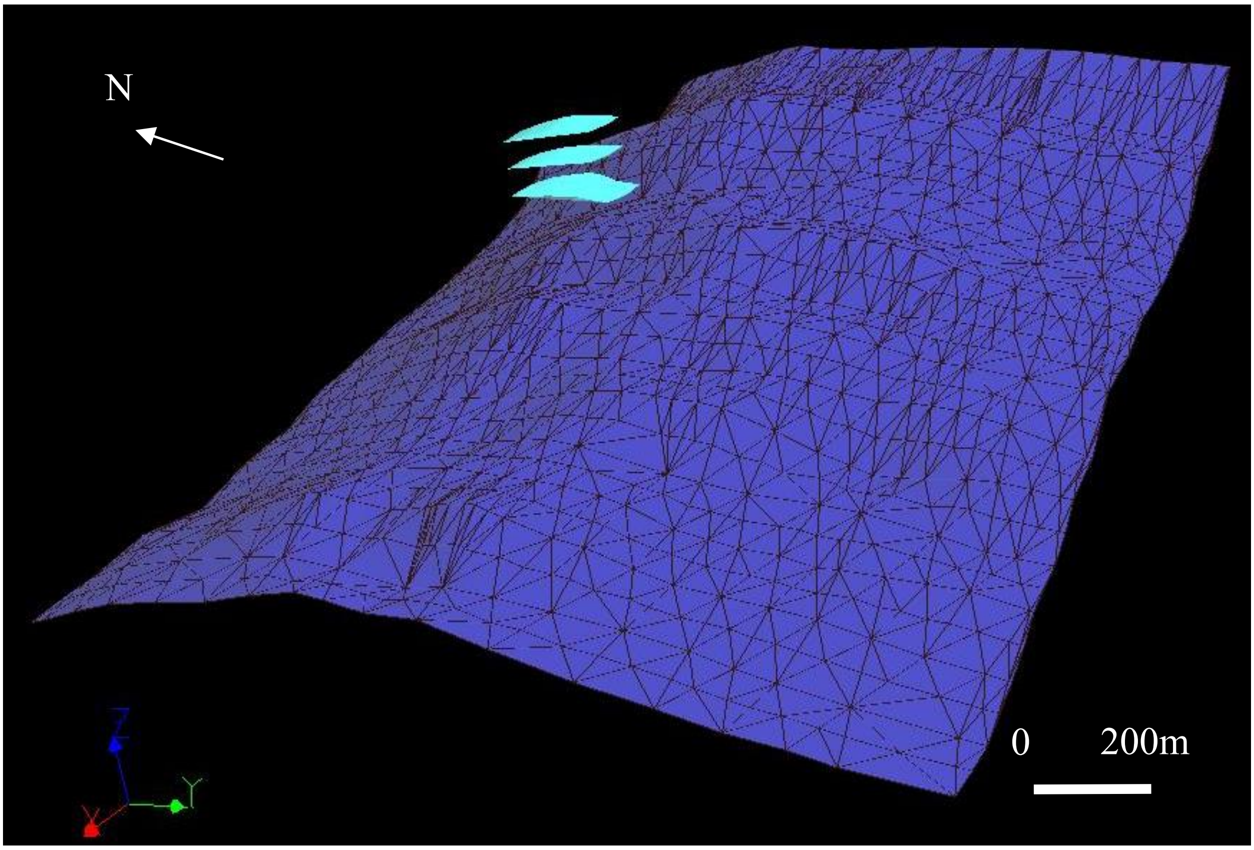


Figure 13. 3D model of lens-shaped albitite feldspatic rocks (episyenites) above the contact surface between gneisses of the Barrigas Formation (below) and marbles of the Alcantil Formation (above).

