1. Classification *INPE-COM-10/PE* *549(814):629.783:525*	2. Period	4. Distribution Criterion internal ☐ external X
3. Key Words (selected by the author) *São Francisco river area* *LANDSAT-1* *SLAR* *Geology* *Remote sensing*		
5. Report Nº *INPE-841-PE/017*	6. Date *March 1976*	7. Revised by *Amitava Dutta-Roy*
8. Title and Sub-title *A REGIONAL MAPPING PROGRAM AND MINERAL RESOURCES SURVEY BASED ON REMOTE SENSING DATA*		9. Authorized by *Fernando de Mendonça* *Director*
10. Sector *CRT/SMI* Code *422*		11. Nº of Copies *10*
12. Authorship *Aderbal Caetano Corrêa*		14. Nº Of Pages *34*
13. Signature of the responsible		15. Price

16. Summary/Notes

17. Remarks *Presented at the Tenth International Symposium on Remote Sensing of the Environment. Ann Arbor, Michigan. October 5-10, 1975.*

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ABSTRACT

The Earth Resources Technology Satellite-1 (ERTS-1, now called LANDSAT-1) has obtained multiband imagery that was used as the basis for the structural mapping of the middle São Francisco River area, eastern Brazil. The synoptic view available from orbital imagery provided the means to detect geological structures already mapped in some areas and to revise small scale geological maps.

The capability of LANDSAT-1 imagery to provide structural data for geological studies was utilized to its full extent. Data from other remote sensors, mainly side looking airborne radar (SLAR) imagery and aerial photography were analyzed when available. The reliability of the interpretation of structural features for the Rio São Francisco quadrangle was further increased by using all the information available from the literature and by field work in selected areas.

Relatively small occurrences, mainly of gold, diamonds, rutile, and lead and zinc ore, found in the study area are restricted to Precambrian units. The identification of new crustal fractures, and particularly the intersection of sets of linear features, which control to a great extent the formation of some types of ore deposits, are some of the data which were considered when defining areas with potential mineralization. These areas are recommended for further detailed study, both in the field or with airborne geophysical techniques.

CHAPTER I

INTRODUCTION

The geological mapping project of the Brazilian Space Research Institute (INPE-Instituto de Pesquisas Espaciais) is part of a research program directed toward the application of remote sensing data to the evaluation of natural resources. This project was proposed in response to the need of more detailed geological maps in Brazil and to show the usefulness of data that are available from satellites in geological research.

Four areas in Brazil, each with 290,400 square kilometers and corresponding to the Rio São Francisco, Belo Horizonte, Goiãs and Brasília quadrangles of the national map on the millionth scale are being prepared. This paper reports the results from the work done in the Rio São Francisco area.

CHAPTER II

THE RIO SÃO FRANCISCO AREA

2.1 - LOCATION

The area corresponding to the Rio São Francisco quadrangle located in eastern Brazil, limited by coordinates 8^{o} and 12^{o} latitude south and 42^{o} and 48^{o} longitude west. Parts of the states of Bahia, Piauí, Maranhão and Goiás are comprised within the area that is named after the São Francisco river flowing through its southeastern side.

2.2 - PREVIOUS WORKS

A great part of this area has already been mapped at the scale of 1:250,000 or smaller. Large-scale maps (most of them at the 1:100,000 scale) are available for areas which were economically interesting, e.g. the Precambrian terrains in the southeastern and southwestern sides of the area, and the Parnaíba sedimentary basin which has been mapped to evaluate its potential for oil.

The northern half of the Rio São Francisco area was mapped by the RADAM Project at the 1:1,000,000 scale (Nunes et al.,1973) using side-looking airborne radar (SLAR) imagery as their main source of information and with a limited amount of field work. The most recent small-scale map of the area was prepared by the Brazilian Geological Survey (DNPM-De-

partamento Nacional da Produção Mineral) and is the result of a compilation of the geological literature concerning the Rio São Francisco quadrangle (Bruni et al., 1974).

CHAPTER III

GEOLOGICAL FRAMEWORK OF NORTHEASTERN BRAZIL

The Rio São Francisco quadrangle is located between the São Francisco and the São Luiz cratons, including parts of Precambrian fold belts and rejuvenation zones of the so-called South American platform (Fig. III.1). This geotectonic unit, comprising the entire Atlantic coast of South America, has remained essentially stable since early Paleozoic times (Almeida, 1971).

Figure III.1 shows the outline of the São Luiz craton which is covered almost completely of Paleozoic or younger sedimentary rocks. South of the Parnaíba basin (also called Maranhão-Piauí basin) is the northern part of the São Francisco craton. The basement of the São Francisco craton consisting of migmatites, gneisses, schists and basic and ultrabasic rocks of Trans-Amazonian ages or older (2,600 m.y.) is covered by a sequence of metasedimentary and sedimentary units.

