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TECTONICS OF THE CENTRAL ANDES

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ABSTRACT

Acquisition of nearly complete coverage of Thematic Mapper data for the central Andes between about 15°S to 34°S has stimulated a comprehensive and unprecedented study of the interaction of tectonics and climate in a young and actively developing major continental mountain belt. The paper briefly reviews the current state of our synoptic mapping of key physiographic, tectonic and climatic indicators of the dynamics of the mountain/climate system.

STRATEGY

We describe in this paper the use of Landsat Thematic Mapper imagery for investigations of the processes that have formed the Andes Mountains of South America. The central Andean Cordillera of South America is a classic young orogenic belt formed by subduction of oceanic lithosphere beneath a continent. Neither collision nor terrane accretion has been involved in the mountain building process during the Cenozoic, so that the tectonic history of the Andes is less complex than the comparable histories of the Alpine or Himalayan ranges. Yet the Andes record a set of constructional and erosional processes that are common to all mountain ranges at some interval of their histories, exposed with unsurpassed clarity in an arid environment.

The region of the central Andean Cordillera for which we have acquired TM imagery (see Figure 1) includes major along-strike changes in both climate and the pattern of tectonism. The region includes the broad volcano-capped Altiplano-Puna plateau located over a segment of oceanic lithosphere subducting "normally" with a dip of about 30°, and a narrow, virtually non-volcanic cordilleran belt to the south located over a zone of nearly flat subduction^{1,2}. The overall pattern of climates affecting the Andes Mountains of South America is determined by the seasonal interaction of monsoonal air masses in the north, Atlantic trade winds and Pacific anticyclonic circulation in the central parts, and mid-latitude westerlies in the south. A major climatic transition occurs in the region between about 23°S and 33°S (Figure 2) extending from the semi-arid to hyper-arid Altiplano-Puna Plateau region, where mountain building has proceeded with a minimum of erosional degradation, southward across a transition region where erosion and glaciation play increasingly important roles. Near 28°S a major north-to-south transition begins from the predominantly easterly moisture sources impinging on the eastern Andes to the predominantly westerly moisture sources characteristic of the Patagonian Andes.

The primary "signal" recorded on Thematic Mapper (TM) images of the central Andes is a geomorphic one reflecting the interaction of a climate and tectonics (including magmatism). These two systems are strongly coupled by isostasy. Erosional removal of mass from the mountain system leads to a compensating isostatic uplift, affects the state of stress in the lithosphere, and can thus affect the thermal regime, magmatism and crustal deformation. Conversely, the uplift of the mountain belt into the atmospheric circulation affects climate on both local and a global scales. Two end-member types of mountain belts can be imagined which illustrate the interaction of climate and mountain building. At one extreme erosion rates can be rapid enough that a steady-state balance is reached between the influx of crustal material by crustal shortening or magmatism

and the efflux of material by erosion. In this case the rate of uplift is limited by the rate of crustal inflow determined by stress and rheology, and the physiography primarily reflects vigorous denudational processes. This situation is increasingly approached in the southern Andes, where rates of shortening decrease while erosion rates increase. A significant erosional factor south of 30°S latitude has been multiple Pleistocene glaciation, which perhaps has removed half of the tectonically generated mass.

At the other extreme, if erosion rates are small compared to the tectonic or magmatic influx, then the amount of uplift is limited by the balance between tectonic and isostatic stresses, as may be the case for parts of the central Andes^{2,3}, and the physiography is more dominated by the tectonic processes in operation. Much of the uplift has occurred in the last 7 million years, when the regional climate has been semi-arid to hyper-arid. The aridity has been accentuated by the rising mountain range. In the most arid parts of the central Andes, so little erosional reduction of the orogenic mass has occurred that the size of the massif may be in fact self-limited by crustal strength and isostasy. The Altiplano-Puna has been only lightly glaciated because of the extreme height and aridity, even though large areas of the plateau are above the 0°C isotherm (Figure 2).

The strong along-strike variations in tectonism and climate in the central Andes thus span the gap between the two extremes and provide laboratory-like variations in critical parameters — rates of erosion and amounts and types of crustal shortening — upon which the strategy of the Cornell Andes Project is based. To study the tectonic/climatic interaction we are integrating TM imagery with geological field studies in western Argentina and syntheses of regional scale geophysical, topographic, meteorological and geological data. The TM imagery is interpreted in close association with a digital elevation model (DEM) developed at Cornell for the entire central Andes between about 12°S and 40°S. The emphasis of our analysis of TM imagery is upon synoptic mapping of key tectonic and climatic parameters on the scale of the major along-strike segments of the mountain belt. The identification of these parameters (discussed below) is based upon our evolving models for the Neogene tectonic evolution of the Andes. The parameters are calibrated by ground truth from field work done by Cornell investigators and Argentine and Chilean collaborators. Examination of the TM imagery has played a critical role in the development of new ideas about Andean tectonics² (Figure 3), and our ongoing systematic mapping efforts are strongly guided by strategies to test and modify those models.

