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Geomorphological and hydrogeological features of the Poços de Caldas caldera and the Osamu Utsumi mine and Morro do Ferro analogue study sites, Brazil

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Poços de Caldas Report No. 5

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GEOMORPHOLOGICAL AND HYDROGEOLOGICAL FEATURES OF THE POÇOS DE CALDAS CALDERA AND THE OSAMU UTSUMI MINE AND MORRO DO FERRO ANALOGUE STUDY SITES, BRAZIL

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Abstract

The Osamu Utsumi mine and Morro do Ferro study sites lie within the Poços de Caldas plateau which is roughly circular in outline with a diameter of 35 km and an area of approximately 800 km². Its general altitude lies between 1300 and 1600 m. The plateau is the eroded form of a caldera which was initially intruded some 80 million years ago.

Geomorphologically, both sites occupy watershed areas adjacent to small streams in the centre of the plateau. The climate of the area has a marked wet season from November to April and is dry the rest of the year. The streams are ephemeral in their upper reaches, tending to dry up in the dry season as they are fed by a declining base flow. In the wet season they exhibit flash floods fed by high-intensity rainfall causing overland flow. The wet season also provides recharge to the groundwater. Natural slopes are steep and the original vegetation was thin forest cover which is now restricted to the valley bottoms; usable slopes have poor quality grass cover used for cattle grazing. The plateau is a stable feature and its surface has been eroding at an average rate of 12 m per million years over a period of 50 million years.

The mine geology is dominantly volcanic to subvolcanic phonolites that have been hydrothermally altered. Fracturing of the rock is extensive. Downward diffusion of oxygen in groundwaters during deep weathering has produced a distinct redox zone seen as a colour change from green/grey to brown/yellow. Morro do Ferro has a more weathered version (laterite/clay) of the same geology penetrated by magnetite breccia dykes. Whilst the area surrounding Morro do Ferro remains untouched, that around the mine has been seriously disturbed by mining activity which has penetrated the water-table. The existing mine has modified groundwater flow patterns and disturbed the movement of oxidising and reducing waters.

Zusammenfassung

Die Untersuchungsgelände Osamu Utsumi Mine und Morro do Ferro liegen innerhalb des fast kreisförmigen Poços de Caldas Plateaus, mit einem Durchmesser von 35 km, das sich über eine Fläche von 800 km^2 erstreckt. Seine Höhe liegt meist zwischen 1300 und 1600 m. Das Plateau ist die erodierte Art einer Caldera, in der zuerst vor 80 Millionen Jahren eine Intrusion erfolgte.

Geomorphologisch betrachtet, enthalten beide Gelände Wasserscheidengebiete, die im Zentrum des Plateaus an kleine Bäche angrenzen. Das Klima des Gebietes hat eine merkliche Regenperiode von November bis April, während für den Rest des Jahres Trockenzeit herrscht. Die Bäche sind in den höheren Regionen saisonal mit einer Tendenz zum Austrocknen während der Trockenzeit, da sie nur durch abnehmende Grundwasserzuflüsse gespeist werden. Während der Regenperiode treten flutartige Hochwasser auf, die durch sehr starke Regenfälle gespeist werden und zu Ueberschwemmungen führen. Während der Regenperiode wird auch die Grundwasserreserve wieder aufgespeichert. Natürliche Hänge sind steil und die ursprüngliche, dünne Bewaldung beschränkt sich heute auf die Talebenen; nutzbare Hänge haben minderwertigen Grasbewuchs und werden als Weiden genutzt. Das Verhalten des Plateaus ist konstant, und seine Oberfläche erodiert seit 50 Millionen Jahren im Mittel um 12 m pro 1 Million Jahre.

Die Geologie der Mine besteht vornehmlich aus vulkanischen bis subvulkanischen Phonoliten, die hydrothermal verändert wurden. Das Gestein ist stark gespalten. Sauerstoff, der im Verlauf der tiefen Verwitterung nach unten in die Grundwasseströme dringt, hat eine deutliche Redoxzone verursacht, die als Farbänderung von grün/grau bis braun/gelb erkennbar ist. Morro do Ferro hat eine stärker verwitterte Version (Laterit/Ton) derselben Geologie, wird aber von Magnetit-Lagen durchdrungen. Während das umliegende Gebiet um Morro do Ferro unberührt blieb, wurde das Gebiet um die Mine empfindlich gestört durch den Abbau, der den Grundwasserspiegel durchdrungen hat. Die vorhandene Mine weist verändertes Fliessverhalten des Grundwassers und gestörte Bewegungen oxidierender und reduzierender Wässer auf.

Résumé

La mine d'Osamu Utsumi et le site de Morro do Ferro sont situés sur le plateau de Poços de Caldas, qui est de forme approximativement circulaire, d'un diamètre de 30 km et d'une superficie d'environ 800 km^2. Son altitude se situe entre 1300 et 1600 m. Le plateau constitue la forme érodée d'une caldera dont l'intrusion a eu lieu il y a env. 80 millions d'années.

Géomorphologiquement parlant les deux sites occupent les bassins versants adjacents à des ruisseaux du centre du plateau. Le climat de la région présente une nette alternance de saison humide de novembre à avril de saison sèche le reste de l'année. Le débit d'eau de ces ruisseaux est éphémère dans leur partie supérieure parce que leur alimentation dépend d'un écoulement de base lui-même décroissant. Durant la saison humide ces ruisseaux présentent de brusques crues en raison de très fortes précipitations qui les font déborder. Les eaux souterraines sont en outre réalimentées durant la saison humide. Les pentes naturelles sont abruptes et la végétation originelle consistait en une légère couverture forestière qui aujourd'hui n'occupe plus que le fond des vallées. Les pentes utilisables ne présentent qu'une couverture herbeuse de mauvaise qualité utilisée comme pâturage pour le bétail. Le plateau forme un élément stable dont la surface a été soumise à une érosion de l'ordre de 12 m par million d'années au cours des 50 millions dernières années.

La géologie de la mine est essentiellement constituée de phonolites volcaniques à subvolcaniques altérées hydrothermalement. La fracturation des roches est importante. La diffusion de l'oxygène vers le bas dans les eaux souterraines lors de l'altération profonde a produit une zone rédox très claire qui se manifeste par un changement de coloration passant d'un vert/gris à un brun/jaune. Morro do Ferro présente une version d'avantage altérée (latérite/argile) de la même géologie pénétrée par des dykes de brèches de magnetite. Alors que la région entourant Morro do Ferro est restée intacte, celle située aux alentours de la mine a été sérieusement perturbée par les activités minières qui ont pénétré dans la nappe phréatique. La mine a modifié la circulation des eaux souterraines et a perturbé le mouvement des eaux oxydantes et réductrices.

Preface

The Poços de Caldas Project was designed to study processes occurring in a natural environment which contains many features of relevance for the safety assessment of radioactive waste disposal. The study area, in the State of Minas Gerais, Brazil, is a region of high natural radioactivity associated with volcanic rocks, geothermal springs and uranium ore deposits. It contains two sites of particular interest on which the project work was focussed: the Osamu Utsumi uranium mine and the Morro do Ferro thorium/rare-earth ore body. The first site is notable in particular for the prominent redox fronts contained in the rock, while Morro do Ferro was already well-known as one of the most naturally radioactive locations on the surface of the Earth, owing to the high thorium ore grade and the shallow, localised nature of the deposit.

The features displayed by these two sites presented the opportunity to study a number of issues of concern in repository performance assessment. The four objectives set after the first-year feasibility study were:

1. Testing of equilibrium thermodynamic codes and their associated databases used to evaluate rock/water interactions and solubility/speciation of elements.
2. Determining interactions of natural groundwater colloids with radionuclides and mineral surfaces, with emphasis on their role in radionuclide transport processes.
3. Producing a model of the evolution and movement of redox fronts, with the additional aim of understanding long-term, large-scale movements of trace elements and rare-earths over the front (including, if possible, natural Pu and Tc).
4. Modelling migration of rare-earths (REE) and U-Th series radionuclides during hydrothermal activity similar to that anticipated in the very near-field of some spent-fuel repositories.

The project ran for three and a half years from June 1986 until December 1989 under the joint sponsorship of SKB (Sweden), NAGRA (Switzerland), the Department of the Environment (UK) and the Department of Energy (USA), with considerable support from a number of organisations in Brazil, notably Nuclebrás (now Urânio do Brasil). The first-year feasibility study was followed by two and a half years of data collection and interpretation, focussed on the four objectives above.

This report is one of a series of 15, summarising the technical aspects of the work and presenting the background data. A complete list of reports is given below. Those in series A present data and interpretations of the sites, while those in series B present the results of modelling the data with performance assessment objectives in mind. The main findings of the project are presented in a separate summary (no. 15).

This report outlines the geomorphology of the study area, including the origin of the caldera and its possible evolution over geological time. Rates of erosion of the land surface have been estimated from several lines of evidence. Present-day conditions of climate, soils, vegetation and drainage are also discussed.

Desk studies and limited field investigations have revealed groundwater flow patterns for two sites within the field area. Data from the investigations have been used to construct mathematical models of groundwater flow to provide estimates of flow velocities and directions. Flow patterns at one of the sites, the Osamu Utsumi mine, have been significantly changed by excavating large volumes of rock below the natural water-table. The other site, Morro do Ferro, remains in a natural state.

Poços de Caldas Project Report Series

Series A: Data, Descriptive, Interpretation

Report No.	Topic	Authors (Lead in Capitals)
1.	The regional geology, mineralogy and geochemistry of the Poços de Caldas alkaline caldera complex, Minas Gerais, Brazil.	SCHORSCHER, Shea.
2.	Mineralogy, petrology and geochemistry of the Poços de Caldas analogue study sites, Minas Gerais, Brazil. I: Osamu Utsumi uranium mine.	WABER, Schorscher, Peters.
3.	Mineralogy, petrology and geochemistry of the Poços de Caldas analogue study sites, Minas Gerais, Brazil. II: Morro do Ferro.	WABER.
4.	Isotopic geochemical characterization of selected nepheline syenites and phonolites from the Poços de Caldas alkaline complex, Minas Gerais, Brazil.	SHEA.
5.	Geomorphological and hydrogeological features of the Poços de Caldas caldera and the Osamu Utsumi mine and Morro do Ferro analogue study sites, Brazil.	HOLMES, Pitty, Noy.
6.	Chemical and isotopic composition of groundwaters and their seasonal variability at the Osamu Utsumi and Morro do Ferro analogue study sites, Poços de Caldas, Brazil.	NORDSTROM, Smellie, Wolf.

Report No.	Topic	Authors (Lead in Capitals)
7.	Natural radionuclide and stable element studies of rock samples from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil.	MacKENZIE, Scott, Linsalata, Miekeley, Osmond, Curtis.
8.	Natural series radionuclide and rare-earth element geochemistry of waters from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil.	MIEKELEY, Coutinho de Jesus, Porto da Silveira, Linsalata, Morse, Osmond.
9.	Chemical and physical characterisation of suspended particles and colloids in waters from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil.	MIEKELEY, Coutinho de Jesus, Porto da Silveira, Degueldre.
10.	Microbiological analysis at the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil.	WEST, Vialta, McKinley.

Series B: Predictive Modelling and Performance Assessment

11.	Testing of geochemical models in the Poços de Caldas analogue study.	BRUNO, Cross, Eikenberg, McKinley, Read, Sandino, Sellin.
12.	Testing models of redox front migration and geochemistry at the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil.	Ed: McKINLEY, Cross, Haworth, Lichtner, MacKenzie, Moreno, Neretnieks, Nordstrom, Read, Romero, Scott, Sharland, Tweed.
13.	Near-field high-temperature transport: Evidence from the genesis of the Osamu Utsumi uranium mine, Poços de Caldas alkaline complex, Brazil.	CATHLES, Shea.
14.	Geochemical modelling of water-rock interactions at the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil.	NORDSTROM, Puigdomènech, McNutt.

Report No.	Topic	Authors (Lead in Capitals)

Summary Report

15.	The Poços de Caldas Project: Summary and implications for radioactive waste management.	CHAPMAN, McKinley, Shea, Smellie.

Contents

1. Introduction

This report describes the geomorphological and hydrogeological investigations carried out at the Osamu Utsumi open-cast uranium mine and the nearby, unexploited thorium and rare-earth deposit of Morro do Ferro. The geomorphological study has concentrated on establishing a rate of erosion of the land surface over the last few million years. It has utilised information on climate, soils, landforms and drainage to provide estimates of the likely rates of erosion and, hence, movement of the oxidation/reduction fronts that are an important feature of the rock mass in terms of their influence on the behaviour and distribution of trace elements. Hydrogeological data on groundwater flow paths and flow rates, past and present, have been collected by desk studies and some limited field investigations. The groundwater flow pattern establishes the environment in which the geochemical transport processes occur.

The detailed geology of both sites is described elsewhere (see Schorscher and Shea; Waber *et al.* and Waber, this report series; Reps. 1, 2 and 3; Webber, 1959; Loureiro and Santos, 1988). The Osamu Utsumi mine is composed mainly of volcanic to subvolcanic phonolites that have been extensively hydrothermally altered. Fracturing of the rock is pervasive. Downward diffusion of oxygen in groundwaters during weathering has produced a distinct redox zone seen as a colour change from green/grey to brown/yellow. The small hill of Morro do Ferro may represent a deeply weathered (laterite/clay) carbonatite intrusion penetrated by magnetite breccia dykes. Geomorphologically, both sites occupy watershed areas adjacent to small streams in the centre of the Poços de Caldas plateau which is roughly circular in outline, some 35 km in diameter and 800 km^2 in area. Its altitude lies between 1300 and 1600 m. The climate of the area has a marked wet season from November to April, being dry the rest of the year. The total rainfall averages 1700 mm/year, varying from 805 to 2700 mm/year for the period from 1941 to the present-day. The streams are ephemeral in their upper reaches, tending to dry up in the dry season as they are fed by a declining base flow. In the wet season they exhibit flash floods fed by high-intensity rainfall causing overland flow. The wet season also provides recharge to the groundwater. Natural slopes are steep and the original vegetation was a thin forest cover which is now restricted to the valley bottoms; the usable slopes have poor quality grass cover used for cattle grazing. Whilst the area surrounding Morro do Ferro remains relatively unchanged, that around the mine has been significantly disturbed by mining activity, which has penetrated the water-table. The existing quarry has modified groundwater flow patterns and disturbed the movement of oxidising and reducing waters.

This report begins by describing the geomorphology of the Poços de Caldas plateau and then provides a detailed examination of the two study sites at the Osamu Utsumi mine and Morro do Ferro. A desk study is presented for each site, with a discussion of previous relevant work. Methods employed for collecting data in the field are documented together with the information. This has been used as a basis for a mathematical model to provide estimates of the rates and direction of groundwater movement.

2. Geomorphological description of the Poços de Caldas plateau

2.1. Description and geological origin of the caldera

The Poços de Caldas plateau consists of a volcanic caldera that is roughly circular in outline, about 35 km in diameter along its NW-SE axis, 30 km along its NE-SW axis and some 800 km^2 in area (Fig. 1). Its general altitude lies between 1300 and 1600 m. Morro do Ferro, located almost in the centre of the plateau, is about 1 km in diameter and rises to an altitude of 1541 m.

2.1.1. The initial form of the caldera

A fundamental factor in the long-term landform evolution of the caldera is the nature of the initial surface, prior to subaerial weathering. The general impression that the plateau is a "deeply eroded" caldera (Amter, 1989) is misleading and a brief summary of information about calderas is thus an important preliminary consideration.

The term itself is coined from *caldeira*, the Portuguese word for kettle or cauldron. Calderas are large volcanic depressions with an approximately circular planform and diameters many times greater than those of the included vents (Williams, 1941). Within the main structure of the Poços de Caldas caldera, some 14 circular structures occur, representing minor intrusions (Loureiro and Santos, 1988). In general, few craters exceed 1.5 km in diameter. Although the ejection of materials is perhaps the most distinctive feature of craters, calderas result primarily from subsidence or collapse.

The essentially circular planform and the saucer-shaped cross-section of the Poços de Caldas plateau is the configuration typical of a collapsed caldera, such as Crater Lake, Oregon (Fig. 2), which is probably the clearest example of a Krakatoa-type caldera (Williams, 1942). Explosion mechanisms play an important role in the origin of such

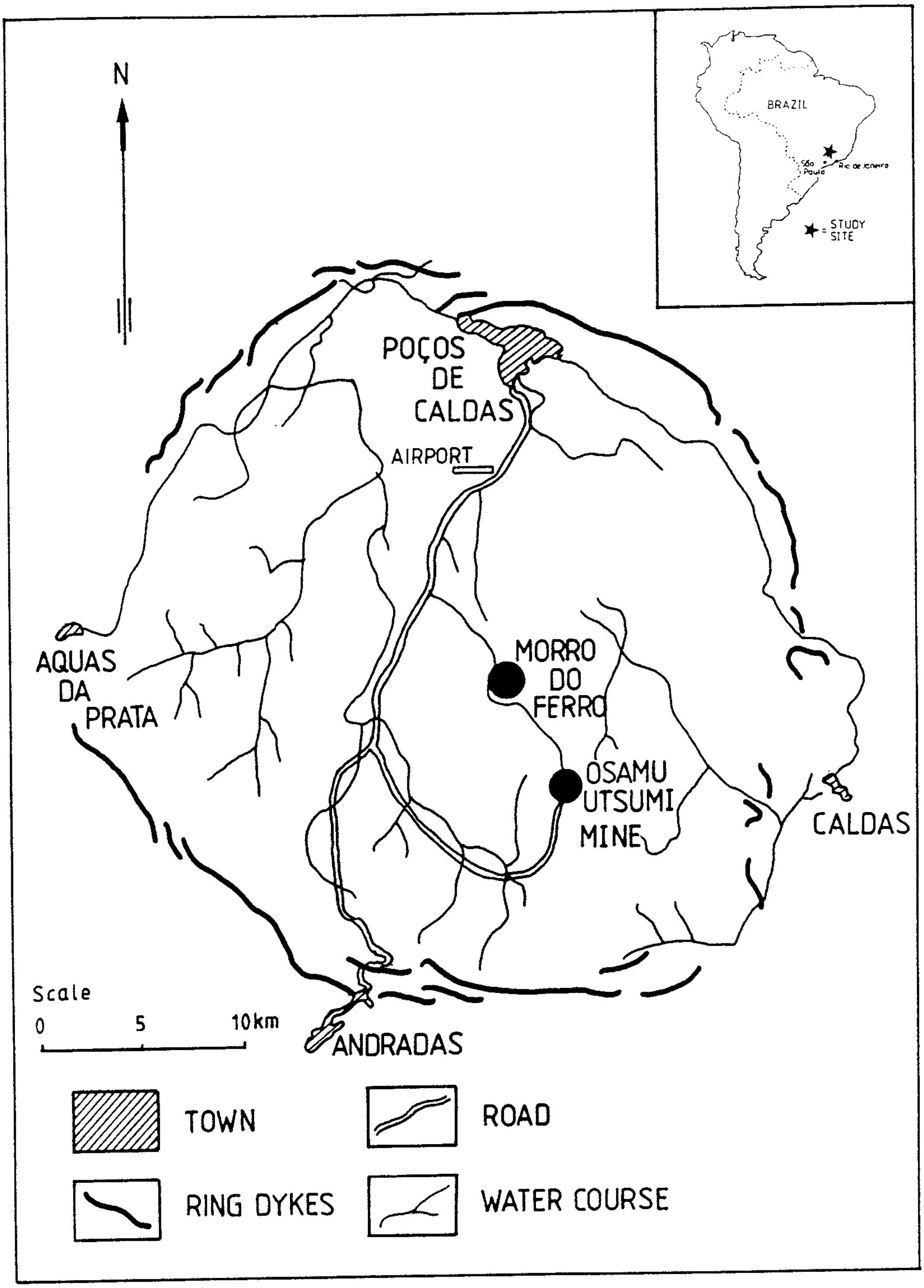


Figure 1. Location of the Osamu Utsumi mine and Morro do Ferro analogue sites within the Poços de Caldas plateau.

