# GEOLOGICAL INTERPRETATION OF AIRBORNE GEOPHYSICAL AND LANDSAT TM DATA

## PUNA AREA ARGENTINA

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## GEOLOGICAL INTERPRETATION OF AIRBORNE GEOPHYSICAL AND LANDSAT TM DATA

**Undertaken for:**

**SEGEMAR**
**SUB SECRETARIA DE MINERIA**
**REPUBLICA ARGENTINA**

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By

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# EXECUTIVE SUMMARY

This report outlines the results of an integrated geological interpretation of recently-acquired airborne geophysical data (magnetic and radiometric) and Landsat TM data in the Puna region, northwest Argentina. The procedures adopted in the interpretation are also outlined. The main objective of this survey was to provide a regional geological-geophysical framework to assist assessment of the mineral potential of the region, and hence stimulate exploration in Argentina.

The interpretation was compiled using 1:250 000 scale Landsat (R:G:B = 7:4:1) imagery, magnetic and radiometric imagery (1km line-spaced data), integrated with existing published 1:400 000 and 1:200 000 geological maps.

The interpretation was compiled as both surface geology maps (two sheets) (from Landsat data), and "solid geology" maps (two sheets) detailing the distribution and structural setting of the main rock units of the region, both in outcrop, and where concealed by Quaternary surficial sediments. Limited field checking was carried out in support of the interpretation.

# 1. INTRODUCTION

SEGEMAR (Servicio Geologico Minero Argentino) has initiated a project for the acquisition of regional-scale airborne geophysical data over key areas of Argentina. The intention of the project was to actively promote mineral exploration in Argentina by providing both Government and Industry with high-quality geophysical and geological data to achieve a better understanding of the regions' geology and mineral potential. This report describes the results of an integrated geological interpretation of airborne geophysical data, satellite image data and existing geological information over the Puna survey area, located in northwestern Argentina. The methodology of the interpretation, acquisition and processing of the data are also discussed.

The Puna survey project consisted of (i) an airborne geophysical survey resulting in regional 1km line-spaced magnetic and radiometric data, and (ii) interpretation of the survey data integrated with available geological mapping and interpretation of Landsat TM data. The interpretations were all carried out at 1:250 000 scale.

The Puna survey area is located approximately 1400 kms northwest of Buenos Aires (see Figure 1). The area is bounded to the north by the Argentinean-Bolivian border, to the west by the Argentinean-Chilean border, to the east by the Cordillera Oriental and to the south by latitude 24°S. Geologically, the Puna is the southern extension of the Bolivian Altiplano, and consists of a high plateau whose base elevations range from 3.5-4.7 km, above which volcanic peaks rise to 6.8km. The Puna plateau is located east of the main Central Andean Volcanic Zone (CVZ), which is a volcanic arc above the moderately E-dipping Nazca Plate (Coira *et al.*, 1993). Extensive Mio-Pliocene volcanic activity occurred along the NW margin of the Puna plateau and in NW-SE transverse lines crossing the plateau

Physiographically, the region comprises several narrow N-S to NNE-SSW trending mountain ranges separated by elongate intermontane alluvial valleys. The valleys are characterised by the presence of large salinas or evaporitic playa lakes. The linear mountain chains and valleys are crested by high volcanic peaks, rising to 5705 metres asl at Cerro Granada.

At the time of carrying out the survey, available geological data over the Puna area consisted of the following published 1:200,000 geological mapping sheets (see Fig. 2): Sheet 1ab-Santa Catalina (Turner, 1965a); Sheet 2a-San Juan de Oro (Turner, 1967); Sheet 2b-La Quiaca (Turner, 1965ba); Sheet 3ab-Mina Pirquitas (Turner, 1982); Sheet 3c-Abra Pampa (Coira, 1979); Sheet 5a-Paso Huaitiquina (Schwab, 1980b) and Sheet 5b-Salar de Cauchari (Schwab, 1980a). Reference was also made to 1:50,000 mapping by Zappettini (1989) over the Santa Ana - Cobres area and to the regional 1:400,000 scale Geological Map of the Northwest Region prepared by DGFM. Subsequent to preliminary interpretation of the Puna data, a 1:500 000 compilation geological map of the Jujuy Province was published (SEGEMAR, 1996).

# 2. AIRBORNE DATA ACQUISITION AND PROCESSING

The Puna airborne geophysical survey generated approximately 40,000 line kilometres of data, and was flown by World Geoscience Corporation Ltd. during the period December 1995-May 1996. Table 1 summarises the specifications of the survey, which was planned so that the flight-line direction would approximately parallel the N-S to NNE-SSW topographic trend, to allow as best as possible height drape of the aircraft in rugged and high-altitude conditions. The average height clearance above ground was 140m. Flying at lower clearance was considered dangerous in such rugged and high-altitude terrain.

Processing of the magnetic data included corrections for diurnal, IGRF, and parallax factors, together with tie-line leveling and microlevelling operations. Processing of the radiometric data was completed along the guidelines of the IAEA report no. 323. This included the removal of aircraft, cosmic and radon background radiation together with the application of stripping ratios and height correction. This processing resulted in well-levelled data that the contractor could use in its own in-house software to produce a range of images, contours and stacked profiles - as summarised in Table 2. More advanced processing of the magnetic data was also undertaken with techniques used including Reduction to the Pole (RTP) and First Vertical Derivative (1VD).

### TABLE 1:
### Geophysical Survey Specifications

| | |
|---|---|
| MAGNETOMETER | Split Beam Caesium Scintrex CS-2 |
| ALONG-LINE SAMPLING | 10 Hz (7m approx) |
| SPECTROMETER | 256 Channel Picodas PGAM 1000 |
| ALONG-LINE SAMPLING | 1Hz (70m approx) |
| DIGITAL ACQUISITION SYSTEM | Picodas PDAS 1000 |
| FLIGHT LINE SPACING | 1 000m |
| TIE LINE SPACING | 10 000m |
| FLIGHT LINE DIRECTION | 000º-180º |
| TIE-LINE DIRECTION | 090º-270º |
| NOMINAL SURVEY HEIGHT | 137m |
| NAVIGATION | GPS Global Positioning System |
| TOTAL LINE KILOMETRES | 39,445 kilometres |
| TOTAL AREA COVERED | 36,363 square kilometres |

**TABLE 2:**
**List of Image Geophysical Data Products**

| Map / Image Type | 1:100 000 | 1:250 000 |
|---|---|---|
| **Flight Path** (black pen on stable transparency film) | 32 | 2 |
| **Black/White Contours** (black pen on stable transparency film) | | |
| Total Magnetic Intensity | 32 | 2 |
| Reduced to Pole Magnetics | 32 | 2 |
| Depth Slice 1 (High Frequency) | 32 | 2 |
| Depth Slice 2 (Medium Frequency) | 32 | 2 |
| Depth Slice 3 (Low Frequency) | 32 | 2 |
| Total Count | 32 | 2 |
| Potassium | 32 | 2 |
| Uranium | 32 | 2 |
| Thorium | 32 | 2 |
| **Colour Contours** (colour pen on paper and laminated) | | |
| Total Magnetic Intensity | 32 | 2 |
| Reduced to Pole Magnetics | 32 | 2 |
| Depth Slice 1 (High Frequency) | 32 | 2 |
| Depth Slice 2 (Medium Frequency) | 32 | 2 |
| Depth Slice 3 (Low Frequency) | 32 | 2 |
| Total Count | 32 | 2 |
| Potassium | 32 | 2 |
| Uranium | 32 | 2 |
| Thorium | 32 | 2 |
| **Stacked Profiles** (black pen on stable transparency film) | | |
| Total Magnetic Intensity | 32 | 2 |
| Total Count | 32 | 2 |
| Potassium | 32 | 2 |
| Uranium | 32 | 2 |
| Thorium | 32 | 2 |
| **Image Processed Slides** | | |
| Reduced to Pole Magnetics - Colour | | 4 |
| Reduced to Pole First Vertical Derivative - Greyscale | | 4 |
| Reduced to Pole with RTP First Vertical Derivative - Colour | | 4 |
| Depth Slice 1 (High Frequency) - Greyscale | | 4 |
| Depth Slice 2 (Medium Frequency) - Greyscale | | 4 |
| Depth Slice 3 (Low Frequency) - Greyscale | | 4 |
| Potassium - Colour | | 4 |
| Uranium - Colour | | 4 |
| Thorium - Colour | | 4 |
| Ternary - Colour RGB | | 4 |
| **Image Processed Negatives** | | |
| Reduced to Pole Magnetics - Colour | | 4 |
| Reduced to Pole First Vertical Derivative - Greyscale | | 4 |
| Reduced to Pole with RTP First Vertical Derivative - Colour | | 4 |
| Depth Slice 1 (High Frequency) - Greyscale | | 4 |
| Depth Slice 2 (Medium Frequency) - Greyscale | | 4 |
| Depth Slice 3 (Low Frequency) - Greyscale | | 4 |
| Potassium - Colour | | 4 |
| Uranium - Colour | | 4 |
| Thorium - Colour | | 4 |
| Ternary - Colour RGB | | 4 |

# 3. SPECIALISED DATA PROCESSING FOR INTERPRETATION

In addition to the standard images and maps documented in Table 2, additional specialised data processing techniques were applied to the Puna data set. These included Reduction to the Pole and First Vertical Derivative: these techniques enhance various aspects of the geophysical data permitting a better and more accurate interpretation.

## 3.1 REDUCTION TO THE POLE

The Reduction to the Pole (RTP) technique was applied to the gridded Total Magnetic Intensity data using the contractor's in-house software. RTP is a well established numerical process (Milligan & Gunn, 1997) which transforms the inclination of the apparent magnetisation vector from that of an ambient field to that of the pole (i.e. I=90$^{o}$). The process therefore transforms dipolar magnetic anomalies to monopolar anomalies centred over their causative bodies. Although the presence of a remnant magnetisation vector may mathematically invalidate the transformation of the anomaly peak, the presence of remnant magnetisation in the region did not prove to be a hindrance in either the interpretation of the data, or the RTP transformation of the total magnetic intensity grid.

The advantage of RTP is that in general the peak response will be located over the "centre" of the causative magnetic body, and that maximum gradients will lie close to the "edges" of the body. Thus the overall picture of the data whether presented as images or contours is clearer with better positioning correlation between a rock and its magnetic signature. RTP is most effective at magnetic latitudes of less than 30$^{o}$.

The RTP data are most useful and necessary when field checking. With the peak response of the anomaly, after the data has been reduced to the pole, being over the centre of the body location of particular units with respect to their particular magnetic response is notably more accurate.

