Why the Rio Quente is a special spring within The Caldas Novas Thermal Aquifer, central Brazil?

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Abstract: - Thermal waters up-rise through Precambrian rocks in the inner part of the Neoproterozoic Brasília Belt (Tocantins Province, central Brazil) and make of the town of Caldas Novas an outstanding tourism place. They have fed a boom in the economy of the region around the Caldas Novas dome, a tectonic structural window ~20 km-long and ~12 km-wide cored by sub-greenschist facies quartzite, metasiltite, meta-argillite, slate, phyllite, and metarhythmite (Paranoá Group) and mantled by a nappe of biotite-quartz schist and garnet-bearing chlorite-muscovite schist (Araxá Group). Multidisciplinary geology studies have been supported from the local community of tourism entrepreneurs concerned with environmental issues, the quality of the underground aquifers, and with the possibility of artificial recharge. Rocks of the Paranoá Group record a passive margin-like basin developed 1300 – 900 Ma ago along the western coast of the São Francisco paleo-continent, and rocks of the Araxá Group record sedimentation/volcanism in a 900-800 Ma back arc basin developed between the paleo-continental margin and an intra-oceanic island arc to the west. Amalgamation of the arc and back-arc rocks to this margin led to ESE-driven transport of a nappe of Araxá Group rocks over the Paranoá Group rocks. All these rocks exhibit evidence of D_1-D_2 ductile deformation and metamorphism according to regional contraction in the WNW-ESE direction, during the first (~750-650 Ma old) stage of the Brasiliano orogeny. A new tectonic pulse (D_3) shortened all D_1-D_2 tectonites, 630-620 Ma ago, and developed, in the southern segment of the belt, km-scale and NNW-trending F_3 folds, such as the Caldas Novas dome F_3 braquiantiform. The anomalous thickness of 1,000 m of quartzite in the core of the dome (geophysical evidence) is likely due to a duplex of basal quartzite layers of the Paranoá Group. In the western margin of the dome the thermal waters flow within Paranoá basal quartzite at a rate of 1.6 m^3/s and reach surface as hot as 50 ^{0}C, forming a true river of hot waters. To the E-NE of the dome, in the Araxá schist flooring the town of Caldas Novas, the water flows at a much smaller rate. Hydrogen, carbon and oxygen isotopes data point to the thermal waters as being meteoric in origin, and the temperature indicates up-rise from depths of about 1,000 m. Data from detailed structural studies strongly suggest that the path for up-rise is controlled by a net of open surfaces that include the S_3 axial planar foliation and fractures associated mostly to the D_3 compression, combined with the stiffness of basal rocks of both the Paranoá and Araxá Groups. The 1.6 m^3/s flow of thermal waters in the western margin of the dome relates to a combination of the thickness and asymmetry of the D_3 duplex with the effects of late-D_3 gravity slide in the area.

Key-words: - Thermal water aquifer; Caldas Novas dome, Brasília Belt, Neoproterozoic, Brasiliano orogeny, central Brazil.

1 Introduction

The area of Caldas Novas, Goiás State – central Brazil, is part of the Internal Zone of the Brasília Belt. This one forms, together with the Araguaia and Paraguay belts, a Neoproterozoic geotectonic unit known as the Tocantins Province (Fig. 1).

The province is bounded by the Parnaíba and Paraná Phanerozoic sedimentary basins, and results from the collision of the paleo-continents precursors of the Amazonian and São Francisco cratons, as recorded by poly-deformed and metamorphosed Archean-Neoproterozoic rocks.

