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ABSTRACT

Three areas in Brazil, located in different geological environments, were selected to be used as case studies on the application of LANDSAT-1 imagery. The satellite images were analyzed using conventional photointerpretation techniques and the results obtained indicate the possible application of small-scale image data in regional structural data analysis, geological mapping, and mineral exploration.

INTRODUCTION

Brazil is a country with more than 8.5 million square kms² which is only partly known with respect to its natural resources potential. Regional evaluation studies of such a large area can be carried out much more efficiently and in less time with the application of remote sensing mapping techniques. Data obtained from spacecrafts especially designed to acquire information for studies of Earth's natural resources are particularly useful because of their capability to provide a synoptic view which is necessary in regional mapping programs.

The satellite LANDSAT-1 (previously known as ERTS-1) has provided multispectral imagery of Brazil which has been available since 1972. This imagery has allowed thematic mapping even in areas where more conventional mapping material (i.e. aerial photography) is difficult to obtain because of prevailing poor weather conditions. The Amazon Region in northern Brazil is a typical example of one of these problematic areas, where for most of the year the weather does not allow photogrammetric flight (Girardi, 1973). The periodic coverage provided by the LANDSAT-1, which systematically obtains imagery over the same area is a relatively inexpensive way to obtain data over such regions.

METHODOLOGY FOR INTERPRETATION

The basic data used in geological interpretation were

LANDSAT's multispectral scanner imagery, especially bands 5 (0.6-0.7 μm) and 7 (0.8-1.1 μm) and color composite images. Conventional photointerpretation techniques were employed in the analysis without the benefit of stereoscopic viewing, except for the area of sidelap which is approximately 15% of the total area.

The results obtained from the study of LANDSAT imagery therefore are highly dependent on the geological knowledge of the photointerpreter and his experience to extract useful information from the images. The photointerpreter is required to take into consideration the influence of topography, color (tone in the imagery), distribution of natural vegetation and cultivated land, sun illumination (sun azimuth and elevation above the horizon), and drainage patterns when extracting geological information from the satellite imagery. The relationships between these factors and maximum use of space images has been discussed by Lee et al. (1974) and was carefully considered during analysis of LANDSAT imagery.

CASE STUDIES

Three areas in Brazil were selected to serve as examples of the application of LANDSAT imagery in geological studies. These areas (fig.1) are located in different geological settings, have been studied already with different degrees of detail, are covered by different types of vegetation and are within different climatic zones.

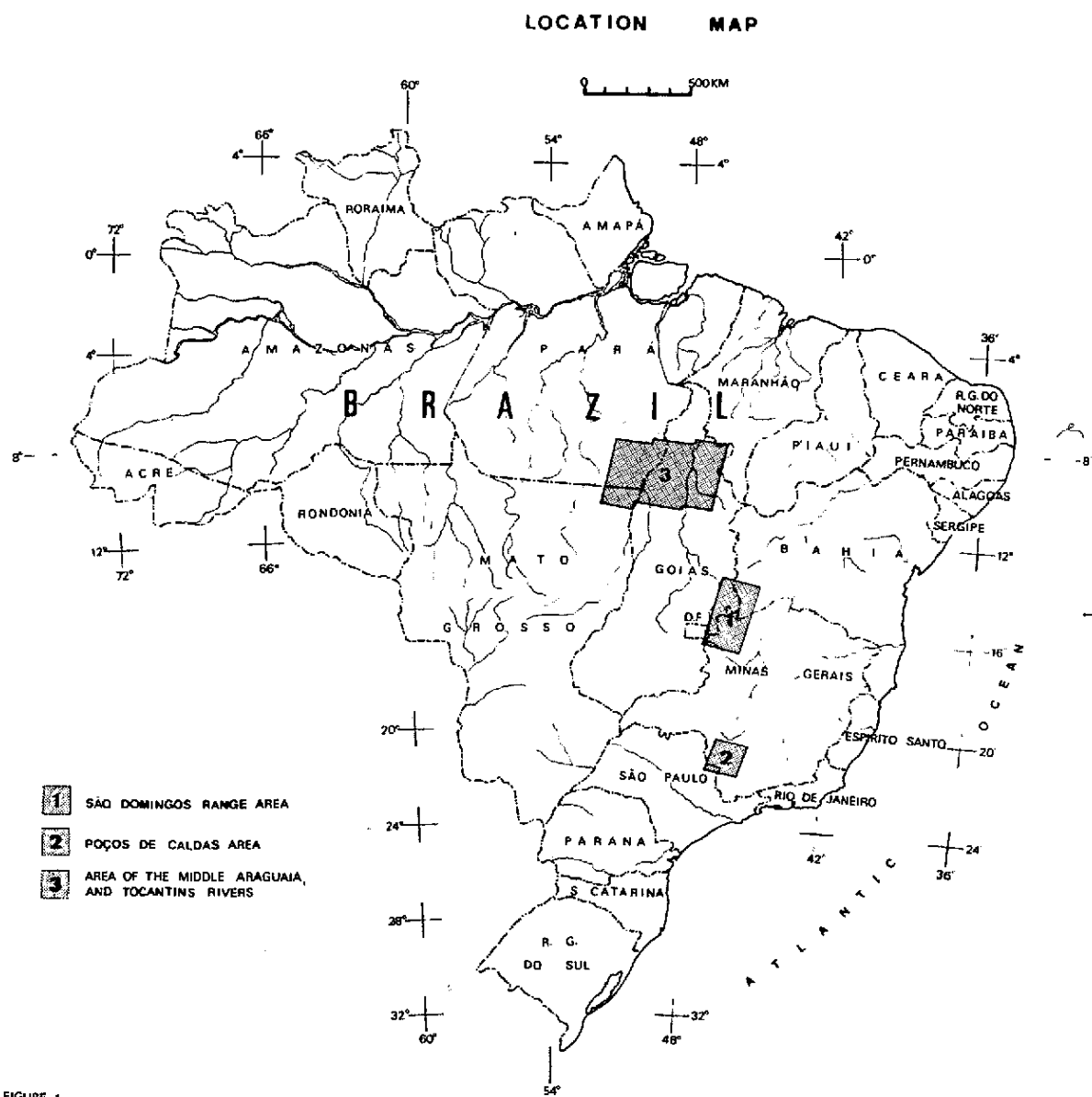


FIGURE 1

Figure 1 - Map showing the location of case study areas.

As a result of geological mapping in Brazil in recent years valuable information has been available about previously poorly known regions, mainly the central and northern parts of the country. Based on this geological knowledge and radiometric dating available today it is possible to outline the tectonic framework of Brazil which will serve as a reference to parts of the discussion in the following sections (fig. 2).

Brazil and the entire Atlantic coast of South America are part of a geotectonic unit known as the South American Platform (Almeida, 1971). Precambrian rocks, locally overlain by a thin sedimentary cover, are exposed in the Guyana, Central Brazilian and Atlantic shield areas (fig. 2). The Guyana and Guaporé cratons (which include the Central Brazilian shield area) may have been a single stable block during late Precambrian time (Amaral, 1970). The large Amazon, Parnaíba, and Paraná sedimentary basins are located also between the shield areas mentioned above (fig. 1).