To the east of the Parnaíba basin is an area of fold belts of the Braziliano orogenic cycle (550 to 900 m.y.) where rocks of the embasement are also exposed, most of them rejuvenated during this orogenic cycle. Two fold belts have been described in this area: The Propria fold belt surrounding the northeastern border of the São Francisco craton and separated from the Caririan fold belt, to the north, by a system of

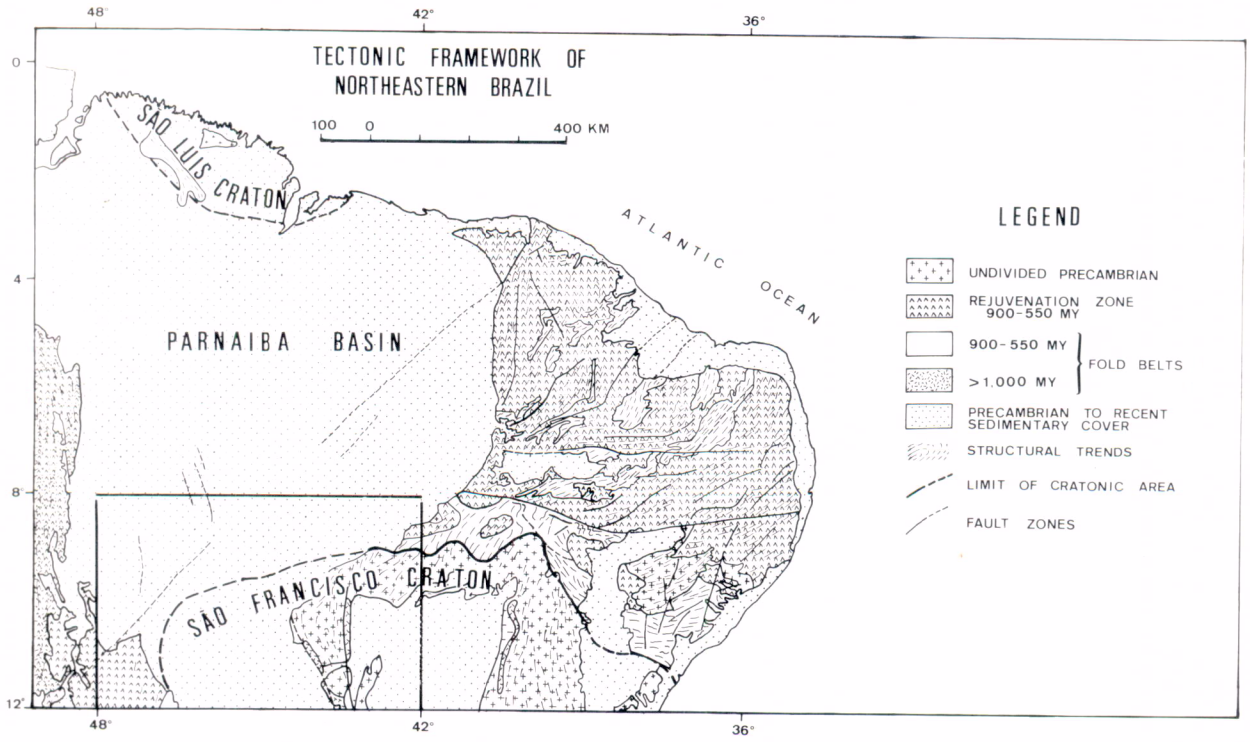

Fig. III.1 - Tectonic framework of Northeastern Brazil.

Rio São Francisco quadrangle area shown by the rectangle at the lower left. Modified from: Ferreira et al., 1971; Almeida et al., 1973; Corrêa et al., 1975. I: Propriá fold belt; II: Caririan fold belt.

transcurrent faults. Brito Neves (1973) suggests that these two fold belts be studied together because they belong to a single tectonic unit which develop between neighboring cratonic areas of São Luiz/West Africa to the north and São Francisco/Congo to the south.

Along the western side of the area shown in Figure III.1 is the oriental side of the Paraguay-Araguaia fold belt considered to belong to the Braziliano orogenic cycle (Almeida, 1968) but that probably is older (approximately 2,000 m.y.) according to Amaral (1974).

In the southwestern corner of Figure III.1 is a region where old structures were rejuvenated during the Braziliano cycle (Almeida et al., 1973).

The tectonic evolution of northeastern Brazil during the Paleozoic is characterized by the deposition of the sedimentary sequence of the Parnaíba basin in a stable environment where the São Francisco and Guaporé cratons were their depositional limits (Chignone, 1972).Beginning toward the end of the Jurassic the South American platform was reactivated due to the South Atlantic opening. The consequences of this tectono-magmatic activation have been outlined by Almeida (1972), and comprise the reactivation of Precambrian structural features, formation of sedimentary basins along the margins of the African and South American plates, intense magmatic activity, and endogenous mineralization as well as the formation of important deposits of oil, gas, sedimentary phosphates, etc. in the

taphrpgenic basins. The effects of this tectonic event lasted until the Tertiary and are related to the formation of a marine sedimentary sequence in the marginal basins.

CHAPTER IV

REMOTE SENSING DATA AND INTERPRETATION

The procedure followed for the preparation of the 1:1,000,000 geological-structural map of the Rio São Francisco consists of three main phases. Firstly, remote sensing data of the area, mainly LANDSAT-1 and SLAR imagery on different scales, were analyzed. Secondly, the photointerpretation was checked during a reconnaissance field work in the area during the month. Thirdly, a reinterpretation of the data was done in order to add the information acquired in the field. The information available from the literature consulted during all three phases was incorporated into the final map and report.

