

Thematic Mapper Studies of Central Andean volcanoes

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## 1. STATUS OF DATA ACQUISITION

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. 36 of the day time scenes requested have been received to date, mostly covering the southern part of the area under investigation. Two night time scenes over path row 233/ 75 have been acquired in photographic form for examination, but the digital data have not yet been delivered. In addition, because of the interest in current volcanic activity at Lascar volcano, north Chile, two further

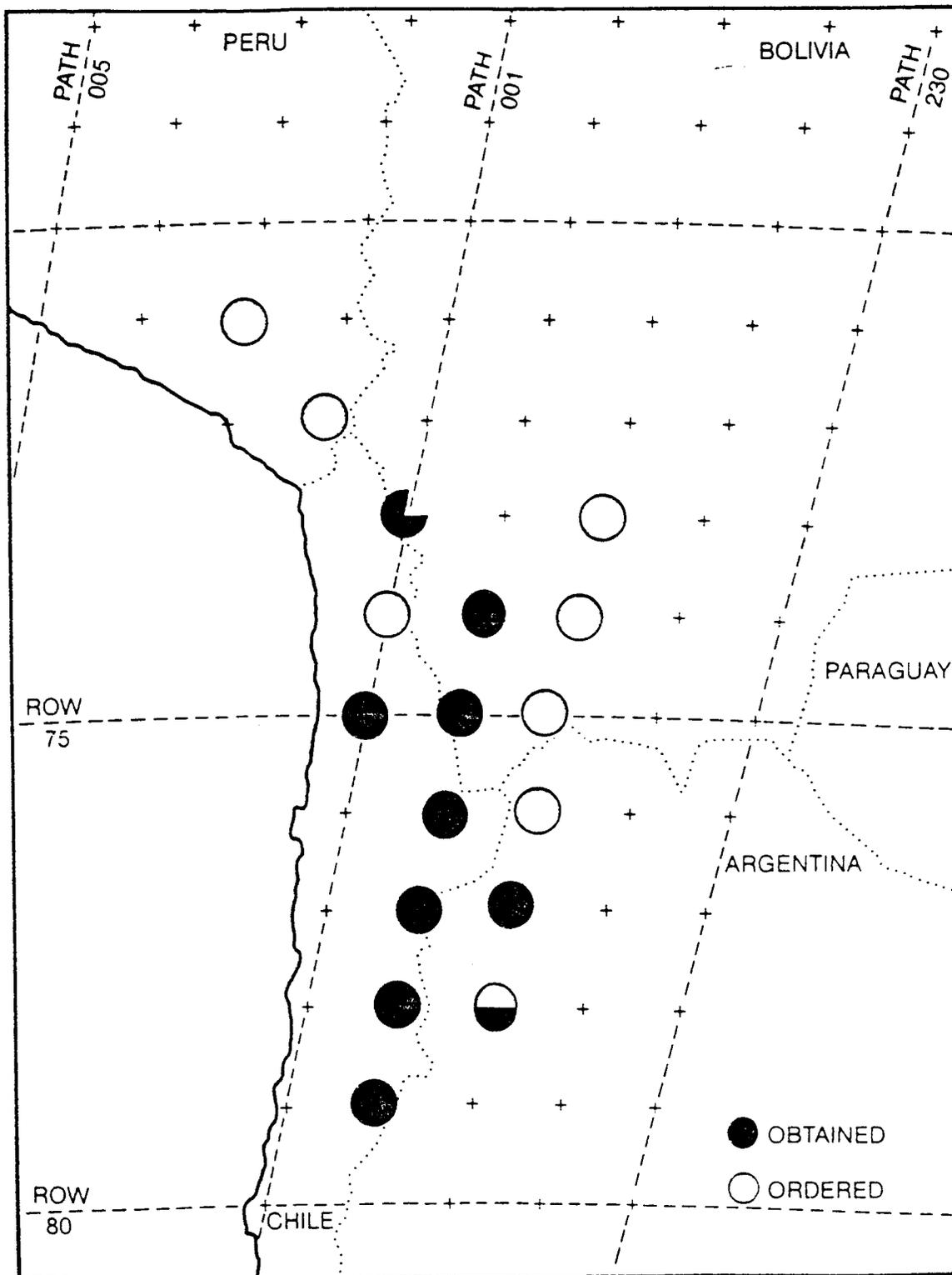


Figure 1. Locations of TM scenes already obtained, and those awaiting acquisition. 90% of the Central Andean volcanic province will ultimately be covered.

acquisitions have been made of path row 233/76, and further digital data are expected. (Figure 1).

