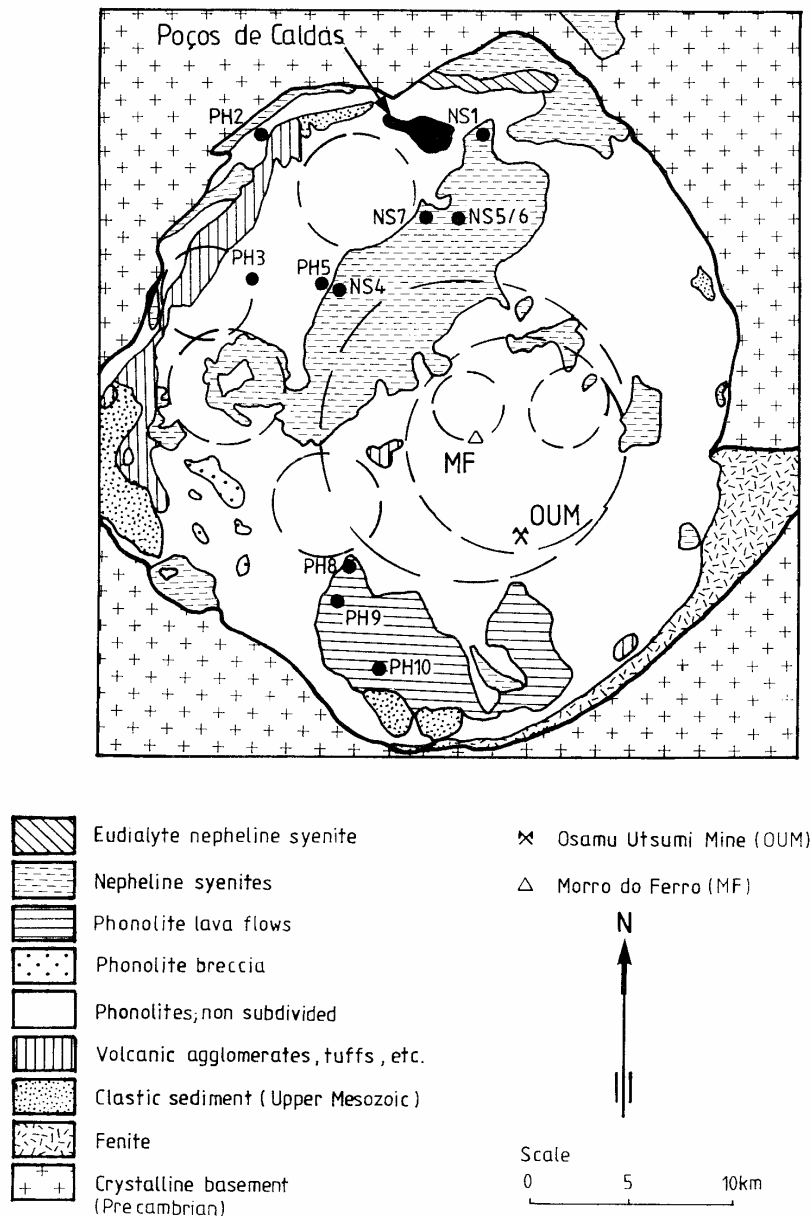


## Morro do Ferro (Poços de Caldas, Brazil)

**Description:** The study at Morro do Ferro formed part of the overall Poços de Caldas Project that was carried out from 1986 to 1990 (Chapman et al, 1992) and was sponsored by SKB, Nagra, UK DoE and the US DOE. Morro do Ferro is located in a ring structure or caldera of Mesozoic age comprising a suite of alkaline volcanic and plutonic rocks (phonolites and nepheline syenites) containing variable amounts of U, Th and Rare Earth Elements (REEs) (Figure 1). The site was already the subject of prior scientific interest since it is one of the most radioactive surface localities in the world where biological up-take studies have been a focus.