In the mapping effort we utilize the “virtual roam” function of the International Imaging Systems (IIS) Model 75 hardware and System 600 software, modified by E. Fielding in our group, so that lines can be drawn while roaming an entire TM quarter scene and captured as a vector file converted to latitude and longitude coordinates for later analysis and presentation. This is done with false color images using TM bands 5, 4 and 2 (red, green, and blue) with suitable scaling. The modified roam and mapping function has permitted us to map on the screen at full resolution (roughly 1:50,000 scale) rapidly enough to cover the large regional extent of the mountain belt. This would be extremely difficult to do with conventional aerial photography, even if such extensive coverage were available. The first-cut mapping has focussed on particularly striking and tectonically important elements, including the extent, nature and overall shape of major geomorphic surfaces, the spatial distribution of volcanic mass, evidence for youthful faulting of the surface and associated special types of volcanic activity, and indicators of modern and Pleistocene climate such as glaciated areas, snowlines, wind directions, and gross measures of the amount of vegetative cover as a precipitation index.

MAPPING EFFORTS

Morphotectonics

The physiography of the central Andes is dominated by the existence of two uplifted "surfaces". The recognition of the regional extents of these surfaces is one of the major new results of our examination of TM imagery. The most extensive one, the "Puna surface", forms the Altiplano-Puna plateau upon which the widespread volcanics of the central Andes are extruded and built. This surface can be traced along the main cordilleran belts north and south of the plateau (it is called the Puna in Peru and in Argentina) into central Peru, and to about latitude 30°S along the Argentina/Chile border, respectively. The second surface, the "Pampean surface" is an exhumed late Paleozoic unconformity, the sub-Gondwana erosion surface, which during the Neogene has been block faulted, uplifted and tilted, and in places possibly folded, to form the characteristic physiography of the Sierras Pampeanas and parts of the Eastern Cordillera and Puna of western Argentina. The tectonism is ongoing as evidenced by the crustal seismicity and faulting of Quaternary cover. The two surfaces interleave in the southern Puna of northwestern Argentina, where the relatively short-wavelength Pampean tectonic morphology⁷ is superimposed upon the long-wave-length uplift of the Puna plateau. The characteristic texture of this "Pampean surface" is quite clear on TM imagery and its extent and morphology is can be systematically mapped.

The overall shape of the uplifted "Puna surface" is an important source of new information about the tectonic processes that have produced the uplift. The shape can be determined only after careful mapping of the extent and nature of the surface and of the volume of volcanic material extruded upon it (Figure 4a). The mapping on TM imagery can be superimposed on the DEM to calculate both the volume of extrusives and the topography of the underlying surface. Within the zone of extensive magmatism along the western side of the Altiplano-Puna plateau, TM imagery clearly reveals both the extent of Neogene extrusives and "windows" through the extrusives that expose the underlying basement surface. The TM images of the great western slope of the plateau show clearly the monoclinical-like flexure that is implied by the model in Figure 3. In the hyper-arid and little eroded central part of the western slope, between about 20°S and 26°S, the monoclinical form is particularly well preserved.

A major new result of our mapping is to trace what appears to be the "Puna surface" south of the southern end of the main plateau through much of the Andean tectonic segment located above the zone of horizontal subduction. The Puna surface narrows considerably south of about 27°S and can be traced to about 31°S where it is finally destroyed by the increasingly vigorous drainage systems that join along a single continental divide along the crest of the main cordilleran belt. The morphologies of this surface and of the major longitudinal valley located east of the cordillera (the Calingasta-Iglesia Valley) seen on TM strongly support a novel model of the tectonics of this segment of Andes originally derived from careful studies of the seismic stratigraphy of the valley⁸. In this model the longitudinal valley is essentially a "piggy-back basin" located between two crustal-scale ramp anticlines. The western ramp anticline is responsible for the morphology of the main cordillera as a geometric consequence of crustal scale fault-bend folding. How this model relates to the monoclinical model shown in Figure 3 for the wide part of the Andean cordillera is a major target of our current research. Careful study of the shape of the Puna surface has thus become critical to this very exciting contest between two novel models, both developed in the Cornell Andes Project with strong input from TM analysis.