LANDSAT-1's multispectral scanner (MSS) images were the basic data used for the mapping. Most of the imagery was acquired from June to November, during the dry season in the area. A few images without intense cloud cover taken outside this period were used for interpretation. The sun position recorded for the imagery obtained during the dry season changes from 39^{o} to 42^{o} elevantion angle and 46^{o} to 51^{o} azimuth during June-July to 57^{o} to 58^{o} elevation angle and 85^{o} to 112^{o} azimuth during October-November therefore for some of the areas features which might not have been clearly observed with given illumination condition could have been detected in images obtained on a different date, (Fig. IV.1).

Fig. IV.1 - Mosaic (non-controlled) of LANDSAT-1 imagery.

Rio São Francisco quadrangle (Band 5: 0.6 - 0.7 micrometers).

SLAR imagery of the northern part of the area was acquired by the Brazilian Geological Survey (DNPM) as part of a radar mapping program (RADAM Project) carried out in northern Brazil, which is presently being extended to the south. The radar system used was a Goodyear APQ 102 with synthetic aperture antenna, operating in the X-band (3.1 cm wavelength). The flight line is most of the Rio São Francisco quadrangle area were north-south and the imaging direction towards the west, therefore the shadow effect in the radar imagery is similar to that in LANDSAT-1 imagery. In the southeast corner of the area mapped by the SLAR system, the images were obtained during east-west flights (Fig.IV.2).

Photographs acquired during SKYLAB missions were also analyzed but since only a few were free of clouds, the results described here are essentially related to the LANDSAT and SLAR imagery.

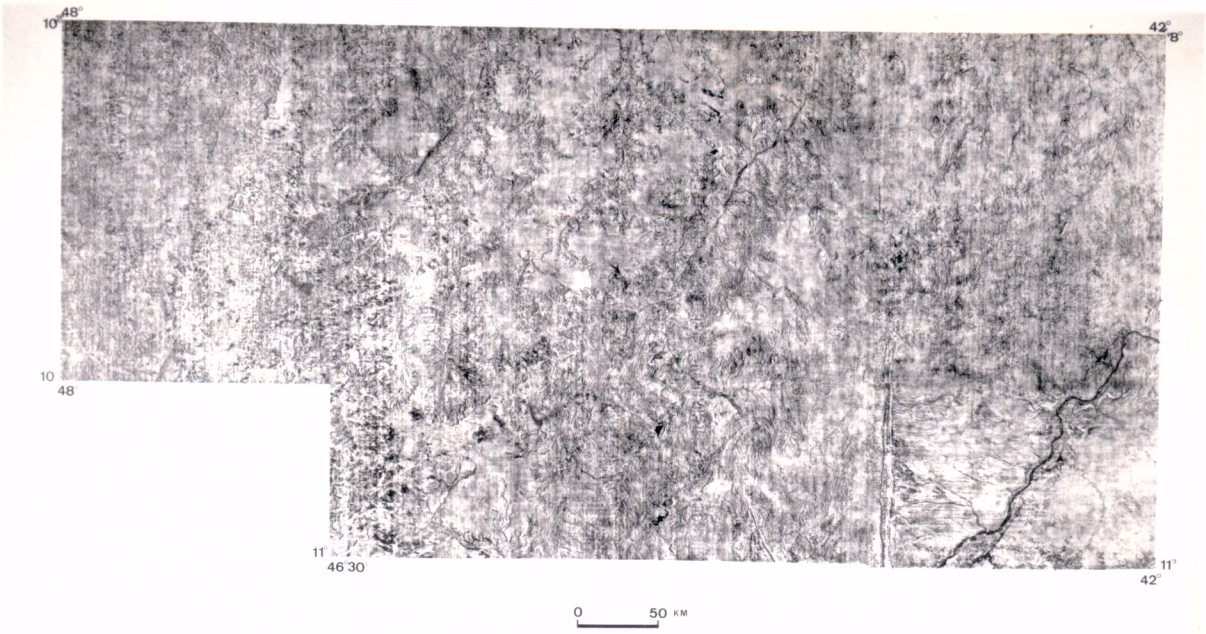

Fig. IV.2 - Mosaic (non-crontrolled) of Side-Looking Airborne Radar (SLAR). Northern half of the Rio São Francisco quadrangle.

CHAPTER V

REGIONAL GEOLOGICAL MAPPING

Most of the information extracted from LANDSAT-1 and SLAR imagery concerns the structural features present in the area. Lithologies however could be identified with good reliability using mainly LANDSAT-1 data which was combined, when possible, with the information from other sensors.

Tone and texture were the main characteristics used to discriminate lithologic units and together with drainage patterns, landforms, vegetation and soil use patterns led to the identification of "remote sensing rock units". Figures V.1 and V.2 show two lithostratigraphic units (pЄC and pЄB) defined by essentially the same rock types which cannot be discriminated properly without field control.

Thick sedimentary units provide the best opportunity for identification of lithologies mainly if dips are steep to moderate (Lee et al., 1974). In the Rio São Francisco quadrangle area, lithologic units of the Parnaíba basin could be mapped with good precision because of their homogeneous tonal and textural characteristics usually contrasting with adjacent units.