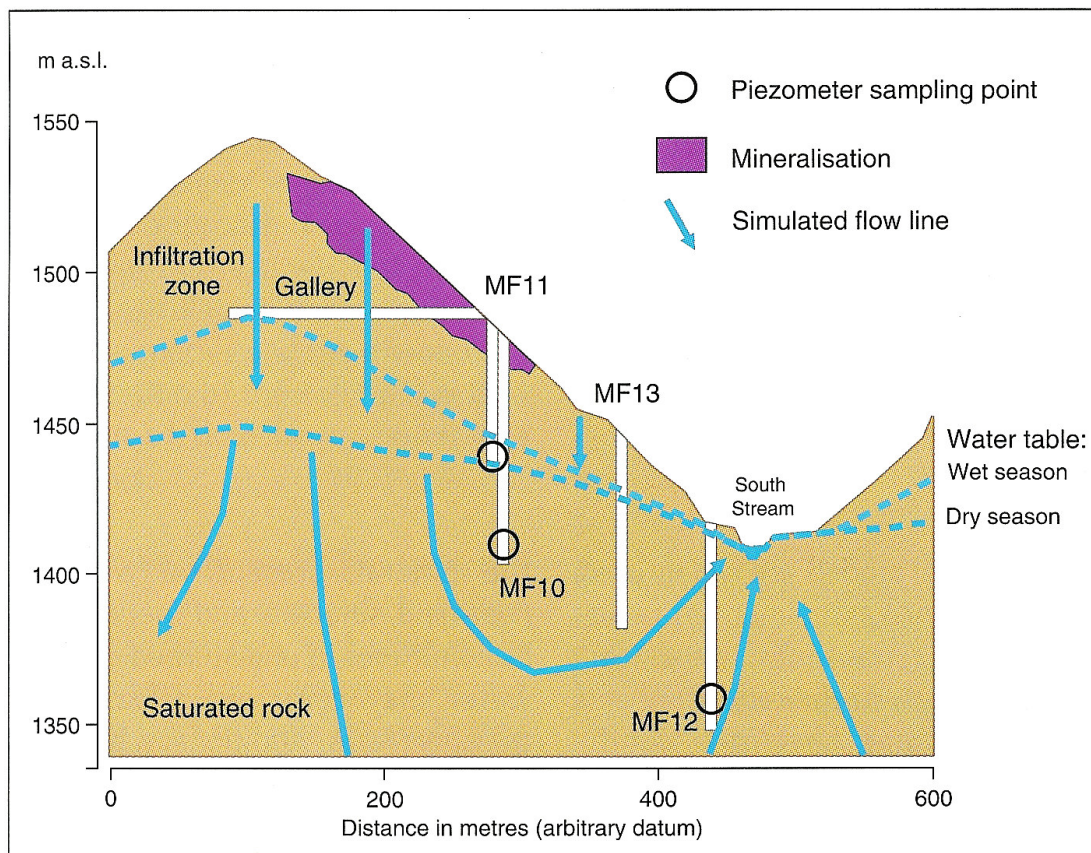
**Figure 1:** Simplified geological map of the Poços de Caldas caldera showing the major rock types and the location of the Morro do Ferro site

Morro do Ferro is a deeply weathered, topographically isolated hill, characterised by a resistant vein breccia of magnetite, and hosting a rich thorium/REE mineralisation with subordinate uranium just below the surface extending from the summit down the south slope of the hill (Figure 2). Studies have indicated that this site may represent a carbonatite complex, intruded into phonolite

rocks similar in texture and composition to those described from the Osamu Utsumi mine. Phonolite was intercepted by borehole MF12, located at the foot of the hill.

Weathering has produced an extensive laterite horizon which now contains the mineralisation. Alteration products such as gibbsite, kaolinite and illite dominate, together with iron and manganese oxyhydroxides. In addition to distinct Th - and REE-bearing mineral phases (e.g. cheralite and thorite), both uranium, in particular, and thorium, are associated with these oxyhydroxide phases which commonly exist as coatings on the clay minerals.

REE chemistry shows a not unexpected correlation with the Th/REE mineralogy; in particular thorium is best correlated with cerium. The correlation of uranium is more variable reflecting its association with the oxyhydroxide coatings on clay minerals, rather than with specific radioactive minerals. Normalised LREE patterns highlight a striking difference in the predominance of positive cerium anomalies in the unsaturated zone (upper 25 m), compared to negative cerium anomalies in the saturated zone. This may indicate a relict from the earlier migration of a redox front.



**Figure 2:** Schematic cross-section through Morro do Ferro showing the surface mineralisation, the gallery, the simulated groundwater flow paths and the location of the project boreholes (MF10-13) (after Nagra, 1993).

Natural decay series data show that near the laterite surface uranium is being lost by a combination of bulk leaching and preferential removal of uranium, the latter also evidenced down to at least 64 m depth. In the phonolite rock at the foot of the hill, the oxidised section (including the overlying laterite horizon) shows uranium accumulation. The deepest sample from the reduced phonolite has isotopic ratios close to secular equilibrium. Studies of radium show that it is either retained where it is radiogenically produced, or is migrating very slowly relative to its decay rate.

The hydrogeology of Morro do Ferro is simple and supports many of the mineralogical, geochemical and natural series distribution observations reported (Figure 2). The water table is a subdued reflection of the topography. Oxidising rainwater percolates through the unsaturated zone to the water table, whereupon flow continues downwards maintained by a vertical component in

the piezometric gradient, and the groundwater becomes increasingly reducing in character. Discharge is mainly upwards at the basal stream. This is reflected by the groundwater chemistry collected at the base of the hill (i.e. longer residence times, greater dissolved ionic content), and supported by the tritium and stable isotope data.

