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Thematic Mapper studies of Andean volcanoes

Six monthly report

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1. STATUS OF DATA AQUISITION

A total of 51 quads of day time TM data were included in the original proposal. Three full night scenes were also requested on an experimental basis, with others to be acquired if the experimental scenes were successful. 18 of the day time scenes requested have been received to date, mostly covering the southern part of the area under investigation.

2. QUALITY OF THE DATA

For the most part, the quality of the data received has been outstandingly good, and its enormous potential for advancing knowledge of Andean volcanoes is already obvious. Some scenes have much more snow than is desirable. The original plan had been to inspect photographic products of each scene for snow and cloud cover before obtaining the CCT, but because of

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pressures arising from Landsat commercialization, we were encouraged to accept whatever data was available. The problems raised by commercialization are addressed in a later section.

Technically, the only serious defect found in the TM data is the well known coarse striping thought to be due to sensor memory effects. This has proved to be a problem in one band (7) in one scene, and has particularly unfortunate consequences when carrying out band ratioing and other processes. In other scenes, band 7 shows no striping effects, although there are similar variations between very bright playa lake surfaces and lavas closely juxtaposed. There are also a few defective lines and pixels in the data, but these are relatively trivial.

### 3. RESULTS TO DATE

Only rather general comments are possible here because the research is still in its early stages. Only a small part of the data has been received and only a small proportion of the data received has been analysed in detail.

#### 3.1 Identifying active volcanoes

The primary objective of the research project is to identify all the "active" volcanoes in the region, and publish a catalog with image data, maps and structural data. According to the IAVCEI compilation of post-Miocene volcanoes of the world, there are approximately 300 named volcanoes in the region between  $16^{\circ}$  and  $29^{\circ}$  S. (For some reason this compilation did not include north-west Argentina). Most of these are large, easily recognisable structures, but little is known about them other than their names, approximate

heights and locations. There are innumerable other smaller and more obscure structures unlisted. Deciding which of these hundreds of volcanoes should be regarded as "active" is not easy. An "active" volcano is conventionally accepted as being one that has been active within historic time, although many of the most lethal eruptions in history have taken place on volcanoes thought to be extinct. A better definition includes volcanoes that have been active in post-glacial times, roughly the last 10-12,000 years. This is a relatively straightforward criterion to apply to the many large, ~ 6,000m high cones in the Central Andes, because although the region is extremely arid at present, during glacial times ice sheets extended down to about 4,000m and left moraine deposits that are easily recognisable on TM (Thematic Mapper) imagery. Problems arise with the smaller volcanoes, however, particularly those on the western flanks of the principal cordillera. Here, precipitation rates are so small that erosion is extremely slow, and volcanic features which appear very fresh may have ages measured in the range of hundreds of thousands of years. Our preliminary studies suggest, however that there may be 50-60 major volcanoes that should be regarded as active.

In this part of the research, it is the TM's excellent spatial resolution that is most valuable so far. In the case of Tata Sabaya volcano, Bolivia, for example, MSS data suggested the possible presence of a major debris avalanche deposit extending into the Salar de Coipasa, whereas in the TM imagery not only is the distinctive hummocky topography of the debris avalanche unequivocally recognizable, but the 'tide mark' left by the flow on the flanks of a neighbouring older cone is also clear. Other morphological features that the TM data have made accessible to study include details of marginal levees on lava and pyroclastic flows, and summit crater structure. Valley glacier moraine

deposits, not easily identifiable on MSS data, are also unambiguous, and provide useful 'marker horizons' on large volcanic edifices which were built up in pre-glacial times but which have been active subsequently. With such high resolution imagery, it is not only possible to identify potentially "active" volcanoes, but also to use standard photo-geological interpretation to outline the history of individual volcanos.