Within the main Altiplano-Puna plateau is a system of internal drainage producing a kind of "cut and fill" reduction of relief that is an important element in the development of the surface. Headward development of drainage into the plateau along its flanks is the primary means for removing the mass of the uplifted plateau. Study of TM imagery has shown that the boundary between these two regimes is not simple but includes both the drainage divides (which are being

mapped accurately), and a mappable boundary in many places that is not coincident with the drainage divide but separates the low relief, mature physiography characteristic of the "Puna surface" and a higher relief, youthful physiography characteristic of the flanking drainage systems. The lack of coincidence between these two boundaries is related to the tectonically controlled shape of the main plateau slope interacting with the climatically controlled variation of precipitation as a function of elevation. Variations in lithology in terms of erodibility are an additional major factor. For example, the batholiths east of La Paz form resistant spires, catch precipitation and thereby increase erosion rates in the surrounding drainage basin (the Beni River drainage). We are developing methods to map the lithology in terms of geomorphic expression and relative erodibility, and our climatic mapping is discussed further below. In general, the mapping of the "boundaries" of the Puna surface in terms of relief characteristics and drainage will provide the key data to understand the way in which mass is removed from the uplifted plateau. This is both determined by and affects the tectonic and magmatic processes that produce the uplift.

The climatic factor is complicated by the fact that the present climate and erosional regime in some places may be quite different than that prevalent during glacial episodes, so to fully understand this we must determine the spatial pattern of Pleistocene climate in terms of precipitation and glaciation. The variations in the pattern and rates of erosion are enormous from the hyper-arid central western slope mentioned above to the Amazonian drainage basins along the northeastern side. We are studying these erosional systems in an attempt to relate quantitative measures of relief, drainage network characteristics, and the extent of Pleistocene glaciation to the erosional and tectonic regimes.

Crustal Deformation

The most extensive mapping with TM imagery thus far accomplished is a comprehensive mapping of Quaternary faults and basalt flows on the Altiplano-Puna^{9,10} (see Figure 4). Field studies of limited areas of the north and south ends of the Altiplano-Puna, between 14° and 28°S, have revealed Quaternary normal/strike-slip faults with relatively small displacements^{11,12,13}. With the TM imagery we are mapping faults in three categories: obvious Quaternary faults that cut glacial features or young surfaces such as alluvial fans or volcanic flows; apparently older but possibly Quaternary faults, whose scarps are less clear and are not seen to cut Quaternary features but do offset somewhat older surfaces; and major late Cenozoic faults of undetermined age which have large-scale scarps generally defining major mountain-block fronts. The results of TM mapping in the southern Puna are calibrated by previous and ongoing extensive field research by Cornell geologists. This field work provides three key types of observations that help us to extend the work beyond the visited areas: (1) more direct evidence of the youthfulness of faulting and the nature of specific units involved¹¹; (2) qualitative and semi-quantitative evaluation of scarp morphology and (3) fault slip data which allow us to quantify the kinematics and dynamics of major active faults^{14,15,16,17}. It is clear after extensive examination of TM images that fault mapping on TM imagery is most effective and complete for the Puna surface in comparison to the high relief areas along eastern slopes of the plateau where field studies have also demonstrated major Quaternary faulting, primarily as low-angle thrusts. The morphology of the eastern slopes is dominated by fluvial dissection which tends to obscure fault traces (and thrust faults tend to bury themselves), while even small and subtle dislocations of the relatively smooth plateau surface can be easily detected.

While age constraints remain a problem, the youngest flows and faults mapped on the plateau are probably Quaternary in age and thus represent the most recent tectonic activity in the area. The basic result of the mapping done thus far (Figure 4) is to support two major conclusions about the tectonics of the plateau. The deformation of the near surface during Quaternary times, compared to that during Late Miocene-Pliocene times, is different both in nature and in magnitude. The latest deformation is predominantly extensional and strike-slip versus horizontal shortening and vertical

thickening, but it is substantially less in magnitude. As demonstrated in Figure 4b the general sparseness of Quaternary faulting and the lack of long, continuous and through-going fault structures do not indicate large amounts of deformation. The plateau has thus changed from a compressional regime with substantial crustal shortening into a more neutral stress regime characterized by minor amounts of extension and strike-slip faulting. The mapping shows that the most important young faulting is confined to the northern and southern parts of the plateau, but not simply along the plateau edges (Figure 4b). At the southern end of the plateau the influence of Pampean structures that overlap onto the southern Puna appears to be important. The results are in accord with the model of Figure 3: compressional shortening of the plateau during late Miocene times became concentrated in the lower crust and in the eastern fold-thrust belt, while the upper crust of the plateau, uplifting above the thickening lower crust, experienced both a change in stress conditions and a general lowering of the level of deformation. The small extensional deformations are thus probably related to this uplift, or possibly magmatism, as indicated by some degree of spatial correlation between the faulting and young basalt and dacite flows, while the strike-slip deformations reflect stress conditions near the along-strike ends of the plateau where the horizontal compressional stresses are oblique to the mountain belt and tend to shear it.