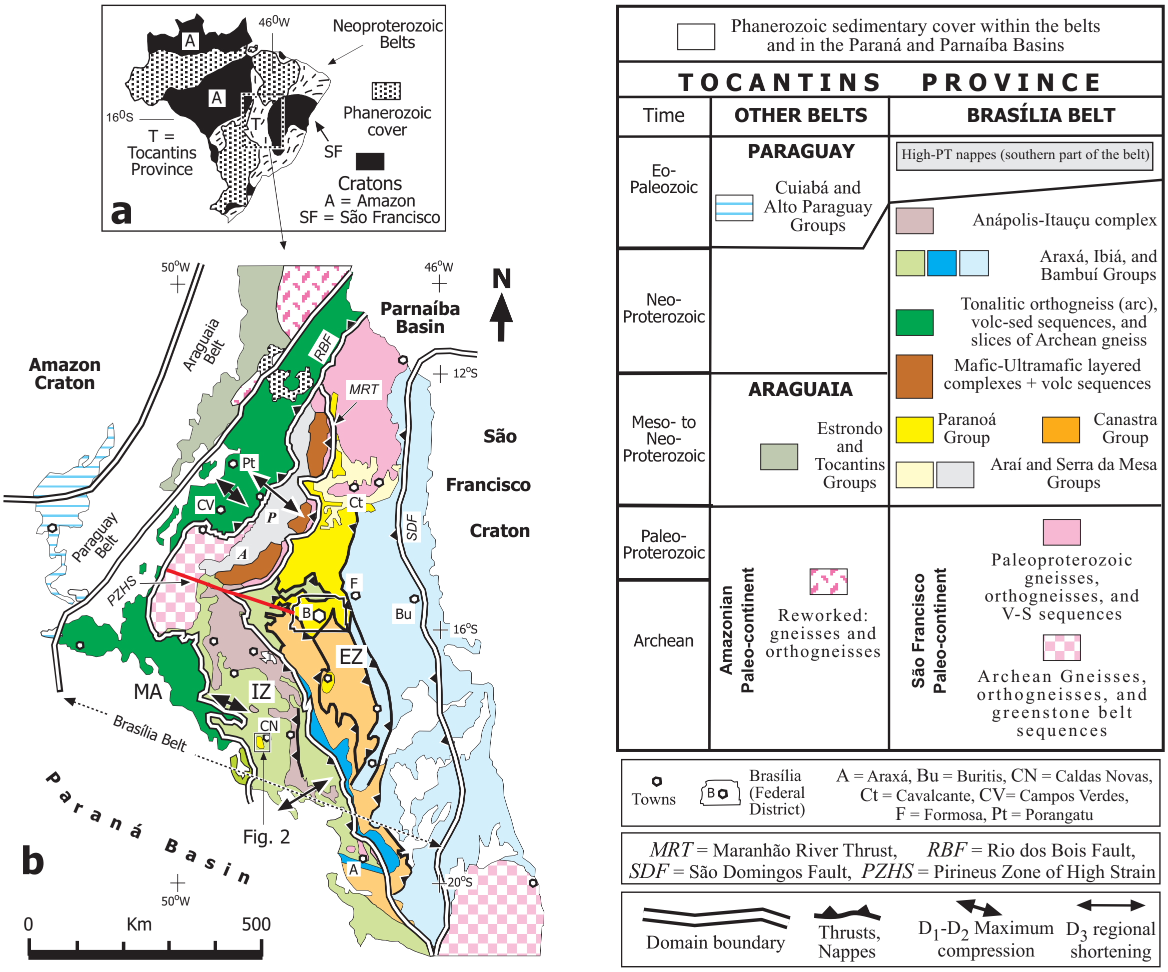


Fig. 1: Summary map displaying the main tectonic provinces in Brazil (**a**) and the central part of the Tocantins Province, as well as the three main lithotectonic units of the Brasília Belt (**b**; legend to the right): the Magmatic Arc – MA; the Internal Zone – IZ; and the External Zone – EZ. The EZ includes part of the Neoproterozoic sedimentary cover of the São Francisco craton. *A* = Araxá, and *P* = Paranoá. Adapted from [1] and [2].

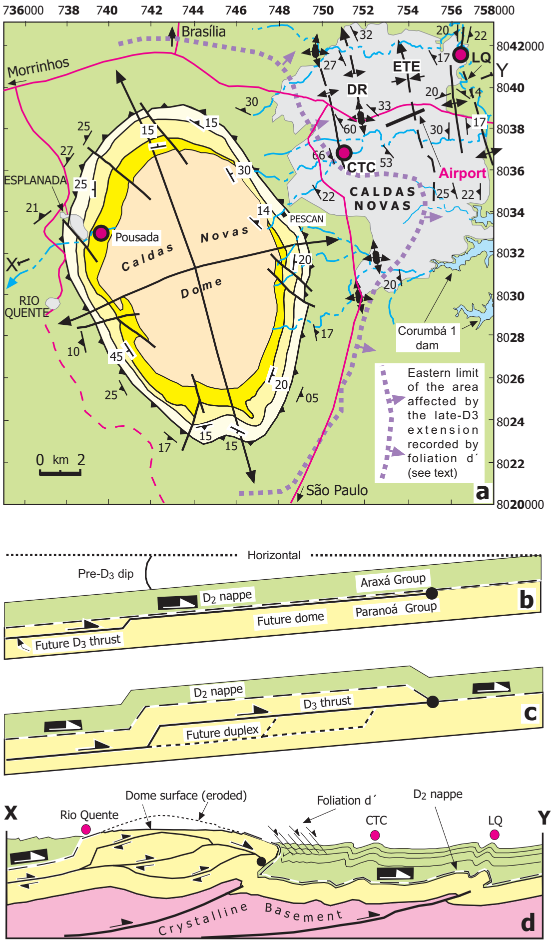
The relevance of the Caldas Novas area rests on a structural dome and on the Rio Quente, Caldas Termas Clube, and Lagoa Quente springs of thermal waters (Fig. 2). The exploration of the thermal waters for tourism and leisure purposes has improved dramatically the economy in Caldas Novas and other two towns in the surroundings (Fig. 2a).

