INTERNATIONAL ATOMIC ENERGY AGENCY
COMISSÃO NACIONAL DE ENERGIA NUCLEAR
EMPRESAS NUCLEARES BRASILEIRAS S.A.

INTERREGIONAL TRAINING COURSE
ON
EXPLORATION DRILLING AND ORE RESERVE
ESTIMATION FOR URANIUM DEPOSITS

APRIL 22 - MAY 16, 1985
POÇOS DE CALDAS, MINAS GERAIS
BRAZIL
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BRAZILIAN URANIUM DEPOSITS

L.C. SURCAN SANTOS
NUCLEBRAS - BRASIL
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NUCLEBRÁS - BRAZIL
For a period of about thirty years, since the creation of the Comissão Nacional de Energia Nuclear (CNEN) which was superseded by NUCLEBRÂS, the systematic uranium exploration in Brazil led to the discovery of several uranium targets.

Many of them were developed to the stage of drilling and can be considered as promising uranium concentrations or deposits like Amorinópolis (Devonian sediments) Campos Belos / Rio Preto (faulted and folded précambrian) and Alecrim (albitites) in Goias state; the quartz-pebble conglomerates in the Quadrilátero Ferrífero, Minas Gerais state (Gandarela and Gaivotas Projects); cretaceous sediments of Tucano Basin in Bahia and others.

Here it will only be considered the areas in which detailed ore reserves calculations were made, in other words, the uranium ore deposits as such.

These are: Figueira, Itataia, Lagoa Real and Espinha-ras.

Poços de Caldas that is under mining operation will be discussed elsewhere in this course.
### Location of Uranium Mines and Ore Deposits

![Map of Brazil highlighting uranium mines and ore deposits.](image)

### Uranium Reserves (Metric Tons of $U_3O_8$)

<table>
<thead>
<tr>
<th>Ore Deposits / Mine</th>
<th>Reasonably Assured</th>
<th>Estimated Additional</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cercado Mine (Osamu Utsumi)</td>
<td>20.000</td>
<td>6.800</td>
<td>26.800</td>
</tr>
<tr>
<td>2. Figueira</td>
<td>7.000</td>
<td>1.000</td>
<td>8.000</td>
</tr>
<tr>
<td>3. Itataia Phos - Uraniferous Province</td>
<td>91.200</td>
<td>51.300</td>
<td>142.500</td>
</tr>
<tr>
<td>4. Lagoa Real Uraniferous Province</td>
<td>61.840</td>
<td>31.350</td>
<td>93.190</td>
</tr>
<tr>
<td>5. Espinharas</td>
<td>5.000</td>
<td>5.000</td>
<td>10.000</td>
</tr>
<tr>
<td>6. Other Deposits</td>
<td>7.500</td>
<td>13.500</td>
<td>21.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>192.540</strong></td>
<td><strong>108.950</strong></td>
<td><strong>301.490</strong></td>
</tr>
</tbody>
</table>

*IAEA Classification*  
*Nuclam*  
*December/84*
FIGUEIRA DEPOSIT

The Figueira deposit is located in the north eastern Paraná, about 5 km from the village with the same name. It covers an area of 3 km² along a north-south strip. (FIG. 1)

Mineralization is found in sandstones and carbonaceous sediments of the Rio Bonito sedimentary Formation (Permian).

1) EXPLORATION HISTORY

In 1956, during examinations of coal samples existing in collection of the Brazilian Geological Survey (DNPM), it was found anomalous radiation in one sample that comes from the Rio do Peixe Coal Field in Paraná.

During 1956 to 1959 a systematic sampling of coal occurrences in Paraná was done looking for anomalous radiation, without success.

In 1969 prospection in the Paraná Basin was restarted with a different approach, looking now for favourable geological environments for uranium concentration.

The deposit was discovered following this systematic survey of the coal basins of southern and southeastern Brazil. The detailed work began in 1969, and environments favourable for uranium were determined from the interpretation of drill cores.

As a result, four areas (Ibaiti, Curiúva, Sapopema and Figueira) were selected for exploration drilling.

During 1970 to 1971 a drilling programme with large spacing was carried out (23,800 m) and Figueira became the more promising target.

During 1971 to 1972 50,000 meters of close spacing (400 x 200 m) drilling was done in selected areas showing already the contours of the Figueira deposit.
FIG. 1

THE FIGUEIRA ORE DEPOSIT

LOCATION MAP

0 200 400 600 800 1000 Km

FIGUEIRA ORE DEPOSIT

GOIÁS

MINAS GERAIS

MATO GROSSO

SÃO PAULO

PARANÁ

SANTA CATARINA

RIO GRANDE DO SUL

ATLANTIC OCEAN

ERASILIA

CURITIBA
During the following years (1973-1974) a fill in drilling was carried out in order to estimate the ore reserves (40,800 meters).

In 1977 a pre-feasibility study for mining and milling in the area was concluded, and underground workings (including shaft and galeries) were done during 1978 and 1979 in order to supply ore samples for processing plants of yellow cake production and also as support for feasibility studies and mining planning.

2) GEOLOGICAL SETTING

The Figueira area lays on a paleotectonic structure of the Ponta Grossa arch.

The local stratigraphy consists of sediments of periglacial, lacustrine and marine environment represented by diamicritites, shales and sandstones of Itararé Group.

Overlaying Itararé sediments occurs the Rio Bonito Formation.