## 2. QUALITY OF THE DATA

As described in the previous report, the quality of the data has been uniformly extremely high, and has not been a problem in the research. Care has been taken to examine photographic products first before obtaining digital data.

## 3. RESULTS TO DATE

### 3.1. Preparation of hard copy data base.

In order to provide a comprehensive and consistent data base for volcanological studies, a series of false color composite images covering the volcanic cordillera has been written to film on the Institute's Optronics film writer. Each image is 45 km square (1536 x1536 pixels) and is constructed using bands 7, 4 and 2 of the TM data. This provides a working data base on which individual volcanoes of interest can be identified. Approximately 100 images have been prepared to date.

### 3.2. Compilation of volcano data base.

A set of Landsat MSS images was used in conjunction with the TM hardcopy images to compile a computer data base of all volcanic structures in the Central Andean province. Over 500 individual volcanic structures were

identified, ranging in age from ~20 my to Recent not including numerous small, monogenetic scoria cones and lava flows. About 75 major volcanoes were identified as "active", or potentially active. Many of these are extremely large composite cones reaching over 6,000 m in altitude. Only fourteen of these were previously known and listed in the 'Catalogue of Active Volcanoes of the World', (Casertano, 1963) but the remainder (about 80%) were not. In principle, an "active" volcano is usually taken as one that may erupt in the future. In practice, the criterion we have is evidence of eruptive activity in post-glacial times, roughly the last 10,000 yr. Glacial moraines are well developed on Central Andean volcanoes down to altitudes of ~ 4,300m (Hollingworth and Guest 1967). Fortunately, the resolution of the TM data is sufficiently good that moraines are clearly identifiable where present. Thus, moraines provide an excellent and consistent stratigraphic marker for most of the study area. The southernmost part of the region (lats. 26- 29<sup>0</sup>S) is exceptionally arid at the present day, and appears to have been so during glacial times also. Moraines are difficult to identify in this area, and thus in this area the best criterion of activity we have used is simply morphologic youthfulness.

A serious problem arises in dealing with the very largest volcanic systems, especially resurgent silicic calderas. These may have very long repose times, perhaps in excess of 1 million years. Given the number of large calderas that exist, criteria for recognising those that are potentially active are urgently required. We hope that the Andean study will provide some important guidelines in dealing with this problem.

### 3.3 Identification of large volcanic debris avalanche deposits.

The eruption of Mount St. Helens on May 18, 1980 focussed the attention of volcanologists on this distinctive mode of eruption, in which catastrophic gravitational failure of a large segment of the volcanic edifice produces a huge avalanche, while the concomitant sudden depressurisation of the volcano's interior triggers a violent explosive blast (Lipman and Mullineaux, 1982). Many other examples of this phenomenon have been identified around the world since 1980. This work has been reviewed by Siebert (1984) and by Siebert et al. (in press). One of the most outstanding examples was identified in Chile at the western foot of the Socompa volcano (Francis et al, 1985, Rothery and Francis., Self and Francis 1986). Debris from this avalanche covers some 500 km<sup>2</sup> of the Atacama desert. TM images have been invaluable in field studies of Socompa because of their high resolution and spectral discrimination. In particular, the TM allows distinction between debris streams with subtly different contents of iron oxide minerals (mostly goethite), such that the trajectories of individual components of the original volcanic edifice can be traced in the debris avalanche deposit.

Since work on Socompa began, we have identified many other major debris avalanche deposits on TM imagery. Their properties are summarised in Table 1. Of these, only Socompa has so far been studied closely in the field. Parinacota has been visited on a reconnaissance basis, and studied in the field by a collaborating group (R.S. Harmon et al., Southern Methodist University, Dallas). The others have been studied only on TM images, and require field investigations to provide 'ground truth', but some conclusions can already be drawn (e.g. Francis and Ramirez, 1985). Because of the generally exceptionally arid environment, the Central Andes provides a unique opportunity to study this