Pleistocene and Modern Climatic Indicators

A major effort is underway to map significant indicators of modern and Pleistocene climatic parameters. This effort has two motivations. One is to determine differences between glacial and modern climates and the effect of Andean uplift on these differences, a component of the larger effort to understanding global Quaternary climate cycles. The other is to use mapped spatial variations in Pleistocene glaciation as indicators of spatial variations in the most important erosive processes acting in a mountain belt.

The goals of our paleoclimate mapping are as follows: (1) map the distribution and extent of the land surface affected by Quaternary glaciation on TM images using characteristic glacial and pluvial landforms including moraines (lateral, terminal and recessional), stranded lake shore lines formed during high lake levels fed by melting glaciers and/or increased precipitation, and the location and size of cirques; (2) map present snowlines and snow catchment areas, periglacial landforms and glaciers, and quantify the spatial variation of these features using historical climatic data (mean temperature and precipitation) throughout the Andes; (3) map modern and Pleistocene wind directions indicated by linear quebradas in ignimbrite flows, yardangs, and sand and salt streaking, modern and relict dune fields, and asymmetric distribution of Pleistocene lake shore lines; and (4) map the spatial variation in modern precipitation as indicated by the TM band ratios sensitive to the net fraction of vegetation.

Our current work on the distribution and elevation of modern and Pleistocene snowlines has led us to hypothesize that, contrary to some general models of atmospheric circulation during Quaternary ice ages, westerly storms did not migrate north and bring snow and extensive glaciation to the southern Puna, but that the snowline was lowered nearly parallel to the modern snowline with moisture sources much as today, although effective precipitation must have increased. The arid southern Puna was thus spared the intense erosional modification suffered by glaciated mountain regions located farther south. The systematic mapping efforts now underway will allow us to separate the roles of precipitation and temperature as factors controlling the snowline elevation as it varies with latitude. The resulting insight into the spatial and temporal variations in Andean climate will have impact on three major areas: (1) global circulation models; (2) effect of Andean uplift on climate; and (3) spatial variations in the amount of mass removed from the uplifting mountain system. From these results and our tectonic studies we will then model the tectonic/climatic feedback loop.

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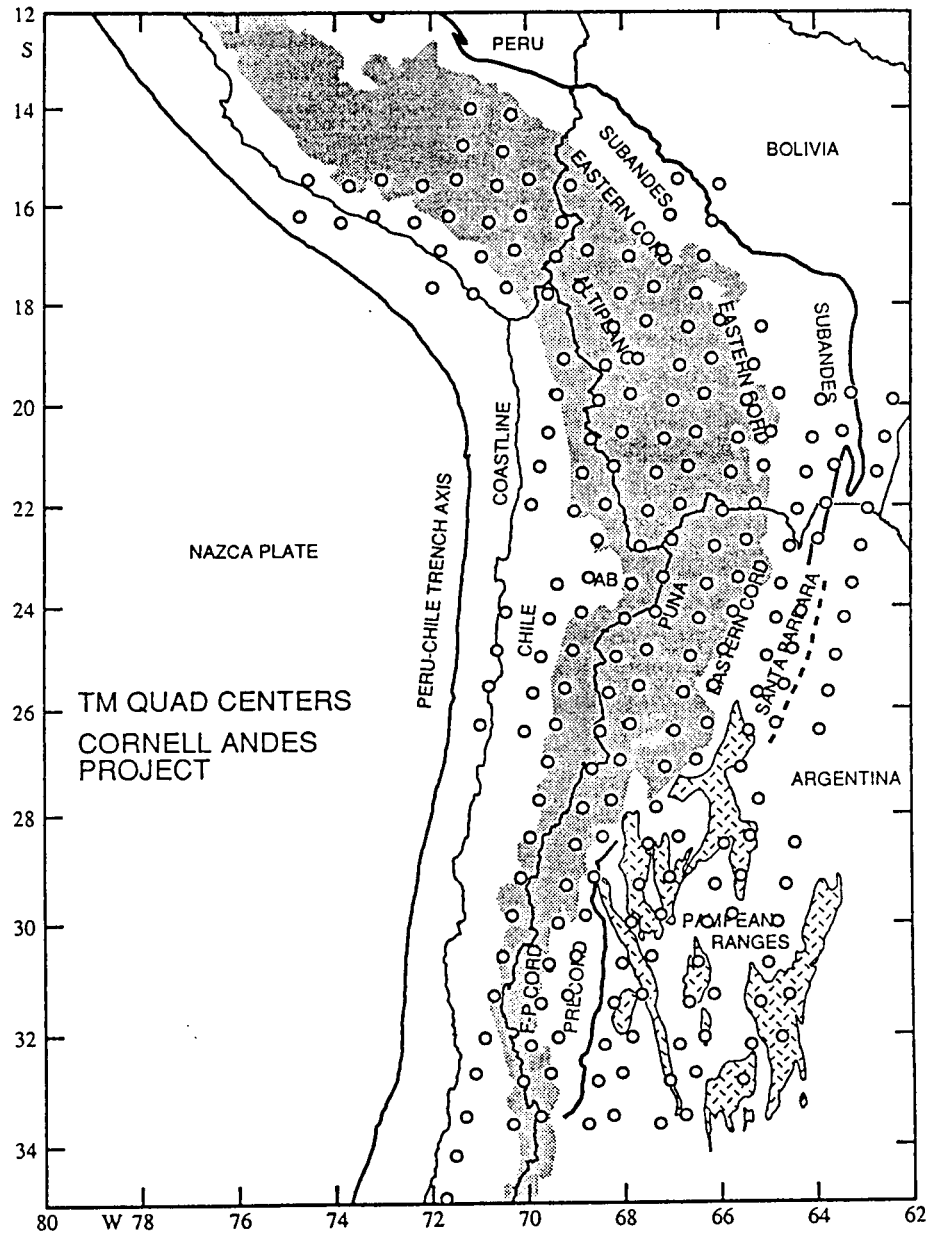