The three areas selected as case studies for presentation in this paper are:

- a) São Domingos Range area
- b) Poços de Caldas area
- c) The area of the Middle Araguaia and Tocantins rivers.

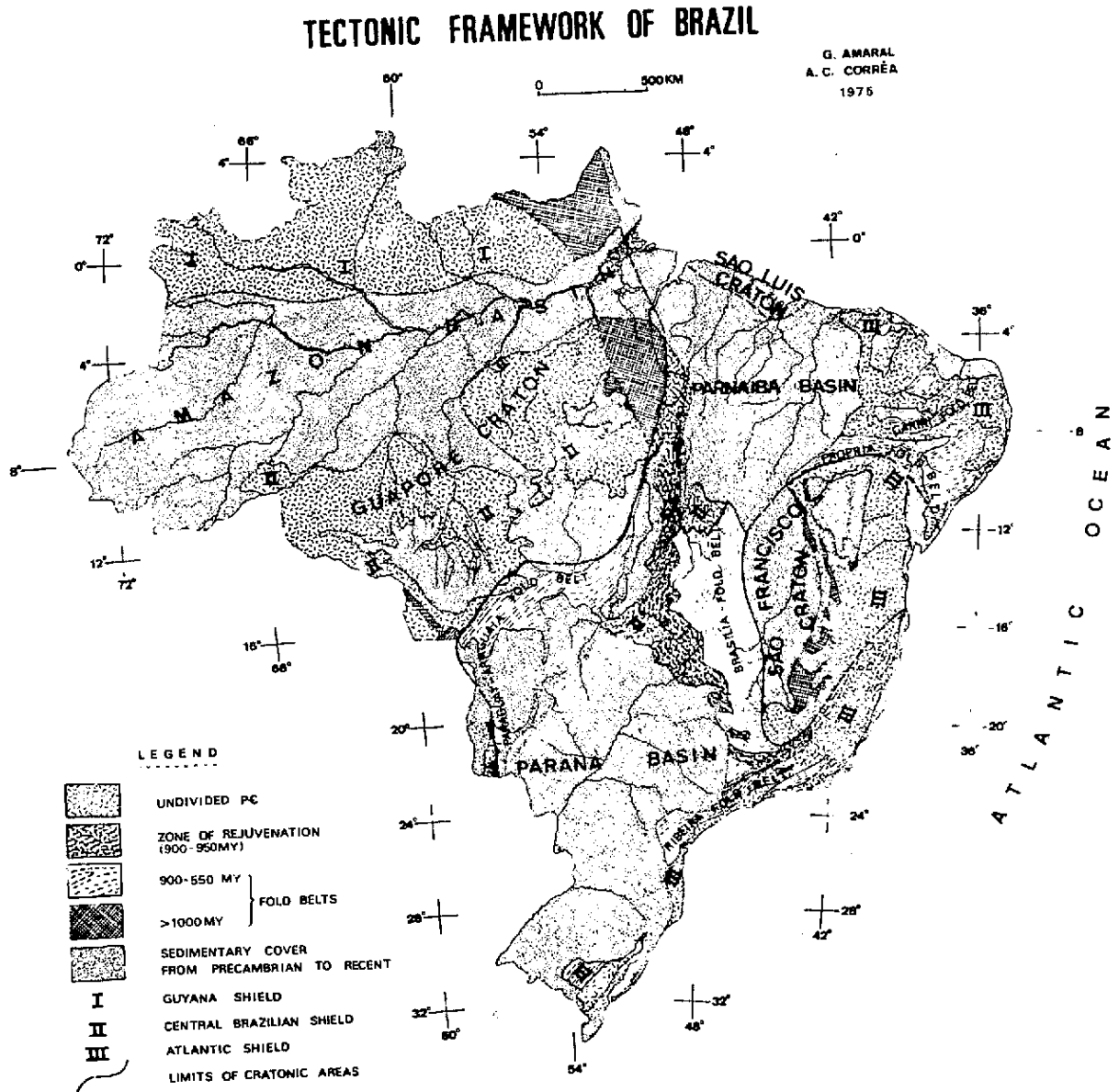


FIGURE 2

Figure 2 - Tectonic framework of Brazil (after Cordani, U. et al., 1968; Ferreira, E.O., et al., 1970; Amaral, G., 1970; and Almeida, F.F.M., 1973).

THE SÃO DOMINGOS RANGE AREA

The São Domingos Range area (fig. 1) includes a representative part of the Brasília fold belt and of the sedimentary cover of the São Francisco craton, besides a few outcrops of crystalline basement rocks. The different types of sedimentary rocks present in this area and the sharp contact between two tectonic domains are some of the interesting observations that can be made in LANDSAT images over this area (fig.3).

This area is characterized by a tropical climate with a dry winter (rainy summer) corresponding to Köppen's Aw type (Azevedo, 1964). The vegetation predominant in the area is a cerrado (savanna-like vegetation) with a small occurrence of tropical deciduous forest along the northwestern side of the area. The images in figure 3 were obtained in August, 1973, during the dry season (winter) and allow a very good discrimination of lithologic types in the area. Imagery taken during the rainy season (not shown here) gives essentially the same information for most of the area as observed in dry season imagery (fig.3). Little geological information however is available in the rainy season imagery from the area covered by the tropical deciduous forest that is well developed at that time of the year.

A stratigraphic column of the São Domingos Range as based on previous geological mapping is given in table 1.

A careful analysis of drainage patterns, landforms, tone, vegetation, and soil use patterns in the area led to the identification of