## 3.2 FIRST VERTICAL DERIVATIVE

The First Vertical Derivative (1VD) was applied to the grid of RTP Total Magnetic Intensity data using the contractor's in-house software. The 1VD of a magnetic field is an approximation at a point of the field's rate of change in the vertical direction. The function can be calculated in either the Fourier or spatial domains (Milligan and Gunn, 1997). The spatial domain adopts a convolution operator. The size of the kernel or window this convolution operator uses affects the wavelengths in the output of the 1VD. Smaller kernel sizes emphasise short wavelength anomalies more than larger kernels. Calculating the 1VD in the Fourier domain is a more theoretically correct approximation of the vertical derivative, as it utilises the entire grid in its calculations. Thus the biasing of the anomaly due to its wavelength is removed, and the high frequency component is maintained.

The 1VD for the Puna area was applied in the Fourier domain. These data were utilised in geological interpretation in the form of a greyscale 1VD image, and 1VD with a colour TMI overprint.

The greyscale image of 1VD has the advantage of highlighting the different magnetic patterns and character of the rock units, as well as the structures affecting the different units. The 1VD is an extremely valuable technique and was used as the basis for the structural framework and regional lithological packaging compiled in the interpretation.

## 3.3 PSEUDO DEPTH SLICING

Pseudo depth slicing is a technique which attempts to extract the magnetic response of different structural levels within sedimentary and basement sections. The actual pseudo depth slices which can be extracted are controlled by the distribution of magnetic material in the section. Non-uniform magnetic body geometry and the inherent ambiguity in potential field techniques typically mean that the pseudo depth slices cannot be interpreted as depth sections.

The technique attempts to separate populations of magnetic response of different frequency, imaging each “population” as a separate “depth slice” image. The highest frequency image (shallow source) is conventionally labelled Depth Slice 1.

The technique has no application for precise depth to magnetic studies. The power of the method lies in examining how the trends in lithology and structure vary as a function of depth. Typically, two or three slices can be identified within a sedimentary section, with the deepest section associated with magnetic “basement”.

Three depth slices were processed for the Puna data. Due to the regional nature of the data, and the poor magnetic response of the majority of units and structures, the depth slices did not aid the geological interpretation of the region at 1:250 000 scale.

## 3.4 MAGNETIC MODELLING

Models of the magnetic data were generated using the Encom ModelVision™ software version 1.30. ModelVision™ software allows the user to take magnetic line data, either extracted from a grid, or actual flight line data, and assign a particular model. The ModelVision™ software can create polygons, horizontal cylinders, ellipsoids, spheres, tabular bodies and plunging prisms with the user having the flexibility of changing the size, orientation, depth and magnetic susceptibility. The modelled magnetic response is calculated for the selected model, taking into consideration the global geographic position of the model, and hence the Earth’s magnetic field where the data was collected. Thus the software requires a number of parameters for the computation of the models. A magnetic field intensity of 23 741nT, inclination of $-17^{o}$ and variation of $-4^{o}$ was used for the Puna area.

The Contractor uses a modified Werner algorithm for the calculation of depth to source solutions. Werner depth solutions have been used as absolute depth reference points where they occur along the selected lines. This demonstrates the use and relevance of the depth solutions to provide a reference point for the magnetic models. Werner Solutions are divided into dyke and contact type solutions which reflect the structure of the geology. Dyke solutions are generated by a change in the vertical derivative and contact solutions are calculated by variations in the horizontal derivative of the total magnetic field data.

The depth solutions were classified in terms of their lateral positions relative to known sediment outcrop, volcanic outcrop or deeper solutions. The results were plotted out at 1:250000. These depths were used as a guide to the top of the block during the modelling process.

# 4. LANDSAT TM INTERPRETATION

The integration of remotely-sensed data to assist with airborne geophysical interpretation is extremely valuable, as fine-scale structure and lithological subdivisions can often be mapped that may not be obvious or are unresolvable in the geophysical data due to the broad line-spacing and lower resolution of the latter.

In particular for the Puna area, it was decided that a 1:250 000 Landsat TM interpretation should be compiled as a first stage to the geophysical interpretation because of the broad, regional nature of the survey (1km line spacing), and the fact that the flight lines approximately parallel a large proportion of the regional structures in the area, making geological resolution of these structures difficult.

## 4.1 METHODOLOGY

### 4.1.1 Data processing

The Landsat TM scenes for the Puna area were acquired after an initial search to select the best images for mosaicing together. The following scenes were acquired from EOSAT in Washington:

| Scene | Acquisition Date |
|---|---|
| 231/75 | 11/9/86 |
| 232/75 | 25/7/86 |
| 231/76 | 10/3/86 |
| 232/76 | 25/7/86 |
| 232/77 | 1/10/86 |

The images were geographically rectified using ground control points selected from the Republica Argentina 1:250 000 topographic maps. The images were rectified to Gauss Kruger conformable projection, datum Campo-Inchauspe: central meridian 66$^{o}$W. A quadratic (2nd order) warping model was used, with a nearest-neighbour resampling procedure.

After warping, the individual scenes were mosaiced to allow final production of scenes matching the Republica Argentina 1:250 000 map sheet series. Prior to mosaicing, the images were histogram-matched to allow seamless production of images. The actual technique of matching involves statistical analysis of overlapping areas between the actual scenes in question. Each scene’s overlapping region is sampled for the mean and standard deviation. The scene to be altered is then transformed using a formula based on all 3 selected TM bands.

Subsequent to mosaicing, the relevant 1:250 000 sheets were subsetted from the main scene. Each individual scene was then edge enhanced and histogram stretched to maximise the information content of each map. Some colour differences therefore occur between the individual scenes.

The scenes were then hardcopied to photographic film to provide the best resolution possible.

TM bands 7:4:1 as R:G:B were used for the interpretation images. This band combination typically provides excellent structural/spatial resolution, while providing geologically-oriented spectral information.

### 4.1.2 Interpretation

The method of interpretation was designed to assist visualisation of regional structure through meticulous annotation of all high-frequency structural elements visible in the imagery, a method proven in other complex terrains (Nash, *et al.*, 1996). In order of importance, attention was paid to annotation of foliation and/or bedding traces (expressed through differential erosion of foliated/bedded rocks, fracture and/or fault traces (selectively eroded linear valleys and gullies), lithological indications (typically expressed as change in vegetation (rare in Puna), texture, colour, soil cover etc.), outcrop boundaries, major drainage features, alluvium, regolith and colluvium distribution.

The following procedure was adopted to obtain maximum information from all images:

1) Bedding and foliation trends were annotated, taking care to accurately follow curvatures and dislocations in the trends.

2) Fracture and fault traces were marked (these are typically distinguished by dislocations or abrupt changes in the attitude of bedding or foliation traces).

3) Lithological boundaries within outcropping areas were interpreted on the basis of colour, textural and geomorphological characteristics.

4) Fold axial traces were interpreted from bedding & foliation trends.

5) Outcrop/Quaternary sedimentary boundaries were traced

The maps were then corrected, coloured, annotated and digitised. Separate levels of vector data were captured, allowing plotting or manipulation of different aspects of the data. Final maps are plotted using Microstation™ software, and the maps plotted as electrostatic plots of all digital coverages. Microstation™ .dgn files can also easily be imported into GIS desktop mapping systems (Arcview™, Mapinfo™).

## 4.2 RESULTS

The interpretation of the Landsat TM data was compiled at 1:250 000 scale and is presented as two sheets. The structural/lithological framework was integrated with existing geological mapping (at 1:400 000 and 1:200 000 scales) to provide lithological control.

The area comprises several different geological terrains, each with a striking geological and geomorphological expression. At the scale of interpretation, the region can be subdivided into:

### 4.2.1 Precambrian-Lower Cambrian (✍⌨p, ✍⌨q)

The south-eastern sector of the area comprises N-S to NNE-SSW trending hills of marine sedimentary rocks of Precambrian to lower Cambrian age (Formacion Puncoviscana). Outcrops are typically grey to grey-brown or rust-coloured in the imagery. The N-S trend is typically dissected by drainage perpendicular to the bedding trend. Bedding varies from poor to well bedded.

An irregular "tear drop" shaped massive to weakly-fractured, grey outcrop within the Precambrian rocks corresponds to a Precambrian granite/granite gneiss (Formacion Quesera – **✍⌨q**).

**✍⌨p** comprises marine sedimentary sequences (sandstone, shale, phyllite, conglomerate), typically with low-grade (up to greenschist facies) metamorphism. N-S to NNE-SSW trending folding of **✍⌨p** is evident.

The Precambrian - Cambrian units are restricted to the SE of the area. **✍⌨p** is bounded to the west near Cerro Potrerillo, where it lies in faulted contact with Ordovician sequences of the "Faja Eruptiva de la Puna Oriental" (abbreviated here as **FEO**).

### 4.2.2 Upper Cambrian – Grupo Meson (⌨m)

The Precambrian rocks in the SE of the Puna region (bordering the Cordillera Oriental) are overlain by sedimentary sequences of the upper Cambrian Grupo Meson (**⌨m**). These rocks typically vary from poorly to well bedded, with minor erosion – resistant horizons forming low ridges within some outcrops. In the Landsat TM imagery the rocks are grey to grey-brown.

Distinction between **⌨m** and **✍⌨p** sequences is difficult in the Landsat TM imagery, and the boundaries are predominantly derived from existing lithological maps.

### 4.2.3 Ordovician - Grupo Santa Victoria (Os)

One of the principal geomorphological features in the region is the occurrence of several linear mountain chains trending N-S to NNE-SSW, separated by intermontaine valleys, and superimposed by Tertiary volcanic landforms. The mountain chains are dominated by interlayered Ordovician sedimentary rocks of Grupo Santa Victoria. These rocks comprise interlayered marine sediments - sandstone, quartzite, shale, siltstone and minor calcareous units.

In TM imagery, the rocks comprise typically well-bedded strata with moderate to steep dips. Individual erosion-resistant horizons locally form narrow ridges. Bedding traces in the northwest and west are locally subdued, possibly reflecting a higher percentage of soft shale bands within the strata. Outcrops are grey-brown to red-brown and orange. Bedding traces reveal a high degree of deformation, with abundant tight (?to locally isoclinal) folding, and near layer-parallel faulting, reflecting a major compressive (fold/thrust belt) deformation episode. Locally, these thrusts host large-scale quartz vein systems, some of which can be discerned with care in the imagery.

Previous investigations (Bahlburg, 1990) indicate that **Os** grades from platformal marine sediments at the base of the sequence to the east where it was deposited onlapping the western margin of the Pampean Craton. Up sequence and to the west the sediments rapidly grade to deep-water submarine fan turbidites, sourced from both the Pampean (east) and Arequipa (west) Cratons. These facies changes are not reflected in the regional geomorphological expression of the units in the TM data.

However, one major tectonic/stratigraphic subdomain is mappable from the imagery: extending N-S across the area, from the Sierra de Cochinoca in the north to Sierra del Cobre in the south, the Ordovician sedimentary rocks have interbedded volcanics and are intruded by numerous coarse-grained syntectonic to postectonic granitoids (**Osg**). This subdomain has been previously named the "Faja Eruptiva de la Puna Oriental" **(FEO).** North of the volcanic centres at Coranzuli, the **FEO** diverges from N-S, trending SW and bifurcating into two mountain belts. South of the Tertiary volcanics (near Susques), the **FEO** comprises two parallel N-S trending mountain belts 10km apart.