A boom in the economy of the area has been possible in the last twenty years because of an exponential growth in the volume of pumped thermal waters from artificial wells, but also brought to light a crescent concern about the capacity of the underground reservoir to maintain the current volume and temperature of the thermal waters.

For this reason, since about two years ago, the local association of entrepreneurs that explore the thermal waters (AMAT) has supported an international and multi-disciplinary scientific project destined to study the area and understand better the geological controls of the thermal aquifer, aiming to find alternatives for future planning.

The Caldas Novas dome is an elliptical structure with a NNW-trending axis as long as 20 km, and minor axis of ~10 km. Since [3] the dome is known as a structural window, as it exhibits a core of sub-greenschist facies quartzite and finer grained siliciclastics rocks of the Meso-Neoproterozoic Paranoá Group tectonically juxtaposed by a nappe of greenschist-amphibolite facies mica schist of the Neoproterozoic Araxá Group.

Nevertheless, solely more recently the area has been the locus of detailed geological studies: [4] described the Paranoá Group lithostratigraphy units; [5] and [6] described the rocks of the Araxá Group, as well as the tectonic structures and the structural-tectonic evolution of the whole area surrounding the Caldas Novas dome, whereas [7], [8], and [9] have studied the main physical and chemical parameters and other aspects directly linked to the thermal waters and underground aquifers.



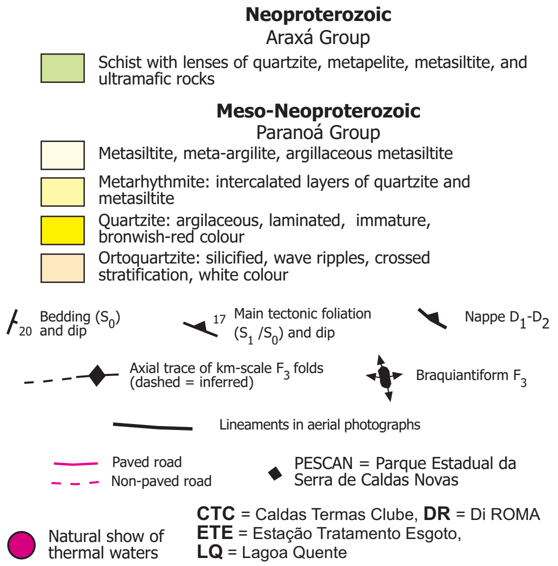


Fig. 2: The main geological features of the surroundings of Caldas Novas (modified from [5], and [6]): a summary geological map (**a**) and one cross-section (XY) explained in three cartoons (**b-d**). A small body of Cretaceous conglomerate mapped by [4] is omitted in the map. See legend to the right and other details in text.

This paper presents the recent advances in the geological knowledge of the Caldas Novas area and the consequences for the origin of the springs of thermal waters. Because of its distinct characteristics, one of the springs is geologically special and more important economically, thus we firstly describe the springs, secondly we focus on the basic geology of the study area and on the origin of the springs, and finally we present a geological model capable to justify their basic differences.

2 The springs of thermal waters

The springs of thermal waters (herein termed TWs) are known for over a century [5].

Among them, the **Rio Quente** (or Hot River) is a 10 m-wide natural stream that starts to flow in the upper part of the western flank of the Caldas Novas dome. The TWs rise on surface at a temperature of ~50 ^{0}C and total rate of 1 m^3/s, from a series of open spaces (described ahead) in the basal layers of quartzite of the Paranoá Group, within the artificial pools of the Pousada Park (Fig. 3).