### 3.2 Large volcanic debris avalanche deposits

The 1980 eruption of Mt St Helens focussed attention on volcanic eruptions in which large scale collapse of part of the volcanic edifice is a key factor. Many other examples have come to light in different parts of the world since 1980, and we have made a special search for examples in the Central Andes. In temperate regions, the hummocky terrain that characterises the surface of an avalanche deposit quickly becomes masked by soil and vegetation, and all surface expression of it may be lost in only a few thousand years. The high, arid conditions in the Andes are particularly favorable for the preservation of such fragile surface features. There are also some grounds for thinking that major collapse events may be more common in the Central Andes than elsewhere, because lavas of dacitic composition are so common. Effusion of viscous dacite from vents high on the volcano produces cones with extremely steep profiles, (over  $45^{\circ}$ ); ideal candidates for collapse. We have been able to identify about a dozen debris avalanche deposits on the TM imagery to date, and expect to find many more. Some of these were known previously or are quite unambiguous on the imagery -such as the Tata Sabaya deposit- but others are more equivocal, and require field checking.

One of the most impressive debris avalanches, which has not been described before, is on the eastern slopes of the Lullillaco volcano, straddling the Chile/Argentina border. This volcano, 6723 m high, is one of the highest in the world, but has been little studied. TM data shows that a great pre-historic debris avalanche cascaded down the eastern flanks of the volcano into Argentina; swept hundreds of metres up and passed around both sides of, an older, 1,000m high cone, leaving a distinct "tide mark", and travelled 25 km before coming to rest in a small playa lake. This deposit has the hummocky terrain characteristic of debris avalanche deposits. It was subsequently partially covered by two other younger debris deposits. These were probably more like volcanic mudflows (lahars) than the first, since they are thinner and their surface textures are much finer. There is no evidence of a major collapse amphitheater left by the emplacement of the large debris avalanche; this has presumably been 'healed' by younger volcanic activity. Interestingly, the small cone partially buried by the avalanche itself has a well defined collapse amphitheater on its eastern flank, and an eroded debris avalanche deposit.

### 3.3 Spectral characteristics

Extracting the compositions of lava and pyroclastic flows from TM data depends more on variations in albedo than spectral signature. Experiments both with radiometers in the field and with the image data show that the chief difference between flows of basaltic through rhyolitic composition is an increase in reflectivity in all bands. Young basaltic or basaltic andesite flows are almost completely black; albedo increases with increasing silica content, so that young rhyolitic ashes have albedos approaching those of snow. Superimposed on this simple relationship are two other factors: age and the

effects of iron oxidation.

As a lava flow ages, it is subject to both weathering and to cover by wind blown dust. Both of these lead to an increase in albedo, sometimes dramatic when the flow is downwind of a source of bright dust, such as a gypsum-covered playa lake. Thus, the albedos of flows tend to converge with increasing age towards the albedo of the surrounding terrain. Vegetation cover can also cause progressive changes in lava albedo, but this is not an important factor in much of the Atacama desert region. Lavas of all compositions may exhibit the effects of iron oxidation, though this is most striking in flows of basaltic to intermediate composition. This may take place on weathering, or when fumarolic or magmatic steam exhaled from the magma converts iron bearing minerals in lavas to hydrous iron oxides such as limonite or goethite. Basaltic or andesitic lavas which have been affected can be distinguished by eye in the field through their rusty reddish color, but in TM images they are unmistakable, since the reflectivity of the oxide minerals is much higher in the mid- infra red than the visible.

This characteristic has proved invaluable in a detailed study of the debris avalanche deposits of the Socompa volcano, north Chile. These deposits were emplaced as the result of a catastrophic collapse of the north-western flank of the volcano, and now cover some 500 km<sup>2</sup>. As in the case of Mt. St. Helens, the volcano did not fail in a single, simple collapse, but a number of events followed in rapid succession. The presence of a number of debris streams characterised by sharply different degrees of iron oxidation has proved critical to tracing the trajectories of materials derived from different parts of the original volcanic structure. An unusual feature of the Socompa debris

avalanche is that the collapse event involved the sub-volcanic basement, as well as the volcanic edifice itself. Underlying the volcano is a dacitic ignimbrite, which has a relatively flat spectral signature (bright in all bands), and this gave rise to other unmistakable debris streams. Individual debris streams with distinct spectral signatures can be traced for many kilometres, tracking the course of the avalanche as it rode over underlying hills, and sliding off again in a different direction.

