

Mountain Building Processes in the Central Andes
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INTRODUCTION

During the first six month period we received about 25% of the requested Landsat Thematic Mapper (TM) coverage of the central Andes, and during that period developed the necessary software to access the data. During the past six month period we have made substantial progress on the first phase of the project. This first phase includes a visual reconnaissance of the imagery to determine the most profitable lines of attack on the fundamental problems of our research. The TM imagery, with its increased spatial resolution and spectral breadth compared to MSS imagery, is giving us exciting and provocative new views of Andean morphology and geology. The visual reconnaissance phase is an extremely important one in which we seek the most effective means to exploit the new data in a way that will have the most significant impact on our understanding of the tectonic and magmatic processes that form the Andes.

Our primary approach has been to examine false color composite images of TM bands 5, 4, and 2 in order to make visual interpretations of geological features. The use of the "roam" mode of image display with our International Imaging Systems (IIS) System 600 image processing package running on our IIS Model 75 has been very useful in this process. Several areas in which good comparisons with ground data have been examined in detail. Examination of image data in conjunction with available geologic ground information facilitates the recognition of such features as recent and ancient faults and folds, young basalt and andesite flows, ash-flow tuffs (ignimbrites), stratovolcanos with varying degrees of erosion, drainage patterns, Pleistocene snowlines and glacial cirques, and various sedimentary rock formations, all of which can be used to constrain the timing and nature of uplift and crustal deformation in the Andes.

Parallel to the visual approach, we are developing image processing methods which allow the complete use of the seven TM bands. We are experimenting with computerized lithologic mapping, and with image enhancement techniques that make possible the observation of finer structural and geomorphic details.

Much of the effort during the first six months was devoted to the organization of the data into easily accessible files and a visual cataloging of the quads (quarter TM scenes) with preliminary registration with the best available charts for the region. In the process, we have performed a quick visual reconnaissance of the imagery that we have received so far. During this first look at the data, and in more detailed studies that have begun, several general points have emerged, as summarized below:

1. Human interpretation of the imagery will continue to be a crucial part of the analysis.
2. The outstanding first-order "signal" is the geomorphic character of the surface, and we have been stimulated to direct a significant part of the future effort of this project towards innovative ways analysing this geomorphic signal. The present

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topography has been produced by the interaction of tectonics, volcanism, and Quaternary climatic variations, and can only be understood if all the phenomena are studied in an integrated fashion. In this respect the combination of disciplines represented in the Cornell Andes Project has proved to be extremely valuable.

3. Structure and stratigraphy is difficult to interpret without field control; the primary use of TM appears to be as an extremely valuable guide to field work (for navigation where there are no adequate maps, for base maps, to select key localities to examine, etc) and as a means to extrapolate interpretations to inaccessible areas by comparison with known areas. "Spectral stratigraphy" looks like a promising avenue of work.

4. Although systematic mapping of compressional structures is difficult without proper ground control, young (Quaternary) normal and strike-slip faults are clearly evident and can be accurately mapped on a synoptic basis. The spatial distribution of these features on the Puna-Altiplano plateau is a critical unknown in constructing models of the uplift of Andes. Folded sedimentary rocks can be detected, but determining the ages of the rocks and their deformation requires field control.

ORGANIZATION OF DATA

During the first six month period covered in this report we received 75 of the requested 300 quad coverage of the central Andes. We have developed a system to reorganize and archive the data to maximize its accessibility on our VAX/IIS system and to minimize usage of the tapes sent to us from EROS and EOSAT. On the original tapes, the data are organized into separate files for each of the seven bands of TM imagery, plus a number of information files. We reorganize the seven-band files into several files that can be directly accessed by the IIS System 600 software, and that are useful for different types of investigations.

For visual inspection of the data, we have found color composites of TM bands 5, 4, and 2 to be the most generally informative. We therefore create for each quad two three-band files using bands 5,4 and 2. One file is sub-sampled by a factor of 7 so that the entire quad fits onto the display monitor. The sub-sampling is done by an averaging procedure to produce a clear image. The second three-band image is created without sub-sampling, but can be very easily viewed with the "virtual roam" function of the IIS System 600 software. A full resolution view of a 512x512 pixel portion of the quad is displayed on the monitor (with contrast enhancement if desired). This window can be moved continuously over the quad by the track-ball and can be zoomed. The location of any point within the full quad is also easily obtained while in roam mode. The ability of a viewer to roam very simply anywhere within a quad at full resolution in contrast-enhanced color is vital tool for our reconnaissance work.