CHARACTERISTICS OF PREVIOUSLY UNDESCRIBED ANDEAN VOLCANIC DEBRIS AVALANCHES

Volcano	Lat. Long.	Summit Height (m) <sup>a</sup>	Max. summit slope (°) <sup>b</sup>	Vert. descent [H](m) <sup>2</sup>	Horiz. run out [L] km	H/L	Area (km <sup>2</sup> )	Azimuth (°)
Parinacota	18°10'S, 69°08'W	6348	35	1900	23	0.08	156	253
Tata Sabaya	19°08'S, 68°31'W	5430	35	1730	25	0.07	331	166
Titivilla	19°43'S, 68°11'W	5050	30	1350	20	0.07	189	68
San Pedro	19°53'S, 68°23'W	6145	45	2845	16 <sup>d</sup>	0.18	118	275
Napa	20°31'S, 68°40'W	5170	21	1450	16	0.09	139	109
Aucanquilcha	21°13'S, 68°28'W	6176	25	2100	17	0.12	59	311
Ollague	21°18'S, 68°11'W	5863	35	2171	16	0.14	113	286
-	22°37'S, 68°01'W	4986	e	-500	3	0.17	5	216
Socompa	24°25'S, 68°15'W	6051	35	3020	37	0.08	606	324
Lullaillaco	24°43'S, 68°33'W	6723	-36	2500	25	0.1	197	114
Rosado	24°46'S, 68°24'W	~5100	e	~960	6	0.16	10	96
Lastarria	25°10'S, 68°31'W	5700	e	1200	9	0.13	18	105

a Summit altitudes given are those of the present volcanoes; the height of the volcanoes at time of collapse was probably different.

b Maximum slopes for the uppermost 500m were measured from topographic maps. They may not be representative of volcano slopes at the time of collapse.

c Vertical height descended assumes present summit height.

d Distal margin has been eroded.

e Detailed topographic information not available.

important phenomenon. Deposits which are rapidly obliterated in temperate environments such as those of Indonesia or Mexico are perfectly preserved.  $^{14}\text{C}$  dates on Socompa, for example, show that the deposit is ~7,000 yr old, yet the morphology of the distal parts is such that it appears pristine.

#### 3.4. Integration of TM with other remotely sensed data sets

The availability in recent years of several new remote sensing techniques have made it worthwhile to explore means whereby the best features of each technique can be extracted and combined with others to maximise the geological knowledge of an area. This seems to be inevitably the direction of future remote sensing research, especially in the 'Space Station Era', when many different kinds of data will be available. Data sets that we have used in a preliminary way include Hasselblad and Large Format Camera photography from the Space Shuttle; Shuttle Imaging Radar and MOMS -01 (Modular Optoelectronic Multispectral Scanner) images. Shuttle photography was obtained over the Socompa test site on several occasions. With the 250 mm lens, the resolution obtained is comparable to that of TM, but its chief advantages for geological interpretation lie in the flexibility of illumination and viewpoint: the Shuttle is not locked in to a sun-synchronous orbit, and photographs obtained in late afternoon or early evening revealed some very important textural features in the secondary deposits of the Socompa avalanche. A further very important asset of the Shuttle photography is the stereo cover; in this regard it forms a valuable complement to the TM images, on which it can often be difficult to interpret slopes.

We have also begun pilot studies combining SIR data with TM for a test

area in north Chile and Bolivia (Cerro Quemado volcano). Although interesting, these data are difficult to interpret at present, because of uncertainties of what the radar signal is responding to. Field work to obtain ground truth is required, but even this may not resolve all the uncertainties - in the test area, some areas covered by young ash deposits appear bright in the radar image; others appear dark. The moisture content of the ash is suspected to be responsible for variations in the returned signal, and this is a factor that is difficult to quantify.

The MOMS-01 was the first high resolution pushbroom device to be used for remote sensing from Earth orbit (Bodechtel et al, 1984, 1985). It was flown experimentally on STS 7 and STS 11 in June 1983 and February 1984. The system has two spectral bands (600 and 900  $\mu\text{m}$ ) and a pixel size of 20m. Coverage of the Socompa test site was obtained on STS 11. Initially, it was anticipated that the higher resolution of the MOMs would offer additional opportunities for textural and structural interpretations of the debris deposit, and that the spectral capabilities would not offer any advantage over the TM. Unfortunately, the optics of the MOMS system turned out to be poorly focussed, and the effective resolution no better than TM. MOMS data proved to be useful in one respect, however: the Socompa orbital pass took place in late afternoon, with a solar elevation of only  $25^{\circ}$ . The low, westerly illumination emphasised and revealed a number of subtle topographic features. By combining the spectral information contained in the TM with textural information from the MOMS, we were able to create images with a potential for interpretation significantly enhanced over either system alone (Rothery and Francis, in press).

The Socompa test area was also been selected as one of the sites for

the preliminary series of PEPS experiments for the French SPOT satellite, in a collaborative project with D. Rothery, Open University, United Kingdom. Our data arrived in the same week that this report was prepared, so no definitive conclusions are possible. However, from preliminary studies it appears that the spectral capabilities of the SPOT system offer no advantage over the TM. The enhanced resolution will certainly prove valuable for some applications, but much the most important advantage will be the stereo facility offered. This has already led to some revised interpretations of the Socompa morphotectonic setting.