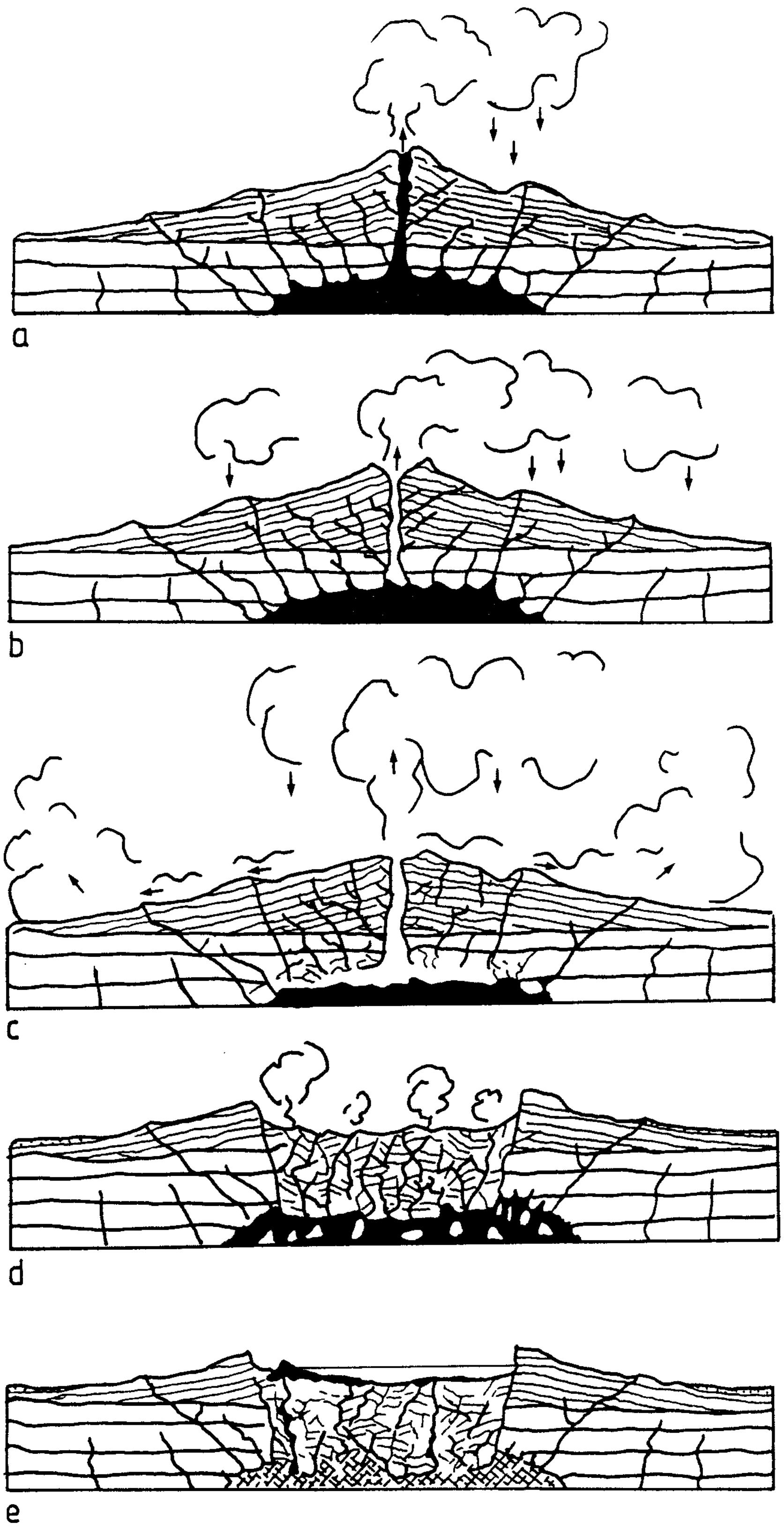


Figure 2. Schematic illustration of caldera formation due to explosion mechanisms and eventual collapse of the magma chamber.

"Krakatoan calderas". However, the volume of fragmental ejecta derived from Krakatoan calderas is far less than the volumes of the depressions. This apparent discrepancy can be accounted for by the collapse of the magma chamber.

The essential feature of calderas, for present purposes, whether due largely to paroxysmal explosion or to subsidence, is that they assume a comparatively low relief at a very early stage in their geological evolution. For example, Mt. Katmai in Alaska lost 240 m from its top as recently as 1912 and a 5 km-diameter caldera was produced (Ollier, 1981).

From the broad geological context, it is important to stress that the initial form at Poços de Caldas, on which subaerial weathering began, was by no means a cone with a basal diameter of approx. 30 km. Given that craters are rarely more than 1.5 km in diameter, the highest points of the initial form at Poços de Caldas may have been little more than 500 m above the present plateau surface.

2.1.2. Faulting

Fault patterns are often an important control on the planform of drainage patterns. The majority of the Brazilian alkaline massifs, intruded into metamorphic rocks, are controlled structurally by the large regional fault systems which were reactivated at various times in the past. These bodies may be genetically related to deep-seated E-W trending faults of probable Archean age, which have been masked by the NE-SW trends of the Brazilian Cycle (500 – 1000 Ma ago) (Loureiro and Santos, 1988).

Within the Poços de Caldas complex, there are three principal fault systems. The first, which strikes N 60°W, is the major regional trend since it extends beyond the complex. These faults were reactivated during uplift. The secondary trend strikes N 40°E and is genetically related to the formation of the collapsed caldera. Thirdly, there are radial and sub-circular faults, related to various intrusives (Fig. 3).

2.1.3. The caldera rim

The intrusion caused metasomatism around the periphery of the complex, accentuated in the vicinity of the eastern and south-eastern contacts, where fenitization was most prevalent (Loureiro and Santos, 1988). Ring dykes, following the periphery of the complex, were intruded along ring faults (Fig. 3). These probably formed after the initial stage of subsidence.

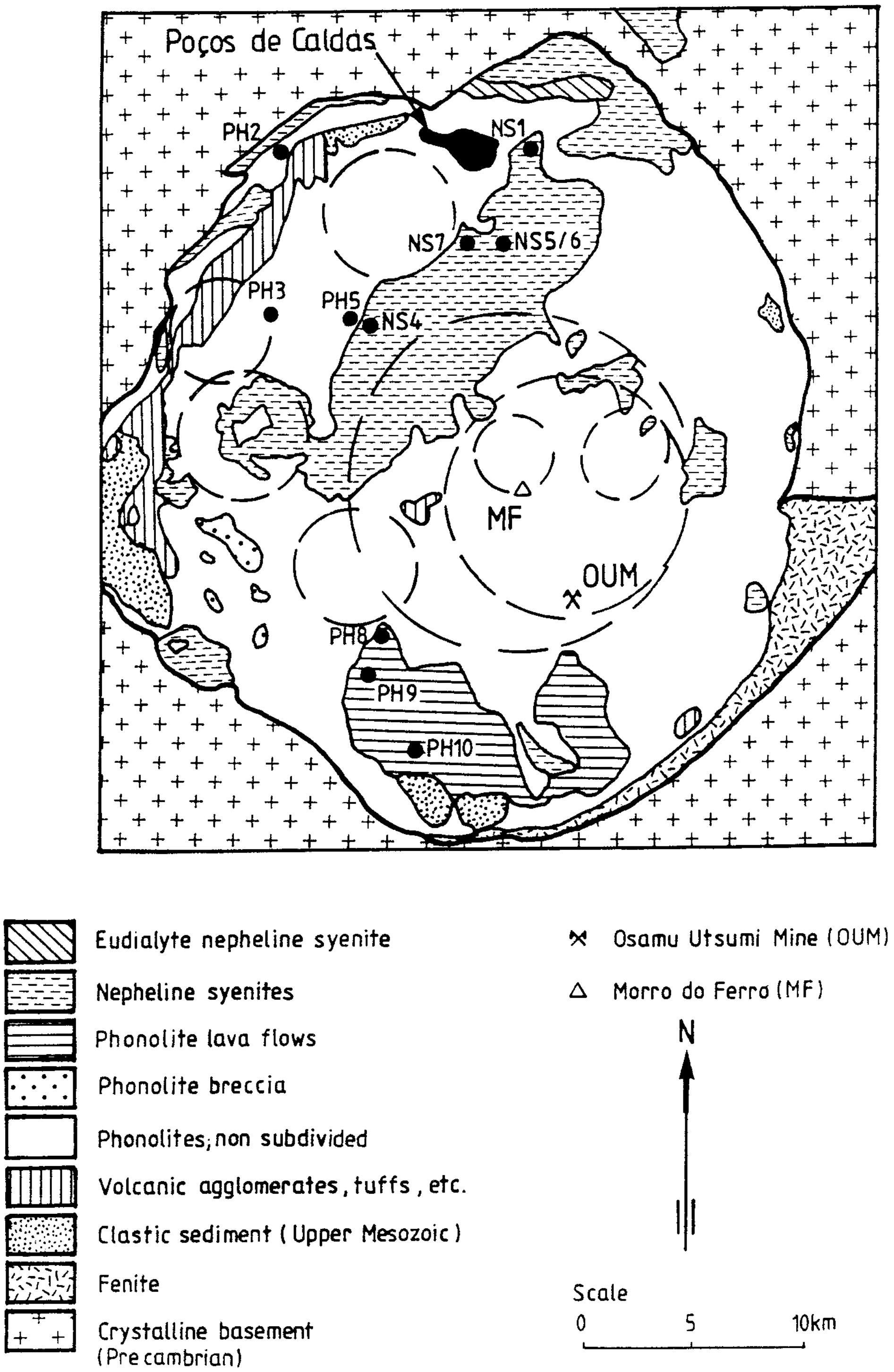


Figure 3. Main geological subdivisions of the Poços de Caldas caldera (after Schorscher and Shea, this report series; Rep. 1).

It is important to stress that the upturned rim of the Poços de Caldas caldera is related to the metamorphic induration of the surrounding country rock, rather than being a worn-down perimeter of volcanic material. According to a literature review and study of aerial photos, Christofoletti (1973) emphasises that the rim is due partly to down-faulting of fault-bound blocks which parallel the outline of the caldera and lie just within its perimeter.

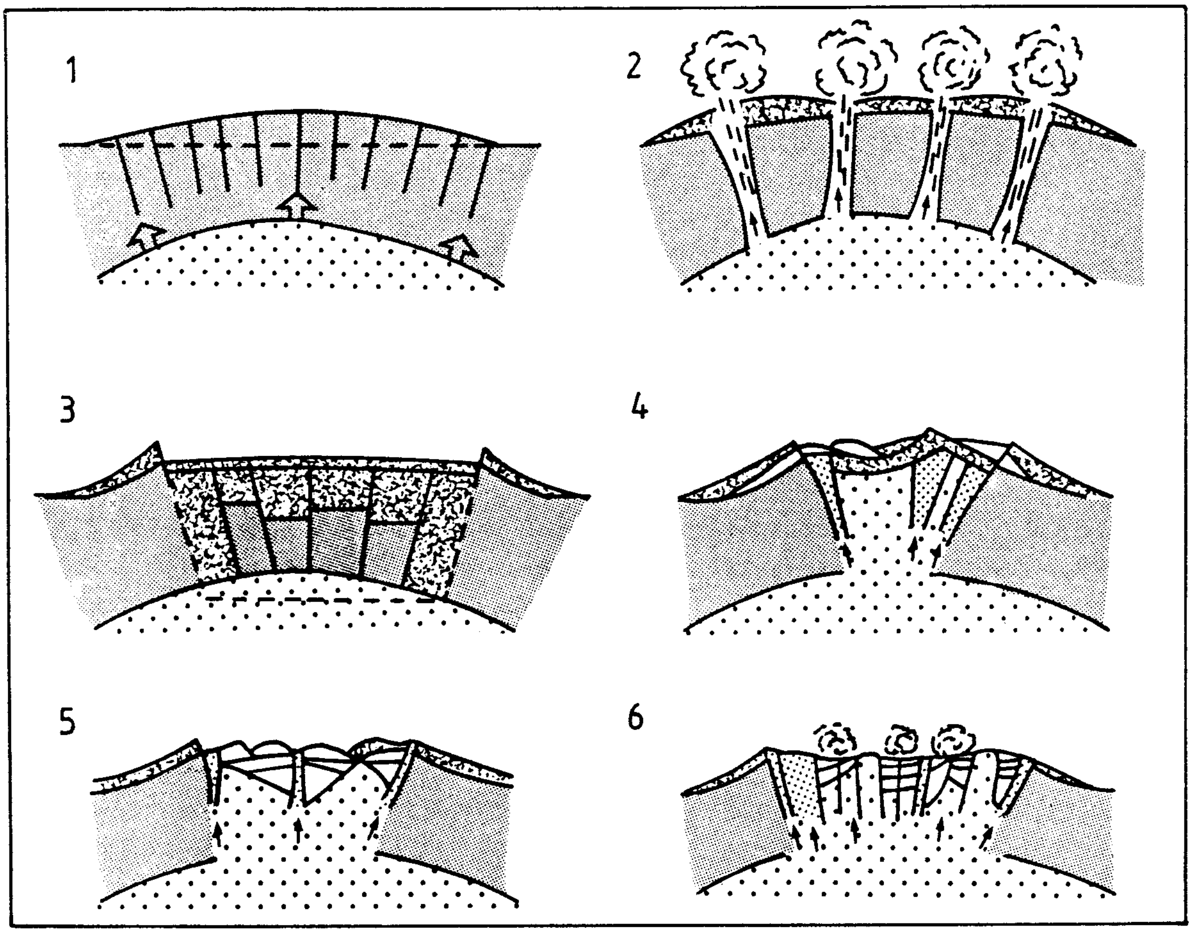
2.2. Geological evolution of the caldera

Earlier whole-rock K/Ar determinations suggested that volcanic activity occurred between 80 and 62 Ma ago (Amaral *et al.*, 1967). Current Rb-Sr analyses (Shea, this report series; Rep. 4) indicate that the central nepheline syenite body of the caldera, representing one of the earlier stages of caldera evolution, is 78 (3) Ma in age. In the same study, Ar-Ar analysis found the age of a lamprophyre dyke, possibly representing the final stage of volcanic activity, to be 76 (2) Ma.

The resurgent cauldron model, proposed by Smith and Bailey (1968), can usefully be applied to Poços de Caldas as shown in Figure 4.

In brief, the evolutionary stages are:

1. Regional uplift of the basement and *en echelon* faulting, attributed to activity in an underlying magma chamber. Such doming, prior to eruption, is observed in many cases, such as the Napak volcano in Uganda (Ollier, 1981).
2. Period of volcanic activity, involving episodes of lava emission and explosion. Note that several vents are envisaged.
3. Caldera collapse, following changes in the magma chamber. Subsidence caused by intense tectonism.
4. Renewed uplift, with intrusions along the radial and circular fractures formed during the first stage.
5. Major ring-fracture volcanism.
6. Intrusions, accompanied by hydrothermal and other late- or post-magmatic activity, such as brecciation and hot springs activity.



1. Basement elevation, distension, fracturing and erosion.
2 Volcanism: phonolites, volcanoclastics.
3. Caldera subsidence.
4.] Nepheline intrusions: tinguaites, phonolites, nepheline
5.] syenites, in ring dykes and minor circular structures.
6. Intrusion of lujaurites, chibinites and foyaites.

Figure 4. Evolutive model of the Poços de Caldas alkaline igneous complex (after Ellert, 1959).

According to Loureiro and Santos (op. cit.), stage 6 "... was characterised by intense erosion". Thus, not only was the initial form of a much lower altitude than a cone 30 km in diameter, but initial erosion was also intense. The combination of these two factors suggests that the relief of the Poços de Caldas caldera has resembled that of the present-day for many millions of years. In planform, a major feature of denudation was the development of annular drainage, a particular feature of some calderas and other circular or concentric structures (Fig. 4).

Apart from subaerial denudation, there was also periodic faulting. In the "A" ore body at the Osamu Utsumi mine, a plug-like breccia, which constituted the interior of a volcanic cone, channeled the primary mineralisation along the regional tectonic trend (N 60°W strike). Subsequent faulting, with a N 40°E strike, resulted in the cutting and partial dislocation of the ore body. Further, the breccias were again cut by a fault system with a N 10–25°E strike (Loureiro and Santos, op.cit.).

2.2.1. Recent tectonics and regional erosion patterns

Recent tectonic movements could have a critical influence on changes in river pattern and orientation. In particular, detailed information from a neighbouring Tertiary sedimentary basin would be the surest guide to long-term environmental changes. For example, the Taubate basin, between Rio de Janeiro and São Paulo, subsided in the Neogene and contains two main successions. The lower formation is a bituminous, shaly saprolite deposited in a swamp or lake in a forested area with a humid climate. Above this, there is reddened, sandy clay with pebble horizons, suggesting that a semi-arid phase ensued. Tricart and da Silva (1959) equate the lower deposit with Miocene times (5 – 23 Ma ago) and the upper deposit tentatively with the later Neogene (2 – 23 Ma ago) "Barreirian Series" of the coastal zone.