The third data file is the full seven-band image, suitable for more detailed analyses of the images. A seven-band image subsampled by a factor of 7 with averaging is also created. The four image data files, plus the associated supplementary, ancillary, and processing information files, are all copied in VAX/VMS Backup mode onto a single tape for each quad. In this way, one or more of the files can be very quickly loaded into disk memory and accessed by the IIS system. For reconnaissance and other primarily visual analyses the two three-band files are rapidly and conveniently available, and take relatively little disk space, while the full seven band image is readily available when needed to examine different band combinations or other spectral aspects.

The TM band 5, 4, 2 composite subaveraged images are each registered to the 1:1,000,000 Operational Navigation Charts (ONC Series) of the Defense Mapping Agency, which are the best available maps with broad, multinational coverage of the area. An 8"x10" color photograph is taken of each of these images with lines of latitude and longitude superimposed. The photographs

are then catalogued together with a copy of the corresponding part of the topographic chart and other information about the quadrant, such as the acquisition date. The catalogue has proved to be a valuable tool for the rapid scanning of quads for a specific investigation.

PRELIMINARY RESULTS

Study of volcanic rocks.

Cenozoic volcanic rocks have been studied in detail on several quadrants from scenes in the Southern Puna. Quadrants 3 and 4 of scene E-50115-13535 (path 232 row 78), show abundant lava flows, cinder cones and ash-flow tuffs. Distinctive reflectance spectra in conjunction with specific morphologies allow the discrimination of several volcanic rock types (Fielding, 1985). Figure 1 shows the spectral reflectance curves of basalt/andesite and ignimbrite, as well as curves for salars, Quaternary alluvium and vegetation, which also can be distinguished on this basis.

The relatively low reflectance in the infra-red and visible wavelengths of recent andesite and basalt flows make them stand out as dark grey to black in composite false-color images of bands 5, 4 and 2. Several of the flows visible in this scene were reconnoitered in the field in November 1985 by E. Fielding. The reflectance of the basalt (or basaltic andesite) flows appears to be related to the extent of erosion, weathering, or degree of covering by wind-blown sand, which in turn can give an approximation of relative age of the flows. The extent of erosion at flow boundaries also constrains relative age, as do stratigraphic relations (superposition) between volcanic units. Ash-flow tuffs, or ignimbrites, generally stand out as easily recognizable features due to both form and reflectance. These units are usually relatively high in silica and low in iron, giving them greater reflectance in the visible and near infra-red than most volcanic rocks. Ignimbrites that are richer in iron may be dark-colored like the less viscous flow units but can be distinguished by their morphology.

Initial studies have also been undertaken in scene 50298-14015, quadrants 3 and 4 (path 233 row 78). A subset of quadrant 3 was mapped in detail by an Argentine geologist associated with the Cornell Andes Project and included major element geochemistry and several radiometric dates. TM-based maps have been made of the same area, allowing correlation and comparison of field lithologic and constructional units with the TM images. The presence of several dated stratovolcanos and ignimbrite flows of various ages that are identifiable on the TM images has permitted us to begin calibrating the relationship between age and visual appearance of volcanic units.

Discrimination of volcanic units by supervised multispectral classification schemes has also been explored, using a target area within the scene 50298-14015. Pre-classification image enhancement was first carried out by a combination of contrast stretching and thresholding in order to improve visual interpretability. Various band combinations and ratios were then tested to optimize the application of the supervised maximum likelihood classification. Several training sites for supervised classification were selected from the image in which superposition relationships between ash and lava flows on or adjacent to stratovolcanos can be observed.

Discrimination of volcanic rock classes depends on texture, composition, and degree of erosion and weathering of the volcanic deposits. Degree of weathering of dark volcanic flows is a function of age, and it appears that there is a correlation between age and overall reflectance (albedo) of the flows, older rocks having higher albedo. On the basis of this relationship, basaltic lava flows can each be decomposed into several relative age subclasses which correspond to mappable geologic units. Some of the older stratovolcanos in the study area are deeply eroded, with cores that are easily distinguished in certain band ratios. The unusually colored (in TM band 5,4,2 composites) areas associated with these eroded stratovolcanoes have a high value in the ratio

of bands 5 and 7, presumably caused by clay and/or carbonate mineral absorption in the mid-IR TM band 7. These anomalous areas, which are 100 km east of one of the major copper mining districts in Chile, are probably zones of intense hydrothermal alteration and possible mineralization.