The Rio Bonito Formation varies in thickness from 120 to 130 m and was divided into three stratigraphic intervals based on electric and lithological logs. The basal interval (15 to 30 m) is composed of very fine grained to conglomeratic sandstones which are light to dark grey in colour with intercalations of arkoses, siltstones, coal, dark shales and occasional beds of grey limestones. These sediments frequently possess a calcareous cement in addition to pyrite. This interval has been interpreted to have been deposited in fluvial channels, flood plains and in swamps. The middle interval (85 m), consists of grey, green or yellow siltstones intercalated with variegated marls and light to medium grey limestones. White to red sandstones, characterized by parallel lamination are also found in this interval. These sediments were probably deposited on a marine shelf below wave base. The upper interval (~20 m) consists of very fine grained laminated sandstones with intercalations of siltstones. These sediments were probably deposited on the shallow part of a shelf or close to the shoreline. (FIG. 2).
<table>
<thead>
<tr>
<th>CHROMOSTRATIGRAPHY</th>
<th>LITHOSTRATIGRAPHY</th>
<th>LITHOLOGICAL DESCRIPTION</th>
<th>SEDIMENTARY STRUCTURES</th>
<th>DEPOSITIONAL ENVIRONMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONTENT SYSTEM SERIES</td>
<td>GROUP FORMATION THICKNESS (m)</td>
<td>LITHOLOGY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P A L E O Z O I C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PERMIAN</td>
<td>SERRA ALTA 50</td>
<td>ARGILLITE, DARK GREY TO BLACK</td>
<td>PARALLEL LAMINATION</td>
<td>RESTRICTED MARINE</td>
</tr>
<tr>
<td></td>
<td>IRATI 45</td>
<td>LIMESTONE, DARK GREY, ARGILITE, BLACK, SHALES, BITUMINOUS</td>
<td>PARALLEL LAMINATION</td>
<td>RESTRICTED MARINE</td>
</tr>
<tr>
<td></td>
<td>PALERMO 80</td>
<td>SANDSTONE, FINE GRAINED, SILTSTONE, SANDY, GREY-GREEN, BIOTURBATED WITH SILICEOUS HORIZONS</td>
<td>IRREGULAR LAMINATION, BIOTURBATION, BIOTURBATED BY WORMS</td>
<td>RESTRICTED MARINE</td>
</tr>
<tr>
<td>MIDDLE</td>
<td>RIO BONITO 120</td>
<td>SANDSTONE, WHITISH TO YELLOW, FINE GRAINED, SILTSTONE AND MARLS, GLENSHED TO BROWN WITH INTERCALATIONS OF GREY, LIMESTONES AND SHALES, SANDSTONES, YELLOWISH TO GREY, FINE TO COARSE GRAINED WITH HORIZONS OF COAL AT THE BASE</td>
<td>PARALLEL LAMINATION, FLETTA STRUCTURES, CROSS AND OBlique STRATIFICATION</td>
<td>MARINE TRANSGRESSIVE, MARINE, CHARAC- TICAL FLUVIAL AND DELTAIC</td>
</tr>
<tr>
<td></td>
<td>TUBARÃO 130</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOWER</td>
<td>ITAREVE 700</td>
<td>HORIZONS OF COAL, GREY DIAMICTITES, AND PHYTHONIC CONGLOMERATES, SHALES, FINELY LAMINATED CONGLOMERATES, AND SILTSTONES</td>
<td>PARALLEL LAMINATION, FLAT STRUCTURES, CROSS BEDDING, RIPPLE MARKS, HETEROGENEOUS STRUCTURES IN DIAMICTITES</td>
<td>GLACIAL MARINE WITH TURBIDITES, CONTINENTAL FLUVIAL AND LA TOC菟E</td>
</tr>
</tbody>
</table>

*After S. Saad, 1974*
3) URANIUM MINERALIZATION

Uranium mineralization occurs in the basal sediments of Triunfo member of the Rio Bonito Formation, it has then a clear stratigraphic control.

The Triunfo Member which has a thickness of 15 to 30 meters consists of sandstones interlayred with shales, siltstones, arkoses and coal layers.

It is subdivided into three local units with the following predominant lithology (FIG. 3):

- Unit A - shales, siltstones with coal
- Unit B - sandstones
- Unit C - shales, siltstones and limestones (including a datum layer).

Uranium concentration is restricted to the level between the coal layers of A unit till the calciferous layers of C unit.

Mineralization is associated to carbonaceous sandstones, siltstones and mudstones and also to coal itself. Uranium is present as uraninite in sandstones or linked to organo-mineral complexes.

Elements like molybdenum, lead, sulphur, zinc and copper are found associate with uranium, in minor amounts.

The uranium of the Figueira deposit is thought to have come from the reworked sediments of the Itararé Formation (Permo Carboniferous) which contains boulders of the precambrian basement with anomalous concentrations of this element.

An important factor in the genesis of the Figueira mineralization was the local development of several types of depositional environments in response to regional tectonic arching. These environments had distinct paleogeographic limits, sediment-types and mineralization characteristics.
FIG. 3

THE FIGUEIRA ORE DEPOSIT

BASAL SECTION OF THE RIO BONITO FM. - DRILL HOLE 64/G

DEPTH 102.00 m

UNIT-D

LIMESTONE
UNIT-C

UNIT-B

COAL
UNIT-A

RIO BONITO FM
ITARARE FM

PROF 125.00 m

BP
The mineralization which occurred in the basal sediments of the Rio Bonito Formation was the result of both syngenetic and epigenetic processes. The syngenetic mineralization occurred in swamps containing fine grained sediments rich in organic material while the epigenetic mineralization developed in the fluvial-deltaic environments in which the sedimentation was mainly of a sandy character with intercalations of argillaceous and carbonaceous material.