Also, soil conditions in tracts beyond the caldera might suggest typical conditions within it. For instance, Tricart (1958) reports that soils around Andradas, only 12 km south-west of the Osamu Utsumi mine, are not typical clayey latosols. Instead, they are sandy and resemble those of the woody savanna (*agreste*) around Pernambuco. This could, however, be a local factor, relating to the sandstone bedrock which outcrops near to Andradas. There is also a detailed study of soils immediately to the north of Poços de Caldas City, including alluvium on the valley floor of the Antas River, downstream from the highly significant local base level at the Bride's Veil Falls (Setzer, 1956).

Finally, useful inferences can be made as to weathering and tectonic conditions on land from sediments on the Atlantic Ocean floor (Damuth and Fairbridge, 1970). For example, in the Santos Basin offshore from Rio de Janeiro, sedimentation was relatively continuous and rapid during the Neogene (2 – 23 Ma ago), with potential hydrocarbon source rocks being sealed by mudrocks (Gibbons *et al.*, 1983). The inferences are that weathering was continuous and effective on land throughout this period, and dominantly and increasingly biochemical to account for the mudrock succession.

2.3. Geomorphological evolution of the caldera

Very commonly, the broad outline of an assemblage of landforms is closely linked with contrasts in lithology. The Poços de Caldas complex is characterised by a wide variety of rock types, with a pronounced mineralogical and textural diversity ranging from very coarse-grained to very fine-grained. In the central parts of the complex, many rocks have been highly altered by intense potassic metasomatism (Ellert, 1959; Ulbricht 1983; Waber *et al.*, this report series; Rep. 2). In many locations all the rocks are characterised by deep weathering.

2.3.1. Deep weathering

The weathered zone includes a thick argillaceous laterite from 10 – 100 m depending on rock-type and hydrothermal alteration (Waber *et al.*, op.cit.). Drill-cores suggest that the extensive rock alteration, due in part to weathering, was facilitated by hydrothermal activity (Amaral *et al.*, 1985; Schorscher and Shea; Waber *et al.*; Waber, this report series; Reps. 1, 2 and 3). Outcrops are, therefore, rare. Below the laterite, a saprolitic horizon, highly variable in thickness (1 – 40 m), is developed. In contrast to the laterite, the original texture of the rock is still preserved, although the primary minerals have been completely replaced with very little volume change.

According to Ollier (1981), deep weathering profiles, where supergene enrichment of mineral deposits has occurred, are often ancient and evidently fairly stable. Ollier *et al.* (1988) describe the 100 m profile of deep weathering at Norseman in Western Australia, where they attribute deep weathering to early Cenozoic or even Mesozoic times, i.e. the approximate age of the Poços de Caldas complex.

A four-fold scheme of deep weathering, first outlined by Ruxton and Berry (1957) in the Sudan and the large number of exposures in Hong Kong, has since been widely employed in the study of tropical geomorphology. In Zone I, the soil profile of pedologists, there is no remaining trace of rock features. The base of Zone I is the depth to which plant roots and termites penetrate. Zone II comprises decomposing or rotten rock, but with traces of rock features such as crystal bands, veins and joints clearly evident. Although some zones of the rock have been removed by hydrolysis, others have increased in volume, the end-result being "isovolumetric weathering". The density of the rock in Zone II is only one-half to one-third that of unweathered bedrock. In Zone III, weathering remains isovolumetric, but is evident only along joints and other lines of weakness, where water circulation is good. Nuclei of unweathered rock persist between such preferred pathways. Such nuclei may persist as core-stones, like the residual blocks which weathered out from the regolith south of Poços de Caldas. In Zone IV, slight widening of joints by weathering is detectable and groundwater circulation is enhanced. At the base of Zone IV, however, there is unweathered bedrock and groundwater circulation is more limited below this level.

2.3.2. Rates of tropical weathering

An important indication of tropical weathering rates are the widespread bauxite deposits of the Poços de Caldas area. Bauxites form particularly on crests of interfluves where free drainage ensures the progressive removal of silica. Depletion in silica then allows alumina to remain isolated, instead of combining with dissolved silica to form kaolinite. This is thought to be a very slow process and, according to Tricart (1972), such ridges are inevitably ancient residual landforms. The bauxites on the caldera rim therefore suggest its antiquity as a landform, including the shoulders of the rim which incline down towards the Antas gorge at the Bride's Veil Falls. Antiquity, in terms of bauxite formation, usually means several millions of years, at least.

However, some of the Poços de Caldas bauxites are unique (Webber, 1959) and are inter-related with drainage history in a striking way. Patches of high alluvium have been described close to the northern rim. These are now 50 m above incised river courses, which have already been bauxitized (Webber, op. cit.). This deposit may relate to a time when a different outlet to the present Bride's Veil gorge was in operation. The bauxitization of the high alluvium means that either these deposits "... are unique in being of demonstrably recent age" or that, given the time that bauxitization usually takes, the Bride's Veil gorge and the associated stream downcutting in the vicinity demonstrably occurred a "much longer time ago" (Webber, op. cit.).

2.3.3. Stream development

One very significant effect of deep weathering is the paucity of coarse debris in the stream bed load. The suspended load is dominantly clays, with deposition of mud where the valley floor is wide enough to form a flood plain. Possibly due to the lack of abrasives, the base of hillslopes tends not to be undercut and a meandering pattern to the valley planform does not develop.

The conditions influencing upstream retreat of waterfalls and rapids is very different in the humid tropics compared with other climatic zones. Probably, therefore, one of the most distinctively tropical features of the landforms in the Poços de Caldas area is the longitudinal stream profile and the significance of the Bride's Veil waterfall on the River Antas, 3 km to the NW of Poços de Caldas. This is the point at which the bulk of the drainage from the Poços de Caldas plateau passes through the caldera rim. Such rock bars are extremely frequent on tropical rivers, especially in the forested zone. The larger ones have a Tertiary origin going back several million years (Tricart, 1972).

The Bride's Veil Falls area is a typical tropical rock bar in that, due to a lack of abrasive bed load, there is little incision at the lip. Due to the resistance of the rock bar, flat reaches of stream profiles remain upstream, where deep weathering proceeds. Significantly, too, the evolution of valley-side hillslopes will have proceeded for long periods of time as a function of the same local base level.

Thus, according to Tricart (op. cit.), at a certain distance from the ocean tropical streams are still at the level which they reached during the Pliocene (i.e. at least 2 – 5 Ma ago). He quotes the Felou Rapids, near Kayes in Mali, as an example of a rock bar uneroded during the Quaternary, with an upstream valley floor where there has been no downcutting since the Pliocene.

2.4. Climatic change in the region

Climatic change affects geomorphological processes, partly through the effect on vegetation cover. Clearly, the opulent vegetation of the tropical rainforest is an exceptionally effective screen between the atmosphere and the ground surface.

2.4.1. Tertiary climates

From changes in sediments in south-east Brazil, Tricart (op. cit.) infers that the Palaeocene (55 – 65 Ma) was a rather dry episode of tropical climate. This was followed by a humid climate with associated chemical weathering for the extended period of the Eocene (36 – 55 Ma), with drier conditions returning during the Neogene (2 – 23 Ma). This is supported by the progradation of shelf limestones offshore from Rio de Janeiro during the Miocene (5 – 23 Ma), as described by Gibbons *et al.* (1983).

The notable development of bauxite in the Poços de Caldas area is an additional climatic indicator. Bauxite is not a feature of humid tropics, as this type of environment impedes leaching of silica by lowering pH. Instead, bauxite formation is a feature of semi-evergreen or deciduous seasonal forest climates, which restrict acidification whilst, at the same time, providing sufficient percolating water for some leaching (Tricart, 1972).

2.4.2. Quaternary

Pleistocene

A very wide range of evidence suggests that in South America, where tropical rain-forest exists today, savannas were widespread during the last glacial period (Markgraf and Bradbury, 1982). The mineralogy of sediments in Atlantic deep-sea cores offshore from equatorial South America suggests that semi-arid conditions prevailed during glacials, in contrast to humid interglacials like that of the present-day (Damuth and Fairbridge, 1970).

An impression of the relative importance of such changes is perhaps best gained from the unique 200,000 yr tropical/lithological record, retained at 650 m altitude in Lynch's Crater, north-eastern Queensland. This record spans two glacial/interglacial cycles. Kershaw (1985) shows that rainforest was present four times within this period, but only for a total of some 40,000 years.

Holocene

In the tropical lowlands of South America, the climates prior to 10,000 Ma were cooler and certainly drier than at present. The 8,000 to 10,000 Ma interval was moist, comparable to the present. The interval between 4,000 and 6,000 Ma showed a slight return to drier and cooler conditions, after which the present moisture and temperature regime seems to have become established (Markgraf and Bradbury, 1982). Again, instructive records can be identified in other tropical areas, such as the fluctuations in spatial extent and relative dominance of rainforest, compared with savanna, in West Africa (Sowunmi, 1986).

Such variations appear to have affected geomorphological processes significantly. During a seven month reconnaissance, Tricart (1958) became convinced that, throughout the central Atlantic area of Brazil, there was evidence of erratic episodes in past climates, in which drought and downpour alternated (Poços de Caldas lies in the southern quarter and towards the inland margin of this area). The main evidence was horizons of coarse fluvial gravels in terraces of silty sands, attributed to heavy downpours in semi-arid environments with reduced vegetation cover. Successions are evident in cuttings in the São Paulo motorway north of Rio de Janeiro, with truncated latosol at the base, overlain by gravel, and then followed by 1 – 5 m of clayey silt. Along the interior basin of the Rio Paraiba, the repeated successions of gravel horizons suggest several climatic changes.

In summary, the assumption that deep weathering must be linked with warm wet climates is not necessarily true. "All that is required for deep weathering is deep groundwater and plenty of time" (Ollier, 1988).

2.5. Present-day natural environment of the region

2.5.1. Climate

Temperature: The average annual temperature is 19°C, reflecting the altitude which averages about 1300 masl. The maximum is around 36°C with a minimum of around 1°C (Amaral *et al.*, 1985), the latter figure indicating the possibility of frost during colder climatic phases in the past, which may explain why duricrusts do not appear to be a significant feature of the Poços de Caldas plateau.

Precipitation: Alternating wet/dry seasons are typical. More than 80 percent of precipitation falls between October and March (Lei, 1984). The 30-year average annual precipitation is 1700 mm, although the year-to-year variability is illustrated by a total of 2710 mm in 1983 (Bonotto, 1989). Amaral *et al.* (1985) give the total maximum annual rainfall as 1500 mm (1700 mm in Azevedo *et al.*, 1988), with more than 120 days of rain each year.

Regional orographic controls: The climatic range in north-east Brazil is probably as extensive as that of any long-term climatic change at a particular point. Within a distance of 200 km, the environment changes from coastal humid tropical rainforest to semi-arid inland areas with xerophytic shrubs and cacti (Tricart, 1958). Although less pronounced, the comparatively enduring (compared with possible temporal oscillations) climatic control by the height, alignment and sheer extent of the mountain ranges to the south and south-east of Poços de Caldas must be stressed.

Firstly, along the coast there is the Serra do Mar. This extends some 1400 km, from Santa Catherina to beyond Victoria in the State of Espirito Santo. This barrier is continued northwards by lower hills for a further 1100 km. Secondly, the parallel range inland, the Serra da Mantaqueira, is the highest in Brazil, reaching an altitude of some 3,200 m at the Itatiaiaossu peak. The first range induces and, to some extent, restricts heavy orographic rainfall to the coastal zone. The second range, with the temperature decline with altitude added, introduces a clear break into the regional climate.

2.5.2. Vegetation

Because soils tend to be uniform, due to deep weathering, and the land surface is homogeneous in character, the *campo cerrado* vegetation tends to be remarkably uniform over large areas of inland Brazil (Eiten, 1982). In fact, this shrub vegetation gives its name to the southern portion of the Poços de Caldas plateau. The other main vegetation units are *mata* (evergreen forest), *savanna* (grass) and *agreste* (woodland savanna). The complex layered nature of the tropical forest canopy complicates the linkage of rainfall with infiltration (Jackson, 1975). Due to interception, rainfall at ground level in a tropical rainforest may be 50 – 95 percent less than at the top of the tallest trees (Gilmour and Bonell, 1979). Secondary forest also has high interception rates, due to the dense undergrowth of saplings, shrubs and herbs.

An important distinction between temperate and tropical environments are the very different rates of mineralisation of soil organic matter. Whereas temperate woodlands may have up to 20 percent of total nitrogen contained in the biomass, tropical forests can have 70 percent or more in living tissue (Nye and Greenland, 1960). For example, soils under a mature oak forest in Britain may have up to 7400 kg N ha^{-1} (Ovington, 1962), whilst rainforest in West Africa may have only 120 – 650 kg N ha^{-1} (Bernhard-Reversat, 1975).

Deforestation: The effect of removal of forest cover is to increase runoff significantly. A large volume of literature has been published on this subject since Hoyt and Troxell (1932) first demonstrated increases of 15 – 29 percent in catchments in southern California.

In the tropics, the amplitude of daily temperature oscillations also increases greatly. Tricart (1972) quotes research at Kiendi, near Bondoulou on the Ivory Coast, showing that the daily amplitude increased to 22.6°C on exposed duricrust and to 13.2°C beneath grass, compared with only 3.8°C under forest. The increased desiccation of the soil would have significant effects on soil biochemistry, notably increased oxidation of humic compounds and carbonates. Dehydration transforms hydroxides into the more stable sesquioxide form and iron is precipitated, as is silica, in combination with ferruginous minerals (Tricart, op. cit.).

Some kilometres to the north of the Poços de Caldas plateau, due to increased insolation following drastic devastation of vegetation, mean summer temperatures have increased by more than 1°C and winter means by 0.4°C, in the first half of the 20th century (Setzer, 1956). Reduced infiltration by scanty winter rains, soil erosion and loss of organic matter are also confirmed.

Grass: Grass cover has some distinctive effects on soil and slope hydrology and on biogeochemical cycling. Firstly, its roots reach deeper than those of rainforest and soil desiccation is more probable, which would favour the formation of concretions. Savanna grasses are also silica accumulators. 1 – 8 percent of their ashes consist of silica, part of which is re-cycled, but some is exported by wind and rillwash. Fire immobilises such biogenic silica. In terms of mechanical processes, grass has a comb-like effect on rillwash, both in terms of subdividing waterflow and in limiting sediment transport downslope.

2.5.3. Soils

Soils are predominantly silts and clays. Due to the intense weathering of a tropical climate, surface soils tend to be a fine-textured mixture of kaolinite, gibbsite and limonite. Kaolinite is particularly abundant at Morro do Ferro and several veins of almost pure material have been observed (Bonotto, 1989; Waber, this report series; Rep. 3).

In general, tropical regoliths act like a sponge, damping down variations in stream flow and maintaining spring flow for several weeks after the last rains.

Soil fauna: The constant excavation of the soil by mammals and lizards is noteworthy in south-east Brazil (McLean, 1919). Insect activity is also a distinctively tropical feature, with amorphous termite mounds scattered throughout the deciduous seasonal forest areas. In fact, termites are very active on the hillslopes around the Osamu Utsumi mine and Morro do Ferro, and deserted termitaria are often colonised by much larger bioturbators, with tunnels approx. 15 cm in diameter. The mounds themselves are some 2 – 4 m^3 in bulk.

Stone lines: A distinctive tropical feature is the tendency for resistant residual particles and clasts to accumulate at a particular shallow depth in the soil profile, roughly parallel with the slope surface (Fairbridge and Finkl, 1984). They may reflect some climatic oscillation, in which rillwash has become more marked. Bigarella and Andrade (1965) suggest that the stone lines in Brazil appears to be late Wisconsin, at ca. 18,000 Ma, when aridity affected most tropical areas. Alternatively, they may be a product of bioturbation, with termites and other burrowers able only to transfer particles below a certain size to the ground surface.

Such stone lines are clearly seen on hillslopes to the north of the Osamu Utsumi mine. With minor gullying evident on artificially bared lower slopes, perhaps the colluvium (hillslope sediment) above the stone line here merely reflects the initiation of overland flow, following deforestation. It is difficult to give a satisfactory explanation for the stone lines clearly developed in the vicinity of the mine. However, it must be emphasised that these features are recognised as valuable palaeoenvironmental indicators (Ruhe, 1959).

2.6. Land use

Inland from the strip of rainforest along the Serro do Mar, forest has largely been removed from the plateau. Often, the ground, cleared of the forest by burning, has been allowed to degenerate into rough grassland. This is covered by a rank growth of *Tristegis glutinosa*, a coarse grass (*capimela*) which may reach 1 m in height (McLean, 1919). Burning remains an annual practice on the grassy areas of Morro do Ferro (Bonotto, 1989).

The older parts of the coffee belt in south-east Brazil provide a classic example of a land-use cycle. In his study of its progression from primary forest through crop and pasture to secondary forest, Haggett (1961) uses a graphic description from an early visitor. In June 1867, on crossing the Rio Paraiba near Entre Rios, [Captain] Richard Burton observed that:

> *"Hereabouts the once luxuriant valley is cleaned out for coffee, and must be treated with cotton and the plough. The sluice-like rains following the annual fires have swept away the carboniferous humus from the cleared round hill tops into the swampy bottoms, ... every stream is a sewer of liquid manure, ... and the superficial soil is that of a brickfield."*

The large amount of dissolved organic matter is a feature of tropical streams. It is evident in the name of the Rio Una ("Blackwater"), a right-bank tributary of the Paraiba, draining a 300-km section of the Serra do Mar.

However, in the Poços area, it must be stressed that the annual field burning is a major reason for little humic debris being observed (Bonotto, 1989).

2.6.1. Soil erosion

In his study area near Taubate, in the Tertiary- and Quaternary-filled rift which is now the communication corridor between São Paulo and Rio de Janeiro, Haggett (1961) estimated that a topsoil loss of 20 cm ± 5 cm had occurred since around 1850. This is equivalent to a ground surface lowering in the 1.5 – 2.5 mm yr^{-1} range. This figure is matched by a calculation for the alluvium-filled bottomlands (*varzeas*). These strips, never more than 1 km wide, have increased their area by 2 – 3 times since sedimentation accelerated. Notably, the volume of this sedimentary infill is equivalent to a 1.6 mm yr^{-1} loss from the steeply sloping hills (*morros*). The similarity of the two calculations suggests that a large proportion of the sediment, derived from the hillslopes, remains within sub-catchments, rather than being evacuated.