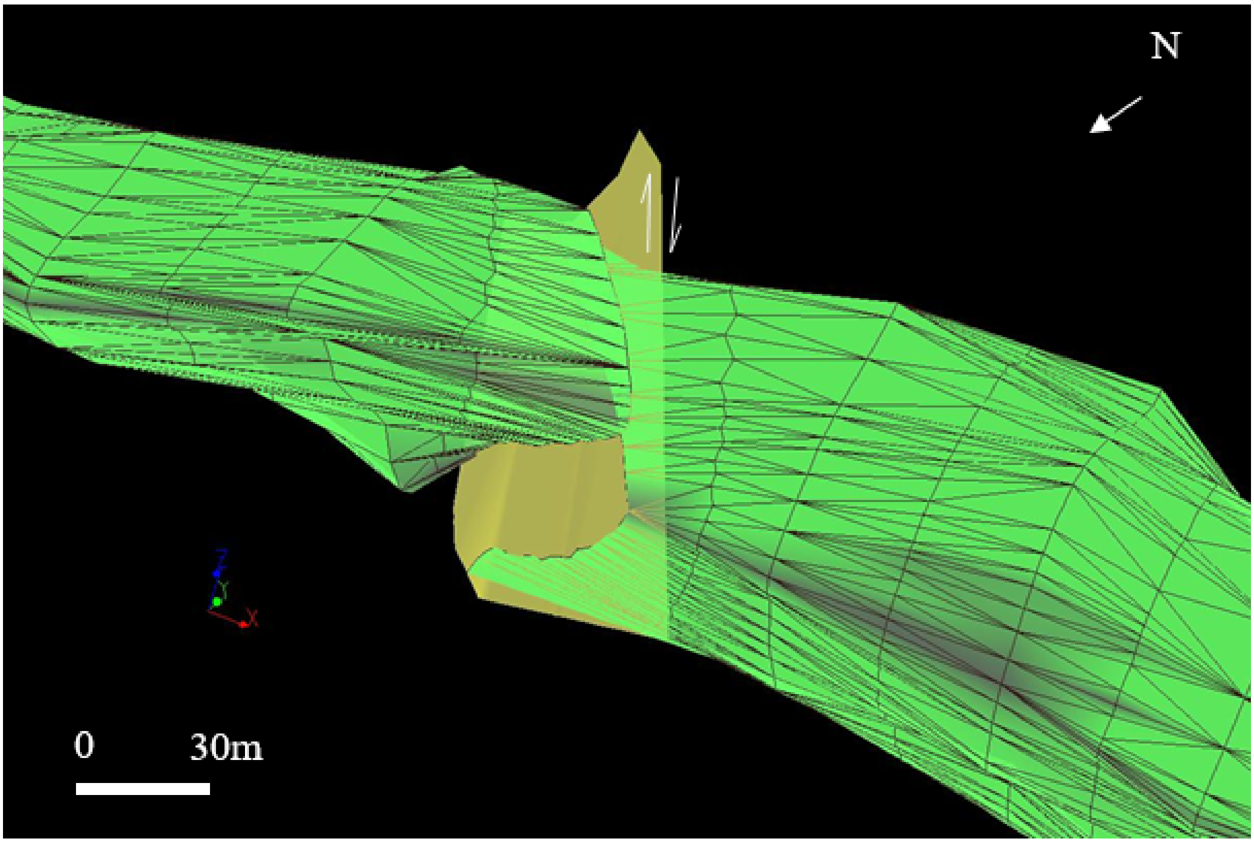


Figure 14. 3D geometric model of a normal subvertical fault in the gneiss from the Barrigas Formation, illustrating a metric slip.

The existence of three repeated surfaces representing the contact between the lithostratigraphic units of the Barrigas (gneisses) and Alcantil Formation (marbles) raises an important question regarding the meaning of this repetition, with two possible alternatives. It may reflect the cyclic nature of sedimentation in the Itataia Group, suggesting periods of marine transgression and regression, resulting in chemical sedimentation followed by pelithic sedimentation associated with sediment flow from the continent. In this case, based on the 3D model, the existence of three sedimentary cycles can be inferred, related to the progressive advance and retreat of the ocean. On the other hand, several studies in the region and in the area of influence of the deposit have highlighted the low-angle tectonic influence and configuration of nappes and thrusts between the units of the Itataia Group (Arthaud 2007, Santos *et al*. 2008, Castro *et al.* 2005b, Arthaud *et al*. 2015, Veríssimo *et al*. 2016). These data, combined with the low-angle foliation planes as well as the highly deformed mylonites in ductile shear zones in the drill core samples of the cross-sections studied, corroborate to the second alternative, which suggests repetition due to tectonic folding associated with rupture and transport along thrust faults.