Fig. 1. Map showing locations of centers of Thematic Mapper quarter scenes being analyzed in the Cornell Andes Project (*circles*) overlaid on major tectonic features. Shaded area has average elevations greater than 3 km. Basement block uplifts of the Pampean Ranges shown in cross-tick pattern, heavy lines mark eastern limit of thin-skinned thrust belts in the Precordillera (Precord) and Subandean belts (Subandes). Dashed heavy line is eastern limit of Santa Barbara thrust belt.

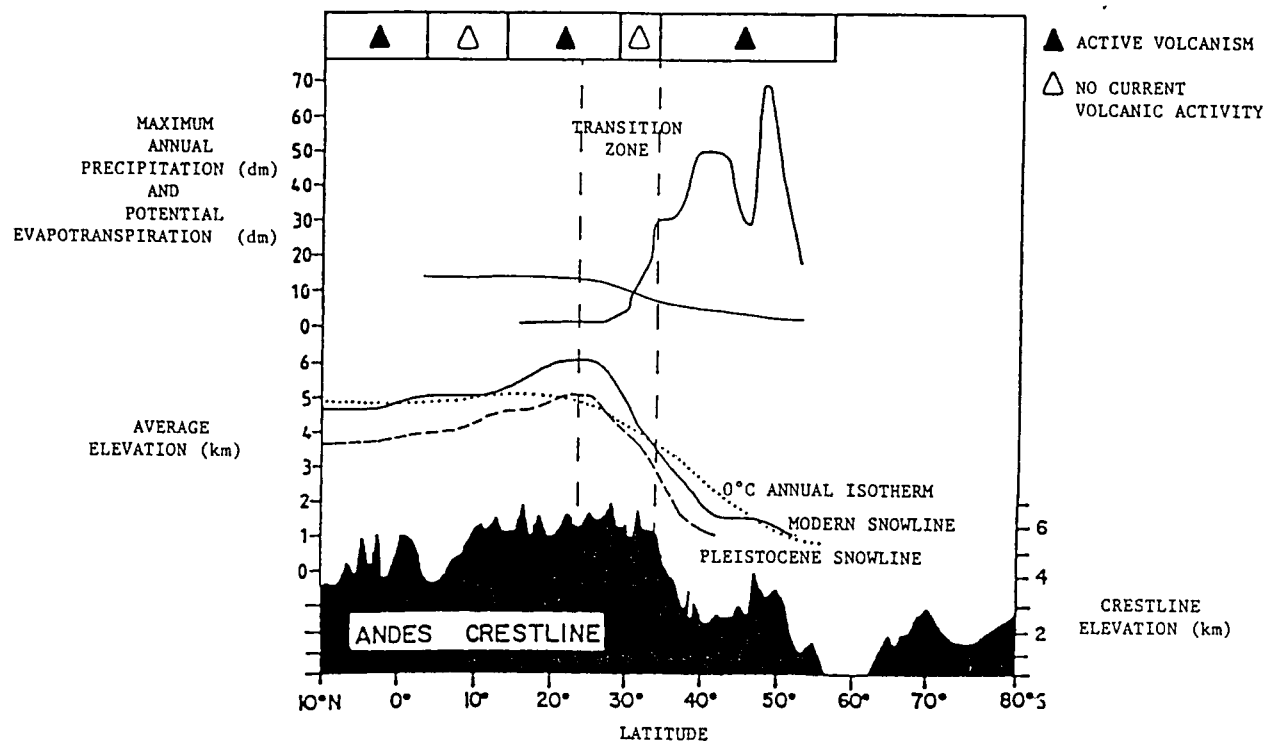


Fig. 2. Precipitation, potential evapotranspiration, temperature, and snowline gradients along the north-south topographic crestline of the Andes Mountains. Note the rapid increase in mean annual precipitation and cooler temperatures south of 30°S latitude, and the corresponding depression of snowline. Climatic data from Henning and Henning, 1981; Nogami, 1976; Schwerdtfeger, 1976^{4,5,6}.