The result of the initial interpretation of LANDSAT and

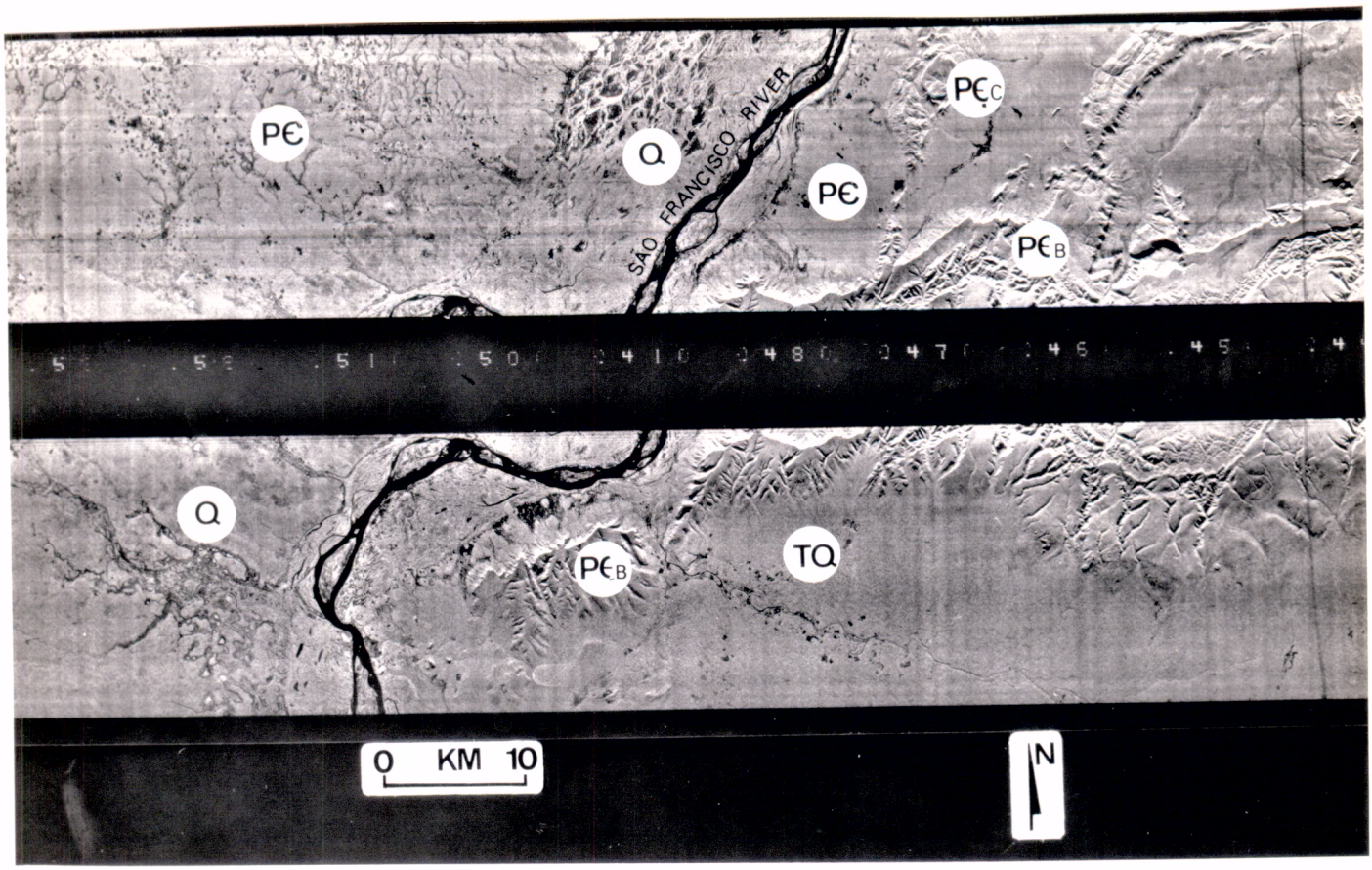

Fig. V.1 - SLAR imagery.

Top: near range; bottom: far range. pЄ: undivided Precambrian; pЄC: Colomi Group; pЄB: Chapada Diamantina Group: TQ: sandy argillaceous deposits and lateritic cover; Q: alluvium.