### 3.4 Volcanic alteration products

A characteristic feature of an active volcano is persistent fumarolic activity, which may continue for hundreds or thousands of years after the last magmatic eruption. A few volcanoes, such as Guallatiri, exhibit fumaroles strong enough to form steam plumes which are visible on TM imagery, but for the most part it is the effects of long continued fumarolic activity on the surrounding rocks that are most conspicuous. Prolonged exposure of rocks to high temperature steam causes the breakdown of silicate minerals such as feldspars and the deposition of native sulphur, chert, alunite and kindred minerals. Related kinds of hydrothermal alteration, leading to the formation of clay minerals are associated with several major types of ore deposit, so the ability to detect such deposits was built in to the TM. This ability depends on the fact that clay minerals exhibit a distinctive absorption in the mid-infrared. On active volcanoes, areas of fumarolic activity tend to be quite small, and to be bright in all spectral bands. These deposits consist mostly of sulphur and other sublimate materials. Older, more deeply eroded volcanoes show evidence of extensive alteration, such that their entire cores appear to have been replaced by high albedo alteration products. The drainages around the

volcano carry this bright material long distances downstream, so an old volcanic center is easy to spot. For the most part, such dissected volcanoes have experienced only low grade alteration (quartz-alunite-native sulphur), but some large, eroded calderas show more advanced clay mineral alteration, and these are potentially good prospects for economic epithermal mineral deposits. One such site, identified initially solely from TM data, proved on subsequent enquiry to be an active gold mine.

### 3.5 Ignimbrites

Ignimbrites (pumiceous pyroclastic flows) are extremely widespread in the Central Andes, and form an essential part of the study on Andean volcanism. They present quite different problems from ordinary lava flows. Individual flows may have volumes far exceeding  $1,000 \text{ km}^3$ , and may travel over 100 km from their source caldera. Because an individual ignimbrite may be exposed over thousands of square kilometers of high altitude terrain, and cross two or three national frontiers, mapping them by conventional means presents formidable difficulties. Fortunately, the generally high albedos and distinctive erosional morphology of ignimbrites ensure that it is easy to identify them as a rock type on Landsat imagery, even on a monochrome MSS product. Problems arise, however, in attempting to distinguish between individual ignimbrite units. Andean ignimbrites are mostly dacites ( $\sim 68 \% \text{ SiO}_2$ ) and show only small variations in major and trace element chemistry. Not surprisingly, many units appear very similar both in the field and on TM imagery. Fortunately, some show significant differences in texture and spectral signature. These differences arise mostly from the most-emplacement history of the flow, which may lead to welding of the pumice clasts or to different degrees of vapor phase alteration.

Fresh ignimbrite surfaces are highly reflective, and appear white to the eye, but on weathering they acquire a reddish surface coating of iron oxides which increases their reflectivity in the mid-infrared. The extent to which their spectral properties are modified depends on the physical characteristics of the ignimbrite, such as degree of welding and grain size. These physical features also give rise to different erosional morphologies and spectral characteristics. Densely welded ignimbrites are dark, glassy resistant rocks, whereas unwelded units are lighter, friable and easily eroded by wind or water. Thus, the combination of spectral and textural characteristics offers a possible means of distinguishing some ignimbrite units from one another. This is a problem that will require considerable further work.