The formation of the epigenetic uranium followed a sequence of phases involving transport and deposition which may have occurred both before and after diagenesis of the host rocks. Ground water of a slightly alkaline nature may have remobilized the $\text{U}^{4+}$ uranium transporting it in the $\text{U}^{6+}$ (oxidized state) to reducing environments where it was redeposited in geochemical cells.

The main ore body is lenticular in shape and accompanies a north-south trending paleochannel. The body is about 3000 m long and an average of 600 m wide (FIG. 4).

In the mineralized unit, uranium is associated with sandstones, siltstones, clays, and carbonaceous sediments including coal. In the sandstones the uranium occurs in the form of uraninite in a calcareous cement in the interstitial spaces. In the siltstones, carbonaceous clays and coals, the uranium mineralization occurs in the form of organo-mineral complexes of phosphate, barium and uranium, mineralogically classified as uranocircite. In the uranium-rich zones, the concentrations of $\text{U}_3\text{O}_8$ vary from about 0.2 to 0.5% and average 1.5 to 3.5 m in thickness. The principal accessory minerals include pyrite, jordosite, galena and chalcopyrite along with sulphides of arsenic and thorium-rich minerals.

Present reserves are 8,000 tonnes $\text{U}_3\text{O}_8$ from which 7,000 tonnes are reasonably assured.
THE FIGUEIRA ORE DEPOSIT
ISOACCUMULATION MAP

LEGEND

DRILL HOLE

ACCUMULATION

< 1000 1900 3300 4300<
ppm U3O8 x m

0 100 200 300 400 500 m
ITATAIA URANIFEROUS PROVINCE

The Itataia region is located about 170 km west of Fortaleza, in the central part of the State of Ceará, NE Brazil (FIG. 1). The climate there is semi-arid all year round. Irregular rainfall may occur from January to April and average rainfall is less than 500mm. Consequently, good and extensive fresh rock exposures are a common feature.

1) EXPLORATION HISTORY

Systematic investigation of the Precambrian basement in the State of Ceará began with a carborne radiometric survey in 1975. This survey covered an area of 35 000 km² in the north-central part of that state. The results of this survey included the discovery of 273 anomalies during 11 167 km of radiogeological profiles along roads and tracks. The equipment used included a portable scintillometer SRAT-SPP-2 mounted on a four-wheel-drive vehicle.

Twelve anomalous areas (FIG. 2) were selected for further study on the basis of common geological factors, geometry and chemical values. All twelve areas had high values of $U_3O_8$ (1000 to 3000 ppm $U_3O_8$ and 12% to 30% $P_2O_5$), and were related either directly or indirectly to vuggy, quartz-poor, feldspathic rocks. The areal distribution of this unusual rock drew attention to the probable regional character of the mineralizing event. The unusual rocks were called albite-syenites on the basis of their mineral content, specifically the absence of quartz. The mineralization was consequently related to alkaline rocks. This approach was later shown to be incorrect.

One of the anomalies discovered during this car-mounted survey was no more than a single boulder lying on a dry stream bed. The boulder was about 50 cm in diameter, reddish in colour, dense, massive cryptocrystalline, and assaying 1500 ppm $U_3O_8$ and 30% $P_2O_5$. This was considered to be of low priority in the schedule of follow-up studies on account to the form occurrence.

However, during a geological reconnaissance survey in July 1976, NUCLEBRAS geologists discovered an extensive outcrop
THE ITATAIA ORE DEPOSIT

LOCATION MAP

0  200  400  600  800  1000 Km

ITATAIA ORE DEPOSIT

MARANHÃO

CEARÁ

RIO GRANDE DO NORTE

PARAÍBA

PERNAMBUCO

ALAGOAS

SERGIPÉ

BAHIA

ATLANTIC OCEAN
of such uranium-and phosphate-rich rock in an area about 1.5 km to the north of this anomaly. These rocks had radiometric value of 7000 to 10 000 cp* (SRAT-SPP-2) and, on chemical analysis, revealed exceptionally high values for this type of association (2500 ppm U₂O₈ and 30% P₂O₅). Pink feldspathic, vuggy and radioactive rocks were also found in the same place. This occurrence was referred to as Anomaly 62 and later became known as the Itataia deposit.

As the result of a preliminary reconnaissance, a 2-km² area was delimited to be investigated in detail. The usual ground techniques of detailed radiometric and geological surveys were adopted in view of the local features of the area, such as:

Topographic and radiometric surveys were carried out on a 1:1000 scale along north-south traverses with lines spaced at 50-m intervals. The mineralized bodies were perfectly contoured by the isorads (FIG. 3).

Detailed geological map was made in early 1977 on a 1:2500 scale in the 2-km² area of the radiometric surveys. The geological mapping was carried out along the traverses used for the radiometry. The mapping team consisted of two senior geologists (FIG. 4).

Shallow test pits and trenches were opened concomitantly with in areas of overburden. This geological information, when considered together with detailed surface radiometric character, often permitted favourable lithologies to be traced between areas where bedrock information was lacking. The general relationships show on the geological map confirmed the isorad contours. The surface expression of the ore body suggested a thick dyke-like structure, but this interpretation was later shown to be mistaken.