2.6.2. Biochemical changes

With the effects of present-day grass-burning, coupled with those of prior deforestation, it should be anticipated that anthropogenic practices will have modified biochemical processes significantly. Several aspects of environmental deterioration, due to anthropogenic causes, must be taken into account in studies of present-day biogeochemical cycling. For example, in the broad valley of the Rio Parahibuna, swamps resulting from accelerated sedimentation have killed off forest (McLean, 1919). Some of these aspects are the subject of research projects; for example experimental work on the role of fire has been undertaken at the cerrado/mato (savanna/forest) boundary at Emas, near Pirassununga, São Paulo (Cole, 1987).

In many locations, the inland decline in rainfall is not sufficient to preclude forest growth. This is evident in the vigorous regeneration of strips of woodland along the tributary gully courses in the Poços de Caldas area. In fact, rainfall here is well above the annual total of 1000 – 1100 mm which is sufficient to support forest.

2.7. Erosion rates and changes in hydrogeological regime

Visual impressions of the Osamu Utsumi mine area are of undulating valleys and interfluves resembling in scale and appearance the relief of the early Pleistocene deposits in Midwest USA. As this land surface ranges in age from less than 600 ka yr to over 2.2 Ma (Hallberg, 1980), yet is excavated in weakly resistant glacial drifts, the analogy suggests that the present-day Poços de Caldas relief is perhaps at least 2 Ma old. Taking into consideration the initial form of the caldera (discussed above), a round-figure maximum reduction of some 500 m relief in 50 Ma seems a reasonable assumption from a tectonic point of view, bearing in mind that this was not a uniform rate of erosion.

Based on mineralogical and geochemical criteria, the erosion of the rock over the last 90 Ma has been estimated to be 3-9 km in depth (Ulbrich, per. comm. 1988).

2.7.1. Denudation rates, isovolumetric weathering and tropical double-front weathering

Elsewhere in Brazil, in areas with climatic conditions resembling those of the Poços de Caldas plateau, erosion rates are comparatively low. Leprun (1987) calculates erosion rates for north-east Brazil, where mean annual precipitation is in the 1200 – 2200 mm range. The Rio São Francisco removes 30 t km^{-2} a^{-1}, significantly less than the Mississippi (91 t km^{-2} a^{-1}) or the Irrawaddy (700 t km^{-2} a^{-1}). Leprun (op. cit.) concludes that a figure between 0 and 20 t km^{-2} a^{-1} is representative for South American conditions. Usefully, these volumetric units are directly convertible to equivalent ground surface lowering i.e. the Rio São Francisco, with headstreams to the NE of the Poços de Caldas plateau, is removing materials equivalent to lowering its catchment, on average, by 30 m in a million years.

A general figure representing denudation in the Poços de Caldas plateau, equivalent to a surface lowering of 50 m per million years, has been suggested as a useful starting point. However, isovolumetric weathering means that half or even two-thirds of such materials are removed without loss in volume and, thus, Webber (1959) observed that changes in Poços de Caldas bauxite "... which have taken place after bauxitization was completed are of minor volumetric importance ...". Further, there is the double front weathering, a hypothesis that assumes additional significant chemical loss from the base of the superficial groundwater body, where it is in contact with fresh bedrock. For a workable figure for input to models, therefore, the estimated general denudation figure could be divided into two, to account for the double front weathering and at least by two for isovolumetric weathering. This could mean that the actual ground surface lowering would be 7.5 m per million years, according to the Rio São Francisco data, and 12.5 m per million years for the generalised figure. This figure is comparable to the longest-term estimate, based on a much reduced elevation, for the initial surface of the caldera.

2.7.2. Drainage directions and tectonics

There is a most striking feature in the pattern of the main drainage from the Poços de Caldas plateau, namely the River Antas. One of its headstreams dewaters the Osamu Utsumi mine from the west before entering the main headstream, the Corrego do Cercado, which flows SSE for its first 5 km. This is directly opposite to its final direction of flow. Further, this main drainage pattern is aligned with lower cols in the southern rim of the caldera, to the NE of Andradas. The lowest point is approx. 1320 masl, which is no higher than the present altitude of the Corrego do Cercado valley floor at the mine. Further, the low col on the rim is in an area of horst and graben (Christofoletti, 1973). It seems reasonable to speculate that this drainage could, at one time, have exited the plateau directly towards the south, before tectonic disturbances in the fault blocks on the southern rim modified the drainage pattern. Such disturbances could include the known continued subsidence of the Parana basin, immediately to the west, with downtilting in that direction increasingly favouring a circuitous drainage northward towards the city of Poços de Caldas.

If this speculative reconstruction is tenable, there should be some subsurface weathering phenomena caused by the upper surface of groundwater being at approx. 1320 masl for a protracted period.

The present pattern of the River Antas, first turning WNW near the Fazendo do Cercado, has not involved any significant increase in gradient downstream from the SSE-directed headstream. In fact, it falls at only 0.5 m km^{-1} for the 10 km WNW, i.e. from 1280 to 1275 masl.

There is a striking contrast in the headstreams of the two main drainage basins which occupy the "Campo do Cercado", the southern portion of the Poços de Caldas plateau (Fig. 5). The Antas drains about 70 percent of this region and the Verde about 20 percent.

However, the contrast in steepness of gradients between the headwaters of these two systems is such that the Verde basin is not utilised for irrigation "... since the terrain topography is not suitable for agricultural activities" (Azevedo *et al.*, 1988). Thus, compared with the 10 km downvalley gradient of 0.5 m km^{-1} for the west-flowing Antas (between 1280 and 1275 masl), the River Soberbo descends for 4 km at 5 m km^{-1} (between 1220 and 1200 masl). It then steepens at its first main confluence. This contrast is evident in the sketch map of relief, centred on the mine (Fig. 6).

To the east, the caldera rim is unusually low in the neighbourhood of Caldas. Christofoletti (1973) suggests that this is due to down-faulting of a fault-bounded triangular tract of caldera floor and rim in this direction. Whatever the explanation for the lower ground to the east, it seems possible that directions of groundwater drainage progressively changed. It is therefore postulated that earlier near-stagnant conditions, established over a protracted period of time (i.e. many millions of years) in relation to a local base level (perhaps at approx. 1320 masl), were gradually replaced by increasingly efficient dewatering towards the east.

2.8. Summary of geomorphological evidence

Evidence collected during the geomorphological study indicates that flow patterns on the Poços de Caldas plateau have changed little over the last 5 million years. Erosion of the interfluves has kept pace with that of the valley floors, causing a general lowering of the land surface at an average rate of 12 m per million years (ranging from values of 1 to 50 m per million years estimated from several lines of evidence). The weathering mechanisms are thought to have been similar over the last 10 million years. The redox front penetration would be expected to keep pace with land surface erosion.

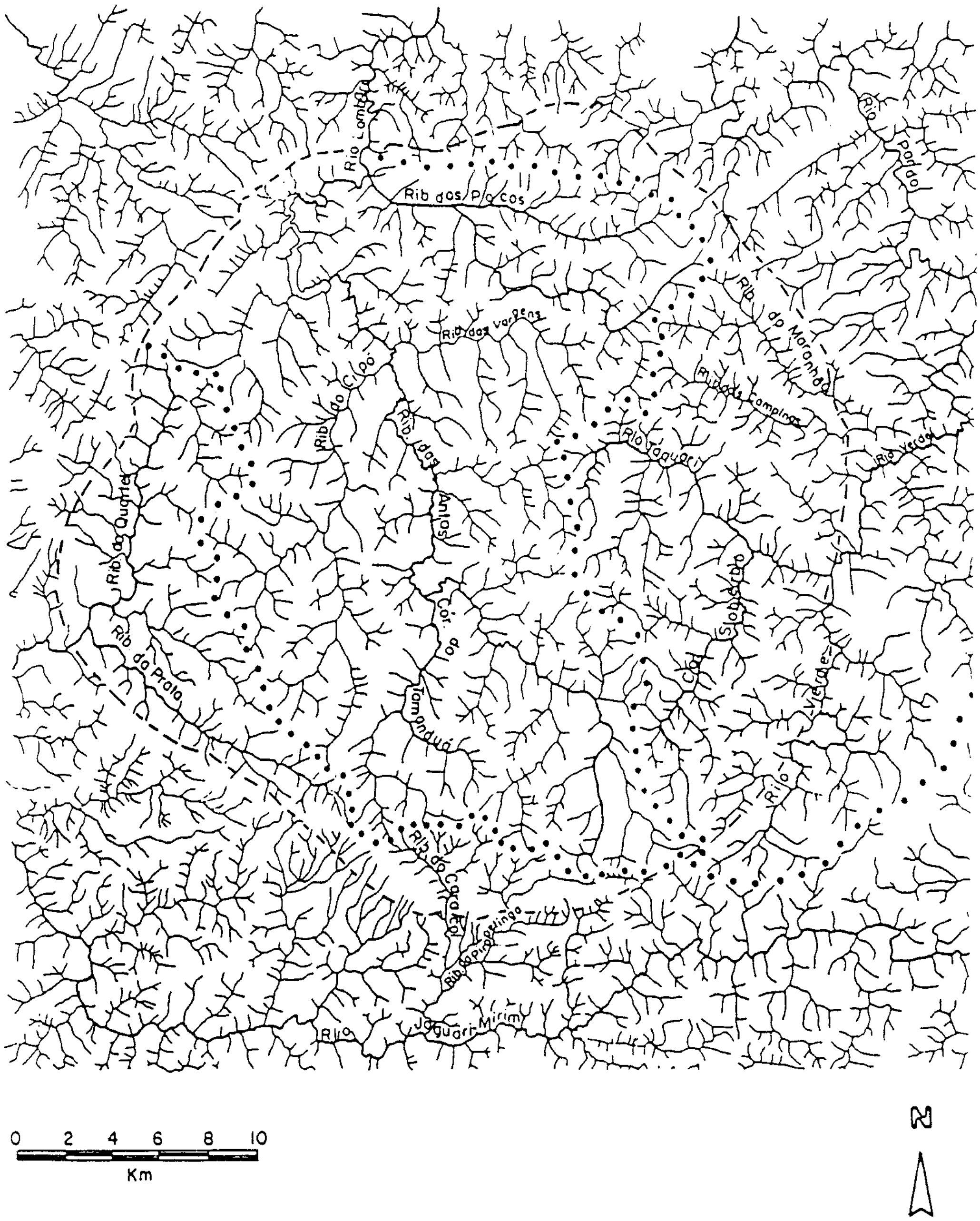


Figure 5. Detailed illustration of the Poços de Caldas drainage system. The edge of the caldera is denoted by the dashed line and the main water divides by the dotted line.

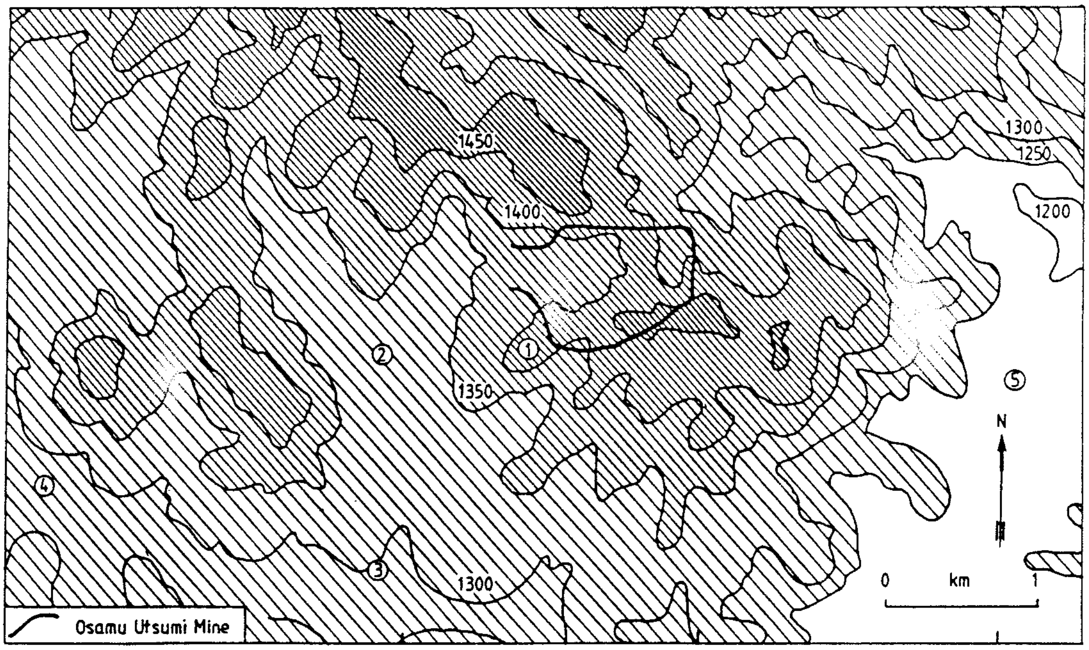


Figure 6. Generalised relief of the Osamu Utsumi mine area showing the locations of: 1) Offices of Urânio do Brasil, 2) Corrego do Cercado valley, 3) Fazienda do Cercado, 4) River Antas valley and 5) River Soberbo valley.

3. Hydrogeology of the two study sites

3.1. The Osamu Utsumi mine

3.1.1. Desk study and previous work

Examination of topographic maps of the area (supplied by Urânio do Brasil), prior to development of the open-cast quarry, shows a series of quite deeply incised, steep-sided valleys containing ephemeral streams. Groundwater flow at this time would have recharged on the interfluves and upper valley sides and discharged into the streams in the valley bottoms. Figure 7a shows this diagrammatically on a sketch map of the area. Water recharging on the interfluves would be oxidising. Transport through the rock would produce chemical interaction with minerals (mainly pyrite) to remove oxygen from the water and make it progressively more reducing. The penetration depth of oxidising water would be controlled by groundwater velocity and residence time and the availability of oxygen-removing minerals in the rock. The redox front should be at greater depth under the interfluves. Water discharging into the streams would be a mixture of reducing groundwaters from depth in the aquifer and shallow oxidising waters. The rock is highly fractured and such fractures would be expected to act as conduits carrying the bulk of groundwater.

Exploitation of the ore started with underground galleries, accessed from a shaft, and progressed to the open-cast method now employed. The quarrying has greatly modified the topography of the valleys by lowering the general land level and removing valley floors and interfluves. These activities have lowered the local water-table and greatly disturbed the old groundwater flow patterns (Fig. 7b). Additionally, the catchment area of the existing mine is larger than the original valley and intercepts groundwaters which originally flowed into other valley systems. The area which discharges reducing groundwaters from the aquifer has been extended. Upward flow of reducing groundwater now occurs through rock which originally received downward-flowing oxidising waters. Some 50 (dry season) to 100 (wet season) cubic metres of water is pumped from the mine per hour to maintain the sump water level at an elevation of about 1316 maod (metres above ordnance datum) and keep the quarry floor dry. The lower levels of the quarry form an enclosed basin which, without pumping, would flood to a level of 1330 maod, the lowest point of possible outflow. Figure 8 shows the relationship between the original topography, the mine and its influence on groundwater flow patterns. The upper diagram shows the original topography as a dark line. Flow through the area in which boreholes F1 and F2 now exist would have been downward. Oxidising water would have become reducing with greater depth. The lower diagram

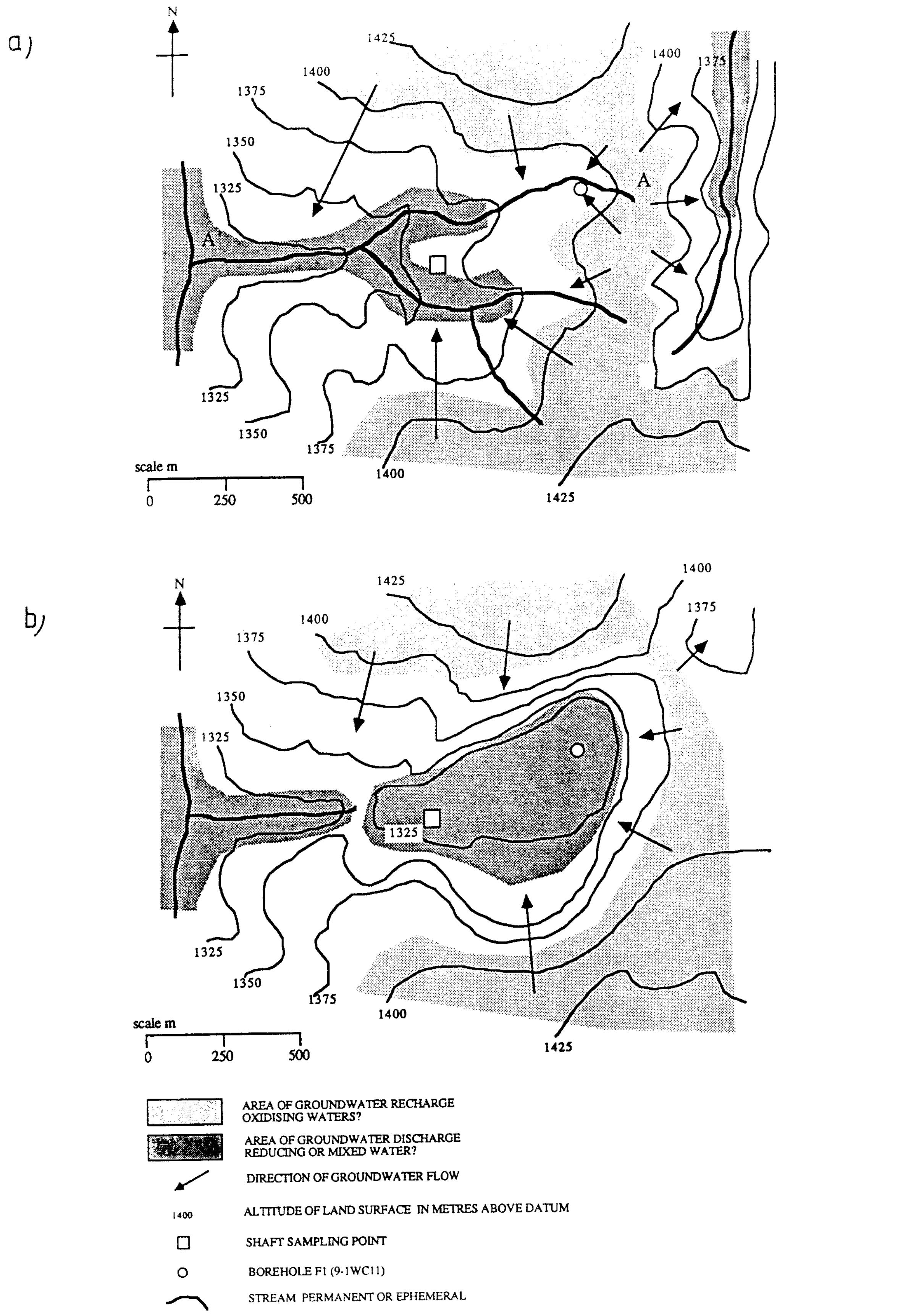


Figure 7. Sketch map of the area around the Osamu Utsumi mine showing assumed hydrogeological conditions a) prior to its excavation and b) after its excavation to 1988.