## 6. CONSEQUENCES OF LANDSAT COMMERCIALIZATION

The full implications of Landsat commercialization to the project are not yet clear, but they do not seem good. At worst, it has been suggested that no more TM data will be supplied than we have already received. It has also been suggested that scenes already acquired by Goddard may be made available at low cost by EOSAT. This is unlikely to be a solution for the Andean work, since new acquisitions are essential to provide coverage.

The essential element of the original proposal was that it would be a comprehensive study, covering the complete Central Andean volcanic province. Anything less than complete coverage, therefore precludes the possibility of a systematic study, and of compiling a catalog that would be of lasting value for

all Earth scientists. The quality of the TM data already received is so good that there is no question that one can do valuable science with it, but it is essential if at all possible to continue with the original research objectives. An integrated study of Andean volcanism is a real and important scientific goal, and one that can only be achieved using TM data.

A more specific problem concerns night-time thermal IR data. Apart from the commercialization issue, there are also apparently technical and scheduling problems that have made this unavaible to date, and the future prospects are also apparently not good. Because no data are available for the region, it is not certain what the full value of night time thermal IR data may be. Thus, it would be highly desirable if at least one scene could be acquired on an experimental basis, so that the full potential can be assessed.

## 7. APPENDICES

i. False color composite TM image of Socompa volcano, north Chile and catastrophic debris avalanche deposit. Bands 7 (red), 4 (green) and 2 (blue), linear stretched, 1536 x 1536 pixels. Image reveals plainly the trajectories of different debris streams in the avalanche deposit.

ii. False color composite TM image of Tata Sabaya volcano, Bolivia. Bands 4 (red), 2 (green) and 1 (blue), linear stretched; 1024 x 1024 pixels. Major debris avalanche which enters Salar de Coipasa was ambiguous on MSS data; is unequivocal on TM image.

iii. Abstract of invited paper presented at IGCP Project 120 meeting on Volcanic Evolution of the Andes, Santiago, Chile November 1985.

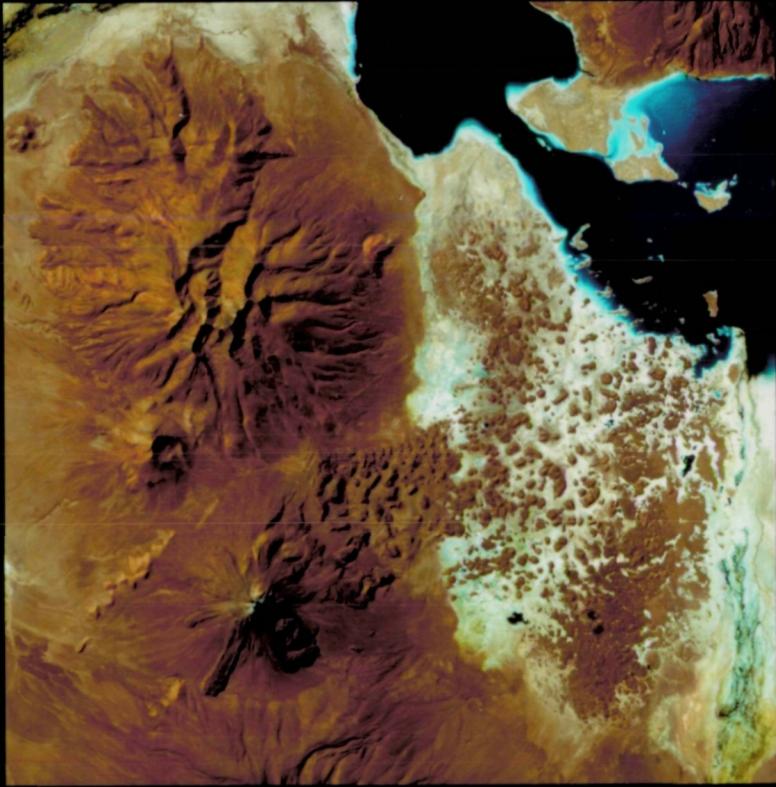


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