The syntectonic to postectonic porphyritic granites within the **FEO** typically appear as massive to well layered (foliated) rugged, hilly outcrops, typically orange to rusty-red-brown. Field observations indicate the granite intruded the Ordovician sediments as sheets concordant to a near bedding-parallel $S_1$ foliation. The surrounding sediments typically have a localised metamorphic aureole. Composition of the granite suggests sourcing from partial melt of the sedimentary pile.

The Ordovician sediments of the **FEO** also host minor syn sedimentary acid and mafic (?spilitic) volcanics. It is unclear whether the mafic volcanics represent early extension-related oceanic material, or are part of a bimodal collisional volcanic arc suite. The volcanic horizons are generally thin, and are not shown at the regional scale (poorly or not resolvable in 1:250 000 scale imagery) except to the west of Sierra del Cobre (Huancar). The nature of the **FEO** has been constantly argued about in the literature (see Coira *et al.,* 1982, Bahlburg, 1990: the author agrees with interpretation of the belt as a late Ordovician volcanic arc.

### 4.2.4 Permian intrusives (Pi)

Two exposures of granitoid at the northwesterrn and southwestern limits of the major granitoid batholith (**JKg**; see 4.2.5) west of Laguna de Guayatayoc have been mapped as Permian intrusives (SEGEMAR, 1996). These exposures are dioritic to monzonitic and appear slightly darker than the younger surrounding **JKg** granitoids in the Landsat TM imagery.

It is likely that other unrecognised exposures of late Palaeozoic intrusives occur throughout the region.

### 4.2.5 Permian sediments – Formacion Cauchari (Pc)

East of Salar de Cauchari, in the south of the Puna region, a narrow sequence of reddish to yellow-orange clastic sediments (Formacion Cauchari) are overlain and/or faulted against Cretaceous Grupo Salta sediments to the east. The Formacion Cauchari sediments are moderately well bedded, with occasional erosion – resistant beds forming low ridges.

### 4.2.6 Jurassic-Cretaceous Intrusives (JKg, JKi, JKis)

A series of Jurassic-Cretaceous granitoids and alkali intrusives were emplaced within the Precambrian-Palaeozoic basement north of Salinas Grandes. The alkaline intrusives are likely related to initial Cretaceous rifting of the Salta Rift System whereas the calcalkaline intrusives are interpreted as related to subduction of the Pacific Plate. Restriction of the intrusives to the eastern half of the survey area suggests the margin to the Precambrian Pampean Craton is a controlling structure in the development of the rift system.

**JKg**. A large (20kmx15km) exposure of granite to granodiorite lies immediately west of Laguna de Guayatayoc. The granitoid is coarse-grained, red-pink to light grey in outcrop; in Landsat TM imagery the granite occurs as rugged, massive to fractured outcrop, pale crème to dark brown. The granite intrudes upper Palaeozoic intermediate intrusives along its western margin. Along its eastern margin, there are significant low outcrops of tourmaline-quartz-feldspar rich greissen, commonly associated with, W mineralisation. The greissen outcrops are indistinguishable from the granite in regional-scale imagery.

**JKi.** In the Sierra Aguilar region, Ordovician sediments are intruded by medium-coarse grained granitoids. In Landsat TM imagery, the granitoids typically appear as rugged hills of massive, fractured grey to crème-brown outcrop. A dark brown contact zone occurs along the intrusive contact with **Os**.

**JKis**. A 2km wide laccolithic sheet of riebeckite granite and syenite is concordantly emplaced within **Os** sediments in the Cerro Rangel region. The intrusive appears as a series of low, rugged hills trending NNE-SSW on the margin of the eastern margin of the Sierra del Cobre. The syenite appears rusty red-brown and well-layered in the TM imagery.

Carbonatite dykes 5-10m thick, trending NE-SW and NNW-SSE occur throughout the eastern margin of the Sierra del Cobre (Zappettini, 1989), but are indistinguishable within the regional-scale TM imagery. The carbonatites are interpreted as associated with the rift-related Cretaceous intrusives.

### 4.2.7 Salta Rift System (Cretaceous -Tertiary sediments and undifferentiated Tertiary sediments)

Throughout the region, the Ordovician sedimentary rocks are tectonically intercalated (folded and thrusted) with continental to marine sediments deposited within rift basins initiated in the Cretaceous (with compressional inversion in the Tertiary). The sedimentary sequences have been divided into the Cretaceous - Tertiary Grupo Salta (**KTs**) and later undifferentiated Tertiary sediments (**Ts**).

#### Grupo Salta KTs.

The Grupo Salta represents a sequence of continental to marine sediments deposited within N-S rift grabens which opened across the Cordillera Central to the east, and across the Puna region. In the Puna region the sediments include marine sandstone-shale and limestone, plus distinctive red continental sandstone-shale-siltstone beds.

In Landsat imagery, the sedimentary rocks appear as well- bedded light to dark grey, olive and pale pink strata, commonly steeply dipping. Tight folding is common. The sediments are typically tightly folded with, and thrust against **Os** (and ✍🖮**C** in the south). The Grupo Salta in the Puna survey area includes the following previously mapped units:

Subgroup Pirgua
Subgroup Balbuena
    F. Lecho
    F. Yacoraite
Subgroup Santa Barbara

## Undifferentiated Tertiary sediments (Ts)

Subsequent to the rift-related Grupo Salta sedimentation, the depositional basins were inverted during Andean Orogeny compression, with associated deposition of a series of marine to continental sediments, plus contemporaneous interlayered volcanics and volcaniclastic sediments. The sequences were deposited unconformably on the Palaeozoic and Cretaceous-Tertiary sequences.

The Tertiary sediments appear in the Landsat TM imagery as well-bedded orange to red-brown strata. The strata are typically soft, resulting in generally low, rounded hills, with occasional erosion resistant horizons forming minor ridges where beds are steep. Where dips are gentle, the sediments form sheets with dendritic drainage patterns. Contacts with the Palaeozoic basement vary from normal faults (?reactivated during the Quaternary) to steep to low-angle thrusts.

The depocentres of the sediments appear to be controlled both by the obvious N-S to NNE-SSW trending (inverted) horst-graben structures initiated in the Cretaceous, but also by oblique NW-SE structural corridors, which appear to have acted as transfer faults during and post sedimentation.

The Tertiary sediments within the Puna region include the following previously mapped units:

- Grupo Pastos Grandes
- Formacion Pastos Chicos
- F. Cerro Morado
- F. Peñas Coloradas
- F. Trinchera
- F. Log Log

### 4.2.8 Tertiary- Quaternary Volcanics (TQv)

The onset of the E-W compressional Andean Orogeny was accompanied by both the Tertiary basin inversion and sedimentation, and volcanism that extended from Tertiary sedimentation to Recent.

This prolonged history of volcanism has given rise to the most spectacular geomorphological features within the Puna region.

The volcanics typically range from andesite to dacite- rhyodacite and minor rhyolite in the Tertiary, with uncommon Quaternary flows of black-brown basalt evident in the field (e.g. at Tuzgle). The volcanics range in appearance, with:

**TQv1:** Caldera-volcano facies - breccias, pyroclastics, and sheet flows, with common resurgent dacite domes. The main caldera structures appear as large (up to 50km wide) composite circular structures, comprising caldera rims cliffs, depressions (occasionally now lacustrine), and massive rounded domes and hills representing resurgent dacite domes.

Major circular collapsed caldera structures occur in the Cerro Vicuñahuasi, Nevada San Pedro - Pairique (northwest), Cerros Coranzuli, Granada and Morado (north-central region). The calderas are commonly associated with surviving stratovolcano cones, such as those at Cerro Granada (north) and Cerro Tuzgle (south). Ordovician-Tertiary sedimentary rocks commonly form periclinal upturned rims to the calderas and dacite domes.

Dacite domes (eg Pan de Azucar, Cerro Leon and Cerro Redondo (Laguna de Pozuelos region), Huaira-Huasi - Cerro Turi Lari Grande (Salar de Olaroz region) typically appear as circular to elliptical domal hills (pale grey to orange-pink or red-brown), and are commonly highly fractured. Breccia, localised pyroclastics and lava flows occur as rugged to rounded hills, with colours ranging from pale grey - olive, orange, red-brown to dark brown.

The great variation in colour represents not only primary compositional variation, but also variation in oxidation state during and after emplacement.

**TQv2:** Distal facies - in the Laguna de Pozuelos region, layered tuffaceous volcanics are interbedded with Tertiary sediments and lahar-flow volcaniclastics. The units have been previously interpreted by Chernicoff *et al.*, (1996) to represent part of a volcanic sequence associated with a concealed caldera beneath Laguna de Pozuelos. These volcanics and volcaniclastic sediments appear in the field as pale grey to white layers within the sediments. In Landsat TM imagery, they appear as well layered, gently to moderately-dipping grey-orange strata.

**TQi:** Ignimbrite. This occurs over a large area of the north and central sectors of the region. Ignimbrite comprises widespread bedded sheets of medium to coarse grained dacite to rhyodacite pyroclastics. The sheets are up to 100m thick, and exhibit thick (>10m) beds. The sheets unconformably overly the Tertiary to Precambrian sequences. In Landsat TM imagery, the ignimbrite appears as typically high-albedo, pink, white and orange (occasionally olive-green) mesas, thin sheets and heavily-eroded hills. Badlands-style incised erosion and outwash is common. An E-W to NW-SE fracture or layering is common throughout the major ignimbrite exposures. Numerous composite circular depressions and fractures occur in the ignimbrite in the Cerro Coranzuli region, likely indicating concealed volcanic vents.

Contacts between the ignimbrite and the breccia/proximal pyroclastics associated with the major volcanic calderas are commonly indistinct, possibly due to both interfingering of the units and erosion of the ignimbrites.

### 4.2.9 Quaternary sediments

The N-S intermontaine valleys separating the Precambrian to Tertiary rocks of the region are infilled by Quaternary alluvial, fluvial and lacustrine sediments.

**Qa:** Alluvial sediments. The Tertiary-Precambrian exposures are fringed by coalescing alluvial fans (including proximal talus cones), which merge into flat-lying peneplain alluvial and colluvial sediments (and soil). The alluvial sediments appear in the Landsat TM imagery as flat to low-angle pale grey to pale brown sheets within the intermontaine valleys. The colour of the alluvial sediments locally varies significantly, depending on the local source rock. Drainage patterns in the alluvial fans are typically incised, and vary from perpendicular to the mountain belts to dendritic.

**Qf:** Associated with the alluvial outwash in the valleys are narrow streams and rivers that drain into the centres of the valleys. In places, these fan into major braided rivers. The channels contain fluvial sediments, including conglomerates, gravels and sands. In the Landsat TM imagery, the fluvial sediments appear as moderate to high-albedo, narrow channels.