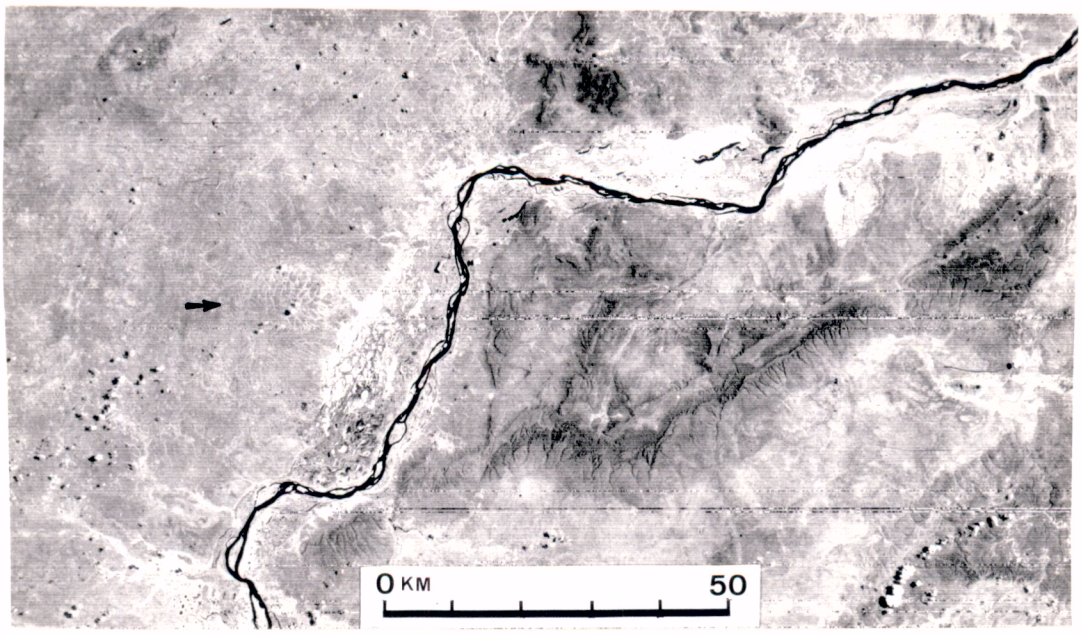

Fig. V.2 - LANDSAT-1 image.

Approximately the same area shown above (Band 7: 0.8-1.1 micrometers, E-1443-12223-7). The arrow shows area with radial drainage indicating intrusive granite.

SLAR imagery was then compared with existing maps of the area and a revised map incorporated also the results of field work in selected areas was prepared. A generalized geological map of the Rio São Francisco quadrangle is presented in figure V.3 while the final map is being drafted.

The structural information extracted from small scale imagery, such as those under discussion, presents a basic problem. In many cases it is possible to identify on the ground those structures (i.e. faults, fracture zones, etc.) which account for the linear features detected in the imagery. In some cases however, it is not possible to find a ready explanation for them. Several authors have already indicated that they may be important in the structural analysis of an area (Rich and Steele, 1974); Corrêa and Lyon, 1974; Corrêa et al., 1975), or to define targets for mineral exploration (Nicolais, 1974; Viljoen, 1974).

A mosaic of conventional aerial photographs was used by Kegel (1965) to identify the structural features in northeastern Brazil including the Rio São Francisco quadrangle area. The major structural trends of the formations belonging to the Crystalline Complex were observed as well as the limits of large tectonic blocks in the area of the Caririan and Propriã fold belts which are separated by xtensive fracture zones. In the Rio São Francisco quadrangle however, a large number of previously unknown structural features were identified which complement Kegel's observations.

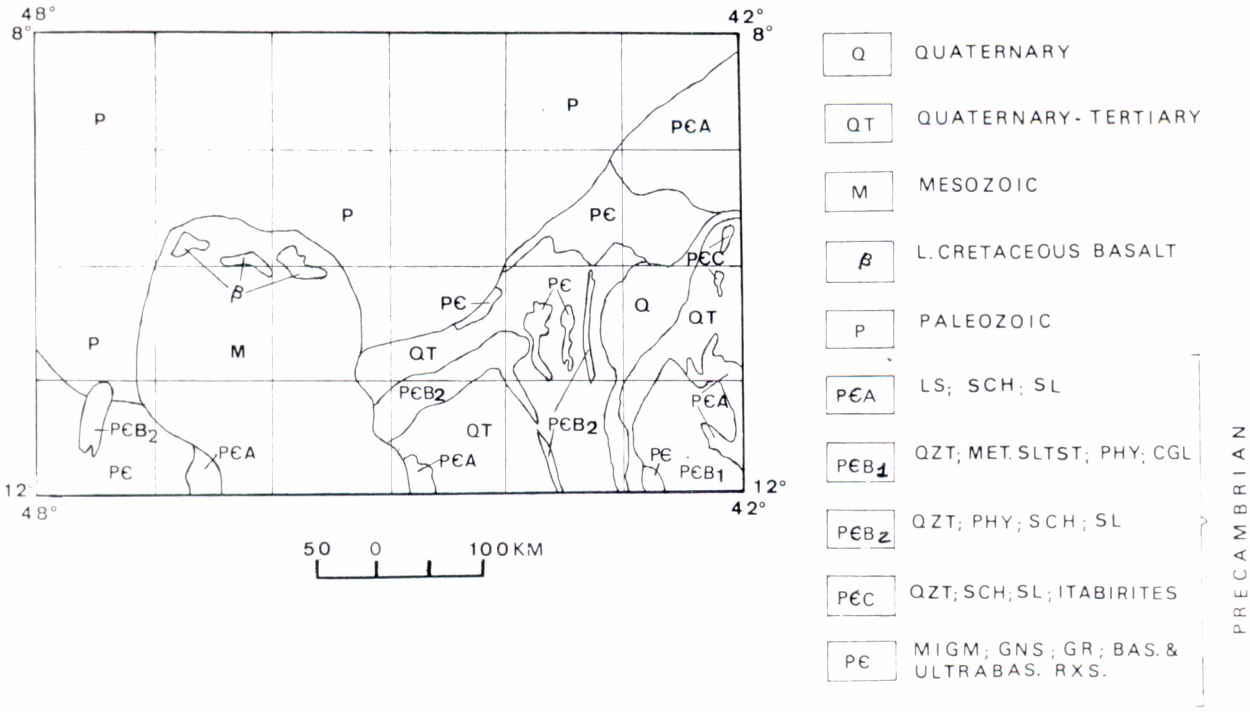

Fig. V.3 - Generalized geological map.