Figures 18 and 19 show different surfaces, representative of gneisses and marbles in the Barrigas and Alcantil Formations (Itataia Group) and their respective tectonic folds.

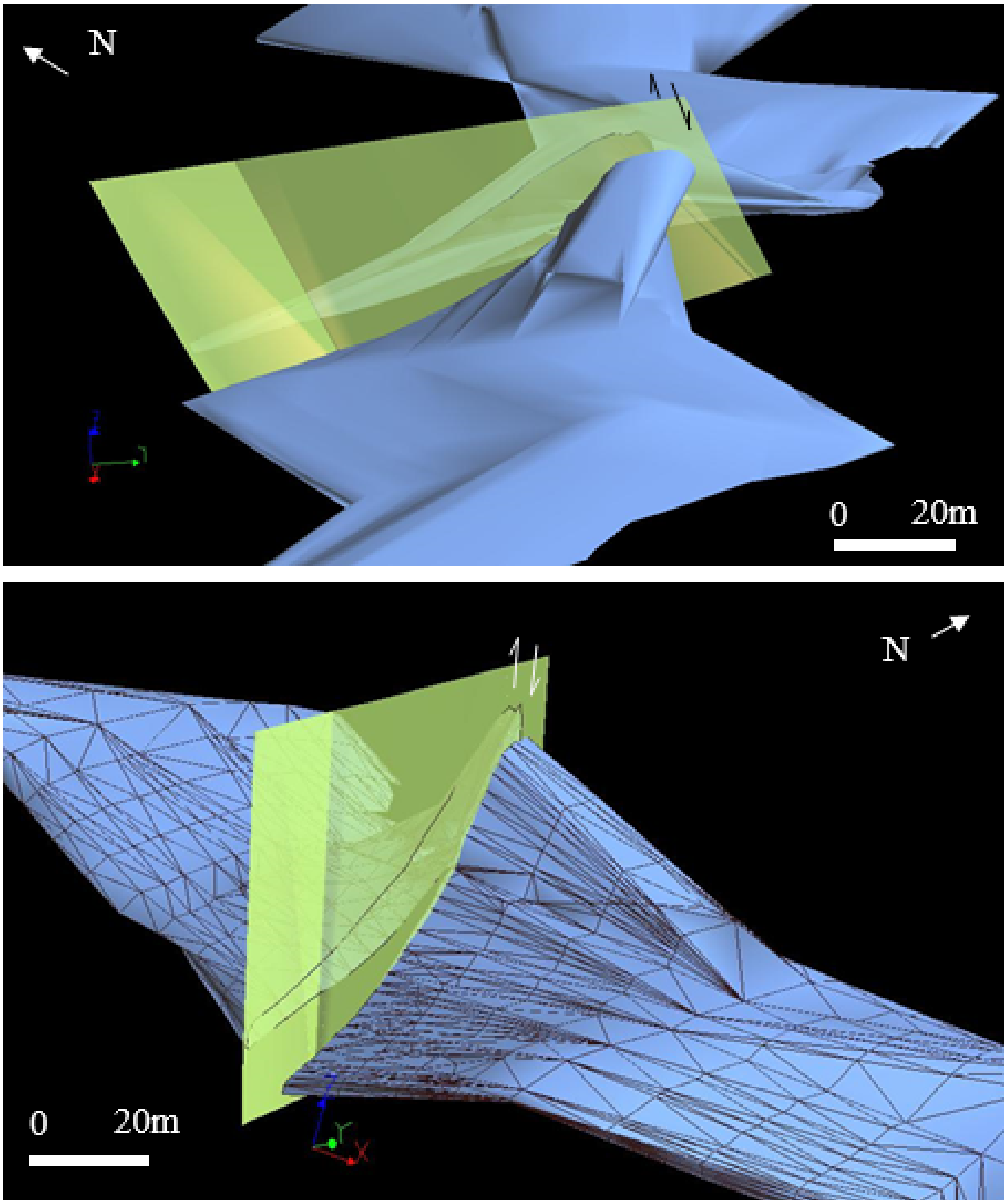


Figure 15. (A and B) 3D geometric model of a normal subvertical fault in decayed ore, illustrating a metric slip. Note the greater thickness and curving of the surfaces near the fault plane.