VLF and electroresistivity were carried out in late 1977 in an attempt to trace the lateral extension of buried structures and mineralized bodies identified during the geological mapping. These methods gave satisfactory results; they confirmed the existence and preferred orientation of some buried mineralized bodies following a strike N70°N. Some faults suggested by the geol...
FIG. 3

ITATAIA DEPOSIT
RADIOMETRIC MAP

SCALE

< 300 1200 4800 > 7100

ISORAD CONTOURS = CPS
(SRAT/SPP-2)

GALLERIES,
PROJECTED WHERE TRACED

○ DRILL HOLES
Drilling Programmes

The surface exposure of the Itataia ore bodies was fully delineated by the geological/radiometric surveys.

The drilling programme began in July 1977. Twenty-nine holes were drilled to a total extend of 5000 m. Cores were taken throughout the entire length of the holes and the recovery rate was about 90% in each core withdrawal. The drill-holes were sited on a wide-spaced grid that could be closed if required. During this programme the average of the holes was 150 m, following which they were all logged with a Mount Sopris 2000 for natural gamma, resistivity and self-potential. In 1979, a Mount Sopris 3000 logger was used for this purpose, allowing all three logs to be recorded simultaneously during a single run. Mineralized rocks were intercepted in all 29 drill holes, and the dike pattern, as suggested by the geological mapping, was shown to be incorrect. Thick veins and lens-like massive bodies were defined up to 150 m depth.

The results obtained during this first drilling programme were highly significant. Allowing for an even distribution of the mineralization, it was possible to infer the existence of at least 18 000 tonnes of U₃O₈ at Itataia, which justified another drilling programme of a further 10 000 m.

In view of the promising results, drilling was reinitiated in mid-1978 and terminated in January 1979. Forty-two holes were drilled to a maximum depth of 300 m each and to a total of 10 129 m during the programme. About 70% of the drilling has as its objective the blocking out of reserves. The remaining 30% was carried out for exploration purposes with specific reference to the lateral extent of mineralization. The holes were sited on a 160 m square grid, including those of the first drilling programme.

At the end 1978, computer calculations based on the conventional method of blocks estimation, indicated reserves of 71 000 tonnes of U₃O₈ of which 34 000 tonnes were considered to be in the
category of measured and indicated reserves (reasonably assured) and 37 000 tonnes as inferred reserves (additional estimates).

**Sampling and Analytical Procedures**

The cores from the mineralized horizons were first sampled according to geostatistical requirements using a support of 0.25 m for homogeneous lithologic segments.

In addition to $U_3O_8$, $ThO_2$ and $P_2O_5$ systematic analyses (delayed neutron and X-ray fluorescence), hundreds of analyses for trace elements by emission spectrography were carried out to determine the geochemical background and to look for other elements of potential economic interest ($Pb$, $Zn$, $Mo$, $Ag$). Concomitantly, radioactive disequilibrium studies were performed in core samples. These studies indicated equilibrium between the chemical and gamma-ray spectrometer values (correlation coefficient 0.96).

In 1979, support of the sampling was increased to 0.50 m in view of the regularity of the mineralization, bearing in mind the aspects of lithological breaks and/or core recovery.

Routine analytical procedures were established for the Itataia ores. Each sample was automatically analysed for $U_3O_8$, $P_2O_5$, $SiO_2$, $Al_2O_3$, $CaO$ and $Fe_2O_3$ to obtain basic information for milling and dressing tests.

**Airborne Survey**

In late 1977, an airborne gamma-ray magnetometer survey was carried out in view of the wide geographical distribution of the uranium mineralization. The main factor in the choice of airborne geophysics as a method of regional prospecting was the excellent exposure, thin soil cover, intermittent stream network, difficulties of access and, principally, awareness that the mineralization was of a regional nature.

Two Norma-Britten Islander and one Douglas DC-3 aircraft were used in the survey in three distinct areas, totalling 38 00 km$^2$. Operational characteristics were uniform and included alti...
tude of 150 m, speed of 220 km·h⁻¹ and north-south flight lines spaced 500m apart. The geophysical equipment used included a gammaspectrometer "Exploranium" DIGRS, Model 3001, containing nine 6 in. x 4 in. crystals as well as a "Geometrics" Model 803 magnetometer.

The data from 78 000 km of flight lines were recorded simultaneously in analog form and digitally on magnetic tape. In the processing, 441 anomalous records were identified which, on the basis of essentially physical parameters, correspond to 42 anomalous zones.

The data obtained during the airborne gamma-ray survey were analysed in 1978 by NUCLEBRÂS personnel. Thirty new anomalies were selected for verification. As a result, fifteen showings of phosphate-uranium mineralization were recognized, among which four were coincident with the Itataia deposit and two have been correlated with anomalies already discovered by the carborne survey carried out in 1975. The remaining anomalies represented new P-U areas.

2) GEOLOGY OF THE ITATAIA DEPOSIT

The Itataia deposit is situated in rocks attributed to the Caico Group. The principal country rocks are paragneisses with a well developed planar fabric. Intercalated with these gneisses is a large lens of carbonate rock at least 10 km long. Lateral gradations are common and include graphite-marbles and calcosilicate rocks.

Both the marbles and the gneisses are cut by several granite and granite-pegmatite apophyses. These intrusive have been affected intensively by deuteritic processes, and drilling has confirmed this at depth. The marbles and gneisses are very highly folded. The latest axial planes are subvertical and the fold axes dip gently to the east (5° to 10°).

The Itataia ore bodies are located on one of the regional compressional release faults and, before the mineralization
sodes, the marbles uplifted on to the gneisses. The tectonic event accounts for the local geomorphology whereby the marbles have their topographic expression as a small hillock.