The interaction between magmatism and structure, which can be seen in several areas on the TM images, is also being investigated. For example, dated igneous rocks such as basaltic or ignimbritic flows can be used to interpret the timing of fault movements that are either overlain by the deposits or cut through the deposits (Fielding et al., 1985). On the other hand, major structures such as the El Toro-Olicapato lineament seem to exert a measure of control over the distribution of Quaternary volcanic rocks, which have a characteristically high potassium content.

Structure and deformation.

Morphotectonics is the geomorphic expression of tectonic features. When interpreting geologic structures in satellite images, the morphology of the land's surface is visible as combinations of linear and curvilinear features which result from differential erosion along fault and fracture systems, unconformities, and bedding surfaces. It has been found that the high spatial resolution of the TM data images, in combination with the common lack of vegetation and soil cover in the central Andes, facilitates the interpretation of such structural features at reconnaissance scale. Standard airphoto interpretation techniques also have been found effective in identifying structures in vegetated areas because the illumination angles of the images are often low enough to show the relief due to shadows.

Much of the structural work to date has been done in conjunction with available geologic data. However, in much of the Central Andes existing geologic maps are sketchy. We have already discovered new tectonic features by examination of TM data. Quadrants 2 and 4 of path 233, row 78 and quadrants 3 of and 4 of path 232, row 78 show several previously unrecognized geologic structures in rocks of Paleozoic and Cenozoic age in the southern part of the 4 km high Puna plateau of the Central Andean Cordillera (Fielding et al., 1985). A tentative sequence of events has been interpreted from the images and existing regional geologic maps in the region near 26°S and 67°W:

- (1). a compressional episode of folding in what were previously mapped as Tertiary rocks and thrusting of Ordovician over the Tertiary (?) rocks, perhaps corresponding to the Quechua phase of Andean deformation identified elsewhere in the Puna;
- (2). a period of erosion of these structures and deposition of an alluvial bajada;
- (3). renewed erosion and partial removal of the bajada with uplift of the earlier structures along N-S trending, apparently high angle faults that may have normal displacement, since nearby Quaternary alluvial fans are cut by high angle normal faults.

Field work done in November 1985 (by E. Fielding) showed that the structural interpretation of the images was basically correct. The deformed units, however, proved to be of probably late Paleozoic or Mesozoic ages rather than the previously interpreted Tertiary ages. Prints of color composites of the TM imagery proved invaluable for navigation in the field in this area, as there are no good maps available. Key localities could be selected to check the identity of the major structures and stratigraphic units, and routes determined to get to the important outcrops, an important consideration in the Puna, where access is very difficult to impossible. Several of the young fault scarps that were observed in the TM imagery were also observed in the field, but lack of accessibility prevented closer examination. It remains to be seen whether these faults are normal or reverse faults.

In the same images, basalt and basaltic andesite flows and ignimbrites of various ages, common in many areas of the Puna, show rotation and faulting on the TM images that help bracket the ages of deformation. Fairly extensive ignimbrite sheets 4 Ma and younger in the area indicate that there has been little deformation in the late Tertiary. However, 50 km to the west, a late Cenozoic flow is cut by a series of normal faults spaced about 1 km apart, with offsets on the order of 100m, that form small grabens. This is a good example of the clarity with which young extensional features are exhibited on TM images.

A possible meteorite impact crater appears on both quad 3 of path 232, row 78, and quadrant 4 of path 233, row 78, in the area of overlap between the two quadrants. The relatively small size (700m across) prevented it from being detected on MSS imagery. The overlapping coverage allows the viewing of this feature in stereo, though the low vertical exaggeration of the Landsat data limits the vertical resolution of the topography.

In the Subandean Belt in Bolivia, images from rows 74, 75 and 76 of path 230 are being used to map the foreland deformational front. Nascent drainage is being studied on enhanced images in order to detect subtle topographic features in the foreland basin in front of the Andean Cordillera and address the possibility of thrust propagation beyond the current Subandean fold-thrust belt.

Experiments with different TM band and band-ratio combinations to enhance structural marker beds are also being done. In the Precordillera and the Eastern Cordillera, for example, there are prominent carbonate marker beds within clastic red bed sequences and these can be used to define the structure. The reflectance contrast between the carbonates and the clastics, although not pronounced, appears to be separable in some bands. Contrast-stretched "natural" color (using the visible-wavelength TM bands 3, 2, and 1) appears quite useful for detecting a Cretaceous carbonate unit. In areas of some vegetation, it may also prove possible to separate these lithologies using a vegetation index, carbonates being able to support a greater amount of vegetation in arid and semi-arid settings.