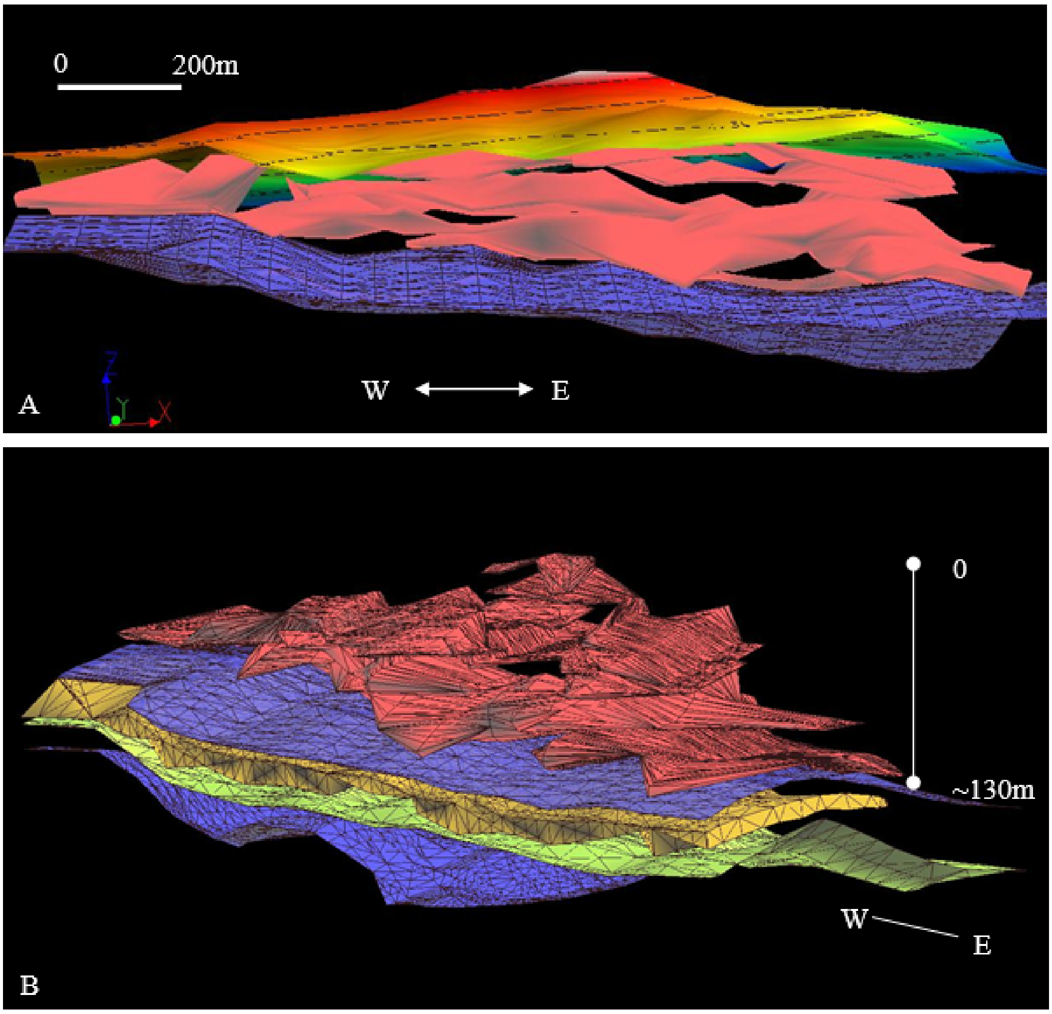


Figure 16. (A) 3D geometric model illustrating the upper and lower limits of collophanitic ore occurrence (red) between the topographic surface and contacts between the marbles (above) and gneisses (below) (blue). (B) 3D model of the Itataia metasedimentary sequence, illustrating the upper and lower limits of collophanitic ores and the predominantly E-W trend of ore bodies (red).