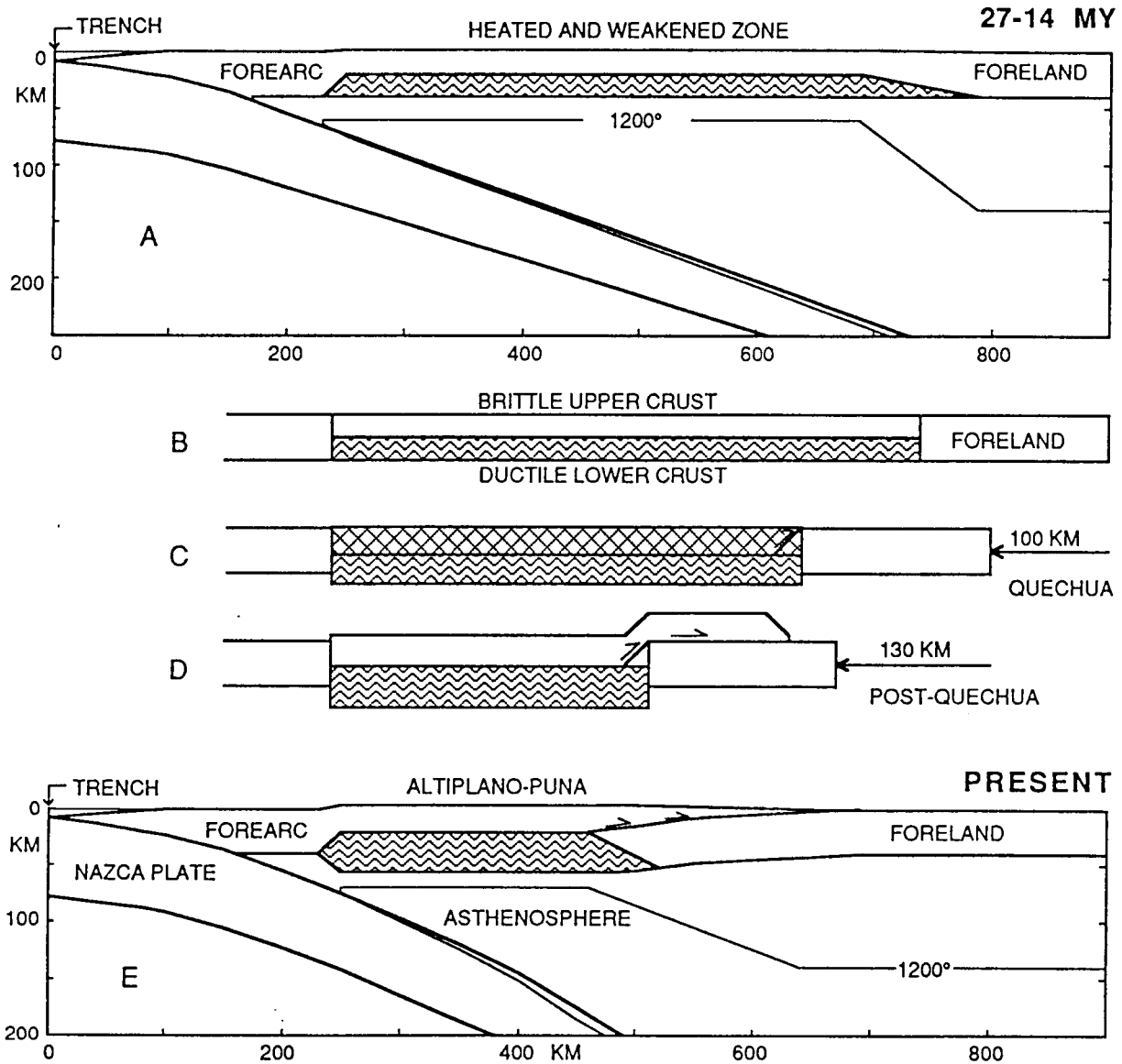


Fig. 3. Simplified model of late Cenozoic evolution of a section near 21° - 22° S. Faults are shown as lines and ductile lower crust is shown as wavy lines. The initial and final stages are depicted in the (A) upper and (E) lower sections, while the three middle sections show a very schematic (but balanced) block model of the crustal deformation. (B) is a simplified initial crustal section. (C) The cross hatching indicates pervasive shortening of the upper brittle crust during the "Quechua" phase of deformation. (D) For clarity the overthrusting of the upper crust onto the foreland is shown without any isostatic flexural adjustment; (E) the isostatic adjustment is shown.