**Qs:** Evaporites. Within the intermontaine valleys lie extensive continental salinas, which capture all the episodic drainage in this desert region. The salinas typically are elongate N-S along the valleys, with Salinas Grandes in the southeast oriented ENE-WSW. The salinas comprise fine to medium grained evaporitic carbonates, chlorides, borate, and sulphates. The salinas are fringed by fine-grained silt with abundant evaporitic salts, and minor regressive aeolian dunes.

In the Landsat TM imagery, the salinas appear as high to low albedo white-blue to black depressions. The black areas commonly correspond to the margins of the salinas as mapped (see 1:250 000 topography maps), although the correlation is not consistent. The larger area of salina evaporitic sediments shown in the geological interpretation reflects the greater size of the salinas before the present.

**Ql:** Recent lakes within the intermontaine valleys. These appear as dark, low albedo regions within the Landsat TM imagery.

# 5. SOLID GEOLOGY INTERPRETATION MAP

The following section outlines the overall concept, methodology and results of integration of the Landsat TM interpretation with the magnetic and radiometric data to produce the final Solid Geology Interpretation map. A Solid Geology map is designed to portray the rock units of interest in a region, extending form outcrop to regions concealed by surficial material or units deemed of no interest for the particular purpose the maps are produced for.

In the instance of the Puna area, the Solid Geology map is designed to portray all the different rock sequences known from surficial mapping, extending beneath the surficial Quaternary sediments.

## 5.1 LIMITATION OF AIRBORNE GEOPHYSICS IN GEOLOGICAL MAPPING APPLICATIONS

Evaluation and interpretation of airborne geophysical data sets generally enables a much improved geological and geophysical understanding of the survey area. However, there are a number of fundamental limitations which restrict both the level of detail and the geological discrimination which may be derived from the airborne data, but which do not lessen the advantages and conclusions from the survey.

1) The resolution possible from the magnetic and radiometric data in an airborne survey. In the Puna survey, the flying height of >130m limits the resolution of the survey. Magnetic units either less than 130m wide or separated by less than 130m can not be readily resolved. The flight line spacing of 1km also restricts the resolution of the Puna survey, as bodies that are less than 1km wide and weakly magnetic may only show as a 1-line anomaly. The flight-line direction in the Puna survey is also a limiting factor in geological resolution. The flight lines are parallel (or close to) the overall main structural geological trend of the region. With a wide line-spacing, this means that much of the fine-scale detail in the geology will not be resolved.

2) Another flying parameter which influences the possible resolution is the rate of recording for magnetic and radiometric data. Along flight lines, magnetic readings are recorded every 0.1 secs, which corresponds to every 7 m on the ground (approximate). Radiometric readings are summed every 1 sec interval, and thus correspond to approximately 70m on the ground. Hence, radiometric images have much lower resolution than corresponding magnetic images.

3) The magnetic characteristics are related to the degree of magnetisation, which is influenced by the concentration and distribution of magnetic minerals, principally magnetite (Clark, 1997). The usual geological lithology or rock type, as defined by broad

geological parameters, is sometimes not a reliable guide to the concentration of magnetic minerals.

Factors such as the original pressure, temperature conditions, oxygen availability, environment of deposition, subsequent history of diagnoses, metamorphism, alteration and weathering also greatly influence the formation, preservation and destruction of magnetic minerals. Within rock units present in the Puna area, there are examples of units that in the field appear uniform, but display a great variation in magnetic intensity. Conversely, there are significantly different rock units may have essentially the same magnetic character, highlighting that the magnetic signature is not unique. The most difficult to distinguish due to their identical non-magnetic to weakly magnetic signature were the sedimentary sequences, from Precambrian to Tertiary.

4) Remanent magnetisation, where the direction of magnetisation in rocks may not be parallel to the modern Earth's field, can cause complexity in any magnetic interpretation. In the Puna area, several areas exist where rocks with high susceptibilities coincide with zones of negative magnetic field intensity in the airborne data. These areas of apparent conflict may indicate the presence of remanence. Remnant magnetisation can originate in a number of ways:- chemical, detrital, isothermal and thermal. Igneous rocks upon cooling pass through the Curie point - the temperature at which magnetite retains a proportion of the magnetic intensity, inclination and declination at the time of cooling. All the rocks of the Tertiary - Quaternary volcanics have cooled through the Curie point, and thus potentially could preserve remnant magnetic vectors. Magnetic-lithological subdivision of the volcanics in the Solid Geology map is likely reflect both differing compositions and ages of extrusion.

5) Gamma rays - the active components of radiometric data are highly susceptible to absorption by surficial sediments. If the regolith is predominantly residual and contains detritus from the underlying bedrock, then it will have a similar radiometric signature to the bedrock. Conversely, transported alluvium and lacustrine deposits in the intermontaine valleys will mask the radiometric signature of the underlying bedrock. In addition gamma rays are effectively absorbed by the atmosphere, so that radiometric data is also sensitive to flying height. The combination of flying height, rugged terrain, high percentage of transported alluvium/lacustrine sediments and along-line sampling have made lithological interpretation from Ternary (K:U:Th) imagery at a regional scale inappropriate in the Puna area. This data is best utilised as flight-line profile data over selected exploration targets. For the purpose of the regional solid geology interpretation, the potassium-channel data was displayed as an image clipped to show the maximum 5% of values, therefore highlighting possible high potassium content alteration systems (commonly associated with many styles of mineralisation). This

interpretation is qualitative, and does not give a quantitative interpretation of the %K.

## 5.2 SOLID GEOLOGY INTERPRETATION MAP CONCEPT

The scale of features and the style of lithological subdivisions to be portrayed on a Solid Geology map from integration of geophysical and field mapping/remotely-sensed surface mapping depends greatly on the line-spacing of the data and the geophysical response of the various rock units.

A detailed (200m or less line spacing) magnetic survey can provide additional fine detail to surface geological mapping, and allow detailed mapping of the units in the subsurface. Conversely, broad-spaced data will be best interpreted as regional - scale data, with portrayal of regional structures and structural zones, and magnetic-lithological sequences that represent a hybrid between lithological assemblages and tectonic subdomains. This is particularly true for the Puna area, where the main structural grain is parallel to the broad-spaced data, and there is limited or no variation in magnetic signature for many of the lithological assemblages present in the area.

Therefore, the integration of the detailed Landsat TM interpretation of the surface geology entails portrayal of more simplified, regional-scale structures and broad lithological-tectonic sequences rather than individual lithologies in most instances. Portrayal of these sequences in beneath Quaternary cover is difficult in part, and some of the boundaries are subjective. The magnetic data also allows the portrayal of previously unknown (concealed) magnetic intrusives, volcanic/hydrothermal vent structures and magnetic/lithological subdivision in the Tertiary-Quaternary volcanics.

The regional Solid Geology map therefore outlines a comprehensive regional portrayal of the lithological/tectonic framework of the Puna region, and is designed to be used concurrently with the Landsat TM Geology map.

## 5.3 ATTRIBUTION OF DATA AND DESCRIPTION OF SOLID GEOLOGY INTERPRETATION MAP

As outlined above, integration of the surface geology and the geophysical data for the Puna survey entailed simplification and generalisation of both some structures, and in particular, the sequences of rock units portrayed. The following is a description of the different magnetic-lithological sequences portrayed on the map, and their overall magnetic characteristics.

For simplicity, the geology of the Puna region may be considered in terms of a series of tectono-stratigraphic domains (Mon and Salfity, 1995). From east to west These include the Pampean Cratonic margin (Precambrian/Cambrian), the Ocloyic Orogenic Belt (Upper Cambrian-Ordovician), the Salta Rift System (Mesozoic-Tertiary), and the Cenozoic Andean Orogenic Belt with its associated volcanism. These tectonic subdivisions are described more fully in Section 7 of this report.

### 5.3.1 Pampean Craton Margin (✍▭▭ - Precambrian to Cambrian sediments-metasediments).

This sequence comprises low grade (greenschist facies) metasediments to unmetamorphosed sediments of the Formacion Puncoviscana. The sequence as shown on the Solid Geology map may also contain unrecognised interlayered volcanics, and unresolved areas of Ordovician sedimentary sequences. The sequence is typically nonmagnetic to moderately magnetic. The shallow magnetic response in the SE of the region is superimposed by a series of broad regional magnetic highs associated with a deep magnetic body. This body is portrayed as a series of possible Jurassic-Cretaceous intrusives, but may also be related to concealed magnetic crystalline rocks of the Pampean Craton. A similar association between Precambrian sequences and deep magnetic sources has already been noted in the Precordillera San Juan-La Rioja survey (Nash, in prep.). The Precambrian Formacion Quesera granite (✍▭**q**) has a strong magnetic signature.

### 5.3.2 Ocloyic Orogen (Upper Cambrian-Ordovician sedimentary/intrusive sequence Os)

The Upper Cambrian-Ordovician fold/thrust belt sequences of the Puna region are typically nonmagnetic to weakly magnetic, with no magnetic marker horizons to enable detailed structure to be traced. The synsedimentary volcanics and syntectonic granitoids within the **FEO** have identical nonmagnetic to weakly magnetic signatures, and cannot be differentiated in the geophysical data at this regional scale. The Palaeozoic terrain therefore incorporates the Grupo Meson and Grupo Santa Victoria marine sediments, plus synsedimentary volcanics and the syntectonic to post tectonic granitoids. The 1km line spacing and N-S survey direction do not allow detailed resolution of the tight fold/thrust deformation within these subdomains.

However, the Palaeozoic terrain has been subdivided into 5 lithological/tectonic subdomains on the basis of previously investigated lithological characteristics (facies mapping by Bahlburg, 1990), and the presence of major bounding structures. The subdomains are partly in tectonic contact with each other, and partly separated by Mesozoic-Tertiary sedimentary sequences, and overlain by Tertiary-Quaternary volcanics.

**Os1:** ***Sierra Aguilar - Cordillera Oriental region***. This subdomain includes platformal sandstone-shale units originally unconformably overlying the Precambrian-Cambrian sequence on the margin of the Pampean Craton. The platformal facies grades up sequence and to the west into deep water submarine-fan turbidites. Later deformation has tectonically intercalated **Os1** with the Precambrian - Cambrian sequence. The subdomain typically has a strong regional broad magnetic high intensity, reflecting deep magnetic material. This regional magnetic anomaly possibly correlates with crystalline basement of the original continental margin of the Pampean Craton. The superposition of the western extent of this gradient with a major N-S fault zone in the **Os** sequence is taken as the western margin of **Os1.** The subdomain is interpreted to extend as a narrow tectonic slice west of the Salinas Grandes, where it is in thrust contact with both **PcC** and **Os3**.