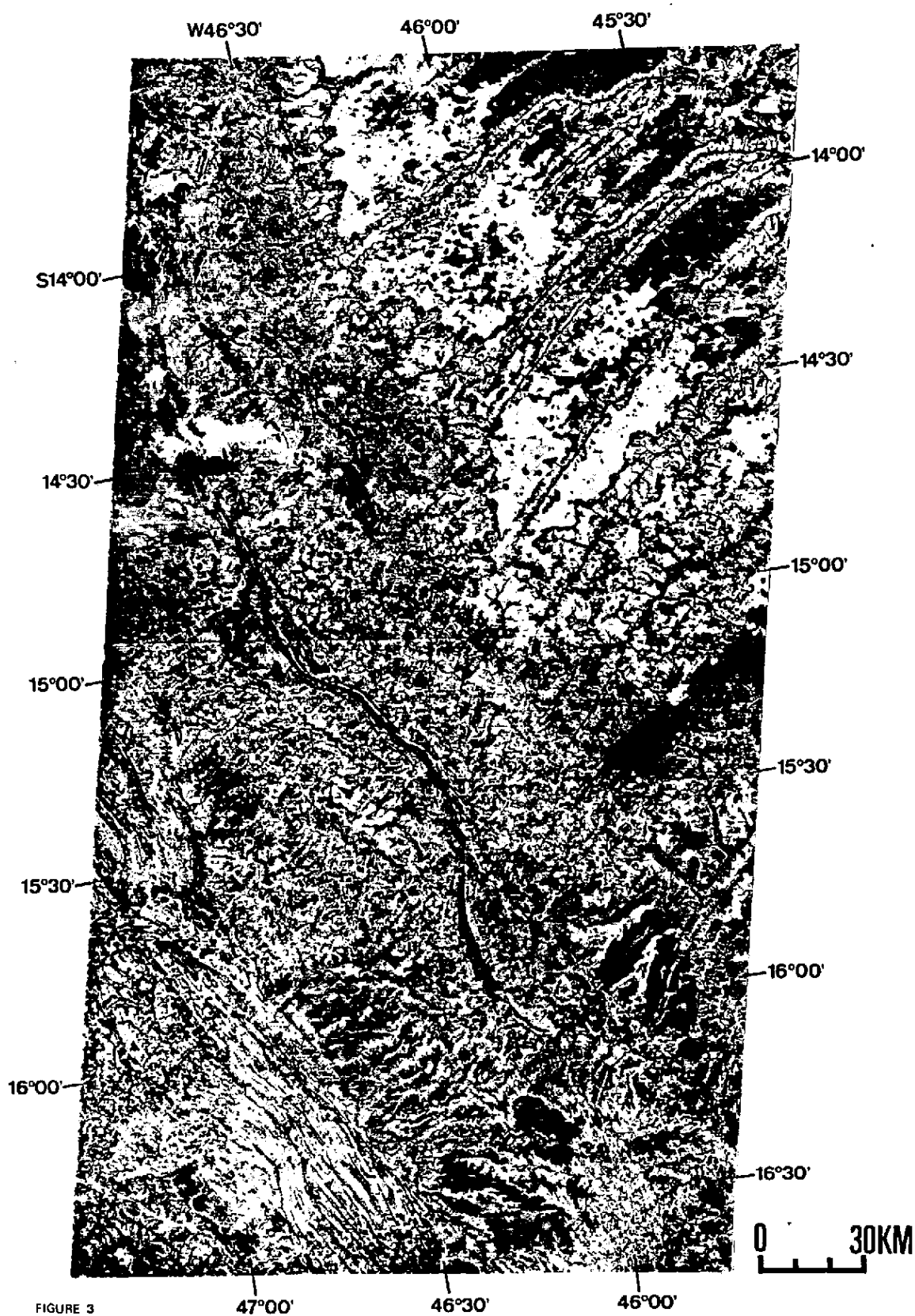


Figure 3 - Photomosaic of the São Domingos range area from LANDSAT's multispectral scanner imagery (band 5: 0.6-0.7 micrometers). Imagery obtained on August 18, 1973 (Top: E-1391-12362, bottom: E-1391-12365).

-Table 1 - Generalized stratigraphic column for the São Domingos^o Range area (after Braun, 1968; DNPM, 1965/68 a,b, 1968 a,b; Ladeira, 1971).

AGE	LITHOLOGIC UNITS		SUMMARY DESCRIPTION
Quaternary	Alluvium deposits		Sand, clay and gravel.
Tertiary (?)			Sandstones, conglomerates and argillaceous sand deposits.
			Lateritic cover
Cretaceous	Urucuia Formation		Red sandstones, argillites and a basal conglomerate.
Upper Precambrian/ Eocambrian (?)	Bambuí Group	Três Marias Fm.	Arkose, micaceous, siltstone, and arkosic sandstone.
		Paraopeba Fm.	Carbonatic and pelitic rocks.
		Paranoá Fm.	Quartzites interbedded with fillites and metasiltstones.
Precambrian (undifferentiated)	Crystalline Basement		Granite and gneiss complex

"remote sensing rock units". A tentative correlation of remote sensing rock units with stratigraphic units is presented in the legend of figure 4, but it is emphasized that in some cases there is not a unique or complete correlation between these two types of mapping units.

A comparison between the geological interpretation (fig. 4) and maps available at a larger scale for this area (DNPM, 1965/68 a,b; 1968 a,b) shows that stratigraphic units defined by a single or few rock types and cropping out in large areas can be well defined in the imagery. The best results in discrimination between stratigraphic units was attained for alluvium (unit Qa) and the sedimentary deposits designated as Tq, both of them including unconsolidated sediments. The Tertiary lateritic zone (unit Tql) found throughout the area is characterized by a uniform image tone and smooth topography and has been identified with good precision from LANDSAT imagery.

The sedimentary sequence of the Urucuia Formation, composed predominantly of sandstones, overlies unconformably the Bambuí Group and forms the large plateau in the northeastern side of the area where a typical parallel drainage pattern can be observed (fig.3). The areal extent of the three remote sensing rock units identified in the São Domingos Range area (Kus, Kum, and Kui) is correlated in part with the distribution of the Urucuia Formation shown in published maps and is discussed in more detail below.

From the geological analysis of satellite imagery it is possible to identify units Kus, Kum and Kui each one with its own spectral