The Rio Quente is unique, and there is not another natural spring of TWs in Paranoá quartzite layers elsewhere around the dome. The TWs of the Rio Quente start to flow at 700 m above sea level and remain relatively warm down stream, until the town of Esplanada (Fig. 2). The chemical composition indicates high Ca and Mg contents, suggesting interaction of the TWs with carbonate rocks at depth, according to U. Tröger [9].

The other two springs occur within the Araxá schist of the town of Caldas Novas. Historical data about the **CTC** spring indicate a flow of 0,1 m^3/s, but it stopped flowing since ~25 years ago [9]. The **LQ** spring also flows at a rate of 0,1 m^3/s [9] and consists of three much focused brines enclosed in a 1000 m^2 site. Two of these are 1 m^2 each, and occur just beside the western margin of a voluminous river of cold waters. The third brine occurs in the bottom of a hot pool.

3 Summary regional geology

The Araguaia and Brasília Belts record the time life of a large ocean. Its spreading from ~1.3 to 0.9 Ga is recorded by sedimentary rocks of two passive margin-like sequences represented by the Paranoá (and Canastra) and the Estrondo (and Tocantins) Groups, respectively mapped in the Brasília and Araguaia Belts.

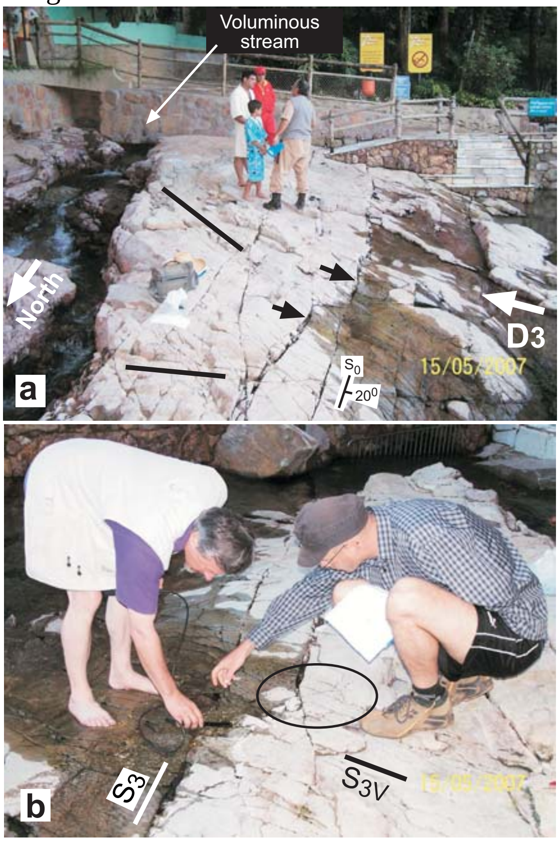


Fig. 3: Partial view of the TWs spring in two of the artificial pools in the upper part of the Pousada Park. The pools were deliberately emptied for direct observation of the TWs show on the bedrock. (**a**) The quartzite layers dip 20^0 to the west and exhibit a superb set of open surfaces. The longer of these form an anastomosed array of N-S trending and sub-vertical surfaces (S_3 foliation) along which the water comes up from depth (black arrows). The voluminous stream shown to the left corresponds to a mixture of hot (~50 ^{0}C) and normal waters (25 ^{0}C) that come up mostly along the contact between quartzite layers, along open S_3 surfaces, and along sub-vertical oblique fractures (black lines) related to D_3 shortening (indicated to the right). (**b**) U. Tröger (left) and J. Fornaçón measuring the temperature of TWs flowing up along S_3 surfaces. Note the S_{3V} surfaces sub-perpendicular to S_3 and, in the ellipse, the oblique fractures.

From 0.8 to 0.65 Ga a multi-stage intra-oceanic magmatic arc formed and was amalgamated, together with at least two back-arc basins adjacent to the western margin of the São Francisco paleo-continent [2], consequently nappes of the back-arc basin-like rocks (Araxá Group) propagated onto the Paranoá Group rocks (Fig. 1). From ~750 to 650 Ma all the rocks in the belt were shortened in the NW-SE direction, under D_1-D_2 deformation events typified by frontal ramps (summary of data in [2] and [5]).

Final closuring of the ocean brought the paleo-continents into collision 650 to 590 Ma, and led to D_3 deformation. The event D_3 shortened regionally the nappes, but shortening is recorded in two nearly orthogonal directions, relative to the Pirineus Zone of High Strain (*PZHS*) that separates, in the Brasília Belt, a NE-trending northern segment from a SE-trending southern segment.