**Os2:** ***La Quiaca region***. This subdomain trends N-S in the north of the area, to NE-SW in the central sector, where it is overlain by Tertiary magnetic volcanics. The subdomain is dominated by nonmagnetic to weakly magnetic deep-water submarine fan turbidites. The eastern margin is the N-S to NE-SW fault contact with **Os1.** The western margin lies in contact with **Os3** along a major N-S trending fault zone in the far north of the region. The subdomain has an overall moderate regional magnetic intensity, suggesting possible thinned Precambrian crystalline basement at depth (however, no clear magnetic gradient could be separated to estimate a depth to the “basement”.

**Os3***:* ***"Faja Eruptiva de la Puna Oriental”*** (**FEO**). The subdomain is characterised in outcrop by the presence of interbedded syn-sedimentary volcanics and syntectonic to post tectonic granitic rocks. The sedimentary/igneous sequence is typically weakly to (locally) moderately magnetic. To the north, the subdomain is oriented N-S, and is bound to the east by fault contact with **Os2** and **KT** sediments**,** and to the west by faulted contact with **KT** sediments. Weak magnetic trends parallel to the bounding faults partly observed in the Landsat TM data swing NE-SW towards the central sector, where the subdomain , apparently bifurcating into two belts, is obscured by **TQv** magnetic volcanics. Continuity of some of these major faults is expressed by reactivated faults evident in the overlying volcanics. To the south of the volcanics, the two bifurcated belts of the subdomain are partly obscured by a N-S zone of magnetic volcanics. This subdomain represents a major magmatic arc within the Ordovician sedimentary pile, and has been previously interpreted as a volcanic arc (Coira *et al., 1993)* initiated during convergence of the Iquique and Pampean Cratons in the late Ordovician.

**Os4:** ***Rinconada-Carahuasi belt***. This subdomain is dominated by deepwater submarine fan turbidites, with a high percentage of shales. The sequence is typically nonmagnetic to weakly magnetic, with an overall low to moderate regional magnetic intensity gradient. The boundary with **Os3** to the east is obscured by an overlying deformed **KT** sedimentary basin. The boundary to the west is taken as the western extent of the broad regional magnetic gradient superimposed with a shallow "mottled" magnetic texture. The contact with **Os5** to the east is obscured by overlying **KT** sediments.

The southern extent of the subdomain abruptly trends NW-SE along an apparent regional dextral strike-slip fault. This fault influences Tertiary volcanics, but may reflect a preexisting (Palaeozoic) tectonic margin to **Os4**.

**Os5:** ***Minas Pirquitas - Sierra de Lina belt***. The subdomain is dominated by submarine fan turbidites, with minor sandstone interbreeds within a shale-rich sequence. This subdomain trends N-S in the north, but unlike the other Palaeozoic subdomains trends NNW-SSE in the west and south. An intense suite of early thrusts and intense folding (evident in the Landsat imagery, and hinted at in the magnetic data) intercalates tectonic slices of later **KT** sediments (this occurs in all subdomains, but is particularly marked in **Os5**). The northern and western part of the subdomain is largely obscured and overlain by magnetic **TQv** volcanics. To the south, the subdomain lies in faulted contact (NW-SE orientation) with the **TQv** volcanics. Evidence from Bahlburg (1990) of a volcanic arc sedimentary-volcanic sequence in the Ordovician to the west in Chile suggests the NW-SE fault at the south of the subdomain may reflect a primary tectonic contact in the Palaeozoic sequences. The subdomain is typically nonmagnetic to weakly magnetic.

### 5.3.3 Permian intrusives (Pi)

The Permian diorite to monzonite stocks in the Tusaquillas region have variable magnetic character. The diorite stocks at the southern end of the exposed Cretaceous granite are moderately magnetic, and a series of multiple intrusive centres can be interpreted from the data. The exposures at the northern end of the granite do not have a magnetic signature substantially different from the surrounding Cretaceous granite. The Permian intrusives do not appear to have a unique or characteristic magnetic signature, and therefore occurrences of these rocks not identified as Permian in the field may not have been separated from the more widespread Mesozoic intrusive suite in the Solid Geology map.

### 5.3.4 Permian Sediments – Formacion Cauchari (Pc)

The Formacion Cauchari is restricted in outcrop to a narrow N-S trending belt of deformed sediments east of Laguna Cauchari. The sediments are weakly to nonmagnetic, and cannot be distinguished from the early Palaeozoic and Mesozoic-Tertiary sedimentary sequences in the region from the magnetic data. The extent of this sequence shown on the Solid Geology map represents the tectonic limits of the fault-bound sediments visible in outcrop. It is likely that this formation has a greater extent in the subsurface, but cannot be geophysically mapped at this scale.

### 5.3.5 Salta Rift System (Jurassic-Cretaceous intrusive rocks and Mesozoic-Cenozoic sedimentary rocks)

The composite Palaeozoic- Precambrian terrain was reactivated by regionally N-S rifting in the Mesozoic, and associated emplacement of intrusives and sedimentary deposition. Intrusives were predominantly emplaced during the Jurassic-Cretaceous, although minor late Palaeozoic intrusives have been recognised in the area. The magnetic signatures of the various intrusives are not characteristic of different age suites at this scale; unrecognised Palaeozoic intrusives may be included within the Mesozoic intrusives portrayed on the map.

### (a) Alkali intrusives (JKi, JKis, JKim+, JKim-)

This comprises a suite of variable-composition intrusives, ranging from granitoids to pyroxenite. The intrusives are generally <10km wide or long.

**JKi** comprises granitic rocks, exposed as a major body in the Sierra Aguilar region, where it intrudes Ordovician sediments. The contact zone hosts the Mina Aguilar Pb/Ag deposit. The body has a nonmagnetic to weakly magnetic signature, with a superimposed regional high gradient evident in the magnetic data. The magnetic signature has a "mottled" texture. The unit likely includes relict host sedimentary rocks and other minor intrusive phases. Contacts with the surrounding sediments are indistinct from the magnetic data, possibly due to a transitional greisen or alteration zone: contacts are taken from the Landsat TM interpretation and modified by reference to weak trends in the TMI/RTP 1 VD data.

**JKis** comprises the pale white-grey syenite laccolith mapped in the surface and interpreted from Landsat TM data. The syenite is typically nonmagnetic to weakly magnetic, and lies close to the flight-line orientation. Combined with a narrow width to the body, the laccolith does not appear in the regional magnetic data. The boundaries have been adapted from the Landsat TM interpretation.

**JKim+** comprises a suite of strongly magnetic intrusives, varying from diorite (host to the Abra de la Mina Pb/Ag/Ba mine) to layered pyroxenite and hornblendite (small body intruding Ordovician sediments 15km west of Susques). The magnetic signatures range from positive to dipolar. The majority of the magnetic signatures of the intrusives appear broad, indicating the intrusives are emplaced beneath the present surface level. The majority of the intrusives are concentrated in two NW-SE corridors in the SE of the region (near Cobres - Esquina Grande and Abadon Castro Tolay). The concealed magnetic body (broad, diffuse magnetic gradient) in the southeast of the region has been portrayed as a possible **JKim+** intrusive. The width of the body is portrayed as much narrower than the magnetic anomaly to more realistically reflect the causative body, although the boundaries are arbitrary at this scale. The NE-SW and NW-SE orientations of the intrusive corridors suggests emplacement along the primary rift- fault and secondary transfer fault orientations during development of the Salta Rift System. These trends parallel the emplacement of narrow carbonatite dykes mapped at surface. The dykes have no magnetic signature, are narrow (5-10m), and therefore have not been portrayed in the solid geology map at this scale.

**JKim-** represents several non-magnetic to reversely - magnetised interpreted intrusives, represented by elliptical low magnetic zones in the TMI/RTP data. These are most likely part of the same general suite of intrusions as **JKim+.**

**Granite - granodiorite (Kg).** This unit represents the major granite-granodiorite pluton exposed in the Tusaquillas region. The body is non-magnetic to weakly magnetic, and has a characteristic "mottled" texture. Contacts with the Ordovician sediments/intrusives are vague in the magnetic data, and are portrayed as a modification of the mapped outcrop extent with modification from weak NE-SW magnetic trends. **JKg** intrudes Permian diorite-granodiorite at the northern and southern ends of the pluton at Tusaquillas.

**Greissen (JKgr).** A coarse-grained quartz-tourmaline greissen is associated with the eastern margin of the **JKg** granite (known from outcrop), and has a slightly elevated magnetic susceptibility compared to the granite. The regional magnetic data shows a broad, irregular diffuse zone of low to moderate magnetisation to the east of **Kg** , extending east beneath the quaternary salinas to the **JKi** of the Sierra Aguilar region. This zone is interpreted as a region of greissen and alteration associated with **JKg** and may imply a shallow roof surface of **JKg** beneath the zone. The zone likely includes patches of Ordovician sediments (possibly altered). The zone is also characterised by a series of broad linear magnetic highs, trending E-W. These are interpreted as probable magnetic mafic dykes (**Kd**) associated with the Cretaceous intrusive suite. An alternative interpretation may be that these anomalies represent intense alteration within the greisen zone along E-W fractures.

### (b) Mesozoic-Tertiary sediments (KTs)

The Mesozoic N-S trending rift deformation initiated continental-marine sedimentation, initially within N-S extensional grabens (Cretaceous-middle Tertiary Grupo Salta), extending to unconformable deposition of middle-Late Tertiary sediments during basin inversion associated with Andean Orogeny E-W compression.

The sedimentary rocks within **KTs** comprise the Cretaceous - Tertiary Grupo Salta and the later undifferentiated Tertiary sediments. Although each of these sequences is readily mappable as separate stratigraphic packages in the field and from Landsat TM data, the magnetic signature of all of the sediments is identical within the regional data, and therefore individual sequences cannot be traced with any confidence into areas concealed by Quaternary sediments. Therefore, the sediments are portrayed on the regional solid geology map as domains of Cretaceous through to Tertiary sedimentation.

The sedimentary sequences are typically nonmagnetic to weakly magnetic, with only variations in the regional magnetic gradient evident between separated domains of sedimentation.

**KTs** sediments have been involved in folding and thrusting with the Precambrian-Palaeozoic basement, and the current distribution of the sediments reflect intense deformation with and between the various basement subdomains. Regional-scale folds and faults within and bounding **KTs** are locally evident as weak magnetic trends. The current distribution of **KTs** is dominated by elongate N-S to NNE-SSW domains bounded by major faults against elongate domains of Palaeozoic - Precambrian basement. The inverted basins have in part an en echelon distribution, with offset of sequences across NW-SE to NNW-SSE fault zones. These structures appear to be reactivations of early transfer faults developed during initial rift development in the Mesozoic.

The non- to weakly magnetic character of **KTs** is very similar to identical to the signature of the surrounding and tectonically intercalated Palaeozoic sequences (**Os**). Therefore, extrapolated boundaries between **KTs** and **Os** have been taken, where possible, as major tectonic breaks (fault zones) visible in the magnetics as subtle (weak) linear demagnetised zones. This treatment is somewhat subjective considering the local complexity of the boundaries observed in the field and in the Landsat TM imagery, but gives at least an approximation to the distribution and nature of the sedimentary basins. Therefore, **KTs** as portrayed in the solid geology map represents a lithological-tectonic domain rather than a stratigraphic sequence, and is likely to contain, at least in part, portions of unrecognised Palaeozoic basement.