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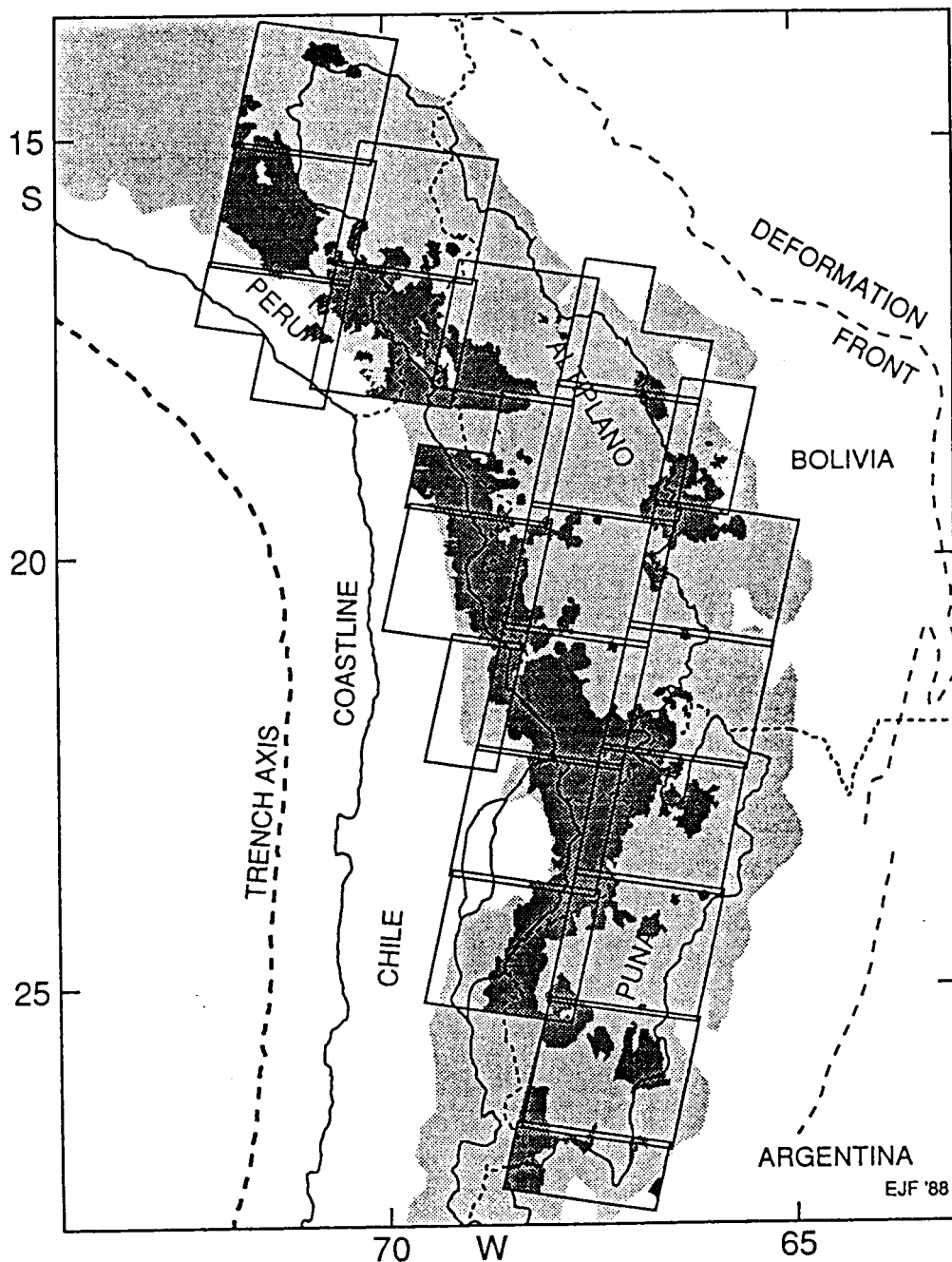


Fig. 4. Preliminary map of results to date from mapping of faults and volcanics in the Altiplano-Puna. (a) Boxes show TM scenes and partial scenes mapped so far (total of 61 TM quarter scenes) overlain on geographic and tectonic features, with light gray showing >3 km average elevations and deformation fronts as in Figure 1. Medium solid lines are drainage divides outlining internally drained plateau of the Altiplano-Puna. Dark gray shows area of major late Cenozoic volcanism, with white patches where there are "windows" through the volcanics into the underlying sedimentary or basement rocks. Note that volcanics control much of western and eastern drainage divides on the plateau.