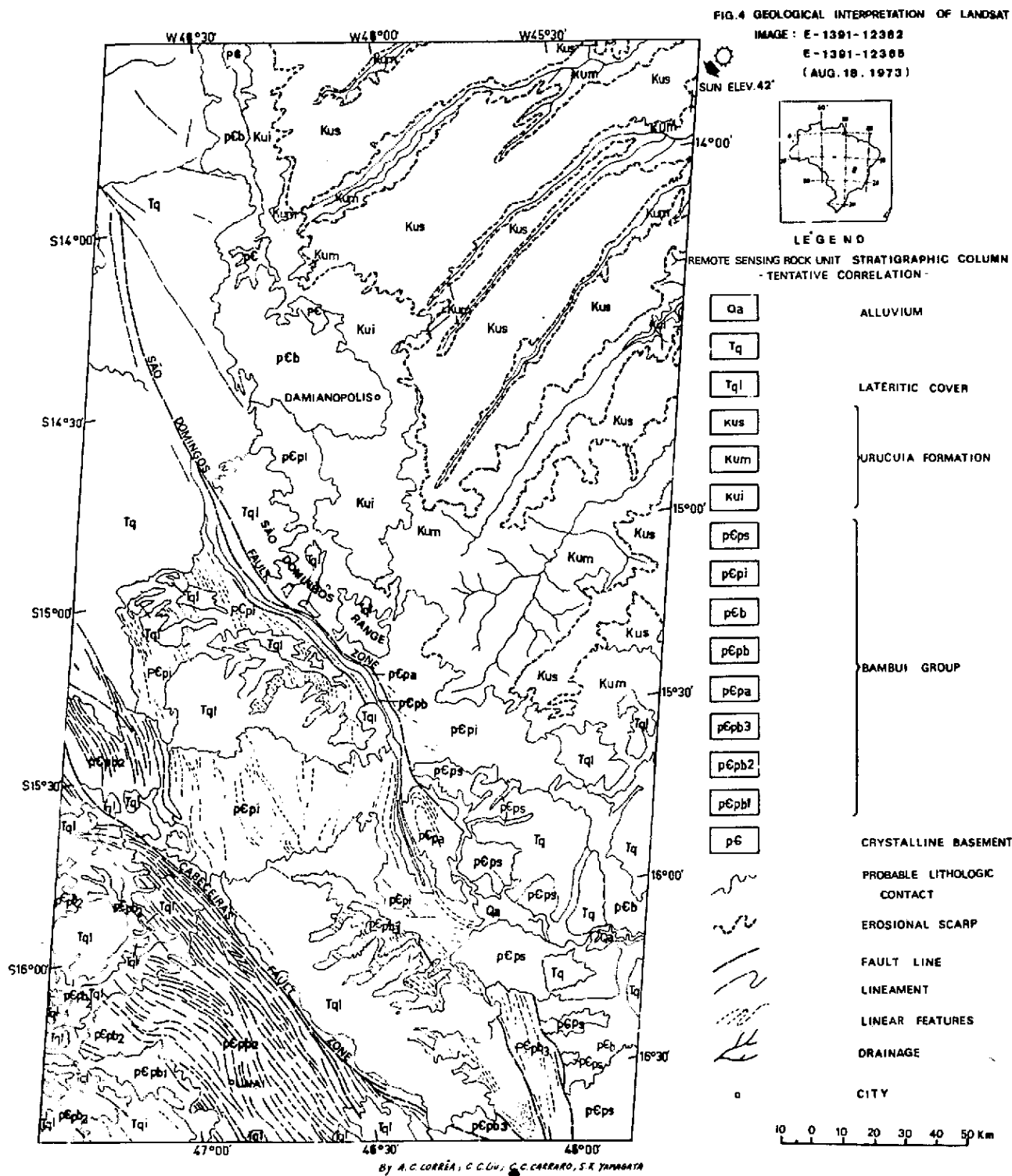


Figure 4 - Geological interpretation of the São Domingos range area based on LANDSAT-1 imagery.

and textural characteristics (fig.3). The uppermost unit, Kus in figure 3, is separated from the other units by a very steep erosional scarp (fig.3) which is clearly visible in the images (fig.2). This remote sensing rock unit indicates the areal extent of the sandstone upper member of the Urucuia Formation (Oliveira, 1967). The other units, Kum and Kui in figure 3, enclose areas where previous maps based on photointerpretation of 1:60.000 aerial photographs and some field work (DNPM, 1965/68a), indicate the presence of scattered lateritic cover. At the 1:1,000,000 scale however these patches of laterite cannot be detected and it is believed that units Kum and Kui correspond to the sequence of shale, siltstone and silty sandstone of the lower member of the Urucuia Formation (Oliveira, 1967).

The other stratigraphic unit present in the area, the Upper Precambrian sequence of the Bambuí Group has a more diversified lithology and its outcrops in a region structurally complex are relatively small. While the Bambuí Group has been divided into three formations it is not possible to identify them accurately in LANDSAT-1 imagery.

The crystalline basement rocks in the northern part of the area, because of their relatively small outcrops, are very difficult to identify in LANDSAT-1 images.

The São Domingos Range area comprises the contact between the ancient São Francisco craton which is covered by Precambrian and younger

sediments, and the Brasilia fold belt (fig. 2). The change in structural features between these two tectonic units is well defined in the images.

The Brasilia fold belt is characterized in the area under discussion by a series of northwest trending, elongated anticlines and synclines. These structures cannot be individually identified in the space imagery because of their relatively small lateral extension which makes the determination of the attitude of their flanks extremely difficult. The linearity shown by fold axes however permits a precise indication of the dominant structural trend in the area. Lineaments shown in the geological interpretation map include both folds and probable fractures in the area of the Brasilia fold belt (fig.4). The term lineament is used in this paper to indicate those lines observed in the imagery which are structurally controlled.

The region between the Cabeceiras and São Domingos faults can be considered as the contact zone between the Brasilia fold belt and the São Francisco craton. Structures detected in this zone have been called linear features, a term used to indicate features with uncertain origin, some of which are certainly structurally controlled. Previous maps of the area at the 1:250,000 scale (DNPM, 1965/68 a,b) show a few folds in this zone which do not account for all of the linear features detected in the imagery. Braun (1968) observed also that folding in this general area decreases toward northeast and that there are no indications of structures east of the São Domingos fault zone, where bedding is almost horizontal. Probably the linear features observed in space imagery with a trend parallel

to the Brasília fold belt, indicate that this zone could have been affected to a small degree by the tectonic activity in the fold belt.

THE POÇOS DE CALDAS AREA

The area considered for analysis in this section lies on the border of the States of Minas Gerais and São Paulo in southeastern Brazil (fig.1). The larger feature just to the southwest of the center of the LANDSAT-1 image which outlines the Poços de Caldas alkaline complex has attracted the interest of geologists for some time (fig.5). Derby (1887) wrote the first geological report on the area indicating the presence of this alkaline intrusive and was followed by others that described with more detail the geology and mineral resources.

The Poços de Caldas alkaline complex is one of the several alkaline intrusive located along the northeastern boundary of the Paraná Basin and scattered along the Atlantic coast (fig.2).

The Poços de Caldas alkaline intrusive is emplaced in granite and gneiss of Precambrian Basement Complex which occupies most of the area in the imagery. The contact between the Precambrian igneous and metamorphic terrain and the sedimentary sequence of the Paraná Basin can be outlined with a very good precision using bands 5 and 7 (fig.6). The alluvial deposits (Unit Qa) surrounding the Furnas Dam area are identified also using these two bands. The alkaline intrusive rocks in the Poços de