3) URANIUM MINERALIZATION

Two types of ore bodies have been recognized. The first consists of uniform massive collophanite and the second of veinlet and stockwork ores in marbles and "episyenitic" rocks as well as in impregnations in gneisses. In fact, impregnation is a general feature which affects all the lithologies in varying degrees.

Uranium and phosphorous show different grades in the different rock types:
- In Collophanite 800 to 2000 ppm $U_3O_8$ and 12% to 30% $P_2O_5$
- In Marbles (Stockworks): 150 to 1100 ppm $U_3O_8$ and 2% to 15% $P_2O_5$
- In Episyenites: 300 to 1400 ppm $U_3O_8$ and 9% to 20% $P_2O_5$

The mineralization extends downwards 400 m below surface.

Uranium is evenly distributed in the collophanite, as shown by fission track and microprobe analysis. Two views have been proposed on the nature of the uranium in the collophane. The first is that calcium has been isomorphously replaced by uranium in the collophane structure. The second holds that the uranium is associated with finely dispersed oxides or that it has been adsorbed by the collophane. However, it is significant that no discrete uranium species has yet been found.

There is convincing evidence that metasomatism was the key process in the uranium mineralization at Itataia.

Related to metasomatic process Itataia shows the following features:

a) There is metasomatic alteration of different types of rocks like granites, gneiss and marbles.
b) Compositional granitic rocks (granite and gneiss) were transformed through desilification, albitization, analcization and chloritization into albitized rocks, in many cases keeping the original structure.

c) Due to its chemical nature marbles went under deep alteration involving scapolitization and strong dissolution with replacement by a rock rich in phosphate (collophanite).

There was widespread replacement of calcite by phosphate in the marbles.

d) During a final stage phosphate was deposited in large quantities both by replacing of marbles or filling fractures and cavities.

e) Granitic bodies of brazilian age (400 to 500 m.y.) has been affected elsewhere by the same mineralizing process which clearly indicates that uranium mineralization is younger.

f) One of the chemical alterations undergone in the original rocks was the liberation of Fe$^{3+}$ of mafic minerals (mainly biotite) and oxidation of ferrous into ferric iron producing a pervasive hematitization which appears as minute crystals giving a reddish or pinkysh colouration to the metasomatized rocks, including the newformed collophanite.

All these evidences indicates a close relationship between uranium mineralization and the metasomatism.

During the final stage, cryptocrystalline hydroxyapatite was extensively deposited from saline heated fluids (~130°C, and approximately 22% equivalent CaCl$_2$) which impregnated the pore-spaces and cavities formed before.

Transport of large quantities of calcium phosphate would have been possilbe only in acid medium (low-pH fluids). Movement of these fluids in the host marbles provoked an increase in pH, the alkalinity favouring rapid deposition of uraniumiferous collophane. Such conditions of rapid deposition are apparently confirmed by the cryptocrystalline fabric of the collophane and the absence of uranium minerals. The uranium would have been
adsorbed by the collophane with, possibly, some replacement of Ca in the apatite.

Fluid inclusions in the apatite indicate formation temperatures of the order of 136°C and high salinity (≈19.5% to 22% equivalent CaCl₂), while quartz filings in cavities in the collophane indicate temperatures of 50°C and low salinity (≈ 5% equivalent CaCl₂), evidence of a distinct decrease in salinity during deposition of the late minerals. The low CO₂ content suggests low pressure deposition.

It is believed that the brazilian orogenic cycle had structurally affected the original metasedimentary rocks and along zones of compressional release associated with regional faults ascendent fluids had caused metasomatic alteration of rocks.

Phosphate and uranium present in the original metasedimentary rocks has been remobilised and concentrated during the metasomatic process by replacement or by impregnation and filling of cavities.

Marble has played a leading role in the deposition of uranium and phosphate at Itataia, making it a large deposit distinct from the other occurrences where marble is missing.

Finally the entire region went through a deep erosional process during a long period of time, attested by the presence of detrital fragments of U-P mineralized rocks in sandstones of Devonian age in the Parnaiba Basin (Serra Grande Formation) and a large amount of residual collophanite in low lands at Itataia area.

Also weathering has affected the setting of mineralized zones in marble by its dissolution and argilisation, changing the original pattern after mineralization.

Exception made for aspects resulting of role played by the marble, the remaining features in Itataia are common to others metasomatic uranium occurrences in the northeast.
LAGOA REAL URANIFEROUS PROVINCE

The Lagoa Real Province is located in hilly country of the central-southern part of the State of Bahia, some 20 km northeast of the town of Caetité (FIG. 1).

The Lagoa Real Project covers an area of 4.540 sq.km.

Uranium mineralization occurs in albitalic bodies parallel to its foliation which lays on metasomatised and cataclastic rocks of Archaean basement.

1) HISTORICAL BACKGROUND

Due to the presence of uranium bearing quartz-pebble conglomerates in the ferriferous quadrangle (Minas Gerais) and also in Jacobina (Bahia) a carborne survey was launched in 1971, to investigate the Northern Espinhaço region. Nouraniferous conglomerate was found but from the resulting anomalies an airborne survey was suggested.

During 1974/1975 the Espinhaço Setentrional Project (airborne gammaspectrometric survey) covered an area of 60,000 sq.km with 4 km spacing lines.

In 1976/1977 another airborne survey-Diamantina Project-which covers an area of 145,000 sq.km with spacing lines of 2 km was carried out.