Vegetation indices are also helpful in mapping young faults in the crystalline basement. Some of the faults appear to be conduits of water and are thus zones of consistent vegetation in otherwise sparsely vegetated regions.

Modern Sedimentary Rocks

Three sets of TM scenes have been selected for study of distinct problems in distribution of modern basin sediments. The first group includes parts of scenes at path 230, rows 80 and 81, and path 231, rows 80 and 81. These scenes span an active, "broken" foreland basin developed between Sierra Velasco (located to the west of the basin, with a fault on the eastern side) and Sierra Ancasti (east of the basin with a faulted western flank.) The basin is structurally closed to the north and open to the south. A major alluvial fan is seen at La Rioja (west side) extending to near the foot of Sierra Ancasti while a secondary fan system is fed from the basin's northern apex and interfingers with the major fan and narrow apron of sediments derived from the Sierra Ancasti scarp. This sedimentary pattern is unusual given the structural symmetry of the basin, i.e. roughly equal faults on both sides of the basin. In future investigations, we plan to examine facies distribution and the continuity of sub-drainages within this system.

Farther to the north, scenes from path 230, rows 74, 75, and 76, contain the front of the Subandean thrust belt and the most proximal 100 km of the foreland basin to its east. One major river system and two minor rivers are imaged continuously from the thrust belt across the basin; two other major river systems are partly missing due to a lack of TM scenes received so far. Four

distinct alluvial fans are associated with those rivers and interfinger with one another. It is interesting that the fans associated with the minor rivers cover a larger proportion of the area in the proximal part of the basin than do those from the major river, while the major river transports its debris beyond that zone and creates fans in a more distal position. The westernmost part of the plains has evolved from a depositional to an erosional realm, signalling continued encroachment of the thrust belt on the basin and incipient uplift of the edge of the basin. Near the northern boundary of the imaged part of the basin, the alluvial fans either interfinger with or are overlain by north-trending eolian deposits in a zone with a reputedly quite moist climate. We will examine facies distribution in the alluvial fans and attempt to associate onset of deformation and erosion with the existing drainage systems.

Sediments derived from laterally variable bedrock lithologies are readily distinguished in arid climate zones on the TM scenes of the Atacama Desert on the western side of the Andean Cordillera. Quadrants 2 and 4 of path 001, row 76 show striking examples of this. These will be examined in detail to evaluate the distance from the source area over which distinctions between source lithologies are maintained in sediments deposited in such an arid environment.

Paleoclimates

TM images between 25°S and 28°S are being used to study modern and Pleistocene snowline trends. The magnitude and frequency of past glaciations clearly decreases from east to west in the investigated sector. The Pleistocene snowline rises from lower altitudes in the east to extremely high elevations in the western part in the Chile/Argentina border area. This is similar to the trend of the recent snowline which reflects the dependence on moisture from easterly directions. Thus, previously hypothesized large-scale changes in wind and precipitation patterns of the west wind system did not occur in this part of South America. If during Pleistocene time, prevailing winds had come from the west, then Pleistocene snowline trends would decrease in elevation westward. Glaciation in this part of the Andes therefore appears to be a phenomenon solely related to depressed mean annual temperatures, without any major changes in the prevailing wind systems.

Stereogrammetry

We have demonstrated that a TM scene and a SIR-B scene can be co-registered to provide a realistic stereographic image of the topography. Initial calculations have treated the TM scene as an orthographic projection, whereby the displacement of any pixel on the radar scene toward the radar antenna from its corresponding pixel on the TM scene is a simple trigonometric function of the height of the ground point above the plane of the coregistration. In principle, the ocean, or a series of lakes, or even a flat alluvial plane can be used for coregistration, and reasonable heights can then be calculated for adjacent hills and mountains. Further refinement of the method is in progress.

SUMMARY AND INTERPRETATION

The results discussed above are preliminary, but they show many intriguing avenues for continued work. Preliminary interpretation and analysis within separate categories has been largely incorporated into the four headings above. Integration of the data into a complete approach to the problems of uplift, deformation and magmatism in relation to the Nazca-South American plate interaction is at an initial stage.

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