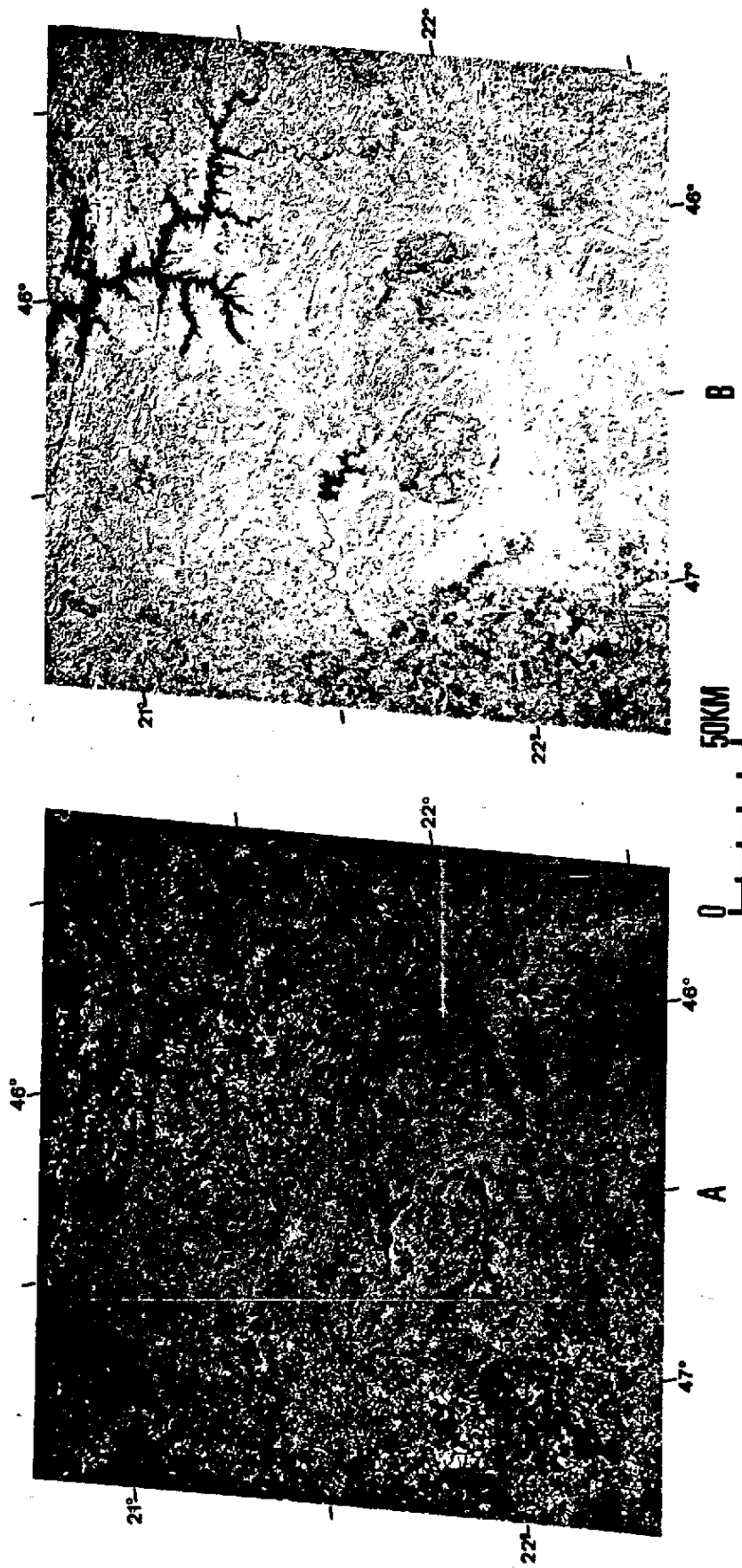


FIGURE 5

Figure 5 - LANDSAT-1 images of the Poços de Caldas area. A) Band 5 (0.6-0.7 micrometers). B) Band 7 (0.8-1.1 micrometers). Imagery obtained on September 09, 1972 (E-1048-12330).

Caldas district do not present in band 5 any difference from the surrounding igneous and metamorphic terrain. The medium gray tone and smooth texture observed in band 7 for the area enclosed by the circular structure delineates very well the extent of the intrusive rocks (Unit K). A reconnaissance mapping of the circular structure immediately south of the Poço Fundo Dam, which has approximately the same gray tone in band 7 as that of the Poços de Caldas district, has not revealed the presence of outcrops of alkaline rocks (Almeida Filho and Paradella, 1975).

The geological interpretation of this LANDSAT-1 frame identified a large number of previously unknown fault zones, lineaments, linear and circular features. The Poços de Caldas area is located in Precambrian terrain that was rejuvenated during the Upper Precambrian and Cambrian (fig.2). The large approximately east-west trending fractures in the Furnas Dam area and south of the Poços de Caldas district may be related to the deformation associated with the Brasília and Ribeira fold belts respectively (fig.5). The Mesozoic activation of the South American Platform which caused an increase in subsidence rate of the Paraná Basin and intense magmatic activity (Almeida, 1972), was responsible for important fissure volcanism which covered with basaltic lava most of the basin. The fissure volcanism during the Jurassic extending until the Albian (Amaral et al., 1966) was simultaneous with the intrusion of alkaline centers in southern Brazil. The volcano-plutonic magmatism which is present in the Poços de Caldas district occurred during the Upper Cretaceous (Senonian) and is associated with trending fractures in a zone of monoclinial flexure between the Paraná Basin and the São

Francisco craton (Almeida, 1972). The alkaline intrusive bodies are also considered to represent the rejuvenation of zones of rifting or fracturing which were active at the time of the initial separation of the South American and African continental plates (Neill, 1973).

The alkaline intrusive centers associated with the Mesozoic activation of the South American Platform area of great importance because of the economic mineralization. The underlying rocks of the Poços de Caldas district are mainly of nepheline syenite (referred to also as foyaite) and phonolite (minor amounts of volcanic and sedimentary rocks are present also) which are deeply weathered in most of the plateau area. In the northern part of the district, aluminous laterite or bauxite is the product of weathering forming commercial deposits (Teixeira, 1937; Weber, 1959) that are being mined today.

Uraniferous zirconium deposits are associated with the Poços de Caldas alkaline intrusive and a preliminary delineation of radioactive anomalies was accomplished with data acquired by airborne and ground radiometric surveys. The deposits are located in three main areas within the circular structure: the east-central part of the Poços de Caldas plateau (Pocinhos area), the west central part (Cascata area) and the south central area (fig.6). The primary uraniferous zirconium deposits are believed to originate from the action of hydrothermal solutions on the zirconiferous syenite and subsequent deposition of the stable oxide (baddeleyite - ZrO_2) and silicate (zircon - $ZrSiO_4$) in fissures (Franco and Loewenstein, 1948;