### 5.3.4 Andean Orogeny (Tertiary-Quaternary volcanics TQv)

The Andean Orogeny involves E - W collision & subduction of the Pacific Plate beneath the South American continental crust. This has resulted in crustal thickening, isostatic uplift of the Puna region, and episodic compression (basin inversion) and extension (back-arc basinal tectonics) throughout the region. The undifferentiated Tertiary sedimentary sequences included in the Salta Rift System **KTs** sequences above, were deposited during the Andean Orogeny. The Orogeny is particularly marked by the emplacement of significant volumes of volcanics.

The Puna region, as seen from Landsat TM imagery, is dominated by large-scale volcanic complexes in the northwest, west and central sectors, plus lesser volcanics in the south. The exposed volcanic complexes are concentrated in a N-S belt along the main Andean Chain on the western border of the survey, and in NW-SE-trending belts running across the central and southern regions.

The **TQv** assemblage comprises the caldera, stratovolcano flows, breccias, ash, debris flows, and dacite-rhyodacite domes (**TQv1&2**), and **TQi** ignimbrites of the surface geological map (**Tqa, Td, TQt** of the published 1:200 000 and 1:400 000 geological maps). Although discrimination of the caldera and volcano facies flows, breccia, domes etc from the widespread sheets of ignimbrite is relatively easy in the Landsat TM imagery, these units commonly have similar magnetic signatures, and are therefore portrayed as one major volcanic complex in the solid geology map.

The volcanics, ranging from andesite through to dacite-rhyodacite, with minor basalt in the younger volcanic centres, have the most striking regional magnetic signature of all the sequences in the region. They are highly variable in their intensity, ranging from non magnetic to strongly magnetic, and typically exhibit a "noisy" pattern overall. The complex, overlapping circular calderas and volcanic centres evident in the Landsat imagery are reflected by overlapping circular to elliptical magnetic patterns, intersected by numerous N-S, NW-SE and NE-SW faults and fractures. A strong E-W fracture/layering fabric evident in the ignimbrite sheets in the Coranzuli region is also reflected by a strong E-W magnetic fabric. It should be noted that numerous circular magnetic patterns, probably representing concealed eruptive centres occur within the regions of exposed ignimbrites. A moderate intensity magnetic zone with an E-W fabric extending south of the exposed volcanics in the Coranzuli region is interpreted as subsurface continuation of the ignimbrites.

Dacite domes in the region, commonly occurring along the rim of collapsed calderas, typically exhibit localised strong magnetic anomalies. These anomalies vary from positive, dipolar and negative (and hybrid complexes), indicating variable remnant magnetisation, and hence variable emplacement ages. Stratovolcanic cones such as Cerro Granada also exhibit dipolar or negative remnant signatures.

As well as mimicking the known (exposed or partly-concealed) circular volcanic complexes, the regional magnetic data provides evidence for a previously suspected, but totally concealed caldera in the Laguna de Pozuelos region (see Coira *et al*, 1996). A complex of broad, diffuse elliptical magnetic high anomalies beneath the Laguna are ringed by complex to simple magnetic anomalies associated with dacite domes at Cerro Redondo (west), Cerro Leon and Pan de Azucar (south), and interlayered volcanics, volcaniclastics and sediments (east). The association of the magnetic high with resurgent dacite domes and proximal volcanic facies suggests that the high magnetic anomalies represent the magnetic core of a collapsed caldera, now concealed by Quaternary sediments.

The volcanics assemblage has been subdivided into three (subjective) subunits:

- **TQvm+** volcanic zones with a moderate to high positive magnetic signature.
- **TQv** volcanic zones with a low to moderate magnetisation
- **TQvm-** volcanic zones with a low to negatively - magnetised signature.

It should be reiterated here that, as with all the subdivisions and boundaries portrayed in a regional scale map from widely - spaced data, the units reflect averages of the geological units within a reasonable volume of the earth.

### 5.3.5 Undifferentiated geophysical anomalies

Throughout the magnetic data there are numerous isolated magnetic anomalies of (typically) only 1 or 2 line-widths extent at best. These vary from positive, negative and dipolar in nature, and occur within numerous geological sequences. Numerous of these anomalies are coincident with known mineralisation, and are therefore interpreted here as isolated epithermal/hydrothermal vents, small scale intrusives and/or localised fluid alteration systems. Many of these anomalies are coincident with volcanic complexes, intrusive contacts, or major fault zones.

The potassium radiometric data indicate the presence of numerous isolated high-potassium anomalies throughout the area. These anomalies were observed from a portrayal of the maximum 5% of K-channel data, in an attempt to isolate the localised high potassium signal often associated with mineralising fluid alteration. The anomalies portrayed were selected on the basis of no or little apparent connection to particular lithological control from Landsat TM imagery in an attempt to reduce the portrayal of primary compositional variations (such as major exposures of granite).

Numerous small-scale isolated anomalies are coincident with the trace of major Tertiary-Quaternary fault zones (for example along faults marking the eastern boundary of Ordovician sediments west of Salar de Olaroz and Salar de Cauchari. Several of these anomalies are also coincident with, or adjacent to small magnetic anomalies, and/or known hydrothermal springs. In several instances, alluvial gold has been or is still recovered in zones near the anomalies.

# 6. MAGNETIC MODELLING

## 6.1 INTRODUCTION

In order to gain an opinion on the depth and structure of subsurface geology of the Puna Region, three flight lines were processed for depth control using a modified Werner depth estimation method. The same lines were then modelled to gain more information on the structure beneath the flight lines. Solutions generated using the Werner method were used as depth control where appropriate in the modelling. There were no known parameters (position, depth or susceptibility) available to be used in the modelling, thus forward modelling was used in all three models.

An automatic Euler 3D depth analysis was conducted across the gridded data. The Euler method produced geologically ambiguous results due to both the regional nature of the data and the poor magnetic response to many of the geological sequences within the area. The results of the Euler depth response are included as Maps 3a,b.

## 6.2 REGIONAL PARAMETERS

Forward modelling of potential field data compares an observed total magnetic intensity with a synthetic signal based on the properties of the synthetic prisms representing lithological units. Prior to starting a magnetic model, parameters of the earth's magnetic field were required by the modelling program. These properties relate to how the synthetic line is generated. The relevant data for the Puna region is a follows :

Field Strength = 23741 nT
Inclination = -17°
Declination = -4°

These figures were calculated from the IGRF model supplied with Geosoft Montaj and are based on the 1995 IGRF model.

The lines used for this part of the interpretation are 27080, 27212 and 27220.

## 6.3 DEPTH TO SOURCE SOLUTIONS

World Geoscience uses a modified Werner algorithm for the calculation of Depth to Source solutions. Werner depth solutions have been used as an absolute depth reference where appropriate along the selected lines. These solutions demonstrate the use and relevance of the depth estimation tools to provide a reference point for the magnetic models. Werner solutions are divided into dyke and contact solutions which reflect the structure of the geology. Dyke solutions are generated by a change in the vertical gradient of the signal, and contact solutions are generated by a change in the horizontal gradient of the data.

The depth solutions were classified in groups that related them to known sediment outcrop, volcanic outcrop or deeper solutions.

The Euler method was applied to the gridded data to determine depth estimates based on a structural index. For this grid to obtain the most appropriate results a structural index of 0.5, which approximates both a contact solution and a dyke solution was used. The results of this were not clear and as a consequence were not used.

## 6.4 INITIAL ASSUMPTION

Initial assumptions for the magnetic modelled bodies were that they were composed of a series of subvertical magnetic prisms, and a relatively high susceptibility based on the underlying volcanics.

Before starting the modelling, the data was passed through an RTP filter. The RTP filter made the data appear to be magnetised directly beneath the source, i.e. as it would be at the north magnetic pole. Modelling was conducted against the RTP data to assure that the source of the body lay directly beneath the signal.

## 6.5 RESULTS

The final results of the Werner depth to source study were overlaid across the known geology map to check the position of the solution against any possible outcrop. The majority of the solutions (95%) occurred beneath the sedimentary basins. It was not possible to assign these solutions to known lithological sources.

The complexity of the magnetic data and the complexity of the underlying geology over such a distance, each line is approximately 150 kilometres long, meant that it was difficult to model each small anomaly in the data. A basic model of the overall geology was made by looking at groups of anomalies that had a similar appearances or had clear boundaries in the signal.

The blocks have been coloured approximately the same colours as the outcrop shown on the 1:250000 Geological map of the area. In many cases a prism represents a change in the susceptibility of a larger block. In some cases up to 8 prisms make up an apparently similar lithological block. However in most of the areas the actual litholgical units are not known, for that reason the prisms have been correctly labelled in terms of their relevant susceptibility to each other, i.e. low, medium and high accordingly.

Although there is some outcrop of magnetic units at the surface, magnetic signatures may not reflect this with a corresponding signal due to changes in the magnetic materials physical properties. Weathering and erosion of the source rock has transported magnetic material within the sediment into the sedimentary basins, causing high levels of surficial noise in the data. Filtering of the data was considered inappropriate so as to maintain the integrity of the data. Low pass filters would alter the wavelengths of the underlying signal due to the sharp wavelength cut off of low pass filters.

The overall susceptibility of the area is very high; the susceptibility is in the order of magnitude of $10^{-2}$ SI units. This is common for areas of high volcanic activity.

Remnant dykes occur frequently along two of the three lines. It is not possible to accurately model these due to a lack of information on The overall susceptibility of the area is very high; the susceptibility is in the order of magnitude of $10^{-2}$ SI units. This is common for areas of high volcanic activity.

Remanent dykes occur frequently along two of the three lines. It is not possible to accurately model these due to a lack of data of the remanent magnetic properties (e.g. the Konigsberger ratio (Q ratio)), and the associated Q dip and Q declination of the magnetic material. Negative susceptibilities were used instead and provide an accurate reflection of the influence that these dykes have on the overall signal.

The models reflect a region with intense volcanic activity intruded by dykes (remanent and induced) containing magnetic material which changes in susceptibility throughout the lithology. Backed up with depth solutions derived from the Werner inversion algorithm, a reasonably accurate picture of the depth of the sedimentary basins can now be seen. These solutions appear as red and blue arrows on the modelled cross-sections. Blue arrows represent dykes and red arrows represent contacts.

## 6.6 INDIVIDUAL LINE COMMENTS

## LINE 27080

*Note: m refers to distance, in metres, (along line) followed by an easting and northing coordinates.*

- Western end of the line (0 – 15000 m, 3419115, 7520516 – 3434361, 7520576) is made up of very shallow high amplitude blocks, outcropping in some area; these have been identified at the surface as andesite.