The limits between both projects was the parallel of 14° which cross-cut the Lagoa Real region. Needless to say that both surveys detected uranium anomalies at the same region which corresponds to the Lagoa Real area.

Another airborne survey done by CGA-DNPM in 1976 which was mainly magnetometry but with gammaspectrometry, also detected uranium anomalies in the same area.

The first ground-check of these anomalies (1977) had shown large extensions of aligned structures (about 3,000 meters) of
FIG. 1

THE LAGOA REAL DISTRICT
LOCATION MAP

0 200 400 600 800 1000 Km

LAGOA REAL DISTRICT

PERNAMBUCO
CEARA
PARAIBA
ALAGOAS
SERRA DE
SANTO AMARO

MIAS GERAIS
albititic rocks with radiometric values between 5,000 to 15,000 c/s.

Detailed ground-check of some of the more promising anomalies had shown the presence of high grades of uranium in albitites.

On March 1978 a programme of evaluation of the anomalies was started and five new anomalies were found.

After these results a detailed airborne gammaspectrometric survey (São Timóteo Project) was done in 1979 with close spacing flight lines (500 m) giving total coverage resulting in 33 anomalies, including those already known.

Ground-check of the above mentioned anomalies started in 1980 resulting in 30 anomalies selected for evaluation which constitutes the Lagoa Real District.

From these, five anomalies were considered as priorities and since 1980 are being under evaluation with detailed radiometric, topographic and geological mapping, trenching and systematic drilling. (FIG. 2).

Ore dressing tests showed high solubilization of uranium with low acid consumptions.

2) GEOLOGICAL SETTING

Uraniferous anomalies are found in a zone Archaean basement consisting of cataclastic granitoids, augen gneisses, microcline gneisses, granodiorites and albitites (FIG. 3).

This zone is about 80 km long and varies in width from 31 to 50 km. To the south, east and north there lays large areas of low relief which are underlaid mainly by gneisses and greenstones of Archaean or Low Proterozoic age. Along its western margin, the massif is frequently faulted against the metasediments and metavolcanics of the Espinhaço Super Group. The region may have been subjected at least to three tectonic cycles during which the rock
THE LAGOA REAL URANIFEROUS DISTRICT—ANOMALY LOCATION MAP

LEGEND

- Geological Mapping area (1:25,000 scale photos)
- 1:5,000 scale photos
- Mines and anomalies under investigation
- Anomaly Es-center
- — Main/secondary road
- ○ Town/Form
- — Lake/Drainage

REMARKS. Photometric basis compiled from the SRUMADO-CÄTITE PROJECT

Coverage limit
were rejuvenated. These include the Guriense (3,000 m.y.+), Transamazonian (1,800 - 2,100 m.y.) and the Brazilian (1,800 - 500 m.y.) cycles.

The microcline-plagioclase-augen gneisses are the host to the albitites which often are mineralized. They always exhibit strong cataclasis and granoblastic texture (FIG. 4).

The structural evolution of these rocks is important for the emplacement of albitites and consequently as a guide for uranium mineralization.

The main regional structural pattern is related to tensional transcurrent domains which produces long lineaments in a north south direction.

There is evidence of thrust faults which affect the EspinhÃµco rocks.

At least two deformational phases has been recognised:

- During Archaean times a low angle ductile shearing zone has been developed, resulting from the thrusting of a basement bloc over another in a mobile belt.

- At Transamazonian times (~ 2,000 m.y.) helicoidal torsion with dextral relative motion, including locally rotational components, were developed without intense shearing.

Locally, albitic rocks emplacement reflects the regional structural pattern.

There are two main arch surfaces, whose trend varies from NE in the south inflecting to NW in the north.

Albitites dips to the west in the southern area being a most vertical in the middle changing to a eastern dip in the northern area, like an "S", characterizing a long sigmoidal structure resulting from helicoidal torsion.
THE LAGOA REAL DISTRICT
ANOMALY-03

PYROXENE ALBITITE
ALBITITE
ALBITE - MICROCLINE - QUARTZ - METASOMATITE
MICROCLINE - ALBITE - QUARTZ - METASOMATITE
The predominant foliation is cataclastic. This foliation controls the mineralized albitites and is superimposed to a low angle pre-existing foliation (1 to 15°).

In the intersections zones between these two foliations cataclastic zones were developed. These intersections zones holds the richest mineralized bodies.

The geological sections made upon drilling show many discontinuous tabular albititic ore bodies wich are concordant with the regional cataclastic foliation (FIG. 5).

The pinch and swell of the mineralized bodies may be a result of the stress composition but it cannot be clearly defined in the field yet.

The albitites bodies varies from few meters to kilometers with width varying up to hundred meters.

3) URANIUM MINERALIZATION

The uranium mineralization occurs in albitites. They are characterized by the presence of sodic plagioclase (albite) and aegerine-augite. The country rocks are invariably microline ortho-gneisses. The foliation of these gneisses is essentially parallel to the regional trend, which within the massif inscribes an arch. The fractures which also follow the strike are often cataclastic and their dip directions, as well as that of the foliation, are helicoidal from south to north. The mineralized bodies of metasomatic albitites surrounded by microcline gneiss are fusiform and likewise accompany the regional structural trends. The length of these varies from 20 to 100 times the width.

The uranium enrichment is of brazilian age which is supported by absolute age dating (U/Pb) of uraninite at 820 m.y. Solutions rich in sodium chloride and methane (found in fluid inclusions) ascended pre-existing fracture planes and zones of weakness within the microcline gneisses causing sodium metasomatism and th
THE LAGOA REAL DISTRICT.