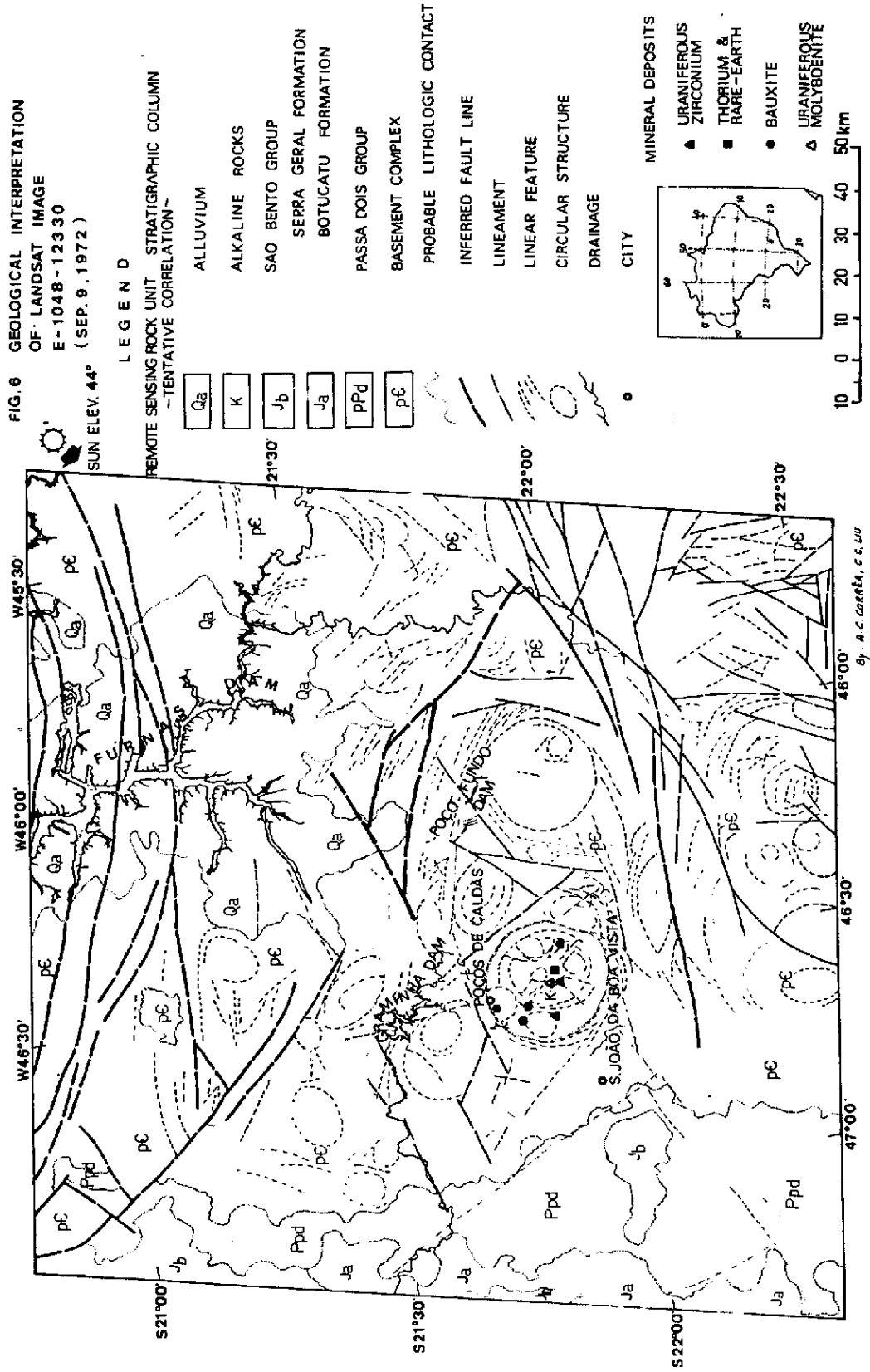


Figure 6 - Geological interpretation of the Poços de Caldas area based on LANDSAT-1 imagery.

Tolbert, 1966). Uraniferous molybdenite mineralization of economic value is found in Campo do Agostinho at the center of the Poços de Caldas plateau. Uranium and molybdenum ore minerals with variable amounts of pyrite and fluorite are found in veins located in fracture or breccia zones in hydrothermally altered tinguaita (Gorsky and Gorsky, 1970).

In the south central area of uraniferous zirconium mineralization, at Morro do Ferro, the alkalic igneous rocks were percolated by mineralizing solutions rich in thorium and rare-earth elements which followed the existing fracture system (Wedow, 1967). Secondary enrichment of rare-earth elements and thorium in the upper part of the stockwork was caused by the deep weathering typical of the Poços de Caldas area (Wedow, 1967).

The geological interpretation of the LANDSAT-1 image suggests that within the large circular structure of the Poços de Caldas district, smaller circular structures and linear features probably indicate secondary intrusive centers and fractures which may have controlled to a great extent the hydrothermal mineralization. These structural features are not all shown in the most recent geological map available for the district (Ellert, 1959). Other previously unknown circular features identified in the Poços de Caldas area can be considered as likely mineral exploration targets and should be examined in the field. One of the authors (A.C. Corrêa) visited the circular feature in the Graminha Dam area (fig.6) but has not found at the surface indication of alkaline igneous intrusive rocks but this does not exclude the possibility of their occurrence at subsurface at that side or

any other area nearby.

THE AREA OF THE MIDDLE ARAGUAIA AND TOCANTINS RIVERS

An area in north-central Brazil was chosen as the third case study for the application of LANDSAT-1 imagery in geological research (fig.1). The Araguaia and Tocantins rivers, flowing towards the Amazon river to the north, cross the region from south to north (fig. 7).

Two climates and vegetation types prevail in the area with a boundary zone located approximately along the Araguaia river. To the west of the river a hot and humid equatorial climate (Köppen's Am type) and a broad-leaf equatorial forest are dominant, while to the east a tropical climate with distinct dry and rainy seasons (Köppen's Aw type), and cerrado (savanna-like) vegetation are present (Azevedo, 1964).

LANDSAT-1 imagery for this area provided structural data that was interpreted in order to outline structural systems which can define regions with similar tectonic style. The small-scale satellite images providing a synoptic view of large areas are extremely useful in the identification of the regional characteristics which are not evident in low-altitude aerial photography.

The purpose of this structural interpretation is not to discuss specific linear features but to identify those sets of structures

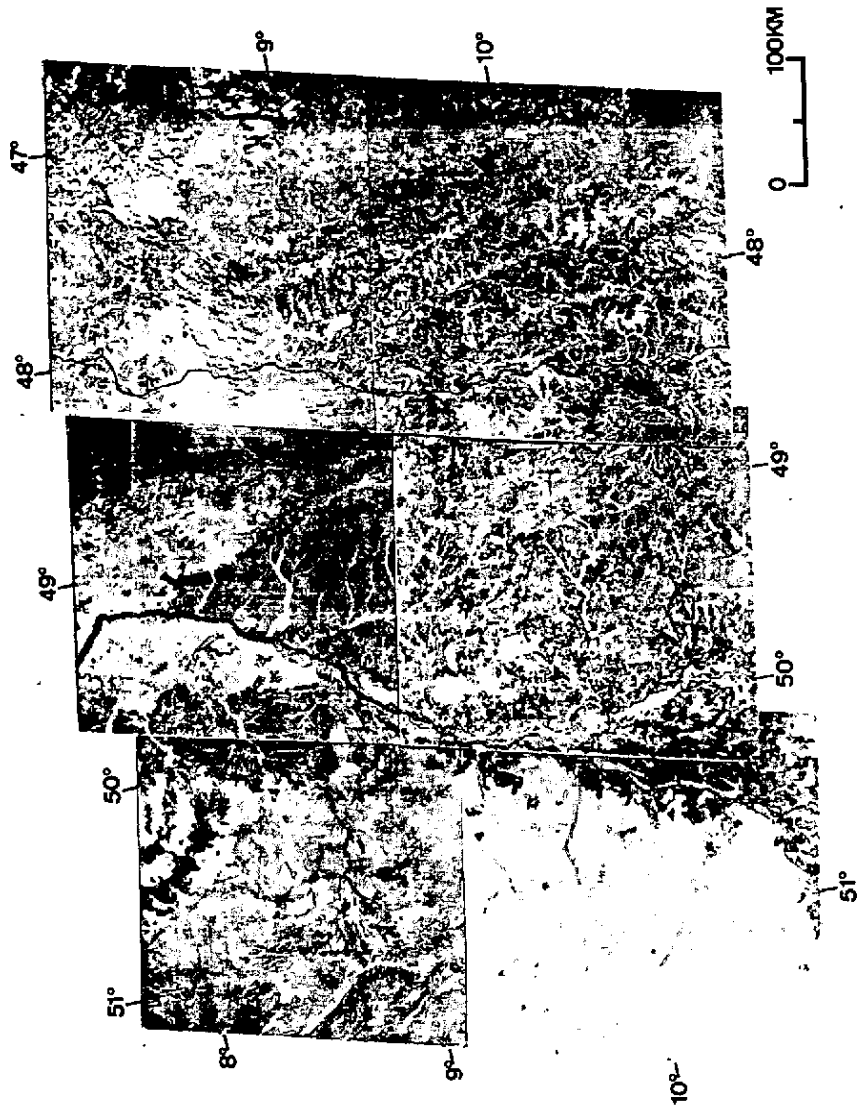


FIGURE 7

Figure 7 - Photomosaic of the area of the middle Araguaia and Tocantins rivers from LANDSAT's multispectral scanner imagery (band 7: 0.8-1.1 micrometers). Identification of LANDSAT-1 frames given in figure 8.

that determine regional trends and to point out their relationship with the other structural systems.

Two basic assumptions are made concerning the discrimination of structural systems (Rich and Steele, 1974). The first is that any system in a given region originates as a result of the action of the stresses present in that region at a certain period of the geologic time. A structural system may have been rejuvenated as a consequence of younger tectonic activity. The second assumption is that the original structural trend has been preserved and that any later changes which could have affected a given trend must have been recorded also in the whole system. Even in the case where a younger system is developed along a trend intersecting an older system, indications of the older system can still be detected, subtly in some cases, in the geomorphic characteristics of the terrain. Recent alluvial deposits or thick sedimentary sequences may also obliterate to some extent trends of old linear systems but erosion and tectonic reactivation which may reinforce pre-existing trends, allow their identification.

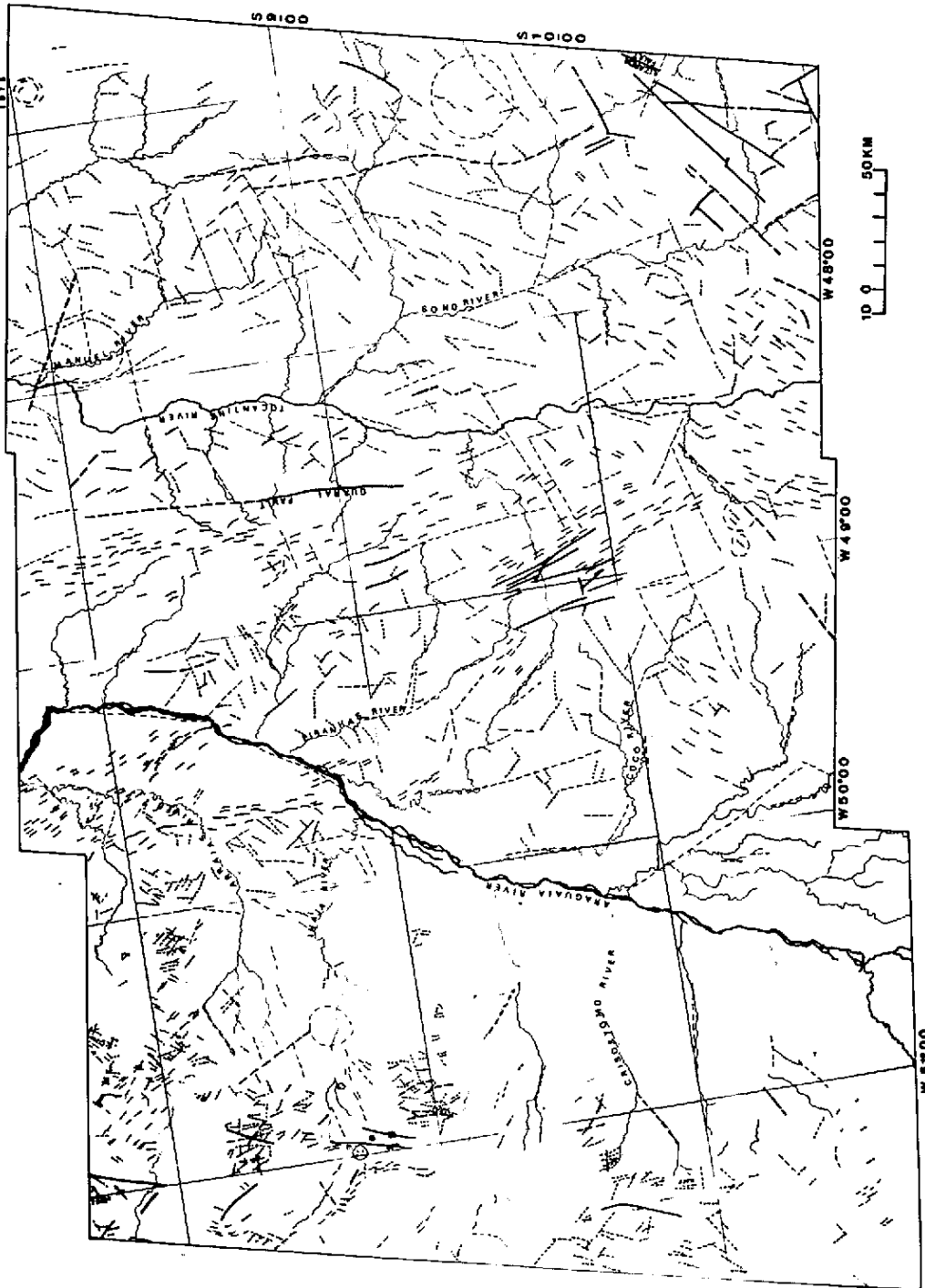
Some of the structural systems detected have been recognized by geologists working in the region, but others have not been identified or described in the available literature and will possibly encourage a reexamination of present ideas.

The preliminary structural map of the area of the middle Araguaia and Tocantins rivers is shown in figure 8. The structural features

PRELIMINARY STRUCTURAL MAP

BASED ON THE INTERPRETATION OF LANDSAT-1 IMAGERY
STATES OF GOIAS, PARA, AND MATO GROSSO, BRAZIL

AUTHORS: A. C. CORRÊA
R. R. MENDES
U. P. SANTOS



LEGEND

- KNOWN FAULTS
- - - INFERRED FAULTS
- - - FRACTURES
- - - LINEAMENTS
- - - LINEAR FEATURES
- - - SYNCLINE
- - - ANTICLINE
- - - CIRCULAR FEATURES
- INTRUSIVE GRANITE

INDEX MAP TO LANDSAT IMAGES

E-1377-12575	E-1376-12551	E-1123-12472
E-1377-12582	E-1376-12552	E-1123-12474

FIGURE 8

Figure 8 - Structural interpretation of the area of the middle Araguaia and Tocantins rivers based on LANDSAT-1 imagery.

mapped were detected using traditional photogeologic interpretation not in the images which were used to make the photomosaic, but also in other images available. The terms lineaments and linear features were used in the same way as defined in a previous section.