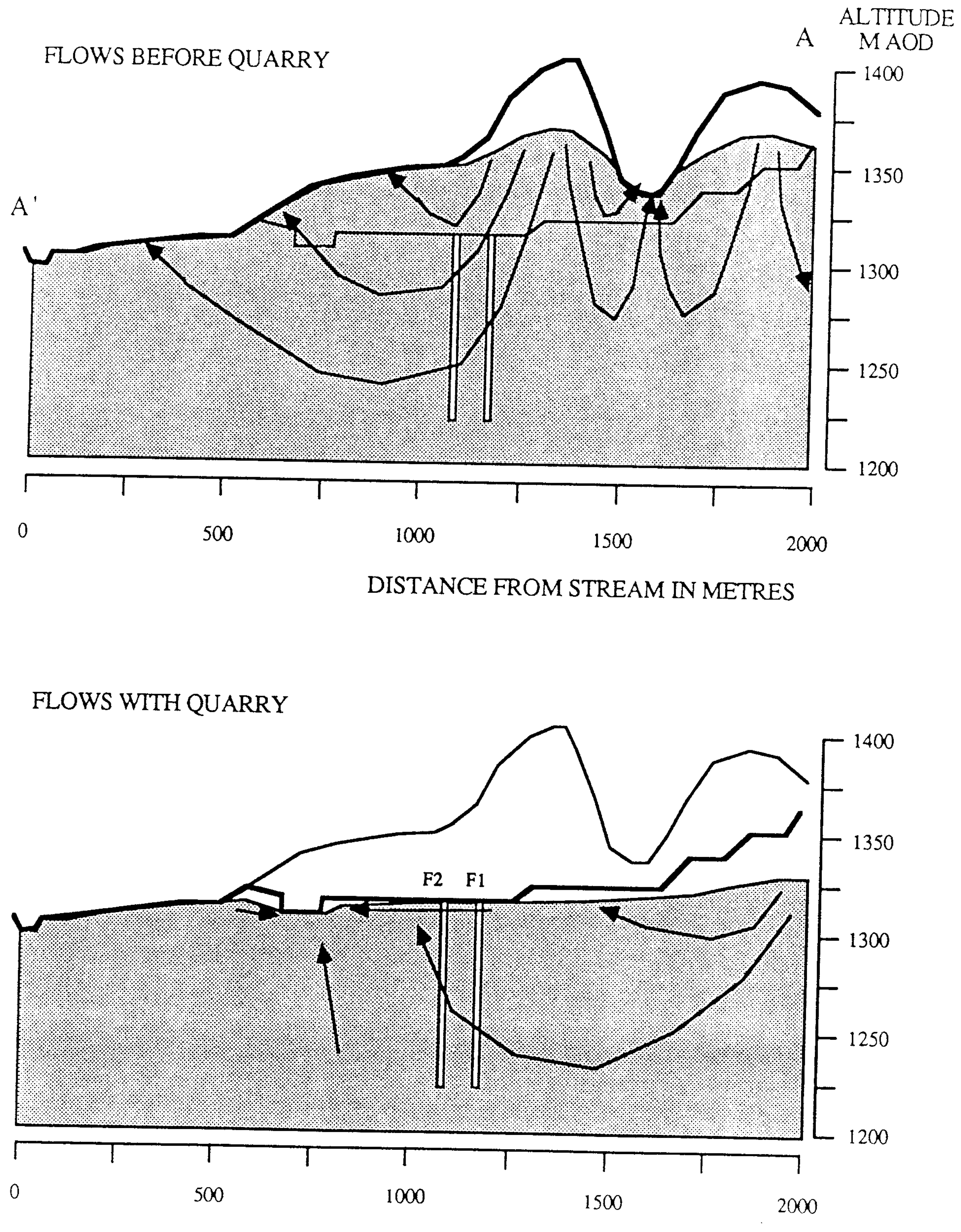


Figure 8. Cross-section of the Osamu Utsumi mine area prior to and post-excavation.

shows the present topography and groundwater flow. The same area of rock now receives the upward movement of reducing water. Flow close to the surface of the quarry is affected by blasting damage which has enhanced permeabilities and generates horizontal flows to the sump. Additionally, the flow pattern and rates will be affected by the large number of exploration boreholes drilled into the quarry floor as part of the reserve estimation programme. Such holes are drilled every 5 to 10 metres to a depth of 40 m below the floor and provide rapid flow paths for groundwater from that depth to the existing surface.

Various piezometers, sampling 5-metre-long sections at different levels in the mine, had been installed prior to this study. Water levels measured in these show a steeply dipping water-table gradient towards the mine sump. Also, those piezometers on the edge of the mine show a slight vertically downward flow gradient, whilst those near the centre of the mine show vertically upward flows. Hydraulic conductivities (the ability of the rock to transport groundwater) measured in the piezometers range from $1x10^{-10}$ to $5x10^{-7}$ ms^{-1}. Water levels responded rapidly to both seasonal rainfall and individual rainfall events.

3.1.2. Field work data collection

Various boreholes were drilled at the mine to provide access to the rock mass for making preliminary hydraulic measurements and the collection of water and rock samples. A pilot hole was drilled using a down-hole hammer driven by compressed air from the 1324 maod level in the mine. Boreholes F1 and F2 were cored at 75 mm diameter to a depth of 124 and 100 m respectively, also from the 1324 maod level. These boreholes were tested to determine the distribution of hydraulic conductivity and environmental head. Boreholes F3 and F4 were drilled for geological information and had a limited testing programme; borehole F5 was not tested. A series of shallow holes was drilled to a depth of 10 – 15 m to determine the nature of the water-table adjacent to the sump and borehole F1.

Hydraulic testing was performed using a double packer system shown diagrammatically in Figure 9. Pneumatically inflated packers with a sealing length of 1.00 m, separated by a 6.55 m straddle, were used to isolate a section of the borehole. Tests were made every 6.1 m down the boreholes. Drill-rods were used to connect the packers to the surface. During the initial testing, some leakage of water from the suspension rods was detected. Great care was then taken to seal all the rod joints using

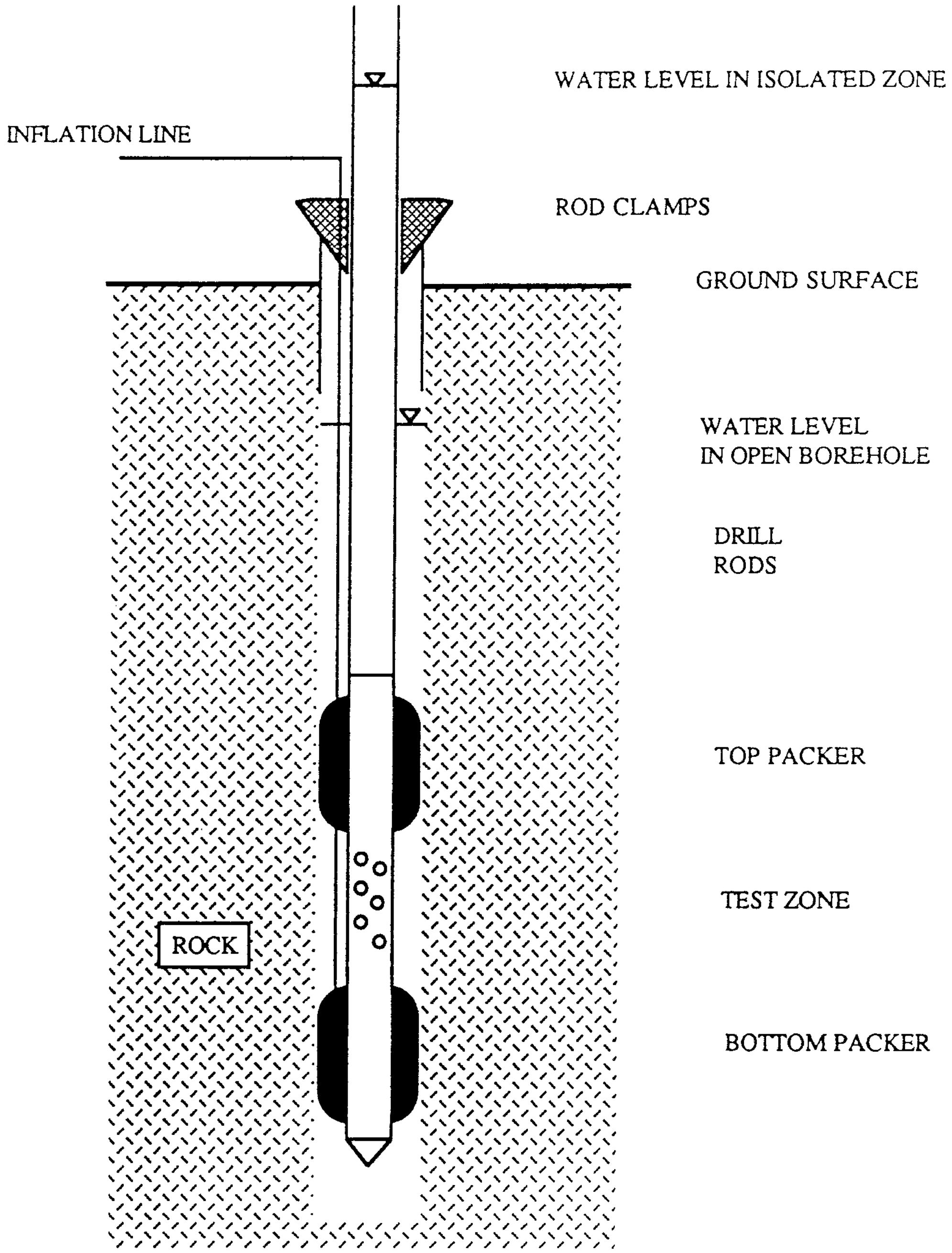


Figure 9. Equipment used in single borehole straddle packer testing to determine hydrogeological characteristics of the rock.

PTFE tape. In operation, the packers were lowered to the test interval and a water level dipper was used to measure the level of fluid both inside the rods and the borehole annulus in relation to fixed datum height. The values should be identical. The packers were inflated and the water levels periodically measured to see how they change. Any difference which develops between the measurements indicates that the packers are effectively sealing against the rock. After a period of approximately 30 minutes, each fluid level approached its own equilibrium value. The level inside the rods is a measure of the environmental head for the test section. With the head relatively stable, the hydraulic conductivity was measured using either a slug test or constant head test. In a slug test the water level in the rods is changed instantaneously using a float. The recovery level is monitored and compared with a set of type curves (developed by Cooper *et al.* (1967)) to determine a value of hydraulic conductivity.

In the constant head test, water is injected or removed from the borehole to maintain a constant head difference from the initial value. Either the change in flow rate or the flow rate under steady-state conditions can be used to calculate the conductivity. The method is presented in Walton (1962). Testing proceeded in a systematic manner to cover the entire depth of the hole. The bottom of each hole was tested beneath a single packer suspended on rods.

In several zones water was abstracted for geochemical samples using either a small diameter electric pump or by allowing the borehole to overflow naturally. Care was taken to remove a sufficient volume from the hole to ensure that water resident in the rock was collected. Also, great care was taken to ensure that the fluid was collected in the absence of oxygen.

Permanent completions, comprising a PVC 50 mm internal diameter casing string fitted with mechanical packers, were installed in boreholes F1, F2, F3, F4 and F5. Sufficient pull-down was applied to the casing string to set the packers. The isolated zones were tested by constant rate abstraction. A simpler completion, using powdered bentonite, was attempted in the pilot borehole. This, however, was only partially successful due to difficulties in emplacing the powder in the narrow borehole annulus.

The results of hydraulic testing in the pilot, F1 and F2 boreholes are presented in Figure 10. Water levels are shown as metres relative to ground level at the time of testing. Water levels are generally higher at greater depth, resulting in an upward potential for groundwater flow. The levels in borehole F1 between 50 and 90 metres below ground level (mbgl) were measured whilst still recovering to equilibrium and would have risen to higher values on longer recovery. Values for F3 are similar to those in F1 and are not presented.

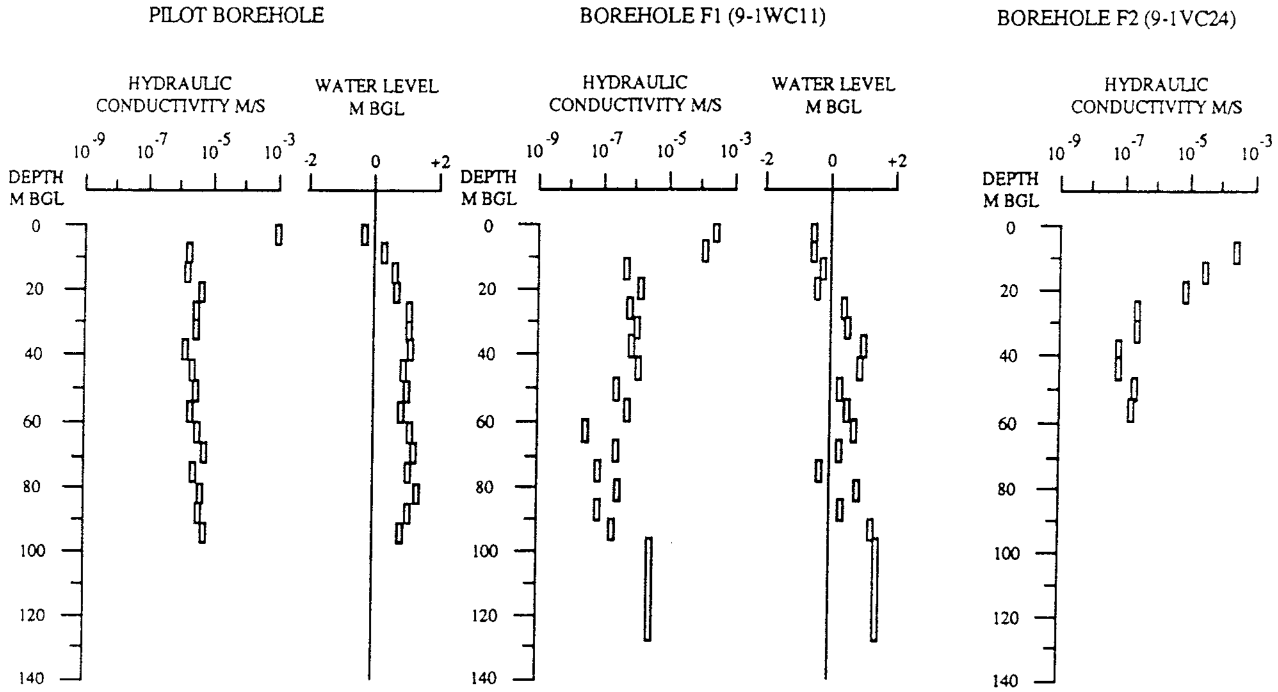


Figure 10. Profiles of hydraulic conductivity and water levels from the pilot, F1 and F2 boreholes at the Osamu Utsumi mine.

Figure 10 also shows the values of hydraulic conductivity measured in the boreholes. Values from 10 to 96 m below ground level vary from 10^{-5} to 10^{-7} ms^{-1} and show a tendency to decrease with depth. From 4 to 10 mbgl the value is very high and coincides with rock damaged by blasting. The value from 96 to 124 mbgl is also high and most water flow probably occurs around 110 mbgl, as indicated on the temperature log. The distribution of hydraulic conductivity is similar in all three boreholes. Testing in boreholes F3 and F4 was intermittent due to problems with the testing equipment. Those zones which were successfully tested yielded similar values for hydraulic conductivity. Because of economic considerations, no testing was carried out in borehole F5.

Shallow boreholes (SW1, 2 and 3) were drilled to a depth of 10 m, at distances of 25, 50 and 90 metres respectively from the edge of the mine sump on the 1324 maod level. Each of these was tested by a constant head abstraction test, over their entire saturated thickness, to determine the hydraulic conductivity. Borehole SW3 yielded a value of $8x10^{-8}$ ms^{-1} and boreholes SW1 and SW2 gave values of $4x10^{-7}ms^{-1}$. Thus the zones of high hydraulic conductivity measured in the upper 10 m in the three deeper boreholes are not found in the shallow boreholes. The values are similar to those for the rock at greater depth. As a result of nearby mining operations, these three holes were subsequently destroyed. Three new holes (SW01, SW02 and SW03) were drilled to 15 m in the near-vicinity of F1, but these were not tested.

Water levels have been monitored in various boreholes by Urânio do Brasil staff since they were drilled. Figure 11 shows the level fluctuations for boreholes F1, F2 and SW1 over a period of five months from 12 December 1987 (wet season to early dry season). The water levels respond to the seasonal recharge and rapidly to each major rainfall event. For example, the level in F1, monitored in the permanent completion at a depth of 95 – 124 m, rose by 0.4 m within 5 hours of a heavy rainstorm. The levels in F1 and F2 are higher than that in SW1, proving the existence of an upward hydraulic gradient. Figure 12 shows, diagrammatically, water levels and possible flow lines relating to groundwater movement in the lower parts of the quarry during the wet and dry seasons. The gradient is towards the sump, which is pumped, and has a steepness which is appropriate to the measured hydraulic conductivity. Water quality in the shallow boreholes will depend on the mixing of groundwater from depth with that recently derived from rainfall and flowing at shallow levels.

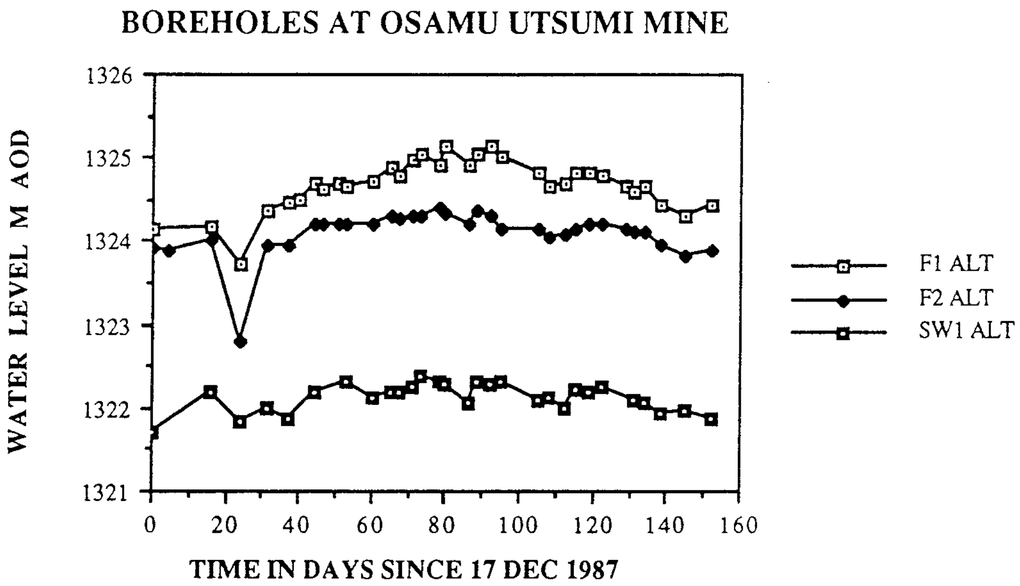


Figure 11. Water level fluctuations in boreholes F1, F2 and SW1 at the Osamu Utsumi mine.