São Francisco quadrangle (SC.23).

Structures observed in LANDSAT and SLAR images with uncertain origin, but certainly including some that are structurally controlled, have been called herein linear features . The term lineament is used to indicate those features related to the geological structure of the area. The other terms used in this paper to identify structures are well defined in structural geology.

The structural map of the Rio São Francisco quadrangle includes not only the result of the interpretation of remote sensing data, but also those structures identified on the ground and shown in previous maps (Fig. V.4). Some of the structural features already mapped, such as faults and folds, despite their significant size, were not detected in small scale imagery. This is probably due to their small (or lack of) topographic expression and/or lack of contrast in relation to surrounding features in the imagery.

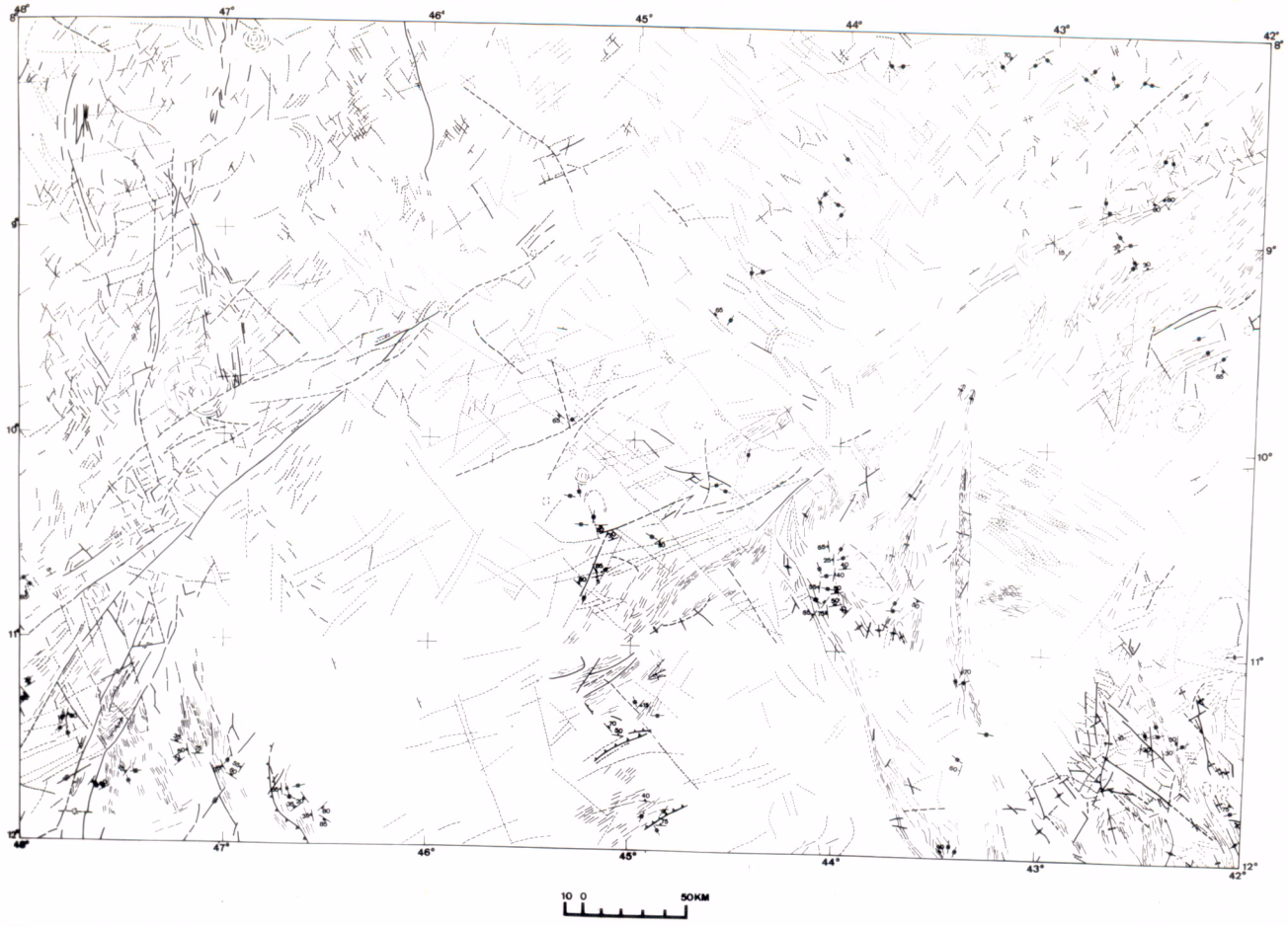

Fig. V.4 - Structural map of the Rio São Francisco quadrangle (SC.23).

- Fault
- Probable fault
- Thrust fault
- Fracture
- Lineament
- Linear feature
- Axis of anticline
- Axis of syncline
- Folded strata of unknown type
- Attitude of strata (photoint.)
- 10° Attitude of strata
- 30° Attitude of schistosity
- 20° Attitude of fracture
- Strike of vertical fracture

CHAPTER VI

STRUCTURAL INTERPRETATION

The structural interpretation presented below is an attempt to identify sets of structures which characterize regional trends and to point out their relationship with other structural systems taking into account the tectonic evolution of the Rio São Francisco quadrangle area.