ANOMALY-03

FIG. 5
formation of the albite-pyroxene-rocks. The uranium was mobilised and concentrated as fine disseminations in the mafic bands of sodic pyroxene.

The uranium mineral is uraninite. B-Uranophane can be observed on fracture planes at surface. The grades of $U_3O_8$ are quite high and may reach 3.50% in exceptional cases. The average grade of the mineralized zone is about 0.3 to 0.2% $U_3O_8$. The concentrations of thorium are low (<100 ppm).

Similar deposits and metallogenetic models have been described by Kazansky and Laverov (1977) in the U.S.S.R.

Besides the evident structural ore control uranium also follows a lithological control as it is restricted to albitites.

But there is non mineralized albitites mineralogically and chemical similar to the mineralized ones. The only conspicuous difference is the greater proportion of mafic minerals in mineralized albitites.

Uraninite is associated with fine bands of mafic and opaque minerals (aegirina-augite, amphibole, biotite, garnet, epidot and magnetite).

During albitization of gneisses there is a relative loss of $SiO_2$ and $K_2O$ and a gain in $Na_2O$, $Al_2O_3$ and Fe.

Oxygen isotope analyses of quartz, albite and magnetite from gneisses and albitites indicates that the metasomatic fluids were of ground-water nature.
ESPINHARAS DEPOSIT

The Espinharas uranium occurrence is located at the small town of São José de Espinharas and from there extends in a NE and SW direction. São José de Espinharas is situated 25km north of the city of Patos in the State of Paraíba, NE-Brazil (FIG. 1).

1) EXPLORATION HISTORY

The radiometric anomaly at Espinharas was discovered in the course of a regional carborne survey by CNEN in 1972. Low uranium values at high thorium/uranium ratios in surface samples discouraged detailed follow-up work.

In 1976, as part of a prospecting programme carried out by NUCLAM the anomaly was looked at more closely. A systematic ground radiometric survey was done, the first trenches and pits were dug. The mineralized rock was believed to be a steeply dipping, old intrusive dike (according to current thinking no longer holds true) but the mineral composition and texture were correctly described and albition was recognized.

In the second half of 1977 limited diamond drilling was carried out to probe the possible depth continuation of the surface mineralization. The drilling approach was based on the assumption of a steep dip angle for the mineralized zone.

After the completion of 13 holes it was indeed concluded that the dip was mainly steeply to the north but in places also vertical or steeply to the south.

At the centre of field activities in 1978 was a second-phase diamond drilling programme totaling 36 holes. This drilling was designed to improve the knowledge of the deposit, determine the average grade of the mineralization with greater accuracy and explore the anticipated downward continuation on the mineralization. Based on the results of this drilling, conventional reserve estimates on vertical longitudinal sections were made. Further leach tests were performed. All tests including two-
THE ESPINHARAS ORE DEPOSIT
LOCATION MAP

FIG. 1

CEARA

RIO GRANDE DO NORTE

Augusto Severo

Currais Novos

ESPINHARAS ORE DEPOSIT

PARAIBA

PERNAMBUCO

SITUATION
of uranium.

The year 1979 was spent studying geological data gathered previously with the purpose to gain a better understanding of the geology and mineralization and simultaneously carry out conceptual mining (open pit and underground), metallurgical, engineering and infrastructure studies with regard to the viability of a mining/milling venture at Espinharas.

By the time the second drilling stage had been completed early in 1979 it had been concluded that the Espinharas "ore body" has an average dip angle of 50° to the NW - a considerable modification to the initial assumption of a near-vertical dip.

When replotting of surface and basic drill hole data on drill sections had advanced far enough to commence with the geological interpretation, the impression gained was that

a) the ore was not a continuous body of mineralization but was made up of discontinuous, lenticular, irregular bodies whose long axes parallel the regional foliation,

b) these lenticular bodies were arranged en-échelon,

c) the plunge angle of these bodies was not 50° but only 20-30° and the plunge direction not perpendicular to the base line (N30°W) but the same as the dip direction of the regional foliation, viz N70°W (FIG. 2).

For the year 1980 the third diamond drilling campaign of the Project was proposed. The original aim of it would have been to probe the inferred down-plunge continuation of the major ore shoots postulated in the new interpretation by means of a row of vertical holes arranged in a fence-like fashion across the plunge direction.

The drilling results obtained in 1980 have confirmed

a) the concordant attitude of the main ore shoots

b) the extension fracture ore emplacement model as being the best choice to explain the structural control of the mineralization, and
TACTITES; 1 MINERALIZED EPISYENITES
AMPHIBOLITE
ULTRABASIC
GRANITE
GNEISSES

GEOLOGIC MAP OF THE ESPINHARAS ORE DEPOSIT
c) the continuation, at depth, of the numerous aplogranite dikes mapped on surface.

A new finding has been the lithological control of the mineralization exercised by these aplogranites. This constitutes a second order ore control and accounts for the extremely shallow dip angles (10-15°) of the shoots known since the reinterpretation of 1979 but hitherto unexplained.

As for the economic aspects, the 1980 drilling has produced the best ore intersections.

2) GEOLOGICAL SETTING

a) Lithology

From the surface observations and drilling data combined with petrographical and geochemical analyses it can be conclude that the process of metasomatic alteration, to wich the uranium mineralization is closely associated, it is one of the latest geological events in the area, being younger than all rock types.

This conclusion came from the simple fact that metasomatic process has affected all existing lithologies.

Being so, there is not a single mineralized rocks type as such, all rocks may show their metasomatised equivalents.