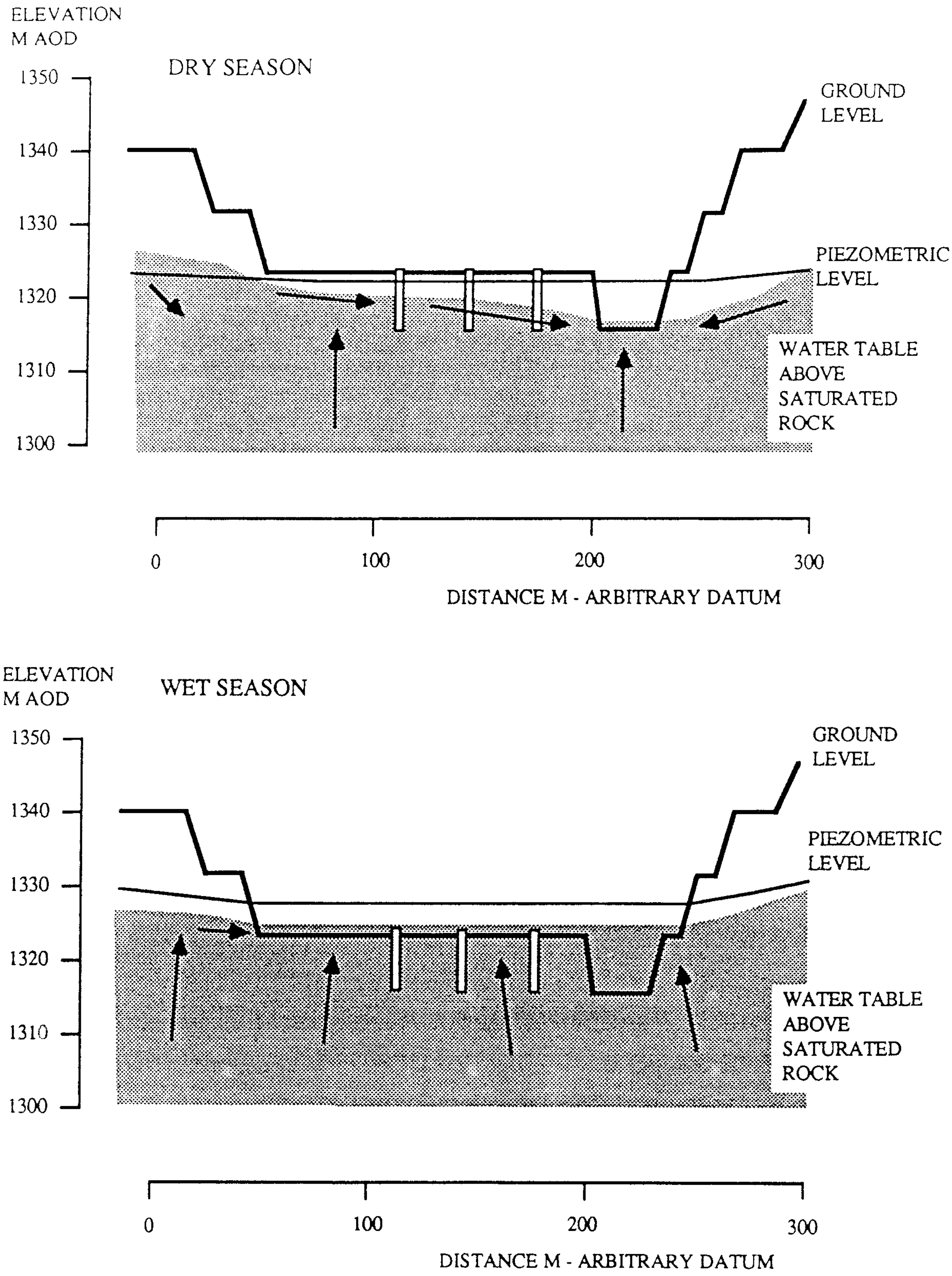


Figure 12. Cross-section of the lower excavation levels of the Osamu Utsumi mine showing relative water levels and flow paths during the wet and dry seasons.

The conclusions drawn from testing the boreholes are

1. Groundwater flow has a significant upward vertical component in the vicinity of the lower levels in the mine. This agrees with results from the desk study and indicates that the hydrogeology of the site has been greatly modified by excavating the quarry.
2. The distribution of hydraulic conductivity indicates that there are few major fracture zones in the rock. The exception occurs at 100 m where borehole F1 intersects a major flow pathway which could have a conductivity as high as $2x10^{-5}$ ms^{-1}. Flow through the rock is generally in closely-spaced fractures (less than a few metres apart), which allows the rock to be treated as a porous medium for volume calculations.

3.1.3. Mathematical modelling

Data on water levels and hydraulic conductivity collected during the desk study and field work have been used in the construction of a groundwater flow model to determine general characteristics of the scale and direction of water movement. The amount of data was small and many assumptions have had to be made in generating the model. The existing conditions have been greatly simplified. However, some of the derived information, notably on flow directions, travel times and water velocities, may be of use during the interpretation of geochemical data. It should, however, be stressed that the model should be considered as only indicating the general magnitude of flow parameters rather than providing absolute values.

This section of the report describes the construction of the model, some of the results and various conclusions on the groundwater flow at the mine.

Boundary conditions: The Osamu Utsumi mine lies at the head of a valley with high ground on three sides. As a result, the groundwater flow regime can be expected to be fully three-dimensional, and a groundwater flow model is required which can accommodate this. The TRANSFLO package (Noy, 1982; Noy, 1985) was therefore used. Two separate flow models were created, one for the flow before the mine was excavated and one for present conditions.

The high ground around much of the mine has been assumed to form no-flow boundaries. These boundaries enclose the mine on three sides but leave a length of boundary which it is difficult to specify *a priori* to the east of the mine where the small valley containing the mine joins another similar valley to the west and forms a larger valley going to the south. This length of this latter boundary can also be expected to have a critical influence on the groundwater flow in the mine area since it forms the main outflow from the modelled region. In view of these considerations it was decided to extend the model to include the small valley to the west and a length of the main valley going south, placing a specified head boundary at the end of this section. This same boundary was used for both the pre- and post-mine models, and greatly simplifies predicted flow paths in a watershed area which, in reality, has a complicated flow pattern.

The programs in use treat only the saturated zone and it is therefore necessary to specify the location of the water-table over the whole area of the model. This surface is then treated as a specified head boundary. Unfortunately data concerning the location of the water-table are sparse and it has been necessary to make systematic estimates based on simple rules. A depressed version of the topographic surface was used for this purpose as follows:

1) the water-table was placed at 50 m below the topographic surface wherever that surface is at or above 1470 maod,

ii) the water-table was placed at the topographic surface wherever that surface is at or below 1375 maod,

iii) a linearly graded depression relative to the topographic surface was used between these two heights.

This procedure gave a surface for use in the model of pre-mine conditions. For the model of present conditions, the water-table surface was further depressed to coincide with the floor of the mine.

The boundary condition used over the lower surface of the calculational grid is no-flow. The location of this surface is determined from a number of competing considerations:

i) the surface should be as deep as possible so as to minimise its influence upon the calculations,

ii) an excessive number of elements should not be used,

iii) an unduly coarse grid should not be used.

The net result of these considerations was that the lower surface was placed at a height of 1050 m above sea level – typically 300 – 400 m below the water-table surface. The complete grid consisted of 2646 linear elements arranged in 6 layers, using 3388 nodes.

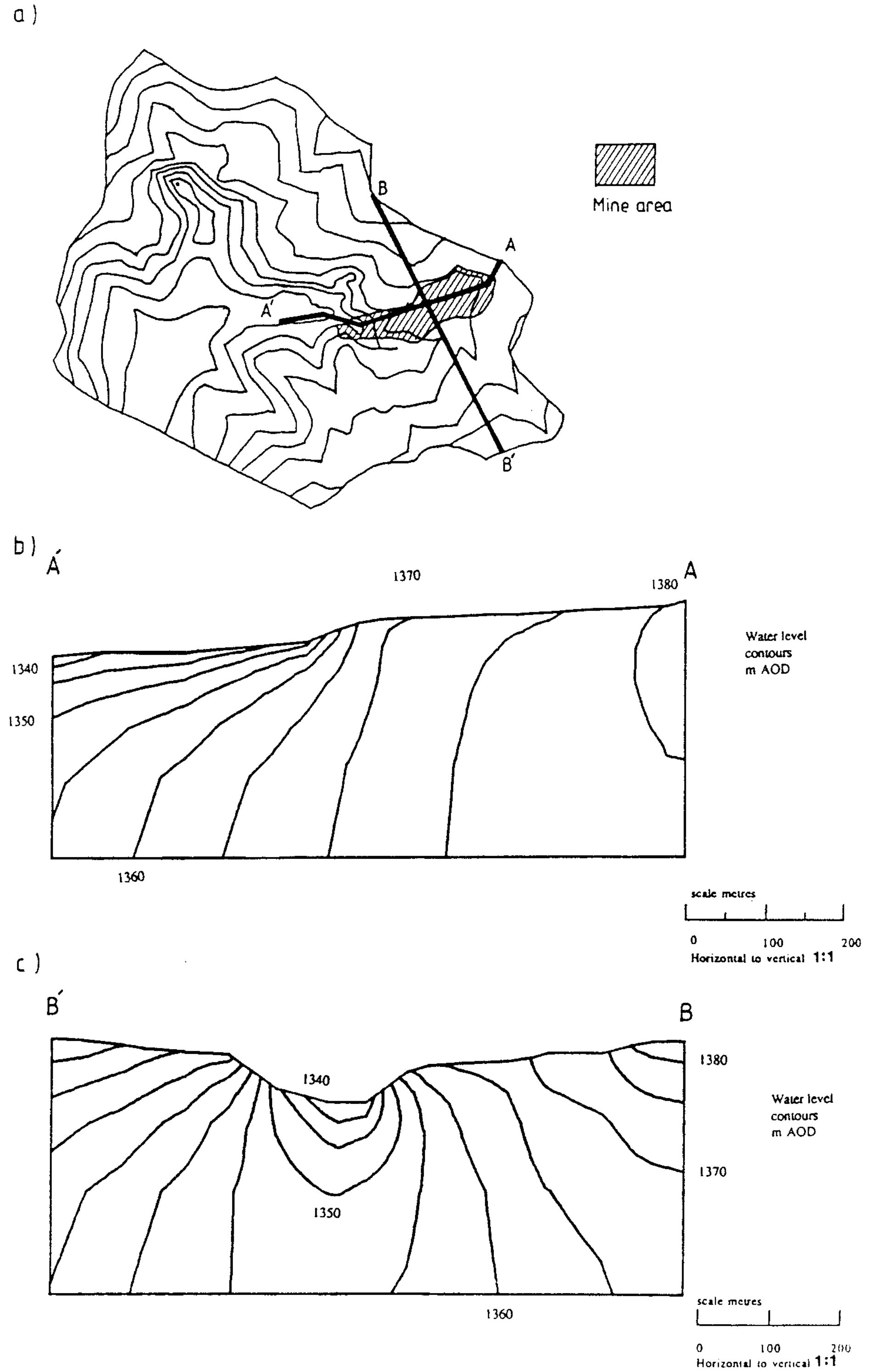


Figure 13. Pre-mine distribution of water levels generated for the Osamu Utsumi mine area (a) and vertical sections showing head distributions along the stream profile; section A-A' (b) and section B-B' (c).

Material properties: For the purposes of these preliminary calculations a uniform conductivity of 10^{-8} m/s was used. Measurements made within the mine area indicate a generally higher value, but there is little evidence as to the likely extent of this more permeable material. There is also evidence of a major fracture in one of the boreholes, but no indication of its orientation or extent. It may be noted that any change in the value of the uniform conductivity used here will have no effect on the calculated heads. Flow rates will be modified in direct proportion to the change in conductivity. A uniform porosity of 10% was used for all the pathline calculations. Changing this will also have a directly proportional effect upon flow velocities and travel times.

Results: Calculations have been performed using two separate grids of elements set up as described above. The values obtained for head are presented in a number of contour plots on selected horizontal and vertical sections. In order to assist in the visualisation of the flow field, pathlines have been traced from a number of locations and plotted as projections onto the same horizontal and vertical sections. This form of projection can cause pathlines to appear to cross. In reality, the pathlines pass at different depths. The pathlines show the route which a "package" of water would follow through the rock. In the diagrams Section A-A′ refers to a section taken along the line of a stream running through the mine and Section B-B′ refers to one running roughly perpendicular to the first.

Figure 13a shows a contour plot of the heads on the top surface for the pre-mine conditions. This is of course just the water-table used for this calculation. Figures 13b and 13c show the calculated heads contoured on the river section. Figure 14a shows the projection of a selection of pathlines onto the horizontal plane and indicates the complex three-dimensional nature of the flow field. Figure 14b, in contrast, shows that pathlines selected to be in the plane of the river section behave in a simple and predictable fashion. Flow rates in the vicinity of the current mine surface are typically of the order of 3 to 5×10^{-10} $m^3/m^2 \cdot s$ directed upwards, though the dependence of these particular values upon the material properties chosen must be emphasised.

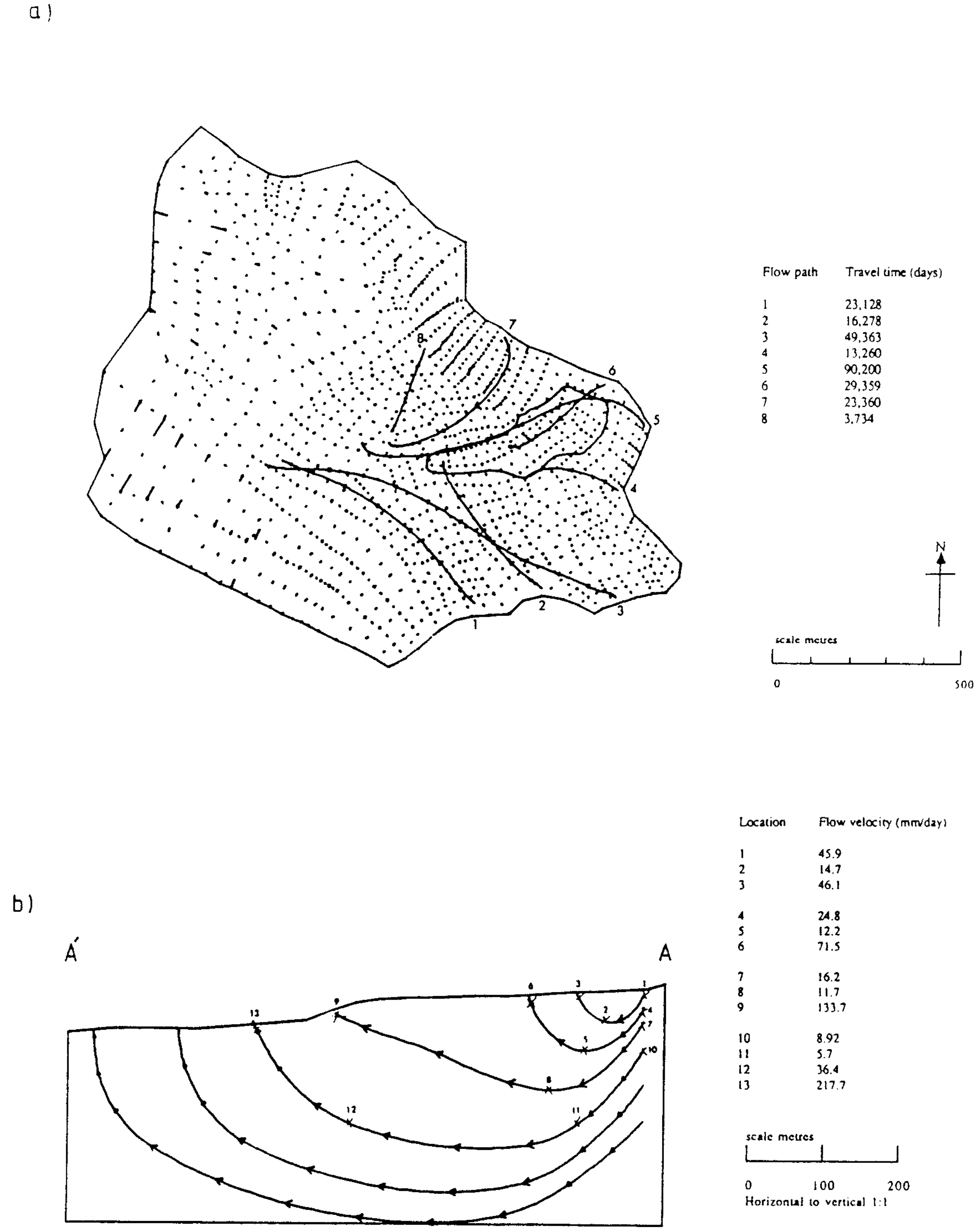


Figure 14. Pre-mine plan of valley area showing flow paths and travel times (a) and vertical distribution of flow paths along valley section A-A′ (see Fig. 13) showing point pre-velocities (b).

Figures 15 and 16 show the effects of the excavation of the mine. Figure 15a is the contoured water-table surface showing clearly the location of the mine. Calculated heads on the river section are shown in Figure 15b. The effect of the mine on the river section is very marked. This is also the case when the pathlines in Figure 16a are compared with those in Figure 14a. The pathlines chosen to run in the two sections are plotted in Figures 16b and 16c. In Figure 16b it will be seen that pathlines from locations within the river section now run almost vertically up into the mine from the bottom of the model. These paths do not, however, represent the bulk of the flow into the mine, which comes instead from the sides of the valley as shown in section B-B' (Fig. 16c). Flow rates just below the mine floor are now of the order of $3x10^{-9}m^3/m^2 \cdot s$.