- The majority of the western portion of line 27080 (15000 – 65000m, 3434361 7520576 -, 3492940, 7520666) appears to be ignimbrite in outcrop, but shows a quiet magnetic response. This suggests the ignimbrites (typically high susceptibility) occur as a very thin sheet over ?Palaeozoic to ?Tertiary sediments. It is likely comprises of ignimbrites as a very thin sheet overlaying marine sediments up as far as the end of the modelled line. Only at the beginning of this line are there any outcropping volcanics (identified as ignimbrites) and these are reflected in the data collected over this line.

- Reasonably shallow remnant dyke in centre of line at location 80000 m (3497152, 7520705).

- Areas identified as medium susceptibility on either side of the dyke and slightly further to the east at 100000m (3516815, 7520771), do not outcrop and their lithological type cannot be positively identified. From the character of the signal they may be a continuation of the sedimentary sequences.

- Further to the east (110000m onward, 3528247, 7520808 and further east) medium to high susceptibility units are probably made up of basic volcanics.

- The depth solutions along this line show the basin outlined quite clearly at depths ranging from 200 metres at the eastern end of the line to 1600 metres in the vicinity of the remnant dyke. The dyke itself is interepreted to have intruded the sediments at a later date, due to the remnant nature of the magnetic properties.

**Line 27212**

- This is the most complex line modelled. Many of the smaller dyke-like intrusions could not be modelled due to difficulty in positioning so many prisms

- Many remnant dykes occur. These can vary greatly in thickness.

- Dyke with non-remnant (i.e. normally induced) magnetic properties intrude the sedimentary sequences.

- Remnant dykes have intruded the sediment to varying heights. Some of these are above the surrounding magnetic prisms and some are below.

- Dips of the prisms vary from vertical and sub vertical to quite shallow dips for some of the groups of units. The beginning of the line from 5000 – 20000m (3378533, 7387223 – 33799753, 7387279) Show a dipping surface to the east at about 60°. Further along the line between 110000 and 135000m (3484633, 7387601 – 3512033, 7387729) The prisms that makes up that unit have dips ranging from about 65° west to about 60° to the east.

Very high susceptibility lithological block, located at the far eastern (110000m, 3484633, 7387601) end of the line; reasonable depth with no outcrop at all. These form the basement of a major sedimentary basin. This part of the line appears to be intruded by single remnant dyke (115000m, 3490608, 7387618).

- The picked Werner solutions have made a reasonably good approximation of the top surface of the magnetic (?)basement, with a few outliers in the vicinity of some of the remnant dykes.

- Depths along this line range from a shallow response of 315 metres at 88000m (3464031, 7387523) to a deep point of 1300metres at 124000m (3500496, 7387690)

## LINE 27220

- This line is made-up of shallow high susceptibility volcanics, next to shallow dipping ignimbrites. A deep dyke appears to cross cut this block but is quite deep and relatively less susceptibility than other dykes in this region. This line is made up of much larger blocks than the previously modelled lines and appears to reflect a change in the magnetic signature and the geology of the area.

- The two main features of the eastern end of the line are the very high susceptibility blocks, these are located at 106000m (3478503, 7377319) and 124000m (3495939, 7377376).

- As with the previous line the basement of the sedimentary basins have been identified using both the models and the Werner solutions. The depth solutions have provided excellent control of the basement complex. The depth ranges are a deep point of 875 metres at 102000m (3474650, 7377322) and a shallow point of 291 metres deep at 60000m (3382400, 7376987).

- One thin, normally magnetised dyke has intruded the surrounding sediment at location 77000m (3450523, 7377196)

## 6.7 EULER 3D DEPTH TO SOURCE SOLUTION MAP

The Euler 3D solution map (Map 3) comprises a series of automatic solutions for depth to magnetic sources, calculated from a gridded “window” mathematically passed over the magnetic data. The algorithm used for the solutions calculates depth based on a narrow, tabular magnetic body (the “dyke” model, or structural index = 1.0). Solutions calculated on anomalies that do not approximate this geometry (e.g. narrow pipes) are likely to represent a minimum depth solution only.

Because of the automated nature of the depth solutions, combined with the lack of rigorous geological control in the area, the map can only be a representation of approximate depth to magnetic sources, rather than a “depth to magnetic basement” solution as commonly used in geophysical analysis of deep sedimentary basins. These depth solutions should be used with caution, and with reference to local geological knowledge or valid geological models.

Several features within the depth solutions are notable for the Poona region:

- Magnetic sources in the region range from surficial to greater than 5 kms
- Shallow sources in the regions of intermontaine Quaternary valley fill commonly range in depth from approximately 100m to 700m. It is assumed here that the sources relate to Paleozoic to Tertiary sequences, and the depths provide a reasonable estimate of nonmagnetic Quaternary (and possibly Tertiary) sedimentary cover. The intermontaine valleys in the south of the region (e.g. in the Salar de Olaroz area) appear to have overall thicker nonmagnetic Quaternary cover than valleys in the north (e.g. Laguna de Pozuelas area).
- Interpreted Tertiary caldera complexes concealed beneath Laguna de Pozuelas coincide with magnetic sources in the range of 2000m or greater; these sources may relate to the originally exposed caldera complex, or to a magnetic fossil magma beneath the caldera. There are a series of similar depth solutions which lie along an ESE-WNW trend, extending for a distance of approximately 30kms from Laguna de Pozuelas.
- The majority of depth solutions associated with circular (?volcanic vent or plug) magnetic feature lie within a range of 500 – 1000m.
- A series of magnetic bodies in the range of 2500m or grater occurs in a discontinuous N-S belt extending from 7540000N 3450000E to 7460000N 3430000E. These bodies lie near the contact between the Tertiary-Paleozoic fold / thrust belt and the main volcanic arc along the western border of the Puna region; the bodies likely represent fossil magma sources for the main tertiary volcanic sequences. One cluster of solutions coinciding with Mina Pirquitas has a bimodal solution population, with a shallower set of solutions in the range of 500-1000m to the mineralised vent structure.

- The most obvious feature of the depth solutions is the dominance of deep (2500 to greater than 5000m) in the southeastern area (Salinas Grandes region), extending NNE towards the zone of thick Salta Group sediments. The majority of these deep magnetic bodies appear related to the presence of crystalline Precambrian basement as original shelf to Paleozoic sediments. However, it is unknown whether the depth solutions relate to either:

- Depth to top of magnetic Precambrian basement,

- Depth to Precambrian intrusives within the basement,

- Depth to later (?Cretaceous – Tertiary) intrusives within the basement.

- The region of interpreted greisen development and possible E-W trending dykes east of Sierra Aguilar have depth solutions in the range 1000-1500m. The validity of these solutions is ambiguous; this may represent a region of diffuse alteration, with consequent broadening and diffusion of magnetic gradients related to both depth and magnetic dispersion.

- Within the Salar de Olaroz region there is a broad (7km x 4km) ENE-WSW trending ellipse defined by a cluster of depth solutions in the range of 1500-2500m. These solutions appear to define a deep intrusive source emplaced within or near a major NNE-trending right-hand stepping inflexion within the main N-S fold-thrust belt. This intrusive may be related to the highly magnetic ultramafic plug emplaced in the north of this inflexion (see Map 2).

# 7. STRUCTURAL AND TECTONIC DEVELOPMENT

The regional tectonic setting and basement structure of northwestern Argentina is depicted in Figure 4 (after Mon and Salfity, 1995). The Puna survey area lies immediately to the east of the Precambrian Arequipa-Antofalla belt (Arequipa Craton) with its superstructure of Cenozoic volcanics. The western part of the survey area is underlain by the predominantly Ordovician Ocloyic Belt, while the eastern part of the survey area is underlain by the Precambrian Choromoro Belt (Pampean Craton), which is part of the Panamerican orogeny.

The tectonostratigraphic setting of the Puna region has recently been reviewed by Mon and Salfity (1995). Several superimposed tectonic stages have been recognised in the Andes of northwestern Argentina. In the east, the rocks of the Panamerican/Brazilian orogeny were amalgamated between 600-700 Ma (Pampean Craton). The Ocloyic Belt is a W-vergent orogenic belt consisting of upper Cambrian to Ordovician marine sediments which were deformed during the late Ordovician Ocloyic orogenic cycle. Siluro-Devonian strata in the Puna area were deformed in Late Devonian-Early Carboniferous times and were the precursor of a Gondwana depositional cycle represented by several Late Paleozoic basins which were inverted in middle Permian times (San Rafael orogeny). The Andean cycle commenced with deposition of rift basin sediments in early Cretaceous-Eocene times (Salta Group rifting). These troughs were inverted during the late Eocene and deformation continued through Miocene and Plio-Pleistocene tectonic events.

Within this framework we can consider the results of the present study. Rankin, (1996) has provided a tectonic subdivision of the Puna survey area based on aeromagnetic interpretation (Figure 5). The following paragraphs contain brief descriptions of the various lithomagnetic domains identified in the area.

## Domain 1:

This domain is located in the south-eastern corner of the study area and is predominantly composed of Precambrian sedimentary and intrusive rocks of the Pampean Craton, unconformably overlain by Cambro-Ordovician platform sediments. The zone is bounded to the west by NE-SW oriented lineaments (thrusts and faults) and to the east by NS Salta Rift faulting. Magnetic trends within the domain are dominated by NE-SW thrust faults.

## Domain 2:

Domain 2 consists of variably deformed Ordovician sedimentary and volcanic rocks. It has been broken down into a number of sub-domains, based on magnetic character and lithology:

### Subdomain 2a:

This small subdomain occurs in the SW corner of the Puna area and is characterised by NW-SE trends. It contains clastic sediments, arc volcanics and volcaniclastics of the Ordovician Coquena Formation which is located to the east of the Arequipa Craton margin.

### Subdomains 2b, 2c and 2d:

These subdomains consist predominantly of Ordovician turbidites (Coquena Formation). The turbidites are essentially non-magnetic thus internal structural observations regarding these belts are mostly from Landsat interpretation (section 4.2.1). The deformed turbidites trend N-S. Bounding faults of the belts are visible on magnetic data and are Cretaceous-Tertiary in age and reflect earlier structures.

### Subdomain 2e:

This is a 20km wide, NNE/SSW oriented belt of Ordovician turbidites, volcanic rocks and syntectonic intrusive rocks emplaced during the Ocloyic orogeny. The belt is also referred to as "FEO" (Faja Eruptiva de la Puna Oriental), and has clear NNE-SSW structural trends.

### Subdomain 2f:

This occurs in the northwest of the Puna study area and consists of Ordovician pelites, arenites and conglomerates which grade into turbidites in the west. Deformation patterns are different to the Ocloyic folding and thrusting

## Domain 3:

Domain 3 consists of Jurassic-Cretaceous intrusive rocks. Subdomains include (i) weakly or non-magnetic intrusives in the Mina Aquilar-Tusaquillas area; (ii) isolated remanently magnetised intrusives in a rift-related NW-structural corridor running from northwest of Salinas Grandes to west of Susques, possibly including alkaline intrusives, and (iii) moderately magnetic intrusives in the Laguna de Guayatayoc area

## Domain 4:

Domain 4 consists of the Salta Rift which is superimposed on Precambrian and Ordovician rocks of Domains 1 and 2. The Salta Rift contains Cretaceous-Tertiary sediments which are non-magnetic to weakly magnetic.