The two major technical objectives from studies at Morro do Ferro were:

- a) To test geochemical equilibrium thermodynamic codes and databases used to evaluate rock/water interactions and the solubility/speciation of trace elements; and
- b) To determine interactions of natural groundwater colloids, trace elements and mineral surfaces and their significance with respect to radionuclide transport processes.

Morro do Ferro, despite being a worst case scenario, i.e. mineralisation at and close to the surface, tropical climatic oxidising conditions, and different mineralogy (illite dominated) to most clay-based disposal concepts, the fact that there is still a mineralisation under these extreme conditions points to the efficiency of the 'clay' host rock to immobilise Th and REEs.

**Relevance:** The deep weathering at Morro do Ferro provides a closer comparison with a clay-based repository host rock (and clay backfill material); only at the drainage baseline at the foot of the hill is unweathered fractured crystalline rock encountered. In this respect, with knowledge of the precise sources of U, Th, REEs and colloid material (near-field analogy), the near- and far-field transport and retardation behaviour of these trace elements as chemical analogues could be evaluated along known groundwater flow pathways. In particular, the efficient filtering of colloid material by the clay-based host rock was demonstrated.

Furthermore, since the main source of radionuclides and trace elements are located in the unsaturated zone, the analogue has potential relevance to unsaturated disposal concepts.

**Position(s) in the matrix tables:** The Morro do Ferro study belongs to the 'Radionuclide Migration at Low Temperature' box of the geosphere matrix under advective saturated and unsaturated conditions. It also falls under 'Radionuclide Migration/Retardation in Barriers' boxes within the near-field matrix.

**Limitations:** Most aspects of the Morro do Ferro site are at variance with a clay-based repository rock environment (e.g. close to the surface, oxidising/marginally oxidising groundwater environment, dissimilar mineralogy).

**Quantitative information:** No quantitative PA information was obtained. Mostly confidence building information, i.e. the potential role of colloids in radionuclide and trace element transport and retardation by confirming/identifying relevant FEPs and their contribution to scenario development. Generally, colloids were used qualitatively to support the assumption that they do not constitute a major problem to repository PA.

**Uncertainties:** On a scale of low-medium-high, the uncertainties are assessed as being medium because of the difficulties of establishing boundary conditions to the processes studied.

**Time-scale:** The time-scale addressed by the study is geological, both Quaternary (<2 Ma) and beyond (>2Ma).

**PA/safety case applications:** Examples of their use in published PA include:

- TVO Use of colloidal information

With respect to PA-related modelling:

- SKB-91 Radionuclide solubility model testing (BPM)

Support that colloids are not a problem.

- TVO-91 Use of colloidal information for model development
- Kristallin-1 Radionuclide solubility model testing (BPM)
- EN2002 Support that colloids are not a problem.

**Communication applications:** Previous uses of the analogue in communication and dialogue material for different audiences include official SKB and Nagra brochures, the SKB mobile exhibition and its inclusion in the CEC-coordinated natural analogue video ('Traces of the Future').

**References:**

Chapman NA, McKinley IG, Penna Franca E, Shea ME and Smellie JAT (1992) The Poços de Caldas Project: An introduction and summary of its implications for radioactive waste disposal. *J. Geochem. Explor.*, 45, 1-24. *In:* NA Chapman, IG McKinley, ME Shea and JAT Smellie (eds.), The Poços de Caldas Project: Natural analogues of processes in a radioactive waste repository. Special Issue of *J. Geochem. Explor.*, 45, pp 603.

Nagra (1993) Poços de Caldas: Nature's experiments. *Nagra Bulletin* (1/93).

**Added value comments:** The analogue could be better used with respect to a clay-based host rock, especially in the saturated EDZ where there is limited oxidation (from radiolysis) and mobilisation and retardation of radionuclides, REEs and other trace elements that can be considered analogous to canister corrosion products. In this respect, these data could be used to test a new generation of geochemical codes looking at speciation, solubility control, precipitation/co-precipitation, surface complexation, *in-situ* Kds and organic complexation etc.

**Potential follow-up work:** Colloid filtration is not yet fully understood and more material from the unsaturated/saturated interface (where most of the filtration is thought to take place) would be worthwhile. In addition, hydraulic tests (particularly tracer testing) is necessary to confirm the groundwater flow paths to ensure that filtration is actually taking place rather than tapping into an unknown down-gradient pathway devoid of colloid material.

**Keywords:** Thorium, rare earth elements, colloids, model testing.

**Reviewers and dates:** John Smellie (June, 2004), John Dalton (January 2005)