Discussion: The model provides an upward flow rate into the existing mine area of about $3x10^{-9}$ $m^3/m^2 \cdot s$. The lower levels of the mine have an area of 61,000 m^2, producing a total inflow calculated by the model of 20.3 m^3/day. In reality groundwater entering the mine collects in the sump to be pumped to waste. This measured pumped volume averages 1200 m^3/day during the dry season when groundwater flow dominates inflow to the mine. The ratio between the measured and calculated flow rates, 60:1, can be used to scale the model values of hydraulic conductivity, flow rates and travel times to make them more realistic. The water-table and boundary conditions of the model are assumed to remain the same.

Scaling increases the model value of conductivity from $1x10^{-8}$ to $6x10^{-7}$ m/s. This new value is similar to those measured in the investigation boreholes and is considered to be a representative value.

Travel times and flow velocities have been calculated for several flow lines in the pre-mine and post-mine models. Scaled travel times are tabulated in Figure 14a for the pre-mine and Figure 16 for the post-mine states. In general, the construction of the mine has increased groundwater gradients and modified flow path directions. Travel times have been significantly reduced. However, vertical flow paths follow similar trends in the pre- and post-mine models as water is recharged in the high topographic areas and discharges in the valley. As the mine was constructed following the trend of the valley, its presence reinforces the general recharge pattern. However, patterns in the valley floor have been disturbed. The disturbance may be greater than the modelling suggests. There are some indications that the stream in the original valley may have been ephemeral, that is flowing in the wet season only, near the watershed. During the dry season, flow in the upper valley may have been totally underground following the direction of the surface stream.

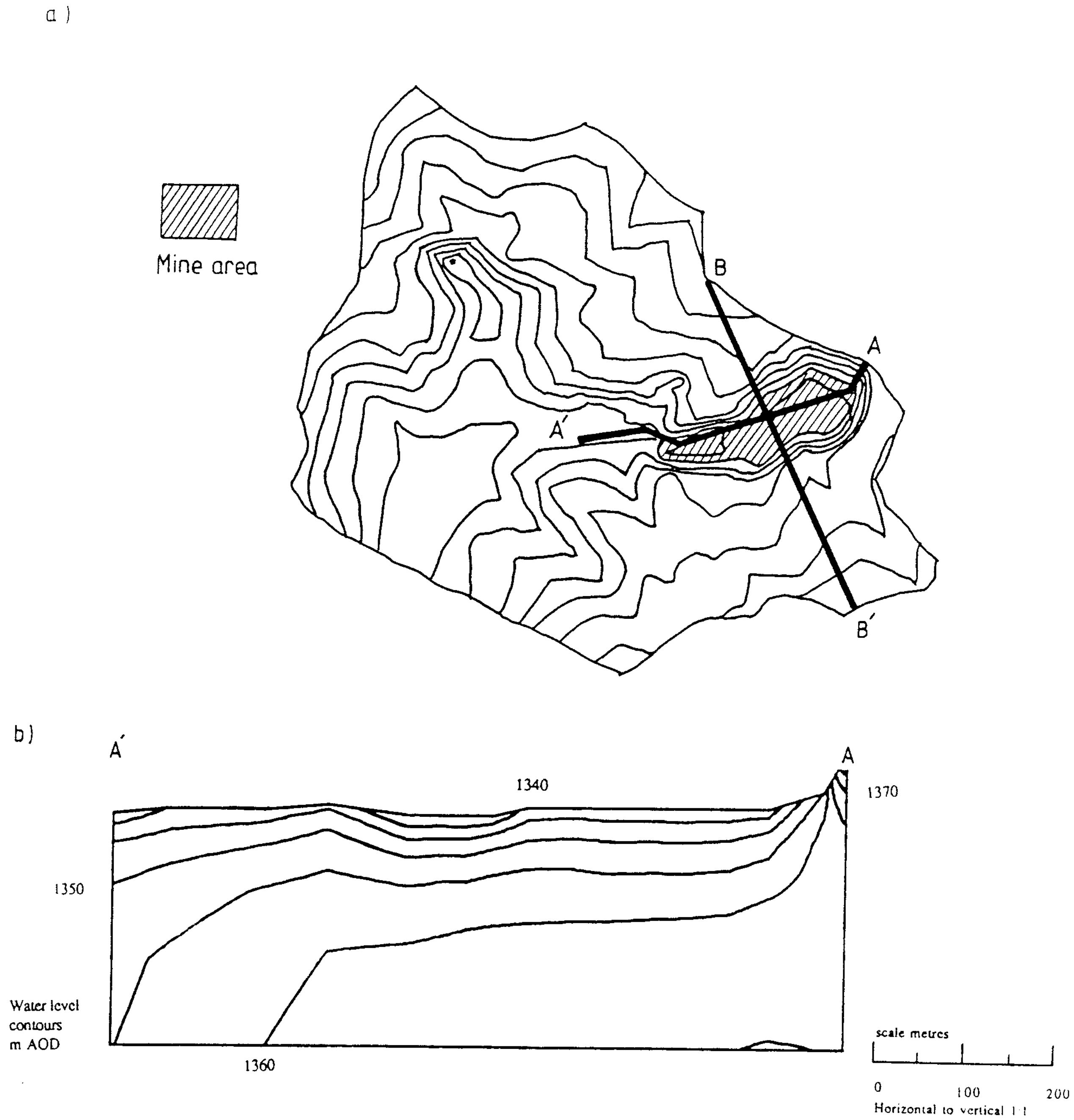
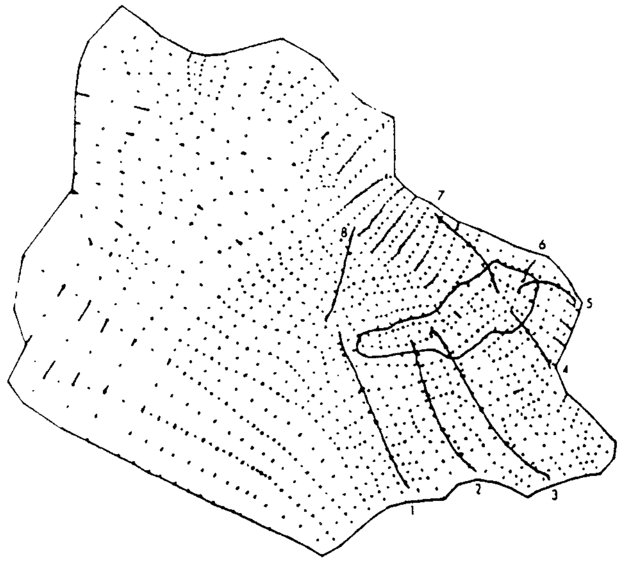
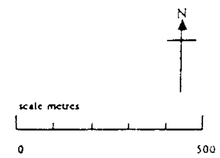


Figure 15. Post-mine distribution of water levels generated for the Osamu Utsumi mine area (a) and a vertical section (A-A') showing head distributions along the stream profile (b).

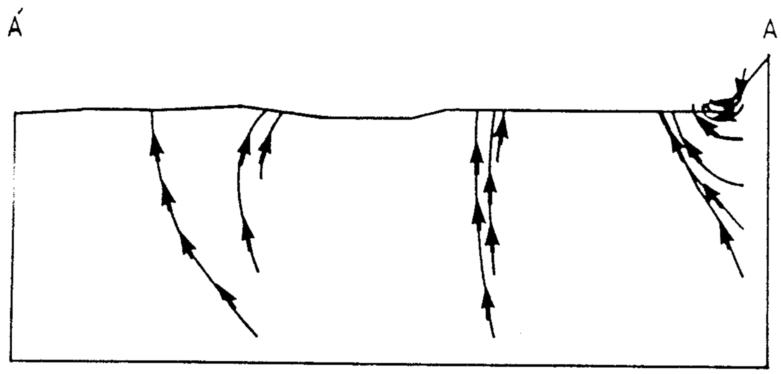
a)



Flow path	Travel time (days)
1	19,849
2	12,268
3	27,770
4	3,159
5	4,982
6	630
7	8,292
8	4,425

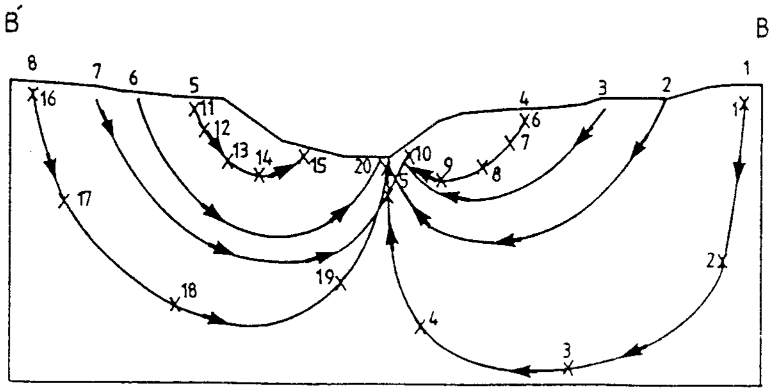


b)



Horizontal scale is 920 m.

c)



Location	Flow velocity (mm/day)
1	106.3
2	26.3
3	32.9
4	28.2
5	137.4
6	69.5
7	71.5
8	91.8
9	132.7
10	297.5
11	174.7
12	154.5
13	134.2
14	125.4
15	239.5
16	145 6
17	69.5
18	40.7
19	30.4
20	162 8

Figure 16. Post-mine plan of valley area showing flow paths and travel times (a) and vertical distribution of flow paths along sections A-A' (b) and B-B' (c). See Figure 15 for section locations.

The flow paths for the post-mine model penetrate to great depths and there is some indication that the mine has lowered local water levels to such an extent that deep groundwaters (deeper than 400 m) may be mixing with shallow groundwaters.

Flow velocities in pores, for specific points on various flow lines, are tabulated in Figure 14 for the pre-mine and Figure 16 for the post-mine states. The velocities are quite high, reflecting the high hydraulic gradients and permeabilities of the area. Velocities are higher after the construction of the mine. Generally the flow velocities exceed 20 mm/day and are considerably greater than velocities at which diffusion processes would dominate the movement of chemical species (velocities of about 0.1 mm/day). The quoted velocities are average values for large volumes of rock. On a small scale, at which chemical interactions are occurring, the calculation of velocity is more difficult. Small-scale heterogeneities caused by pore size distributions and fractures will result in a range of velocities existing in the rock. It is assumed that conductivities range from $1x10^{-8}$ m/s (Waber *et al.*, this report series; Rep. 2) to $5x10^{-6}$ m/s (measured field value), porosities range from 2 (fracture flow) to 20 percent (porous flow) and the gradient is 0.02 (field-measured). Velocities will range from 0.08 to 400 mm/day. At the lower limit some diffusive control of species movement will occur, but at the higher limit movement will occur by advective flow.

The above velocity calculations assume dry season conditions. During the wet season hydraulic gradients increase significantly. Measurements at the mine are not reliable but results from Morro do Ferro show that gradients increase by up to 25%. Flow velocities may be expected to increase by a similar percentage at the mine.

Conclusions: A three-dimensional flow model of the mine area has been constructed from sparse data on water levels and hydraulic conductivities. Results have been scaled or calibrated using measured outflow values. Travel times, flow paths and velocities calculated by the model can only provide a general indication of groundwater flow in the area. More specific modelling would require the collection of far more information. However, the model has yielded some useful findings. Firstly, the topography controls groundwater flow which moves towards the axis of a stream valley. The excavation of the mine has reinforced this general flow pattern although the pattern in the valley bottom has been greatly disturbed. Secondly, travel times and velocities, both pre- and post-mine excavation, are relatively high, indicating that advection rather than diffusion controls the movement of chemical species. Residence and interaction times are, probably, quite short and should be measured in days rather than years.

3.2. The Morro do Ferro area

3.2.1. Desk study and previous work

Morro do Ferro is one of the highest points on the caldera. Topographic maps, supplied by Urânio do Brasil, show that the hill is steep-sided and bounded by deeply incised streams which drain the groundwater as can be seen on the sketch map (Figure 17). From previous work reported in IPT (1984), in which 9 piezometers were drilled to sample the upper part of the saturated zone, the water-table appears to be a subdued reflection of the topography. Magnetite dykes, which run across the hill, appear to distort the water-table to a limited extent. At the top of the hill the water-table is at least 80 metres below the surface. In the valley bottoms the water-table is at or near the surface, occurring as seepages or discrete springs.

Figure 18 shows diagrammatically the relationship of the water-table to the topography. The difference in water levels between the wet and dry seasons appears to be at least 20 metres under the central part of the hill. This represents the water which is stored and slowly released as base flow to the stream. Rainwater enters the aquifer by percolating through the unsaturated zone until it meets the water-table. Under the hill, flow will continue downwards, maintained by a vertical component in the piezometric gradient. Near the stream the flow direction will change as water drains into the water course. This groundwater should have had the longest residence time in the rock mass and therefore have experienced the greatest chemical changes. The groundwater under the hill may have penetrated the rock mass to some 100 metres or more below the level of the stream.

3.2.2. Field work data collection

Figure 18 shows the three boreholes drilled for the field investigations. MF10 was designed to recover good core from the mineralised zone in the ore body and provide access for making hydrogeological measurements. The rock was very friable and tended to wash out with standard drilling techniques using water as a flushing medium. Therefore, a simple dry-pushing method was employed using a short barrel. This slow technique achieved good recovery to below the water-table, which was intercepted at a depth of 28.62 m below ground level. Below a depth of 35 m the borehole walls started to collapse and it became necessary to use a metal casing to support the rock as drilling proceeded. Below approximately 60 m, water-flush drilling with a double-wall barrel was

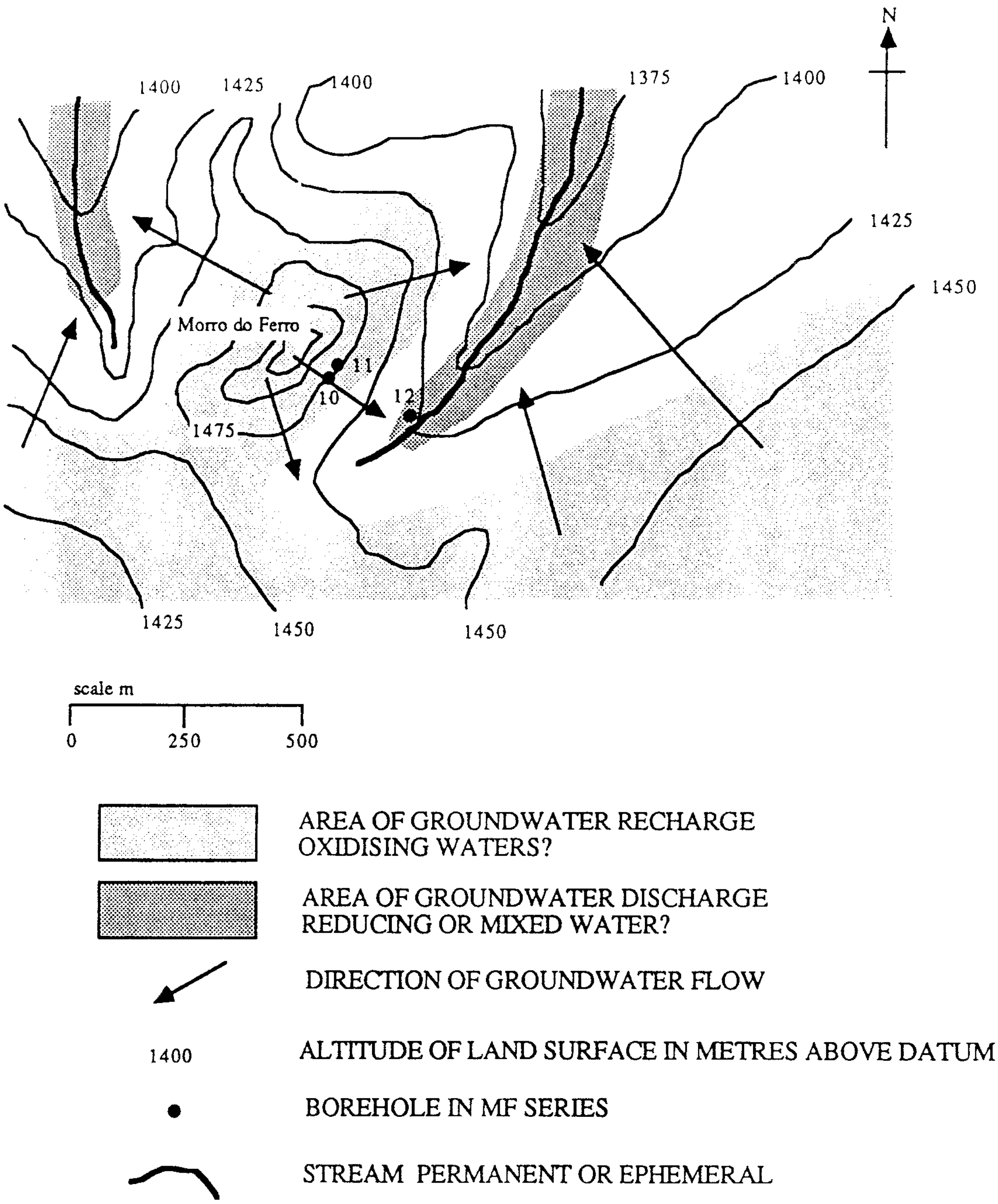


Figure 17. Sketch map of Morro do Ferro showing assumed hydrogeological conditions.