The most important characteristics of the structural features in this area (Fig. V.4) are the concentration of fractures (including faults and joints) in areas of the exposed Crystalline Basement and of linear features in areas overlain by thick sedimentary sequences or by alluvium. Folding is not widespread, seeming to be restricted to the areas of the Precambrian Basement, where long anticlines and synclines seem to be a common feature.

Some of the structural systems described here have been identified already by other geologists who have worked in the area, and one hopes that this interpretation will encourage not only new structural studies but also the application of remote sensing data in geological research and mineral exploration.

The seven structural systems identified in the Rio São Francisco quadrangle area, called São Francisco, Parnaíba, Gilbués,

Lizarda, Tocantins-Araguaia, Boqueirão-Estreito and Pernambuco are described in the following paragraphs.

The basement of the São Francisco craton which is located in the southern part of the area was consolidated before 1,800 m.y. and may have been remobilized to a certain extent during the Trans-Amazonian orogenic cycle (Almeida et al., 1973). This basement is covered by meta-sedimentary and sedimentary units of the Upper Precambrian, and younger sedimentary units. The areas with a small frequency of structural features are overlain either by a thick Cretaceous sedimentary unit (part of unit M in Fig. V.3) or by alluvium, colluvium and scattered lateritic cover (units Q and QT in Fig. V.3).

The structural system called São Francisco is characterized by an orthogonal set of long linears trending northeast and northwest. This system may indicate the basic fracture pattern of the Precambrian Basement which might have been rejuvenated during the Trans-Amazonian orogenic cycle (1,800-2,600 m.y.).(Fig. VI.1).

Pflug et al., (1969) indicate that the structural features and the facies changes observed in the southeastern corner of the area support their idea that two cratons were present before the deposition of sediments along their margin. The identification of the Boqueirão-Estreito structural system within the area of the São Francisco craton seems to support the idea of the Minas orthogeosyncline which developed between the

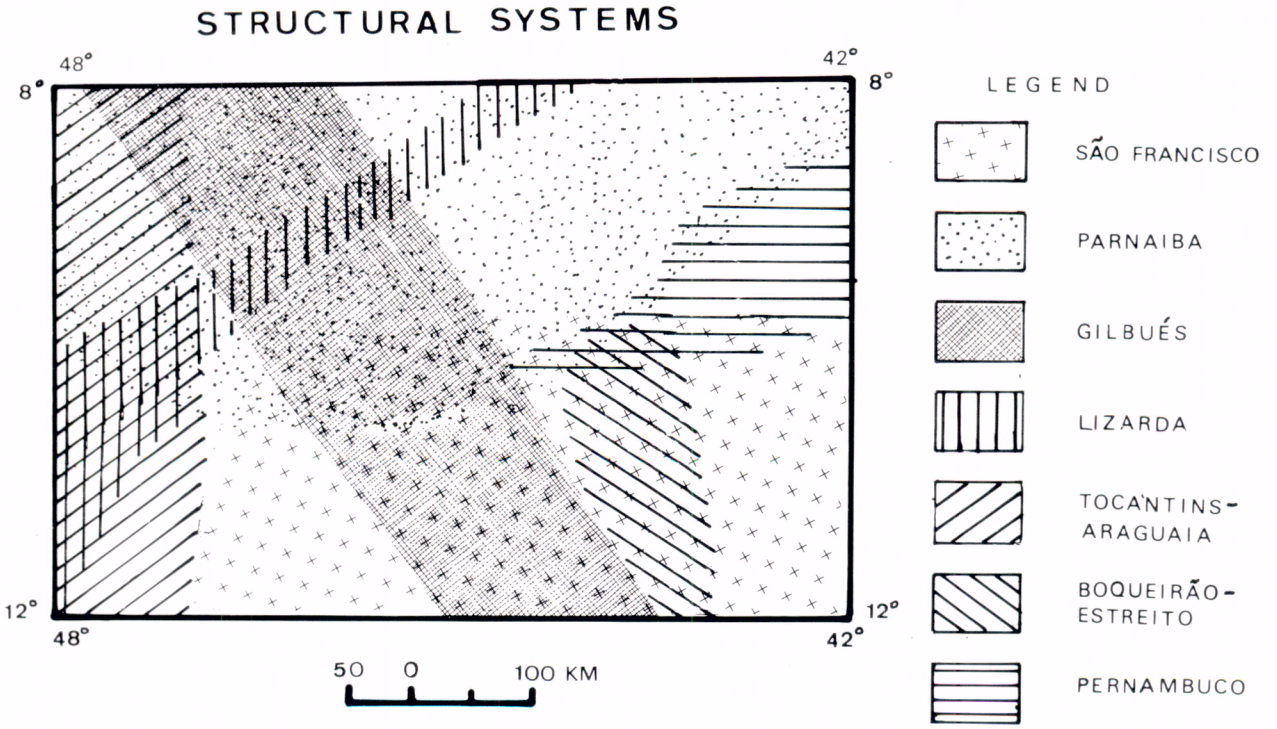

Fig. VI.1 - Structural Systems.