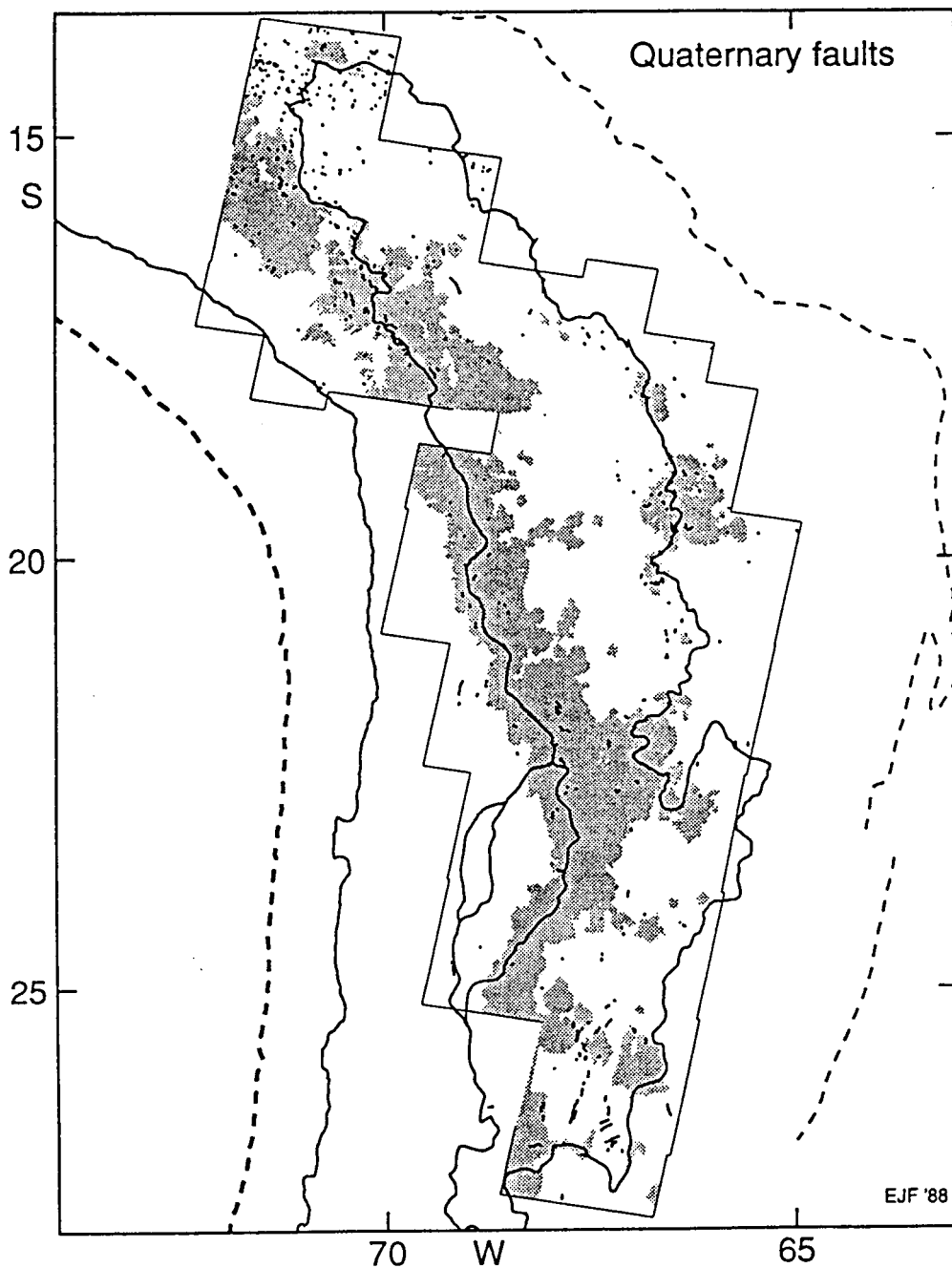


Fig. 4. Preliminary map of results to date from mapping of faults and volcanics in the Altiplano-Puna. (b) Map of obvious young "Quaternary" faults as solid lines in area mapped so far (irregular box outline). Gray area is major volcanism as in (a). Note concentration of young faults in southern Puna and northern Altiplano.