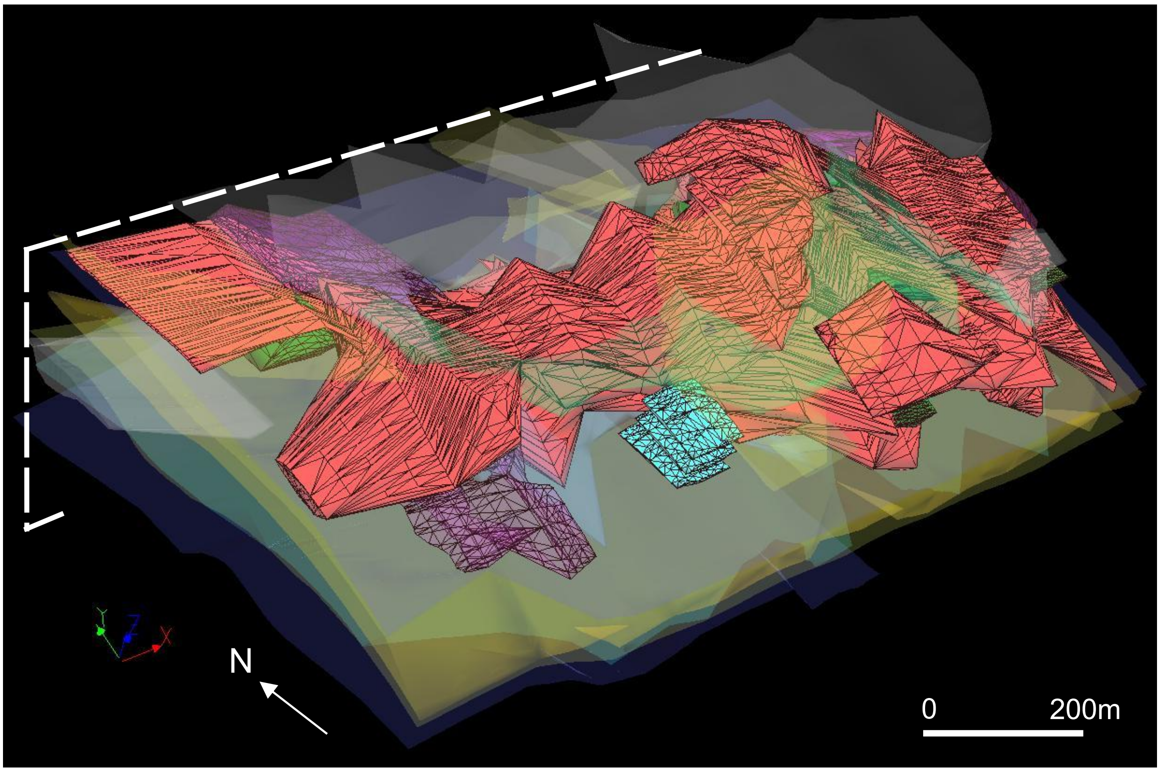


Figure 17. 3D geometric model illustrating the northern and southern borders of the occurrence of collophanitic ore in the Itataia deposit (red). The northern border, related to the fault scarp, is indicated by the dotted white line. The other layers are shown using a transparent effect to highlight the collophanites.