São Francisco craton located to the west of the Boqueirão-Estreito zone, and the Lençois craton, located in the southeastern corner of the quadrangle (Pflug et al., 1969). The Boqueirão-Estreito structural system which is characterized by a NNE and a NW trend, could have been the site of collision between two continental plates during Precambrian.

The western side of the quadrangle is characterized by a NNW and NE trending system with several NS trending normal faults. These faults which cut the Paleozoic sedimentary sequence of the Parnaíba basin are considered to belong to the Tocantins Araguaia structural system (Kegel, 1965; Corrêa et al., 1975) which was rejuvenated during the Braziliano tectonic cycle (900-550 m.y.).

The Parnaíba structural system is defined by NE and NW trending sets of orthogonal structures. These structural trends belonging to the Precambrian Basement probably were reactivated during the Mesozoic when the Parnaíba sedimentary basin underwent rapid subsidence as suggested by Almeida (1972).

The Gilbués structural system is characterized by a predominant set of large NW trending structures and a NE trending set of structures concentrated in the central part of the quadrangle. To the north of the 8^{o} parallel, this structural system is defined by the alignement of cryptovolcanic structures, positive structural anomalies, and a large scale thrust fault (Cunha and Carneiro, 1972). Most of the

circular features (2-5 km diameter) observed in our study are located along this structural system which was formed during the Eocambrian (Cunha and Carneiro, 1972) and was reactivated during the Mesozoic.

The Lizarda structural system (Correa et al., 1975) with its NE trending structures is an extension of the Sobral-Pedro II lineament detected by Kegel (1965).

The Pernambuco structural system which has been identified in the eastern side of the quadrangle probably was formed at the same time as the Lizarda system. Both of them seem to have been active during the Mesozoic (Late Triassic to Cretaceous) as a result of the disruption of the Gondwana continental plate and subsequent fracturing of the South American Atlantic margin. This system is correlated with the Precambrian SW Pernambuco/SE Piauí fold belt (Brito Neves, 1973).

CHAPTER VII

MINERAL DEPOSITS

No large mineral deposits are known in the Rio São Francisco quadrangle partly because alluvium, colluvium, and sand deposits cover most of the Precambrian areas.

Small mineralizations are known in the east, southeast, and southwest of the quadrangle where Precambrian rock units crop out. Besides those areas, the central part of the Rio São Francisco area is the only other region where valuable mineralization has been found.

7.1 - GOLD

Gold placer deposits are found in the southeastern corner of the quadrangle (Diamantina plateau) but to a lesser extent than in the 1930's and 1940's when gold made well known the districts of Gentio do Ouro, Barra do Mendes, Ipupiara and Central (State of Bahia).

Another area where gold has been mined is in the southwestern corner of the quadrangle (Dianópolis and Almas areas, State of Goiás) where gold bearing quartz veins are found in Crystalline Basement rocks.

Gold mineralization is so widespread in Precambrian terrains

that no controlling factor is evident for the Rio São Francisco quadrangle.

7.2 - LEAD-ZINC DEPOSITS

The limestone sequence of the Bambuí group (± 600 m.y.) which is present in several areas of the quadrangle is an excellent target for exploration for lead and zinc ores not associated with eruptives. Recent studies on the origin of these deposits indicate that they are related to fracture zones (Amaral, 1968) which were percolated by solutions that remobilized and concentrate the metals. A NNE trending crustal weakness zone located along the upper and middle São Francisco river (Guimarães,1964) seems to control the location of most lead-zinc ore deposits in eastern Brazil (Cassedane, 1968). This fracture zone is indicated in our study area by the Boqueirão-Estreito structural system which is obliterated to the north by younger systems.

7.3 - RUTILE

Rutile is produced from placer deposits derived from quartz veins or lenses in quartzites or phyllites of a metasedimentary sequence in the Boqueirão and estreito mountain ranges. Primary concentration of the rutile in the original sedimentary rocks probably is due to the erosion of basic rocks in source areas or to volcanic activity during sedimentation of the host rocks (Winge, 1968).

7.4 - DIAMONDS

Diamonds in the southeastern corner of the Rio São Francisco quadrangle originate from the weathering of conglomerate levels in quartzites of the Diamantina Plateau.

In the central area of the Rio São Francisco quadrangle, diamond placers have been mined, in the area of Gilbués and Monte Alegre (State of Piauí). A Kimberlite discovered 15 km northwest of Gilbués is being studied to verify if it is the original source of diamonds (Nunes et al., 1973). Other circular structures which could be proven to be ultrabasic rocks have been detected in radar imagery (Nunes et al., 1973) and again during our mapping program and semm to be restricted to the Gilbués structural system.

CHAPTER VIII

CONCLUSIONS

The results of this regional mapping program show that remote sensing data such as LANDSAT and SLAR imagery are extremely useful to make small scale maps or to revise previous maps with savings in time and money. Some of the structural systems identified in the Rio São Francisco quadrangle seem to be directly related to specific types of mineralization and could serve as guides in selecting target areas for exploration.

ACKNOWLEDGEMENTS

The author acknowledges the help provided by INPE's geologists during the interpretation of remote sensing imagery and field work, especially by Messrs. Paulo R. Meneses, Paulo Veneziani, Athos R. Santos, Ubiratan P. Santos, and Chan C. Liu who drafted several illustrations.

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