### 3.5. Applications of TM data to studies of volcanic thermal anomalies

From the outset of our TM project, it was planned to attempt to use the thermal band to identify and characterise thermal anomalies associated with volcanic phenomena. Given the ambiguities that can arise from the effects of differential solar heating on day time TM data, a special request was made for night scenes to be acquired to minimise these complications, although unfortunately the timing of the night overpass is too early to be ideal (Watson, 1971). The night time scenes have not yet been acquired, but are expected soon. In the meanwhile, a careful search was made with the day time thermal data for evidence of thermal anomalies associated with sites of fumarolic activity on known active volcanoes. Several of the listed 'active' volcanoes have continuously active fumaroles, and a few have steam plumes sufficiently large to be observable at large distances on the ground (~100km), and to be identifiable on the TM imagery (e.g. Guallatiri, north Chile). With one exception, none of these volcanoes exhibits a significant thermal anomaly, and therefore can be regarded as quiescent.

The single exception is Lascar volcano, north Chile, a 5,145 m high volcano located east of the Salar de Atacama. This volcano has a complex summit area of six nested craters, the largest about 1 km in diameter and 200 m deep. Located in a deep pit crater at the centre of the complex is a small (<200m) but intense thermal anomaly, sufficiently intense that it radiates not only in the thermal infrared (band 6) but also in mid-infrared bands 7 and 5. This anomaly has been observed on scenes acquired on two separate occasions, March and July 1985. Temperature calculations in bands 7 and 5 give values of 300-400<sup>o</sup>, but these may not accurately reflect the actual temperature of the hot body, because of the likelihood that it is observed through a drifting veil of steam or vapor. (Francis and Rothery, submitted). The following volcanic phenomena may account for the observed thermal anomaly:

1. A lava lake in a deep pit crater, with a solid or semi-solid crust (cf Erebus, Antarctica; Giggenbach, et al 1973; Kyle, 1986).
2. An extrusive dacite lava dome, with a relatively cool, fractured surface and a hotter interior (cf Mt St Helens; Lipman and Mullineaux, 1982).
3. An area of strong fumarolic activity, heated by superheated steam or gas escaping at the surface, indicating the presence of hot magma at shallow depths (cf Poas, Costa Rica; Barquero 1985).

This exceptionally interesting observation is important in two regards. First, it reveals Lascar to be in an unusually 'active' condition, with the possibility that it may erupt at some point in the short term future. Lascar therefore is certainly worthy of further study and monitoring. Second, and of more general importance, it demonstrates that the TM provides a means

whereby even rather small (<100m) and rather cool (<400<sup>0</sup>C) volcanic manifestations can be confidently identified. The TM thus represents a powerful new tool for the monitoring of active or potentially active volcanoes, especially in remote or inaccessible regions.



Landsat Thematic Mapper (Band 5) image of Lascar volcano, north Chile. Image is 15 km across. Thermal anomaly is white spot at center of summit crater complex. Measured temperatures are approximately 360°C. Image acquired March 1985

ORIGINAL PAGE IS  
OF POOR QUALITY

MARCH 16, 1985

			356	350	336
303	304		>381	372	342
304	317		367	377	
				317	

Band 5

JULY 21, 1985

	195	222			
		300	331	288	
265	282	367	360	222	
	343	345	337	298	

Band 5

		203	246	240	
	211	244	>270	>270	241
226	251	>268	>268	>268	247
221	263	265	>267	>267	234
	235	234	257	260	214
				198	

Band 7

	183	210	188		
148		243	274	211	
	194	234	276	275	221
	214	248	>279	276	211
		226	240	245	220

Band 7

Temperatures derived from Landsat Thematic Mapper for Lascar volcano, north Chile, thermal anomaly, bands 5 and 7, March and July 1985

Publications arising from this work in the last six months:

Francis, P.W. and Rothery, D.A.; Using the Landsat Thematic Mapper to detect and monitor active volcanoes: an example from Lascar volcano, north Chile. Geology; submitted

Rothery, D.A. and Francis, P.W. Synergistic use of MOMs 01 and Landsat TM data; Remote Sensing Letters, in press

Allmendinger, R.W.; Eremchuk, J.E. Sosa Gomez, J; Ojeda, J. and Francis P.W. The Pasto Ventura pull-apart and the southward collapse of the southern Puna plateau, Geology , submitted.

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