It is possible, both on trenches and drill-cores, to follow a gradational change from a country rock like a biotite-amphibole-gneiss into a metasomatised and mineralized gneiss with the same structure.

In order to distinguish among the several rocks types a microscopic criterium was used to recognise metasomatic alteration.

This distinction was confirmed by mineralogical and chemi_
Metasomatized rocks show a typical pink color due to hematitization of feldspars and also a typical vuggy texture which allows distinction between mineralized and non-mineralized rocks.

The present thinking is that the mineralizing event forms part of a metasomatic process post-dating all rock and affecting them in varying degrees near a mineralizing structure.

What the now metasomatized rocks were before metasomatism can still readily be determined visually in drill core and outcrop thanks to the perfect preservation of original rock textures and structures.

Common to all radioactive rocks is thus a replacement process that has individually changed the original rocks dependent upon their respective mineralogical/chemical composition and internal texture.

It was possible then to characterize the existing lithological types into two main groups.

**LITHOLOGIC TYPES**

<table>
<thead>
<tr>
<th>Pre-metasomatic Country Rock</th>
<th>Mineralized equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Biotite-Amphibole Gneiss</td>
<td>1) Albitised gneiss</td>
</tr>
<tr>
<td>2) Granite-gneiss</td>
<td>2) Layered Albitite</td>
</tr>
<tr>
<td>3) Aplogranite</td>
<td>3) Massive Albitite</td>
</tr>
</tbody>
</table>

**Regional (Country) Rocks**

1) Biotite-Amphibole Gneiss

This texturally and compositionally very variable group of rocks is by far the most plentiful country rock in the mineralized area. It usually forms long, monotonous, uniform intersections in
the drill holes and trenches but, on account of its low resistance to weathering does not usually make large outcrops.

This group of rocks comprises porphyroblastic gneisses, schistose gneisses and amphibole schists which may have either sharp or gradational contacts with each other.

2) Granite Gneiss

Concordantly intercalated in the amphibole-biotite gneisses are quartzo-feldspathic layers ranging in thickness from a few centimetres to 30 m and exhibiting a gneissosity parallel to that of the surrounding amphibole-biotite gneisses. More commonly it pinch and swell over short distances. This rock unit is light colored and granular and consists of quartz, microcline, plagioclase and some biotite.

3) Aplogranite

Extremely widespread in the deposit area and beyond are quartzo-feldspathic dikes or sheets ranging in thickness between a few centimetres and several metres (exceptionally 15 m) whose most peculiar feature are their shallow dip angles (0-20°). Hundreds of structural readings on surface and in drill core show them to be clearly intrusive, forming discordant contacts with the gneissic foliation. The aplogranite is a light coloured (pinkish, yellowish, whitish) rock.

The aplogranite is the youngest rock in the area, intruding all other lithological units. It frequently carries xenoliths, usually displaced and rotated, of country rock and is thought to have intruded along well developed fracture zones created during orogenic stage.

Mineralized Rocks

1) Albitised Gneiss

At first glance, albitised gneiss differs from the unaltered gneiss only by the pinkish colour of the feldspars and the small vugs. In some parts, however, common, hornblende in the amphibole-biotite gneiss was replaced by riebeckite and arfvedsonite
(sodium-rich amphiboles) giving the rock a distinctly bluish tint. Other minerals constituting this gneiss include plagioclase, hornblende, chlorite, titanite, apatite, opaque minerals, carbonate, cummingtonite, biotite and epidote.

2) Layered Albitite

Layered Albitite is the metasomatically altered equivalent of Granite Gneiss whose original foliation is well preserved and even accentuated by biotite flakes partly epidotized and by the alignment of pore space owing to the dissolution of the free quartz.

3) Massive Albitite

This is the metasomatic equivalent of aplonranite. It is porous owing to the removal of most of the free quartz.

Some of the pore space is filled with small crystals of secondary quartz and more commonly with calcite. Most characteristic is the strong pinkish-reddish colouration common to all radioactive rocks at Espinharas. Albitite and/or oligoclase, forms up to 90% of the rock, followed by orthoclase and some biotite. Other minerals found include apatite, pyrite, chalcopyrite, sphene, monazite, hastingsite and glaucophane.

3) GENETIC MODEL FOR THE ESPINHARAS MINERALIZATION

There is convincing evidence that metasomatism has played a leading role in the deposition of the uranium mineralization at Espinharas. Fractures are known to form starting-places for such replacement, and for Espinharas the hypothesis is advanced that tension fractures provided channel ways for ore bearing solutions. The metasomatic process started to affect the adjacent rocks from such tension fractures created under the influence of a couple of forces in a local stress field. Extension fractures opened up essentially along zones of weakness, parallel to foliation planes in the gneisses and also parallel to the numerous aplogranite dikes which themselves were previously emplaced along fracture planes (FIG. 3).

The development of such an extension fracture zone stopped short of the formation of a true thrust fault. The termination
FIG. 3

ESPINHARAS DEPOSIT
MINERALIZATION MODEL

A
DIRECTION OF GRANITIC BODIES

B
REGIONAL FOLIATION

MINERALIZED ROCK
of the development of a fault zone at such an early, rudimentary deformational phase may even have been favourable to the fracture-controlled metasomatism.

The metasomatic process appears to have been the last major geological event in the area, accompanying the movements that took place during the formation of the huge Patos lineament and associated structures some 30 km to the south of Espinharas.
BIBLIOGRAPHY

This text was based mainly upon the following references:


