

BASEMENT TECTONICS FROM LANDSAT IMAGERY IN MINING EXPLORATION

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ABSTRACT

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The mineral potentials of basement cratonic areas are evaluated on the basis of mechanical analyses of their tectonic framework, obtained from LANDSAT imagery. Tensional release targets are selected through the application of different deformational models and the identification of the stage and type of deformation.

Correlation between tensional release zones and epigenetic hypogenic mineralization in different cratonic areas of South America has been successful in several mining exploration programmes.

INTRODUCTION

The first Gemini and Apollo images caused a booming development in geological interpretation but changes in method and technology were only achieved when the LANDSAT images were widely used in different fields of the Earth Sciences.

Experience of cratonic areas has shown that the application of global tectonics to regional geological features derived from LANDSAT imagery can supply an important tool for mineral prospecting of basement areas. To obtain the tectonic framework two basic linear features must be recognized: lineaments and lineations<sup>2)</sup> (L a t t m a n, 1958). Techniques and methods to obtain an objective regional lineament pattern of an area have been extensively dwelt on (L a t t m a n & M a t z k e, 1961; v a n d e r M e e r M o h r, 1966; R e n n e r, 1968; etc), but, although the identification of linear features is relatively easy (it can be done perfectly by non-geologically trained people) a correct evaluation of their geological significance is still a matter of discussion and subjective interpretation.

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2) lineation: fracture trace expressed on aerial photos continuously for less than one mile.

lineament: Linear feature expressed continuously for at least one mile, but which may be expressed continuously or discontinuously for many miles.

linear: Any straight or circular feature of an aerial photo with or without structural significance.

regmatic fracture: ancient weakness zone of the Earth's crust developed at the earliest stages of consolidation.

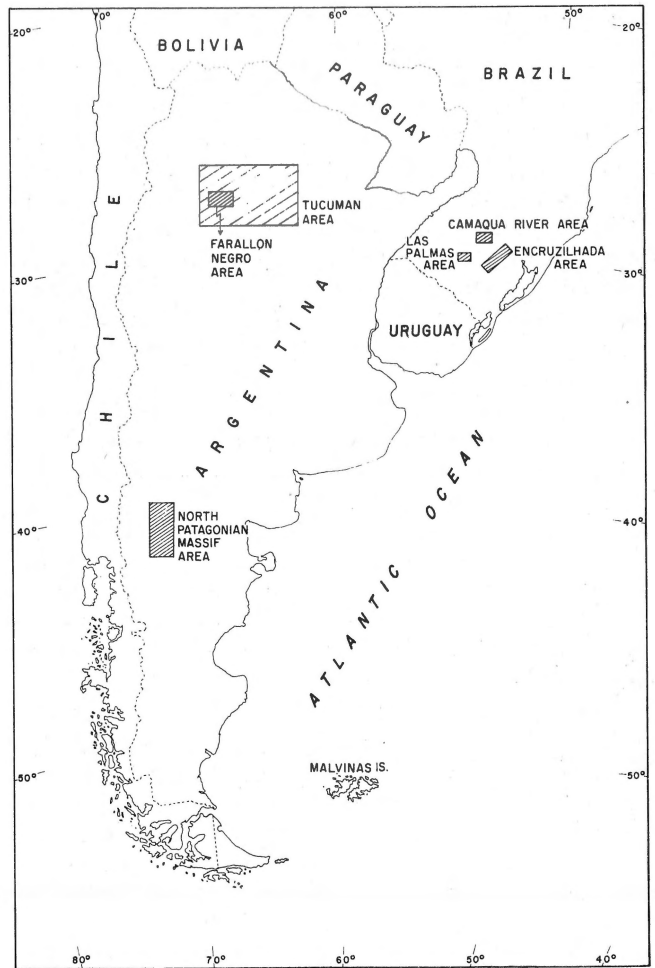


Fig. 1 Location map.

During the last few years this evaluation has taken two different approaches:

1. The so-called "pixel technology" tried to get geological data from LANDSAT images through sophisticated computerized methods. Many examples of enhanced images produced by colour additive viewers, density splicers or computerized ratios between bands, and programs to digitize the linear features are available in the LANDSAT literature. This approach tries to substitute geological reasoning by statistical analyses from large populations of measurements.

2. The second approach is based on the geological evaluation of the linears<sup>2)</sup> obtained from LANDSAT images, through a set of comprehensive steps based on the structural analysis and plate tectonic hypotheses developed by Sales 1968; Thomas, 1971; Wilcox *et al.*, 1973; Saunders *et al.*, 1973; etc.

The author's experience on isofrac maps, first and second-derived intersection maps, etc. indicates that none of these methods can replace the basic geological evaluation proposed here.

### BASEMENT TECTONIC ANALYSIS

Since Lapworth's (1892) and Hobbs (1912) studies, it has been established that the segmented nature of the crystalline basement is controlled by a series of weakness zones. Vening Meinesz (1947) and Sonder (1947) have interpreted these zones as worldwide fracture systems, named regmatic<sup>2)</sup> fractures by Sonder, which were developed at the earliest stages of the evolution of the Earth crust. Katterfeld & Charusin (1970) showed that global fracturing is inherent not only to the Earth but to most of the planets; similar systems are developed on Mars, Mercury and the Moon.

Moody & Hill (1956), and more recently Moody (1973) and Gay (1972; 1973) recognized their repetitive geometric style and related them to wrench faulting.

#### *Simple Shear Systems in previously segmented materials*

If the segmented nature of the basement is accepted, then strain and stress must be related by simple shear mechanics (Maxwell & Wise, 1958; Thomas, 1971; Atwater, 1972; etc.).

The identification of regional lineaments through LANDSAT images can be used for recognition of basement segmentation. These lineaments outline the different basement blocks that, under orogenic stress, adjust laterally, with the development of coupling between blocks. The interaction of this coupling in a single weakness zone or lineament produces a different behaviour along its trace. Laboratory models have proved (Thomas, 1971), that lineaments can be variously expressed as flexures, monoclines, reverse faults, etc. Figure 2 depicts the different types of movement along lineament X-X' as deduced from a scale model. The first segment

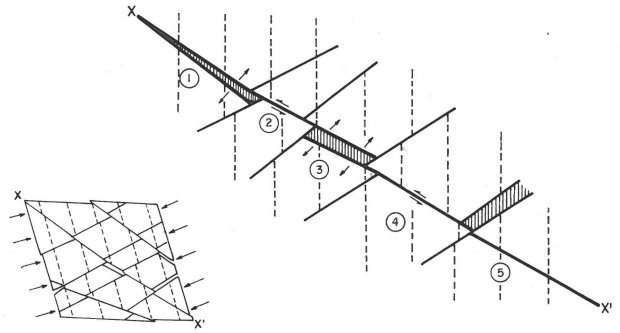


Fig. 2:  
Interaction of different blocks along a lineament in a segmented basement.

is expressed as a normal fault with an increasing offlap to the east, the second and fourth segments are left lateral slip faults; the third one is a normal fault, while there is no relative movement on the fifth.

This complexity shows the drawback of a simplistic interpretation of lineament movement. On the other hand, if the geometry of the segmented basement is known, it is possible to determine the general behaviour of the relative movements by mechanical analysis.

If two conjugate systems of fractures are present in an area, one of the systems will have a better development depending on the orientation of the main stress. It is extremely rare that the primary stress bisects the preexisting conjugate fractures, to produce an equal development of both systems. But if that situation occurred it would produce a lateral adjustment in both systems, one as a left lateral shear and the other as a right lateral one. In fact one system is usually dominant. Laboratory experiments have demonstrated that when that occurs, the dominant system, most transverse to the main stress, will be laterally adjusted. The subordinate system will be activated as a tensional zone (Fig. 3).

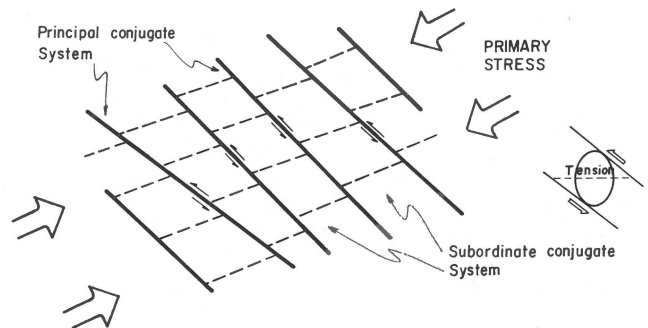


Fig. 3:  
Lateral and tensional adjustments of a conjugated system with stress not coincident to the bisectrix direction.

### Stage-development of a simple shear system

After the lineament framework is established evidence of relative movement along the different segments of the linear feature should be sought. Direct evidence, such as truncation and offset of lithological units or of contacts, is not frequently found. Analysis must be based on indirect evidence, such as secondary structural elements related to the lineament trace: drag folding, minor faults, dikes, structurally controlled intrusives, alignment of volcanic centres, etc.

Moody & Hill (1956), Thomas (1971), Saunders *et al.* (1973), Wilcox *et al.* (1973), Moody (1973), etc. have presented different models where these secondary elements are interpreted. The static configuration of folds and shear planes associated with a wrench fault proposed by Moody & Hill (1956) is invalid when applied to previously fragmented basement areas subjected to tangential stresses, because of its inhomogeneity and segmented nature. Two important facts must be kept in mind:

– The angle between the associated fold axes and the lineament (known as  $\Theta$  angle), varies with the intensity of lateral movement and it may not be related to a certain fixed order of folding.

– At an early stage, a fracture may be activated by tension into a normal fault. As stress increases subsequent lateral adjustment might take place and eventually might be reactivated as an upthrust.

Thus, without knowing the complete structural picture of the area, no putative conclusions can be drawn. Two different dynamic models are suggested depending on the presence or absence of a sedimentary cover.

#### Rigid basement without or with a thin sedimentary cover –

The proposed dynamic model applies to high metamorphic and plutonic environments with negligible plastic deformation. This model is based on previous work of Sales (1968) and Thomas (1971). As the intensity increases during deformation three continuous stages may be identified (Fig. 4):

**I: Incipient Stage:** A set of blocks are formed with  $\Theta \approx 45^\circ$ . Flank faults of uplifted areas are normal. Postorogenic intrusives are commonly associated with these uplifted areas as

established by Moody (1973). Extension transverse faults generally control the emplacement of igneous dikes and quartz veins. Tensional release is generally confined to these extension faults.

**II: Moderate Stage:** As orogenic forces increase, the value of  $\Theta$  decreases and lateral adjustment occurs at the previously formed flank faults which coincide with the synthetic fracture direction. At this stage incipient lateral adjustment may be produced in the antithetic sets. Sometimes the drag-folded-uplifted area shows a decrease in  $\Theta$  in the vicinity of the major lineaments.

**III: Advanced Stage:** Under extreme orogenic forces the flank fractures may become active upthrusts. The  $\Theta$  angle reaches a minimum value of about  $11^\circ$  with the main lineament.

These three theoretical stages show the evolution of a basement tectonic framework if consecutive and ever increasing orogenic forces acted along the same directions. The interaction among plates may often produce significant changes in the stress field complicating the application of the model.

**Rigid basement with sedimentary cover –** In those areas where a thick cover of undisturbed sedimentary rocks overlies the basement, deformation is concentrated along certain trend of lineaments. A dynamic model following Wilcox *et al.* (1973) is proposed here according to the degrees of deformational intensity:

**I: Initial stage:** The first evidence of shear coupling in a sediment-mantled area is the development of tensional joints or normal faults. These tensional fractures soon disappear as lateral displacement increases. The orientation of these extension faults is oblique to the coupling (Fig. 5).

**II: Moderate Stage:** As displacement increases, compressive structures such as folds and conjugate faults become more prominent as either joints or faults, depending on the intensity of the compression. A conjugate fracture system is developed. One set, the synthetic strike slip faults, intersects the lineament trend at an angle between 10 and 30 degrees and has the same type of displacement. The other set, the antithetic system, intersects the lineament trend at an angle between 70 and 90 degrees and has an opposite displacement. As adjustment increases synthetic faults tend to rotate

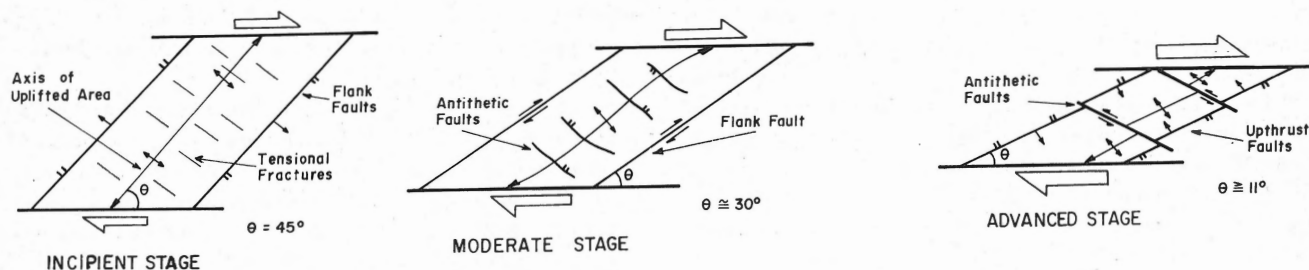


Fig. 4:  
Increasing deformation stages in a rigid basement under coupling.

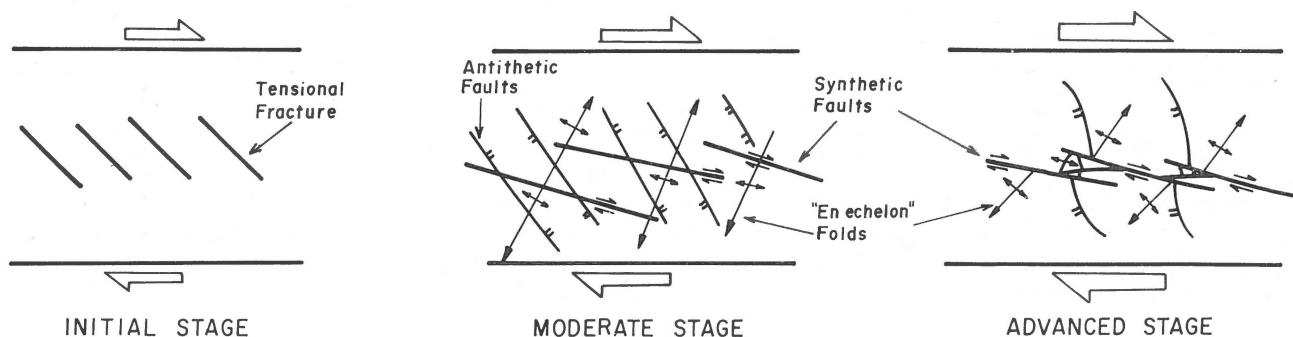


Fig. 5:  
Deformation stages in a rigid mantled basement under coupling.

toward the lineament trend. Antithetic faults tend to become perpendicular to the main lineament and therefore lateral adjustment is generally small compared to the synthetic faults. Antithetic fractures inherit some of the early tensional components and become nearly vertical normal faults, with negligible lateral displacement. An "en echelon" fold system that forms an angle less than  $45^\circ$  with the main lineament, develops synchronously to the conjugate faulting. The left or right-handed orientation will depend on the main shear movement.

III: *Advanced Stage*: The antithetic faults at this stage are flexed at both ends, giving an "S" shape for left lateral adjustment or a reverse "S" for right lateral ones. As intensity increases the main wrench fault gradually emerges as an interconnected series of earlier conjugate faults which offset the previous "en echelon" folding. This interconnection of faults will produce deflection of the main wrench fault. The study and location of these deflections allows a prediction of the tensional release areas at this stage.

#### STRUCTURAL CONTROL OF THE MINERALIZATION

Previous works have shown that a close relationship exists between structural lineament, as weakness zones of the Earth's crust, and mineral occurrences. Many examples of this relationship have been illustrated by Jerome & Cook (1967), Stokes (1968), Metz (1970), and Kutina (1971). But in many cases, Allcock (1973) pointed out, "if one reduces the scale sufficiently" any mineralized area will be neatly dissected by a conspicuous lineament.

The relation between regional lineaments is not so close, as detailed studies of several cratonic areas of South America have shown. The control in basement areas seems to be related to tensional release areas which provide conduits for intrusive and extrusive igneous activity and associated hydrothermal fluids. Further, as discussed above, different stages of deformation produce tensional fractures at different locations. The main problem is to recognize the type and stage of deformation involved in a particular cratonic area.

It is necessary to note that we are trying to find the structural control of hypogenic epigenetic mineralizations and that represents only a fraction of the total metallogenic potential of a basement area. As a general rule the following important types of tensional release areas related to mineralization have been found:

#### *Tension related to subordinate fracture systems*

As discussed above, in those areas where two systems of regmatic fractures are unequally developed, the subordinated system at the first stage of deformation, will concentrate the tensional release. This relationship is seen in several cratonic areas.

*Camaqua River Area* – The southern part of Brazil was examined through LANDSAT images. Enlargements of bands 5 and 7 of Ert's I – 1177 – 12532, at 1:500,000 scale were used to depict the tectonic framework of the area. A frequency diagram of the main linear features established the relative importance of the two conjugate fracture systems of the area. A N  $20-30^\circ$  E trend, was dominant over a N  $50-60^\circ$  W direction. The application of the dynamic model of analysis identified a right lateral adjustment of the north-eastern trend based on some drag-folding in the vicinity of the main lineaments and the offsets of some acid intrusives. A tensional behaviour for the northwestern trend was inferred and corroborated by its association with some transversal grabens, which coincide with rhyolitic ignimbritic flows of early Paleozoic age. Intrusive dikes like the andesitic body outcropping 20 km southeast of Camaqua mine, also have a northwestern trend (Fig. 6).

Some of the well defined lineaments seen in LANDSAT images, and checked also on conventional airphotographs and aeromagnetic maps, show absolutely no displacement features in the field, even though these lineaments can be easily recognized as straight deep creeks several kilometers long. Key beds in the Precambrian quartzitic rocks covering the metamorphic basement could be correlated at both sides of the fracture. However, the aeromagnetic analysis established a clear vertical throw on the underlying basement. After the

deposition of the quartzitic rocks the fault was slightly reactivated. In other sites of this area the aeromagnetic maps were very useful to show the relative vertical and horizontal movements of the previously mapped LANDSAT lineaments.

A moderate stage of deformation was established and the main stress was determined as a WNW-ESE orientation, perpendicular to the continental margin of Rio Grande Shield. In this shield the tensional release was concentrated on the northwestern trend. This stress field lasted from the late Precambrian until Cretaceous times, where the basaltic flows of Serra Geral welled up along fissures of northwestern trend. Synchronously the Atlantic opening had started and a rotation of the stress field was produced.

As mineralization in the area was previous to the basaltic flows and therefore to plate rotation, it is valid to assign the

tensional release to the N 50-70° W trend. These faults exert a close control on the copper mineralization (Fig. 6). In those areas where these faults are related to postorogenic andesitic rocks copper sulfide shows are present with an evident structural control.

*Northern Patagonian Massif* – In a different geological setting an analogous structural control is present. The structure of the area, obtained through objectively weighed analyses of the LANDSAT and SKYLAB images, was established by Coira *et al.* (1975). The area has a complex Variscan rigid basement covered by Jurassic volcanic rocks which are unconformably overlain by Cretaceous sediments.

Structural evidence (Coira *et al.*, 1975) indicates the presence of a left lateral adjustment of the Gastre Norte and Sur lineaments. The folding associated with these lineaments indicates the direction of adjustment of the northwestern

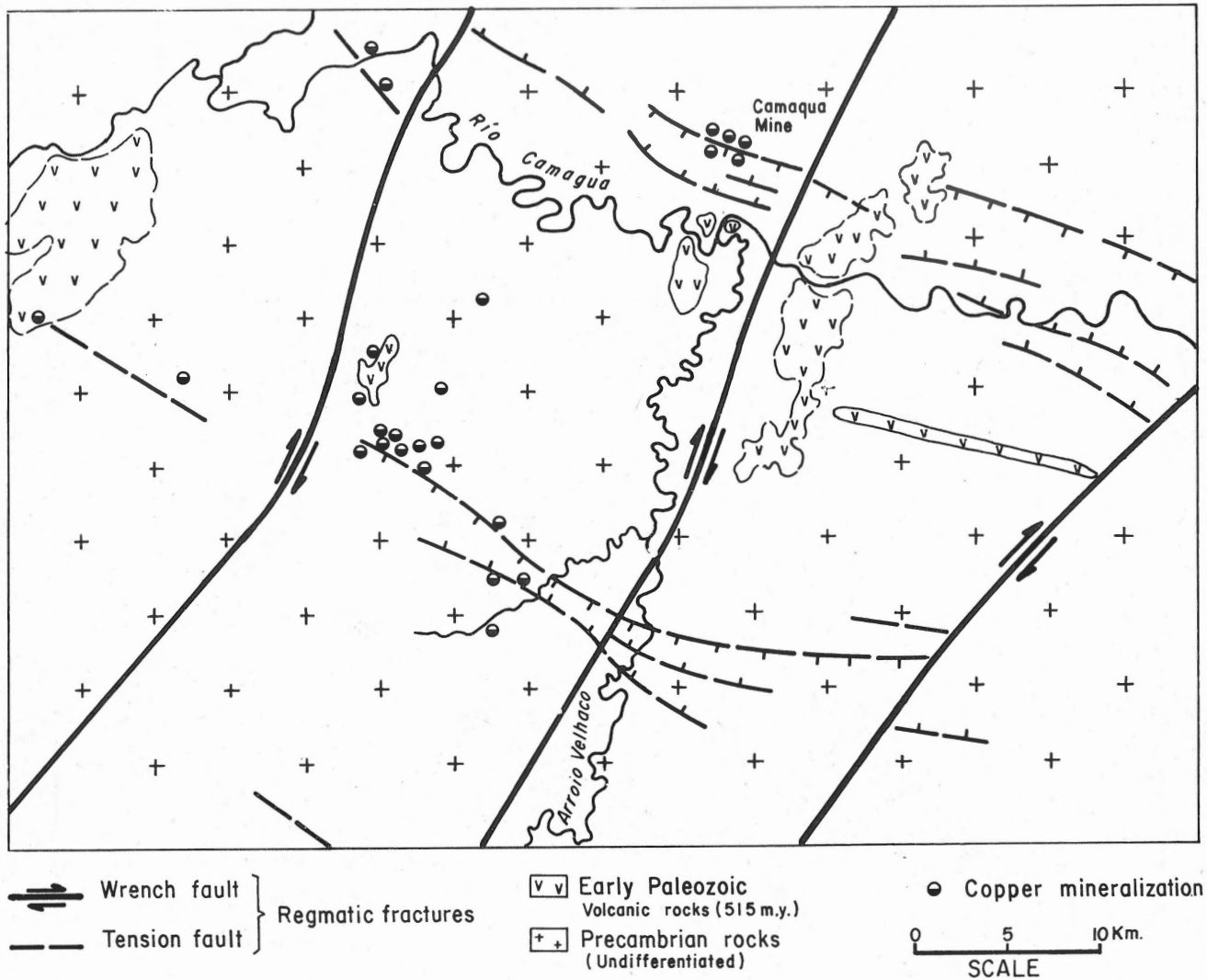


Fig. 6: Regional tectonic framework of a Precambrian basement sector near Camaqua River, Brazil.

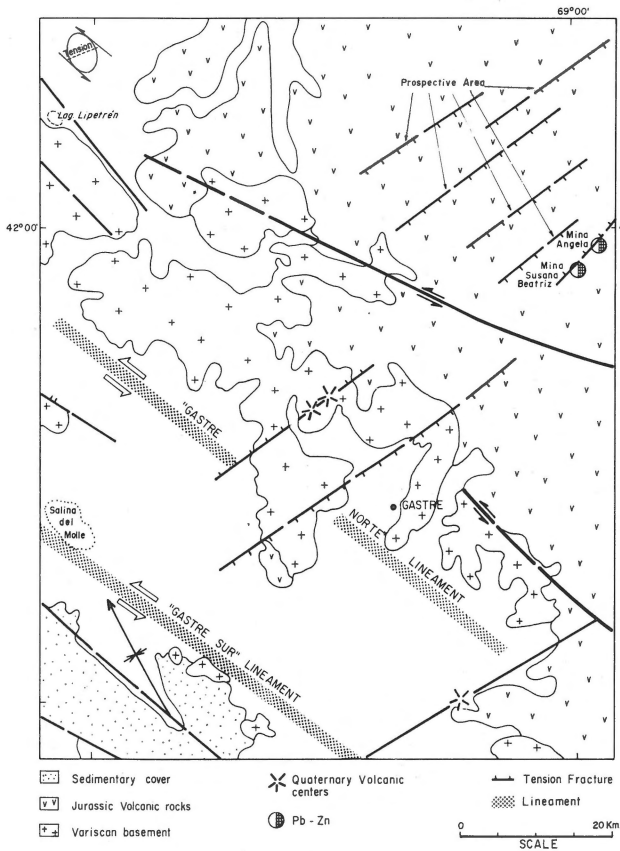


Fig. 7: Basement tectonic analysis of a sector of Northern Patagonian Massif in the Chubut province, Argentina.

trend (Fig. 7). The drag-folding of the thin Cretaceous cover shows a left lateral slip for that system. The Variscan basement has a well-defined tensional behaviour in the north-eastern trend. As pointed out the tensional release is concentrated in the subordinated regmatic system. This trend controls the location of several small basaltic centres that released the stress in the last phases of deformation during the Quaternary.

The lead and zinc mines that have been long exploited are emplaced along this trend. The identification of several fractures in a favorable geological environment makes it feasible to select prospective areas for a geochemical exploration (Fig. 7).

Fig. 8: Regional tectonic setting of the Tucumán area in the Pampean Ranges of Central Argentina.

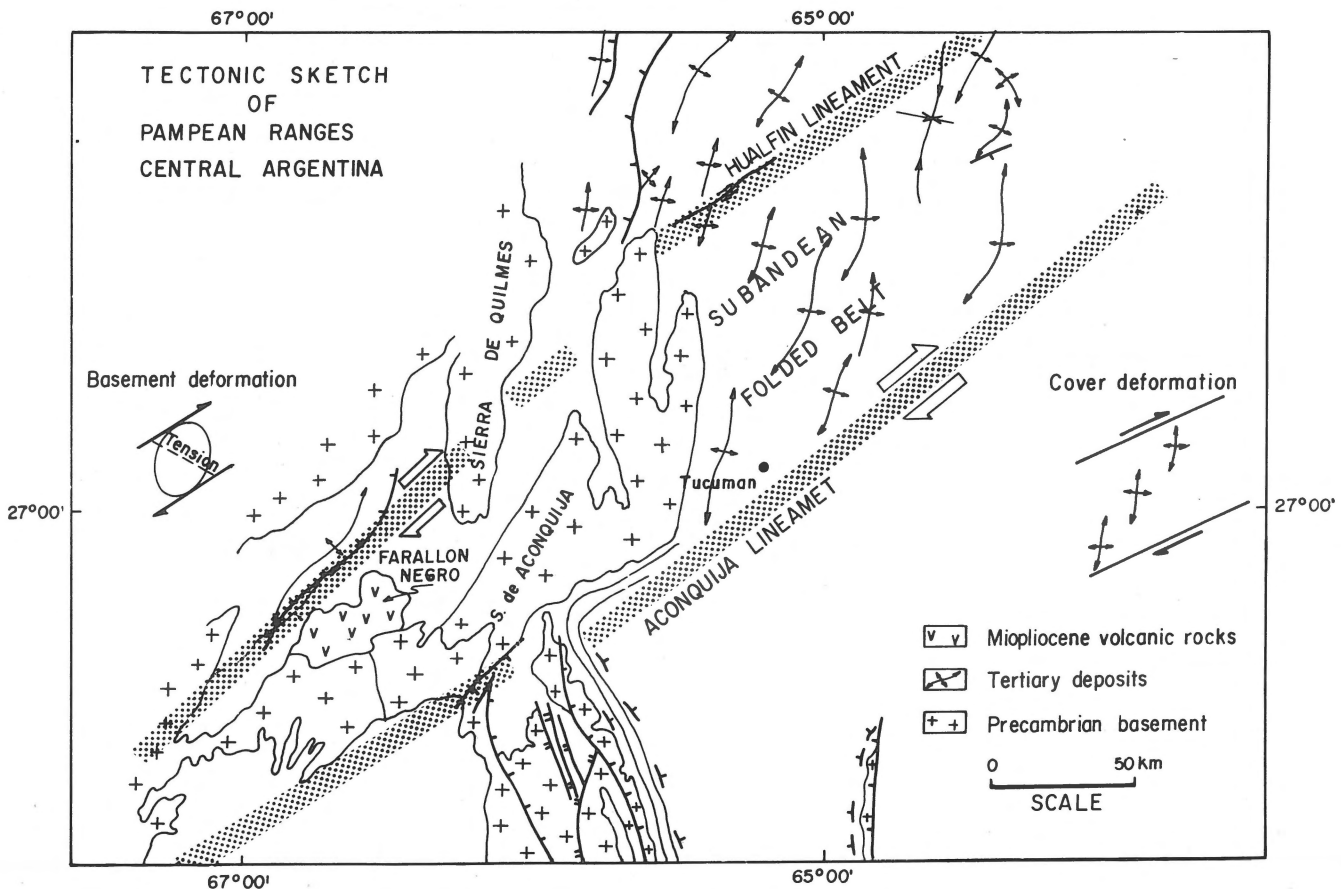




Fig. 9:  
LANDSAT image of Central Argentina showing the location of Farallón Negro volcanic complex and the hydrothermal alteration zones.

### Extension faults related to regional lineaments

In those areas where considerable horizontal adjustment occurred, the extension faults are developed in the vicinity of these lineaments. When the sedimentary cover is thick enough, these extension faults constitute the only evidence of wrench faulting.

There are several examples of emplacement of mineralization along these fractures closely associated with the major lineaments.

**Farallón Negro Area** — The Precambrian basement of central Argentina provides an example of the structural control of the mineralization in the Farallón Negro mining district. In this area the disseminated copper mineralization was located neither along the main lineaments nor in the intersection of important fractures. The existence of two important megalineaments, Hualfin and Aconquija (or Tucumán), had already been recognized by the location of earthquake hypocentres and by the tectonic framework of the Subandean belt (Baldis *et al.* (1976); Mon (1976). A compilation of a LANDSAT mosaic showed without doubt the importance of these lineaments (Figs. 8 and 9).

The study of the truncation of the folding in the Subandean belt and the basement offset of Sierra de Aconquija indicate a right lateral adjustment. This adjustment was also verified in the sedimentary cover by the right-handed orientation of the "en echelon" fold pattern on the Tertiary deposits. At this time (Mio-Pliocene) the Farallón Negro Volcanic complex was emplaced in the rigid Precambrian basement of the Pampean Ranges.

The bleaching of the hydrothermal alteration along two minor fractures is seen in a detail of the LANDSAT image of the area (ERTS 1-2147-13381-7) shown in Fig. 9. Here, due to the deformational intensity, neither of the two conjugate regmatic systems are tensional faults. The antithetic set (N 15-20° W) is represented by upthrusts while the synthetic system (N 55-60° E) has been activated with some right lateral slip. The tensional release at this stage is concentrated along the extension faults related to the Aconquija (or Tucumán) megalineament, which also controls the location of the alteration zones (Fig. 10).

The drilling programme executed in the last two years in the Bajo de la Alumbrera area located up to 500,000,000 tons of ore with a copper grade over 0,6%. The other bleaching areas are still under exploration.

**Las Palmas River Area, Brazil** — Here in the Precambrian basement of Rio Grande do Sul, the mineralization is associated with important lineaments such as Palmas and Camaquá's (Fig. 11).

A set of intrusive dikes emplaced in extension faults are associated with those lineaments. Even though the lineaments were primarily detected in the LANDSAT images, the extension faults were only visible in air photos and aeronavigational maps. The relationship between the andesitic intrusives

and the main lineament trend is obvious (Fig. 11). In some andesites related to these lineaments, copper shows in the form of small veinlets of northeastern trend were identified. These extension faults were only identified in the neighbourhood of the main lineaments.

### Tension related to lineament deflections

Convergence or divergence of lateral adjusted lineaments will produce either tension or compression depending on the local geometry and the sense of movement (Wilcox *et al.*, 1973).

In mining at large scales, the importance of the deflection of a fault plane is well known for the location of ore shoots (Baldley, 1959). At a regional scale the same principles may be applied to the study of conspicuous deflections, in order to identify the location of tensional areas. The Encruzilhada do Sul lineament at Rio Grande do Sul, in Southern Brazil, illustrates this relationship (Fig. 12).

The study of this 320 km long lineament on the LANDSAT images showed one important area of deflection. The detailed study by airphotos permitted the inference of a right lateral adjustment of this lineament (Fig. 12). Some small granitic stocks were introduced along the main lineament in the tensional areas. Two granitic episodes were recognized: The Cordilheira Granite of upper Precambrian age, followed by the Prestes Granite (early Paleozoic) in a younger phase of reactivation of the lateral adjustment).

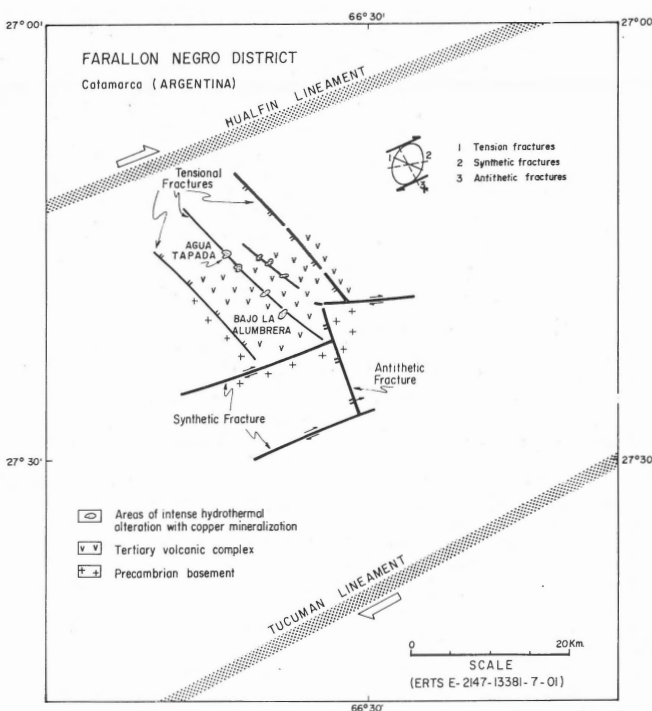


Fig. 10: Structural sketch of the tectonic control of the copper disseminated mineralization of Farallón Negro mining district.

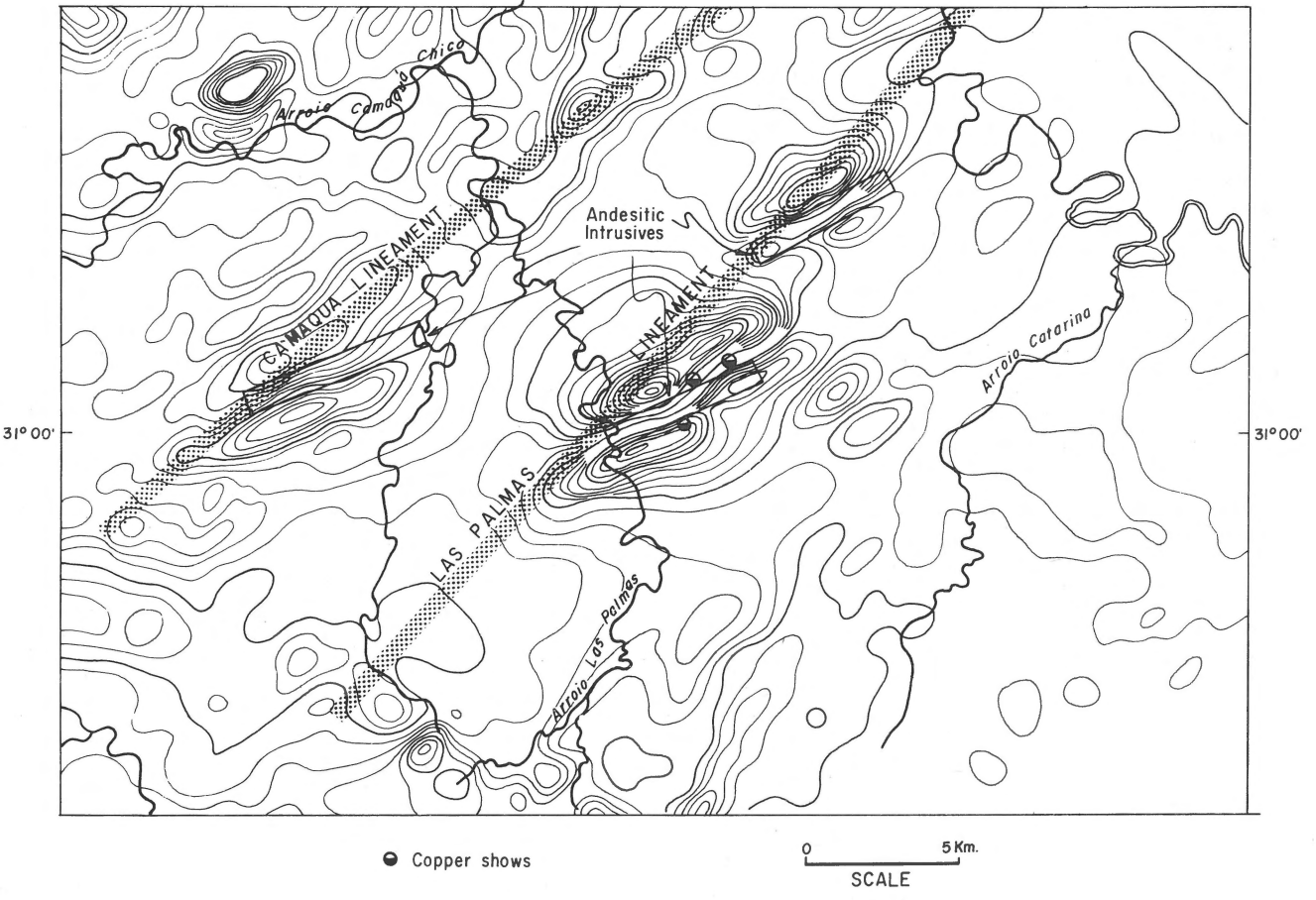


Fig. 11: Detail of an aeromagnetic map of the Las Palmas and Camaqua lineaments showing the emplacement trend of the andesitic bodies.

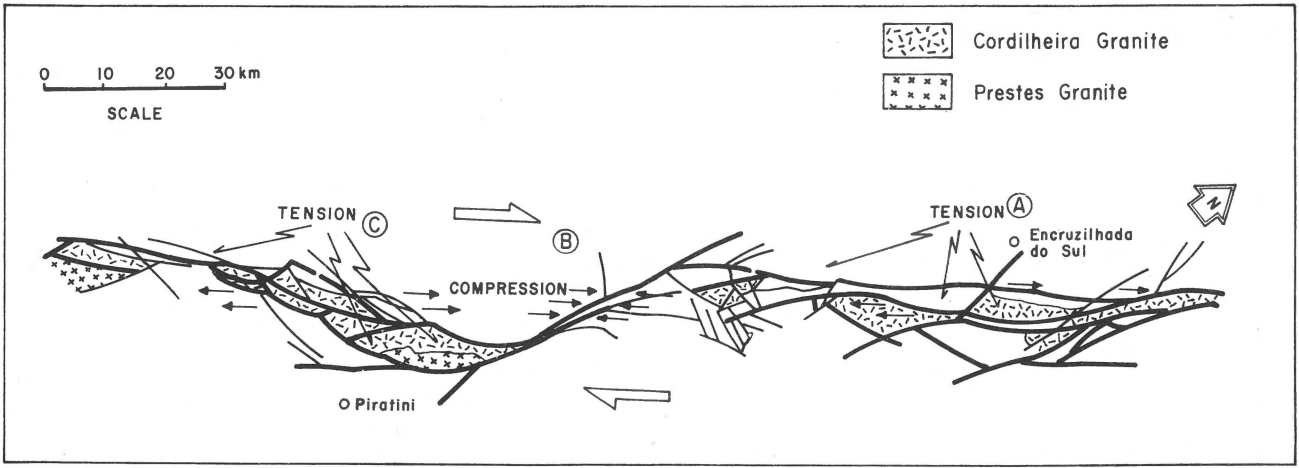


Fig. 12: Sector of the Encruzilhada do Sul lineament at Rio Grande do Sul, Southern Brazil.

Although no mineralization has yet been found in these granites, the importance of the mineralization associated with postorogenic intrusives is well known. This encouraged a systematic mineral evaluation of these granites through a field programme actually under execution.

### CONCLUDING REMARKS

From the application of the proposed method the following conclusions are drawn:

- a) Reliable objective information of the tectonic framework of a basement area was possible through the synthetic view of the LANDSAT images.
- b) Each particular lineament has to be evaluated in the context of a suitable dynamic model of deformation. The presence of a sedimentary cover and the stage of stress intensity may change the location of the tensional release areas.
- c) As the hypogenic epigenetic mineralization will largely depend on the location of tensional release areas, the mechanic analysis of the lineament pattern is an irreplaceable tool for selecting target areas.
- d) In order to evaluate these prospective areas traditional air photographs and field work are essential, combined with aeromagnetic maps if these are available.
- e) The applied method has given encouraging results in the mineral evaluation of large basement areas of South America.

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