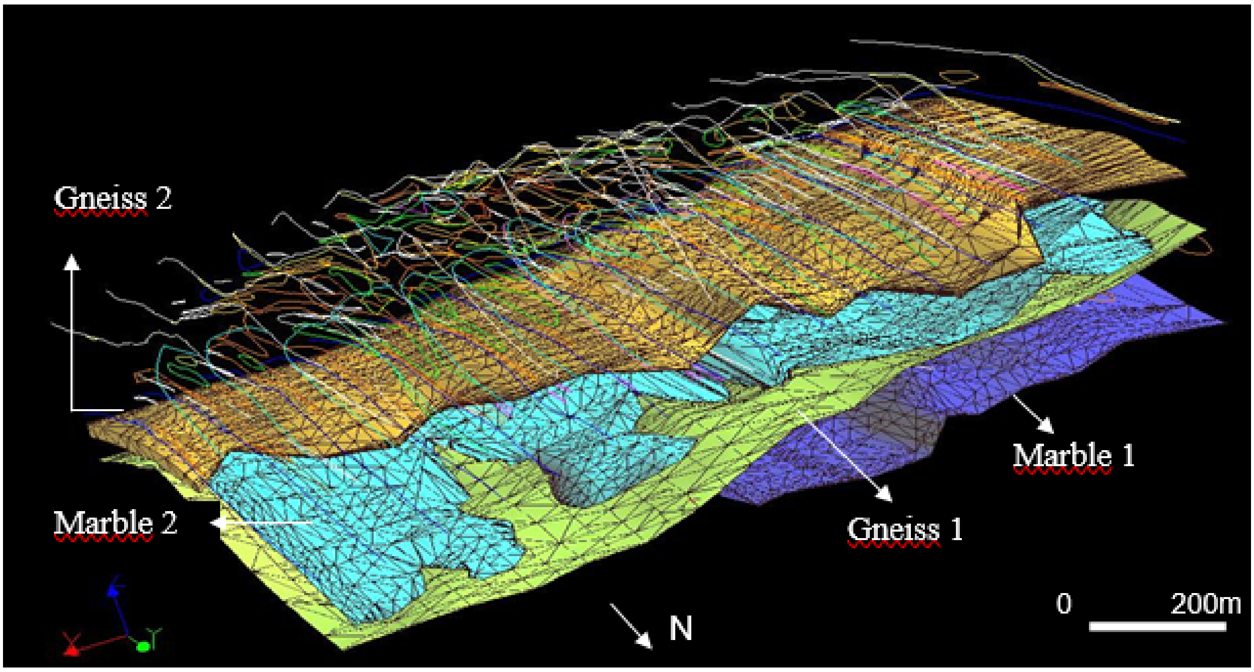


Figure 18. Lower portion of the 3D model, showing two layers of gneiss and one of marble. Below the dark blue layer – gneiss 1, between the dark blue and green layers – marble 1, between the green and orange layer – gneiss 2 and orange layer – marble 2.