Structural Systems

The structural systems identified in the study area are shown schematically on figure 9 and described briefly below.

The western side of the study area is characterized by an orthogonal system of short linears consisting of a north-south or north-northeast trending set and another set which trends east-west or east-southeast. This structural system is called Guaporé, a reference to the Guaporé craton which is outlined by it. The eastern border of the Guaporé craton, which is present in our study area, according to age determinations may be as old as 3,000 m.y., however most ages fall into the 2,600-1,800 m.y. range (Amaral, 1970). This crystalline basement consists mainly of migmatites, gneiss, granite and amphibolite (Amaral, 1974) however in the area under consideration it is indicated by highly fractured granitic bodies. A Tertiary sedimentary cover is widespread and obliterates to a great extent the basement rocks.

In the northwest corner of the area shown in figure 8 there is a predominance of a northwest trending linear structures overprinted on

The Guaporé system. This structural system, referred to as the Carajás system, is related to the sequence of fractured and folded metasediments including iron formations, intrusive granites, quartzites, phyllites, and mafic rocks defined as Serra dos Carajás Group (SUDAM/HIDROSERVICE, 1973) and considered to be more than 2,000 m.y. (Amaral, 1974).

The central area of the structural map (fig.8) is characterized by an approximately north-south set of linears designated as the Tocantins-Araguaia structural system. This system encloses the fold belt along the eastern border of the Guaporé craton where metasediments of the Araxá and Tocantins Groups are present. These two groups according to age determinations are probably 2,000 m.y. (Amaral, 1974) and were rejuvenated during the Brazilian tectonic event (900-550 m.y.) (fig.2) (Ferreira, 1971). These two groups include also iron formations associated with metabasites to a lesser extent than the Serra dos Carajás Group. Small basic and ultra-basic bodies which intruded along the deep fractures formed during the separation of the Guaporé and São Francisco cratons (Almeida, 1967), are part of the serpentine belt located within this structural systems.

The eastern side of the study area corresponds to a border of the Parnaíba sedimentary basin (fig.2). This region is characterized by a predominantly north-northwest to north-northeast set of linears defining the Parnaíba structural system (fig.9). This set of linears observed in the Paleozoic sedimentary sequence may have been present at the basement of this basin. During the activation of the South American Platform, during the

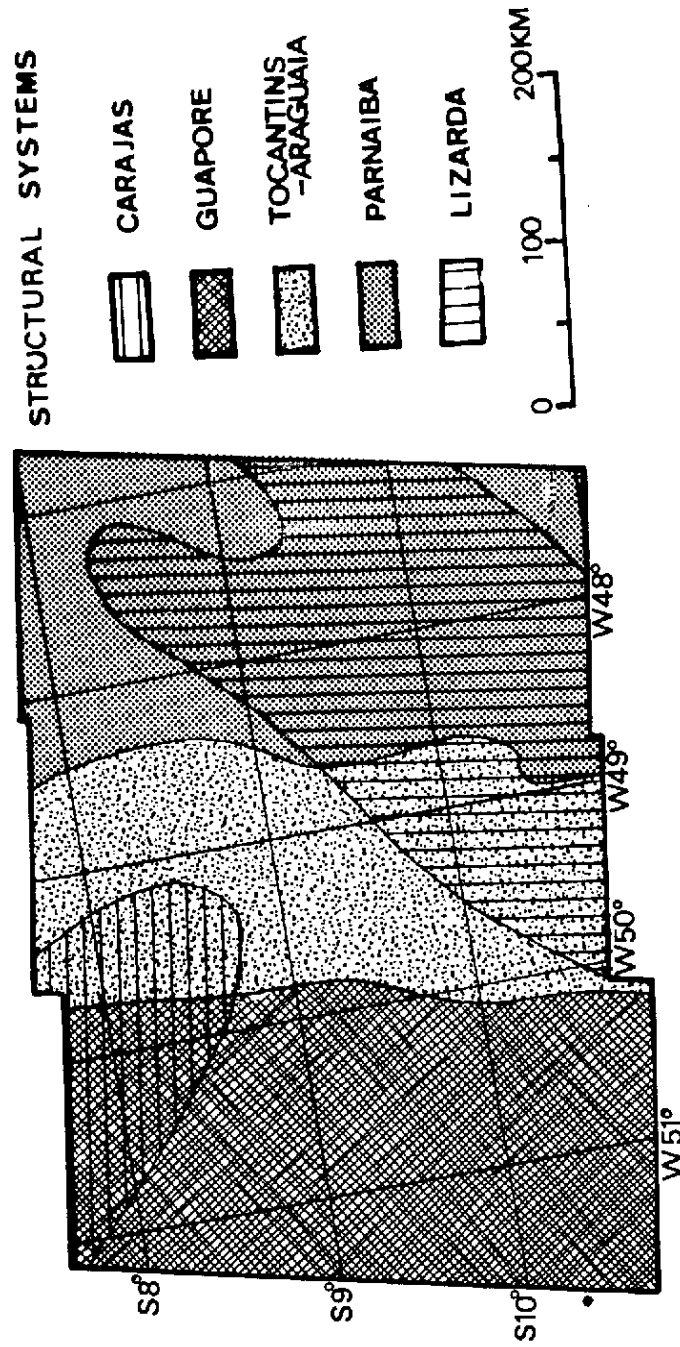


FIGURE 9

Figure 9 - Structural systems defined for the area of the middle Araguaia and Tocantins rivers. Boundaries shown are approximate only, refer to figure 9 for their geographic extent and to the text for their description.

Mesozoic, the Parnaíba basin underwent an increase in subsidence rate (Almeida, 1972) and this old fracture system, partly due to its positions at the border of the basin, may have been reactivated.

The so-called Lizarda structural system, overprinted on the Tocantins-Araguaia and Parnaíba systems in the study area, is characterized by a predominant northeast-trending set of linears. This system may have formed during the separation of the Guaporé or São Francisco cratons and its trend suggests that it may be associated also with the northern boundary of the São Francisco craton. Large northeast trending faults such as the Lizarda fault which extends to the east of the study area (fig.8) are present in this structural system.

Conclusions

Structural information extrated from LANDSAT-1 imagery allowed the identification of several structural systems which may be important for the interpretation of the geologic evolution of north-central Brazil. The structural systems defined mainly by the trends of linears, their size and spacing, seem to be more directly related to the physical properties of the lithosphere and the deformational evolution of a region as pointed out by Corrêa and Lyon (1974), however a chronologic sequence may be suggested.

The Mesozoic activation of the South American Platform

appears to have enhanced the trends of the Tocantins-Araguaia and Lizarda structural systems which are reflected in the younger Parnaíba system. The Carajás structural system is an older system than those mentioned above and was superimposed on the Guaporé system that may contain the fundamental structures of this part of the crust.

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