## Domain 5:

Cenozoic volcanism associated with the Andean orogeny has provided variably magnetic responses throughout the Puna area, which are locally very strong (basaltic/andesitic volcanics). An abundance of circular magnetic patterns indicates the importance of caldera volcanism in the area. Local structural control of Cenozoic volcanism by NE-SW and NW-SE conjugate tensional zones is apparent.

# 8. ECONOMIC GEOLOGY

The following discussion of the economic geology of the Puna survey region is not intended to be a comprehensive appraisal or summary of all the mineral deposits and previous exploration for the region (such a task is outside the scope of this study). Rather, this discussion aims to provide a few salient examples of the geophysical signature associated with some known mineralisation in the region, and draw attention to hitherto unexplored areas associated with geophysical anomalies. Positions of mines and prospects shown on the accompanying maps were taken from 1:500 000 metallogenic compilation maps supplied by SEGEMAR.

The Puna region has been explored for various minerals since the early sixteenth century, with gold prospecting by Spanish Jesuits in the Rosario de Coyaguiama area. Over the years, various commodities have been exploited, including gold associated with Ordovician sediments and Tertiary-Quaternary volcanics, base metal and silver associated with various lithologies, as well as Sn, Sb, plus various evaporitic minerals from the salinas.

The most interesting mineralisation targets with respect to the geophysical survey are:

(i) Au associated with structural traps in the Ordovician sediments

(ii) Au or Au/Cu associated with Tertiary/Quaternary volcanics

(iii) Base metal/Ag deposits associated with alteration systems within the Palaeozoic

The Ordovician sedimentary domains have produced Au at several localities in the past, and the general sedimentary and Palaeozoic tectonic setting are very similar to the Bendigo goldfields of eastern Australia. Gold is known to be associated with quartz veins in fold saddle reefs, footwall/hanging wall fault systems and large-scale thrust faults. The combined Landsat TM and geophysical data has outlined the degree of complexity of folding and faulting throughout the Palaeozoic units, and gives a regional overview of potential zones of high structural complexity likely to be associated with significant veining.

Au is also known to be in association with the volcanic units throughout the region, in particular with resurgent dacite domes such as Pan de Azucar, Cerro Leon and Cerro Redondo. Gold is also known from other complex caldera assemblages throughout the region, and alluvial gold is commonly found near hydrothermal springs, suggesting epithermal/hydrothermal vent sources.

## Mineralisation Associated with Geophysical Signatures

The Puna region contains numerous known mineral deposits which are coincident with, or adjacent to geophysical anomalies within the magnetic and/or radiometric data. Two salient examples are:

## Minas Pirquitas

A Sn-Ag deposit within altered Palaeozoic sedimentary rocks. The mine is directly coincident with a strong, diffuse (deep source) magnetic anomaly. This anomaly is likely a subvolcanic intrusive or fluid vent structure, which has sourced the mineralising fluids responsible for the deposit. The mine is also associated with surrounding K-radiometric high anomalies (coincident potassium alteration). It should be noted that the Landsat imagery of the region shows anomalous circular bedding/fracture trends around the area of the deposit.

## Minas Chinchillas (Pb-Zn)

An explosive dacite pyroclastic vent emplaced within Palaeozoic sediments along NW-SE faults close to major NNE-SSW faults (see Coira & Perez (1996). The vent is associated with an obvious diffuse strong negatively magnetic anomaly. The anomaly may represent either the original intrusive root to the vent, or a fluid alteration system associated with mineralisation.

The reader is referred to Chernicoff *et al*, 1996 for further examples from the Puna Region.

# 9. CONCLUSIONS

Integrated interpretation of imaged airborne geophysical data and satellite image data has been used to investigate the lithology and structure of the 36,000km² Puna survey region of northwestern Argentina. Due to the regional nature of the survey (spacing 1 km line separation), the airborne geophysical data are not suitable for detailed lithostructural interpretation. We have consequently made extensive use of high-quality photographic Landsat TM imagery to investigate the internal stratigraphy and structure of the outcropping geological units of the Puna region. The aeromagnetic and airborne radiometric data are, however, very useful in defining the major lithostructural domains which make up the complex Puna region, which has undergone repeated collision, shortening, extension and arc volcanism from Neoproterozoic to Cenozoic times.

Landsat TM interpretation at 1:250,000 scale is reported as a separate set of maps. The Landsat data proved indispensable in the acquisition of detailed internal structural information, and were interpreted in the form of RGB = 741 photographic hardcopy images. Photogeological interpretation of the Landsat images assisted in the mapping of (i) Neoproterozoic-Paleozoic rocks in the SE of the Puna area; (ii) Ordovician Ocloyic foldbelt; (iii) Cretaceous granitic intrusives related to the Salta Rift; (iv) internal stratigraphy of the Salta Rift; (v) undifferentiated Tertiary sediments; (vi) Miocene-Pliocene Andean volcanics and (vii) Quaternary sediments including extensive salars.

Aeromagnetic/radiometric interpretation is reported as a set of 1:250,000 scale "solid geology" maps, and has been particularly useful in identifying major meridianal fault systems that separate the component tectonostratigraphic terrains of the Puna area. These include the (i) the south-eastern Precambrian block (Pampean Craton and Paleozoic cover) where deep-sourced magnetic anomalies may indicate intrusive bodies or magnetic lithostratigraphy; (ii) at least 6 of discrete volcanic and turbidite hosted sub-domains in the generally non-magnetic Ordovician Ocloyic orogen, separated by recognisable sutures; (iii) mappable Cretaceous granitoids associated with the inception of the Salta Rift, and (iv) strongly magnetic signatures of caldera volcanics formed during Andean (Tertiary-Quaternary) magmatic arc activity.

Numerous small aeromagnetic and radiometric anomalies found during the study may be indicators of mineralisation. Recognisable geophysical signatures are associated with mineral deposits such as the Mina Pirquitas (Sn/Ag) and Mina Chinchillas (Pb/Zn).

# 10. REFERENCES CITED

Bahlburg, H., 1990. The Ordovician basin in the Puna of NW Argentina and N Chile: geodynamic evolution from back-arc to foreland basin. *Geotekt. Forsch., 75, 1-107.*

Bahlburg, H., Breitkreuz, C., Maletz, J., Moya, M.C. and Salfity, J.A., 1990. The Ordovician sedimentary rocks in northern Puna of Argentina and Chile: new stratigraphical data based on graptolites. *News. Stratigr., 23, 69-89.*

Clark, D.A., 1997. Magnetic petrophysics and magnetic petrology: aids to geological interpretation of magnetic surveys. *AGSO J. Aust. Geol. Geophys., 17, 83-104.*

Chernicoff, C.J., Garea, G., Hongn, F., Seggario, R., Zappettini, E., Coira, B., Caffe, P., Chayle, W., Gutierrez, G., Perez, A., Soler, M. and Rankin, L., 1996. Interpretacion geologica del relevamiento aeromagnetico de la Puna septentrional, Jujuy y Salta. *Servicio Geologico Nacional, Ser. Contrib. Geofisica, 1, 46pp.*

Coira, B., 1979. Descripion geologica de la Hoja 3c, Abra Pampa, Prov. de Jujuy. *Servicio Geologico Nacional, Boletin 170.*

Coira, B., Davidson, J., Mpodozis, C. & Ramos, V., 1982. Tectonic and magmatic evolution of the Andes of northern Argentina and Chile. *Earth Sience Review 18, 303-322.*

Coira, B., Kay, S.M. and Viramonte, J., 1993. Upper Cenozoic magmatic evolution of the Argentine Puna-a model for changing subduction geometry. *Int. Geol. Rev., 35, 677-720.*

Direccion General de Fabricaciones Militares. Geologia de la Region Noroeste, scale 1:400,000.

Milligan, P.R. and Gunn, P.J., 1997. Enhancement and presentation of airborne geophysical data. *AGSO J. Aust. Geol. Geophys., 17, 63-75.*

Mon, R. and Salfity, J.A., 1995. Tectonic evolution of the Andes of northern Argentina. *In: A.J. Tankard, et al., eds., Petroleum Basins of South America. AAPG Mem., 62, 269-283.*

Nash, C.R., Rankin, L.R., Leeming, P.M. and Harris, L.B., 1996. Delineation of lithostructural domains in northern Orissa (India) from Landsat Thematic Imagery imagery. *Tectonophysics, 260, 245-257.*

Nash, C.R., (in prep). Geological interpretation of Landsat TM and airborne geophysical data over the Precordillera (San Juan-La Rioja) area, northwestern Argentina. *Unpubl. Rep., World Geoscience Corporation*

Rankin, L.R., 1996. Unidades tectonicas identificadas en el mapa aeromagnetico de la Puna Septentrional. *In* Chernicoff, C.J., Garea, G., Hongn, F., Seggario, R., Zappettini, E., Coira, B., Caffe, P., Chayle, W., Gutierrez, G., Perez, A., Soler, M. and Rankin, L., 1996. Interpretacion geologica del relevamiento aeromagnetico de la Puna septentrional, Jujuy y Salta. *Servicio Geologico Nacional, Ser. Contrib. Geofisica, 1, 2-7.*

Reid, A.B., Allsopp, J.M., Granser, H., Millett, A.J. and Somerton, I.W., 1990. Magnetic interpretations in three dimensions using Euler deconvolution. *Geophysics, 55, 80-91,*

Schwab, K., 1980a. Hoja 5b, Salar de Cauchari. *Servicio Geologico Nacional*

Schwab, K., 1980b. Hoja 5a, Paso Huaitiquina. *Servicio Geologico Nacional*

SEGEMAR, 1996. *Mapa geologico de la Provincia de Jujuy, Republica Argentina.* 1:500 000 scale.

Turner, J.C.M., 1965a. Hoja 1ab, Santa Catalina, Prov. de Jujuy. *Servicio Geologico Nacional*

Turner, J.C.M., 1965b. Hoja 2b, La Quica. *Servicio Geologico Nacional*.

Turner, J.C.M., 1967. Hoja 2a, San Juan de Oro. *Servicio Geologico Nacional*

Turner, J.C.M., 1982. Descripcion geologica de la Hoja 3ab, Mina Pirquitas, Prov. de Jujuy. *Servicio Geologico Nacional, Boletin 187*

Zappetini, E., 1989. Geologia y metalogenesis de la region comprendida entre las localities de Santa Ana y Cobres, Provincias de Jujuy y Salta, Republica Argentina. *Tesis Doctoral, Univ. de Buenos Aires.*

# APPENDIX

FIELD NOTES WITH MAGNETIC SUSCEPTIBILITY
MEASUREMENTS