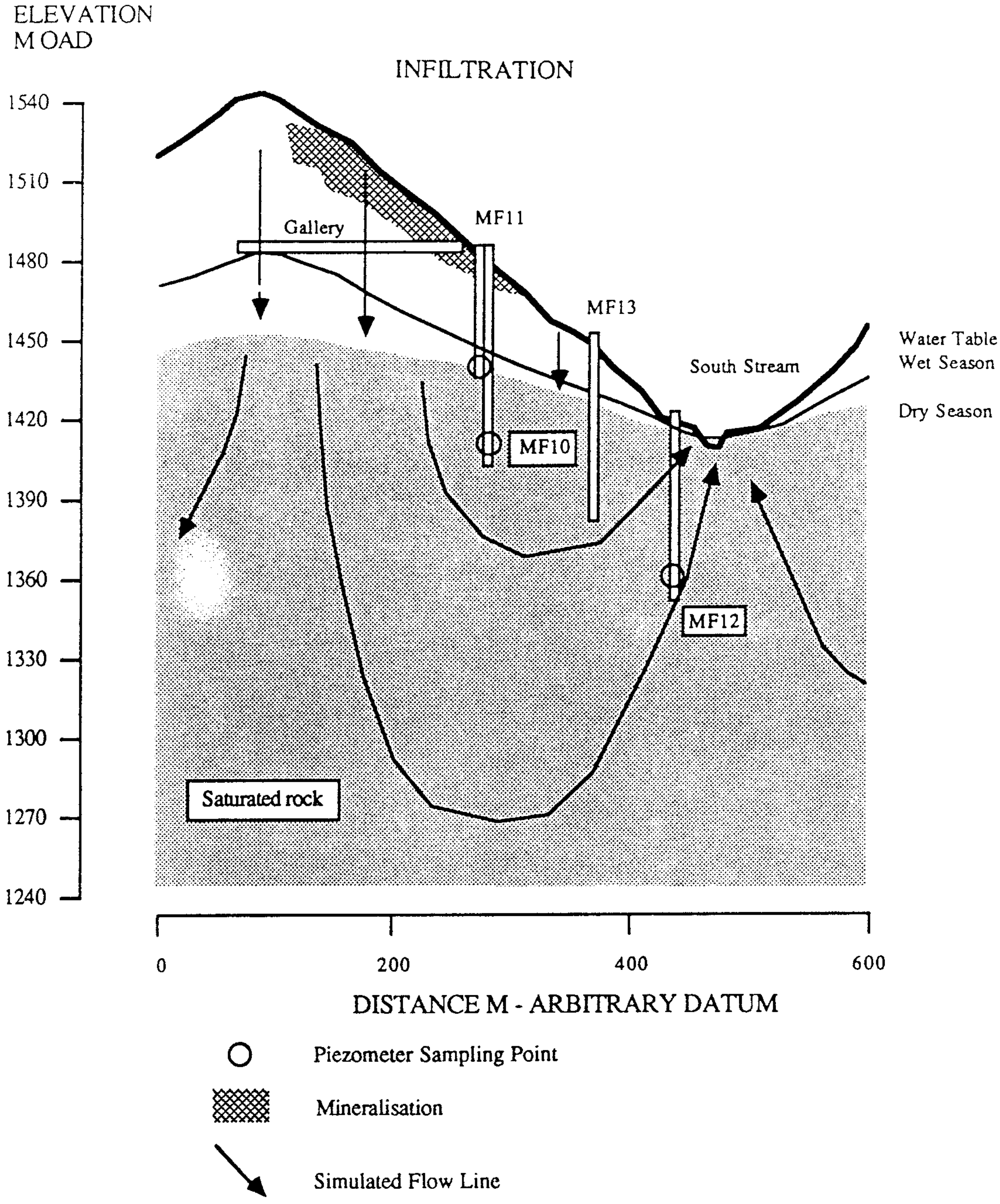


Figure 18. Cross-section through Morro do Ferro.

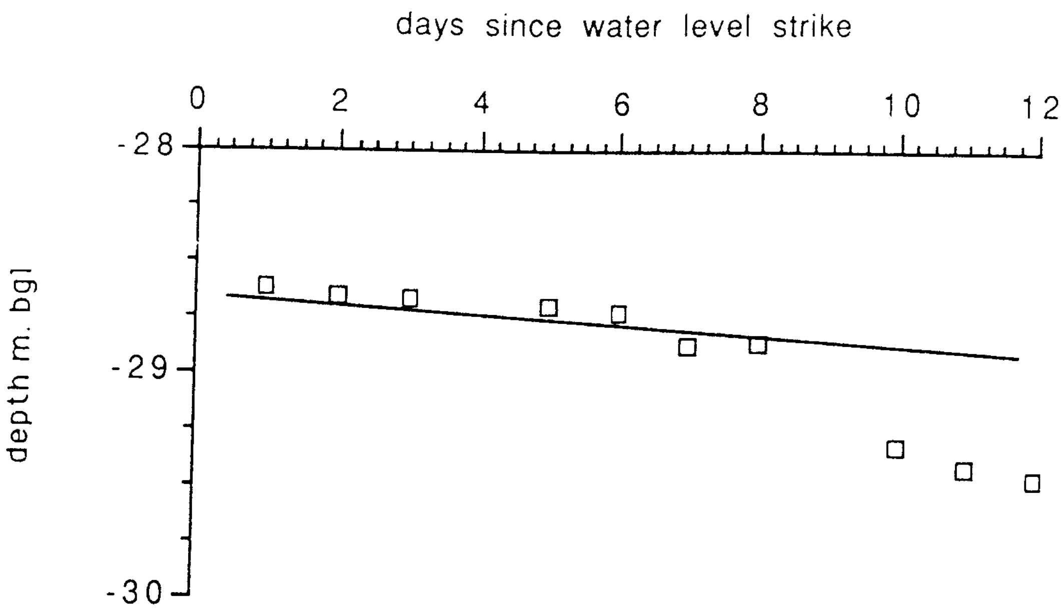


Figure 19. Water-level fluctuations in MF10 while drilling.

employed. Recovery of core was reduced but drilling was more rapid. When the borehole was at a depth of 74 m, with metal casing installed to 62 m, the borehole experienced a severe cave-in near the bottom. Additionally, the casing became firmly stuck and could not be removed. The difficult drilling conditions and unstable wall made straddle packer testing impossible. Some simple slug tests were performed in the open hole as drilling progressed. A packer with a plastic casing string was installed within the casing of the borehole to sample the groundwater at a depth of about 70 metres.

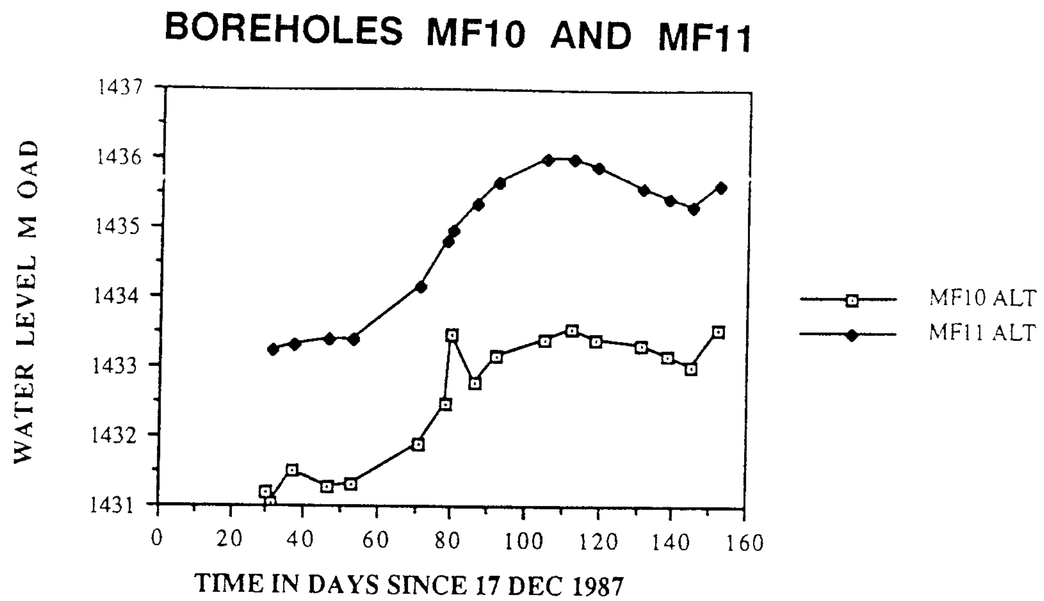
Figure 19 shows water level data collected by dipping the borehole every morning before drilling started, measured in days since first water level strike. Days 0 to 8 show a steady drop in the level, reflecting the general recession of the water-table as water is lost from the aquifer to the base flow of the stream. By day 10 the casing was at a depth of 62 m below ground level and had become stuck in the borehole. Fine-grained rock material had fallen behind the casing and formed a hydraulic seal. Thus the water level from days 10 to 12 represents the value found between 62 and 74 m depth in the rock. This level is about 0.5 metres lower than that measured at first water strike. There appears, therefore, to be a significant downward vertical hydraulic gradient adjacent to the borehole. This was verified by completing MF10 at 70 m and drilling another hole close by to sample water at about 40 m.

Two values for hydraulic conductivity were also measured in the borehole. The first was made when the hole had penetrated the water-table to a depth of about 6 m (28.62 to 34.94 mbgl). A slug test was performed by raising the water level using a metal rod. A value of 1.6×10^{-5} ms^{-1} was determined. 100 litres of water was also collected at this depth for geochemical analysis. A second slug test was performed in the borehole using a single packer to isolate the lower section of the borehole from 64 to 74 mbgl. This yielded a value of 1×10^{-6} ms^{-1}.

Borehole MF11 was drilled immediately adjacent to MF10 to a depth of 40 mbgl to sample groundwater in the vicinity of the water-table for comparison with the deeper water sampled by MF10.

Another borehole, MF12, was drilled adjacent to the valley bottom (see Fig. 18). Friable rock was encountered to a depth of 27.52 mbgl and was succeeded by more competent rock to the final drilling depth of 71.00 m; a redox front was intercepted at 35.71 mbgl. The upper part of MF12 lost significant volumes of fluid during drilling and is assumed to have a high hydraulic conductivity. Drilling problems meant that the zone from surface to 40 mbgl could not be tested.

The competent nature of the rock allowed some straddle packer tests to be attempted and hydraulic conductivity values of 3×10^{-7} ms^{-1} were measured from 40 to 57 mbgl. From



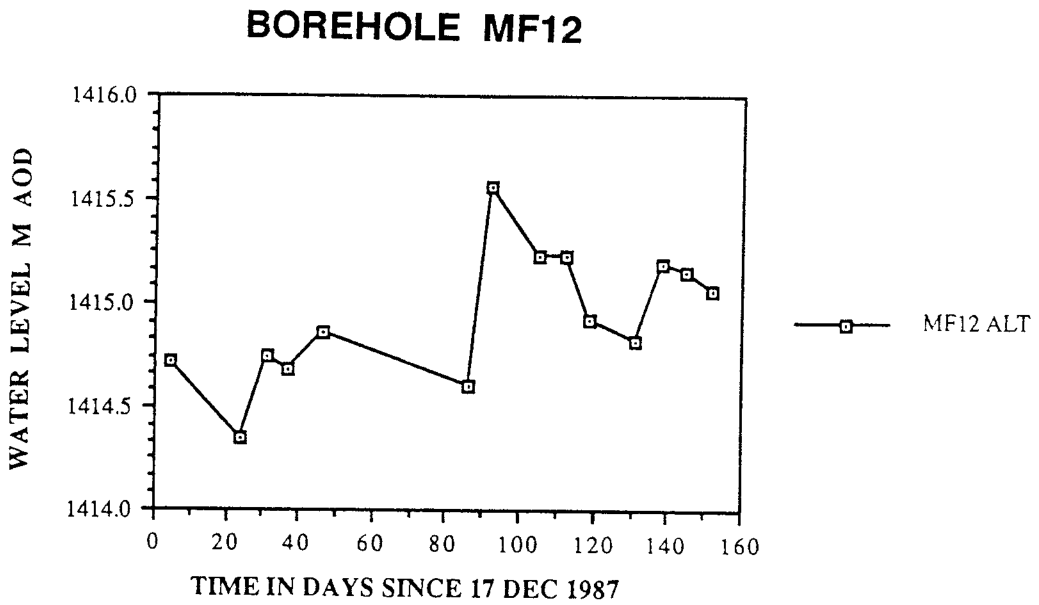


Figure 20. Water-level fluctuations in boreholes MF10, MF11 and MF12 at Morro do Ferro.

58 to 64 mbgl, in competent rock, the value dropped to $7x10^{-9}$ ms^{-1}. Water levels measured during the testing indicated an upward vertical groundwater flow, as would be expected adjacent to the stream. The extent of the vertical gradient remains to be established. A permanent completion, with a mechanical packer, sampling the lower part of this borehole from 45 to 71 mbgl has been emplaced.

Water levels were monitored in the MF series boreholes for a five month period from December 1987 and the results are presented in Figure 20. MF10 and MF11 show a rise of some 2.5 m over this period. The level in MF10 is consistently some 3 m below that in MF11, showing that a marked vertically downward gradient exists. The level in MF12 rase by some 0.75 m over the same period, reflecting the closeness of the borehole to the discharge point in the stream bed.

3.2.3. Mathematical modelling

The limited data from the desk study and field investigation have been used to construct a mathematical model of the Morro do Ferro site to determine flow rates and directions.

Boundary conditions: As interest concentrated on the single hillslope, a two-dimensional model was selected using a cross-section of the water-table from under the hill, through boreholes MF10 and MF12, to the stream as the boundary. The unsaturated zone above the water-table was not considered.

Material properties: The rock mass is assumed to have a homogeneous hydraulic conductivity of $5x10^{-6}$ ms^{-1} and a porosity of 0.3. This porosity is assumed to reflect the weathered nature of the rock. An area some 30 m deep adjacent to the stream is assumed to have an enhanced hydraulic conductivity of $1x10^{-5}$ ms^{-1}.

Flows were determined for two steady-state conditions; the first with the water-table fixed for the dry season and the second with an elevated water-table reflecting wet season conditions. The latter water-table was calculated by raising the water divide some 15 m and leaving the stream fixed. Points in between were raised in proportion.

Results: For each calculation, a series of pathlines was traced which allowed an assessment to be made of the flow rates which can be expected in various parts of the section. In particular, flow rates in the vicinity of the bottom of MF10 were found to be $1.16x10^{-7}$ $m^3/m^2/s$ (dry season) and $1.29x10^{-7}$ $m^3/m^2/s$ (wet season). The pore-water

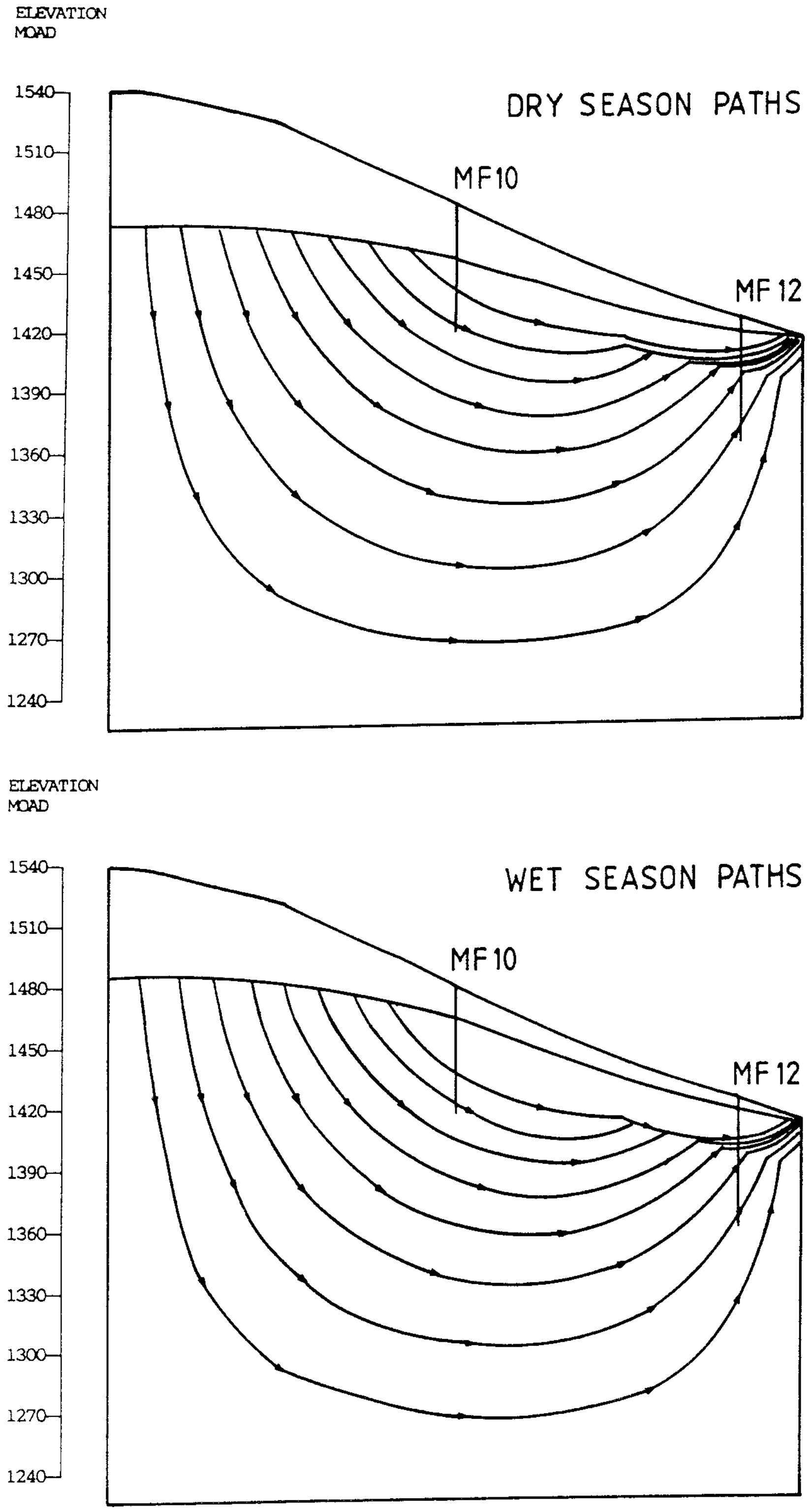


Figure 21. Hydrogeological modelling at Morro do Ferro.

velocities for mass transport calculations are obtained by dividing these values by the porosity. Thus, velocities vary between 33 and 37 mm/day. A package of water starting at the surface of the water-table near MF10 would take approximately 10,000 days to reach the stream; from the water divide at the top of the hill it would require about 20,000 days. Figure 21 shows pathlines generated by the modelling. The effects on these pathlines of the enhanced conductivity zone close to the stream can be clearly seen. There is little difference between the wet and dry seasons.

4. Conclusions

Geomorphological evidence indicates that the land surface of the Poços de Caldas plateau has been eroding at an average rate of 12 m per million years for the last 10 million years. The penetration of the redox front, a product of the deep weathering in the tropical climate, has probably keep pace with the land erosion. The groundwater table is generally a subdued reflection of the topography. This is certainly the case at Morro do Ferro where rainfall recharges on the hillslopes and flows underground to emerge as base flow in the valley bottoms. Water levels respond to seasonal rainfall and individual rainfall events. This simple pattern was also found in the area adjacent to the Osamu Utsumi mine. Excavation of the mine has significantly disturbed the natural flow patterns. Reducing groundwaters now well up through rock which originally received downward-moving oxygenated waters.

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