The D_3 event is responsible for the evolution of regional faults such as the Maranhão River Thrust and the São Domingos Fault (Fig. 1), as well as the *PZHS*. As discussed in [2], there are strong and multi-disciplinary evidence for a time-kinematic compatibility between D_3 and the event of opening/infilling of the basin that originated the Paraguay Belt.

The D_1-D_3 evolution is the record of the Neoproterozoic Brasiliano orogeny and, in the southern segment of the belt, it is quite evident in the Caldas Novas area, and further to the south [5].

4 The Caldas Novas area

4.1 – Lithostratigraphy

The Paranoá Group in the core of the Caldas Novas dome is a low-greenschist facies sequence of four units. These consist of basal quartzite, siliciclastic metarhythmite made of cm- to dm-thick layers of quartzite and metasiltite, white to gray phyllite, and brownish to red meta-argillite (Fig. 2; [4]).

The Araxá Group comprises basal biotite-quartz schist and biotite quartzite, topped by garnet-bearing mica-chlorite schist with thin lenses of quartzite and mafic-ultramafic rocks. Wells data indicate a thickness of ~250 m for the Araxá rocks ([5] and [6]).

Two facts are important for understanding the Rio Quente spring: a - the basal unit consists of 1 m-thick layers of quartzite intercalated with cm- to dm-thick layer of finer-grained siliciclastic material. The thinner intercalations are suitable for inter-layer slip during deformation and also for erosion by the underground waters, thus the bedding is marked by opened spaces between the 1 m-thick quartzite layers (Fig. 4); and b – gravity data indicate anomalous thickness of ~1000 m for the Paranoá quartzite exactly beneath the Caldas Novas dome [5].

The high mechanical resistance of the basal layers of the two groups ([3] and [4]) allows a concentration of strain that is also important for understanding the TWs.

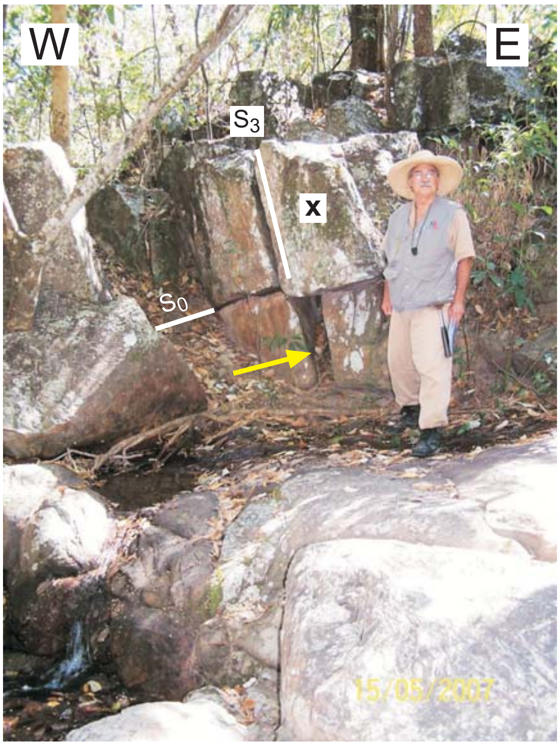


Fig. 4: Thick layers of Paranoá quartzite in the head waters of the Rio Quente, Pousada Park. Note the open space along the bedding (S_0) that dips gently to the west, and along surfaces of the steep-E-dipping S_3 foliation. Differential movement of block **X** during further gravity slide of the upper layer closed the along-S_3 wide space still seen in the lower layer (yellow arrow).

4.2 – Tectonic structures

After [3] and [4]) it is known that the geometry of the rocks in the area is controlled by regional-scale, double-plunging, and NNW-trending, normal to steeply inclined F_3 folds, verging to ENE such as the Caldas Novas dome itself and the CTC, DiRoma, and LQ antiforms, and intervening synform such as the ETE (Fig. 2). Cross-sections based on contrasting electricity resistance [10] fully support the fold interpretation for the Araxá rock layers underneath Caldas Novas (Fig. 2d).

The pre-D_3 structures indicate a ESE-driven tectonic transport along gently-dipping frontal ramps (Fig. 2b), particularly the asymmetry of the S-C pair within the S_1 mylonitic foliation, the S_2/S_1 asymmetry, and the vergence of F_2 folds (Fig. 2b). The ESE-driven tectonic transport during D_1-D_2 is strongly indicated by a pervasive stretching lineation (L_x) that is defined by sheath folds and stretched minerals. L_x trends systematically WNW-ESE across the area, in despite of all the F_3 folds ([5] and [6]).