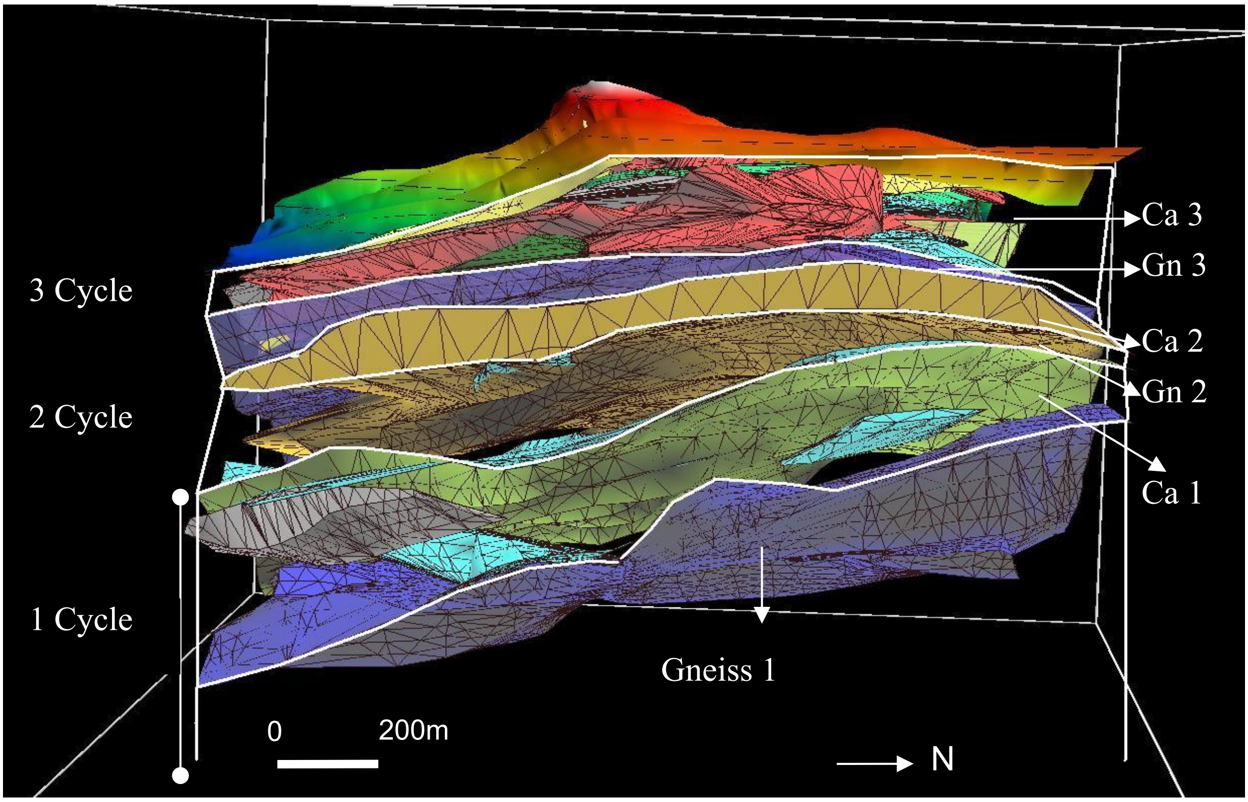


Figure 19. Sequential alternating layers of gneiss and marble in the Barrigas and Alcantil Formations shown in 3D. The repetitions that may suggest transgressive and regressive sedimentation cycles correspond to low-angle tectonic repetition. Each set consists of 1 layer of gneiss (Gn) and one of marble (Ca), with a total of three repetitions due to tectonic folding.

CONCLUDING REMARKS

Three-dimensional geometric modeling using Geological Object (GoCAD) software is a powerful tool for the analysis of the geology of the Itataia deposit, particularly in terms of the geometry of rocks and ore bodies and the processes involved in the genesis of phosphate-uranium mineralization.

The digital surface and subsurface models show the structural control of the ore bodies (massive, stockwork and breccia) in association with the regional E-W trend of the local geomorphology and the extensional fault plane that forms the northern border of the Itataia phosphate-uranium deposit. They also make it possible to visualize the upper and lower limits of supergene processes that generated the enriched ore in Itataia, at an average altitude of 440 m and depth of around 130 m.

The visualization of the surfaces representing the lithologic contacts between the chemical (marble) and pelitic (gneiss) units of the Itataia Group combined with field observations and descriptions of the drill core samples reinforce the tectonic nature of the folds observed in the deposit. This suggests a relationship between layer thickness, repetition and the low-angle tectonic that affected the Itataia Group during the Pan-African/Brasiliano orogeny, generating south-southeast trending nappes and thrusts.

The tabular or rectilinear geometry of the breccias as well as the thickness and curving of the surfaces along the borders of the ore bodies near the fault planes indicate the influence of faults in generating karst breccia ores as well as on leaching and fluid flux.

Other modeling contributions with implications for mining planning and operation processing include: evaluating slope dimensions; optimizing ore extraction and blending operations; re-evaluating reserve estimates. These actions can be performed by applying other tools and modules available in GoCAD (e.g., GoCAD Mining Suite) and/or other types of mining softwares that calculate area and volume and conduct statistical analyses.

ACKNOWLEDGMENTS

We are grateful to Hans Dirk Ebert and José Reginaldo Lima Verde (in memoriam) for their suggestions and constructive insights during the various stages of this research. We are also grateful to the Brazilian Nuclear Industry (INB) for the field support provided. The first author also acknowledges the ANP (National Petroleum Agency) for the scholarship awarded.

ARTICLE INFORMATION

Manuscript ID: 20210022. Received on: 23 MAR 2021. Approved on: 29 MAR 2022.

How to cite this article: Freire R.C., Veríssimo C.U.V., Parente C.V., Nogueira Neto J.A., Castro G.L., Silva J.R.A. 202x. Three-dimensional geological modeling of the Itataia Phosphate-Uranium Deposit (Ceará, Brazil). *Brazilian Journal of Geology*, 52(3):e20210022. https://doi.org/10.1590/2317-4889202220210022.

R.C.F. wrote the first draft of the manuscript and prepared Figures 5 to 18; C.U.V.V. provided advisorship regarding regional and local geology, improved the manuscript through corrections and suggestions and prepared Figures 1 to 4; C.V.P. provided data on the economic geology of de Itataia Deposit, revised and improved the manuscript; J.A.N.N. provided data on the regional geology revised and improved the manuscript; G.L.C. provided data on the Itataia mine geology, revised and improved the manuscript; J.R.A.S. provided data on the Itataia mine geology, revised and improved the manuscript.

Competing Interests: the authors declare no competing interests.

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