The F_3 folds and the pervasive axial planar foliation S_3 affect all D_1-D_2 structures. Because strain was also taken-up by foliations S_{3V} and S_{3H} (respectively sub-vertical and sub-horizontal spaced cleavages related to the **b** and **a** tectonic axes of F_3) as well as oblique fractures and 1 m-wide shear zones sub-parallel to S_3, we assume that D_3 likely records a kind of transpression. The shear zones developed R, R´, P, and Y fractures in the resistant basal layers of the Paranoá and Araxá Groups, and are particularly evident in the western limbs of the Caldas Novas dome (Pousada pools), the CTC, and the LQ folds, coincidently the site of the natural springs.

Moreover, the Araxá D_1-D_3 tectonites adjacent to the southern, eastern, and northern margins of the dome are affected by a late-D_3 cm-spaced extensional crenulation cleavage (d´; Fig. 2; [3] and [4]) due to gravity slide of the schist layers during the uplift of the dome.

During the uplift, the Paranoá layers around the dome and the Araxá schist adjacent to the western margin of the dome were also affected by gravity slide in the form of late F_3 folds, not the d´ foliation. The reasons for d´ to exist in the Araxá schist are discussed in detail by [3].

5 Origin and up-rise of the TWs

A meteoric origin is well accepted for the TWs, based on the stable isotopes and other geochemical data [9]. The temperature indicates that the TWs must rise quickly from depths of about 1000 m, therefore a very efficient structural pathway must exist in the rocks. It demands explanation.

The detailed structural analysis has shown that all the fracture surfaces that can be observed in the outcrops are fully compatible with D_3 deformation, the last event to affect the area during orogeny ([5] and [6]).

The intersection of the planar structures existing in the area may have formed narrow and vertically continuous corridors across the competent basal layers, producing channels suitable for the fast up-rise of the TWs (Fig. 5). Such template is quite feasible because the western limbs of the F_3 antiforms are the locus of strain concentration, specially considering that the d´ gravity sliding of the schist implies further tightening the F_3 folds to the east of the extensional front (Fig. 2). The concentration of strain explains the onset of shear zones in the

CTC and LQ areas, and is also, theoretically, a positive factor for the multi-layer propagation of open brittle fractures through resistant rocks (see analogy in [12]).

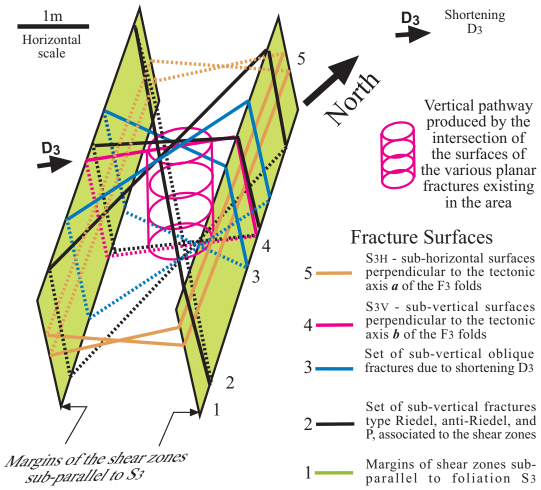


Fig. 5: Mechanical porosity that may exist in the Caldas Novas area. Details in text.

A duplex structure that likely formed underneath the dome (Fig. 2c-d; [3]) explains the anomalous thickness of quartzite and, together with the west-dip of the horses, explains the largest flow of TWs in the Pousada Park. The flow is likely facilitated by a combination of voids opened along S_0 and S_3 (Fig. 4). Actually, because the S_3 surfaces were sub-perpendicular to the direction of gravity slide, the along-bedding slip in the basal quartzite easily opened S_3-controlled large separations (yellow arrows) across the layers.

6 Conclusions

The TWs of Caldas Novas are meteoric waters heated at depth and forced to move up quickly when the temperature creates a sufficiently low density. The upward flow is likely facilitated by channels built along the intersection of syn- to late-D_3 brittle fractures related to the tectonic evolution of the Brasília Belt. A D_3 duplex in the core of the Caldas Novas dome antiform makes thicker the quartzite (= good aquifer) there. The west-dipping horses and better fracturing in more resistant rocks allow the flow of 1 m^3/s that make of the Rio Quente a special spring.

Where is the main area for recharging the aquifers? The answers are still being looked for. They will provide a key for preventing pollution in the aquifer and for future planning.

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