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# Global Mega-Geomorphology



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*Proceedings of a workshop held at  
Sunspace Ranch  
Oracle, Arizona  
January 14-16, 1985*

**NASA**



*NASA Conference Publication 2312*

# Global Mega-Geomorphology

Robert S. Hayden, *Editor*  
*George Mason University*  
*Fairfax, Virginia*

Proceedings of a workshop sponsored by  
the National Aeronautics and Space Administration  
and the International Union of Geological Sciences  
and held at Sunspace Ranch  
Oracle, Arizona  
January 14-16, 1985

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**COVER PHOTOGRAPH:** The Madera Canyon alluvial fan in the Santa Rita Mountains south of Tucson, Arizona. In this oblique aerial photograph two Quaternary fault scarps can be seen cutting the left edge of the fan. (Photo by P. Kresan, All Rights Reserved)

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Sunspace Ranch, Oracle, Arizona



WORKSHOP PARTICIPANTS (See Next Page)

#### WORKSHOP PARTICIPANTS

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(Left to Right)

1st Row: C. Embleton; J. McCauley; W. Bryan; S. Judson; J. Gavin;  
V. Baker; A. Bloom

2nd Row: B. Luchitta; M. Abrams; N. Short; R. Blair; M. Morisawa;  
C. Rosenfeld; R. Williams; O. Huh; A. Walker

3rd Row, Right: J. Everett; F. Sabins; R. Hayden; D. Ritter;

4th Row: C. Twidale; J. Head; R. Sharp; K. Sullivan; L. Rossbacher;  
I. Douglas; W. Bull; J. Ford; W. Melhorn

Missing: R. Greeley; C. Kitcho; L. Lattman; L. Mayer

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## INTRODUCTION

Robert S. Hayden  
George Mason University  
Fairfax, Virginia

In the last two decades, a new technology has provided a rapidly growing volume of geomorphic information which has the potential to create a revolution in geomorphological research. With the advent of manned orbital and space flight and of satellites capable of recording and transmitting pictorial information about the Earth from several hundred or more miles above the surface, it has become possible, for the first time, to observe directly large regions of the Earth's surface and to perceive the Earth as a whole from space. The new technology of space imagery has challenged geomorphologists and other earth scientists to develop theory and research techniques that fully accommodate the new information.

The extension of space exploration to the Moon and to other planets has broadened the scope of geomorphology by providing information on landforms which have developed in environments that differ significantly in fundamental factors such as temperature, pressure and gravity from the environments in which Earth's landforms have been shaped. In some cases the landforming processes themselves appear to be significantly different than any found in the terrestrial environment. Some investigators have suggested that features observed on other planets, such as chaos terrain and labyrinths on Mars, can help us understand Earth's early history better because they may have been formed by processes which were important in the early ages of Earth but have long ceased to be active here. Corresponding terrestrial landforms would have long since been altered or obliterated by subsequent activity.

The new technology of space provides a new perspective which poses new questions for geomorphology and poses old questions in new ways. The classical threefold paradigm of "structure, process, and stage", which has served geomorphology from its inception as a scientific discipline, may require modification both in response to this new perspective and to the new knowledge of the surfaces of our neighbors in the Solar System.

The workshop in Global Mega-geomorphology had its inception as part of a response to the impact of space exploration and the explosion of new information it has produced. Leadership was provided by Dr. Nicholas Short of NASA-Goddard, and co-convenors, Dr. Victor Baker of The University of Arizona and Dr. James Head of Brown University. Thirty geomorphologists and planetary geologists were invited to the Oracle Conference Center north of Tucson Arizona over three days, January 14-16, 1985, for a workshop to consider questions related to the genesis and evolution of terrestrial landforms from the perspective of mega-geomorphology. They were asked to examine matters related to landforms on

a regional and a global scale and to consider the research implications of a synoptic view of large areas of the Earth's surface and of the surfaces of neighboring planets. This was a workshop in the true sense of the word. It was not a session with a few speakers and many listeners. All members were full contributors in long discussions which went from early morning until well into the evening.

Objectives of the workshop included:

Documentation of current understandings on the role of geomorphology in its relationship to the perspective of space.

Identification of quantitative techniques appropriate to present and future geomorphic research.

Determination of future directions for the discipline.

Consideration of questions of the relationships between landforms and global habitability.

The last objective was a response to a proposal from NASA leadership for a program designed to increase our understanding of the various factors which affect the habitability of our planet and its various regions.

Four themes provided a structural framework for the workshop. They were:

Global Geomorphology

Inheritance and Evolution

Process Thresholds

Planetary Perspectives

In addition, opportunity was provided for the introduction of other themes considered relevant to mega-geomorphology. Those suggested and included as a part of the discussions were:

The role of the Antarctic

Submarine Geomorphology

Existing ancient landforms

Remote sensing & sudden geomorphic events

As a part of the preparation for the workshop, each invited participant was requested to prepare a written presentation on an aspect of geomorphology of interest and concern to him or her, and relevant to the overall theme of mega-geomorphology. These written presentations make up the bulk of this volume.

In order to establish a basis for the discussions of the workshop, selected members of the group were asked to make a presentation on one of the workshop themes. Dr. Arthur Bloom, of Cornell University, introduced the theme of global geomorphology asking how we can develop a meaningful regionalization of the world. Should a region be defined in terms of its boundaries or in terms of a central geomorphic concept? Landscape inheritance is difficult to trace on Earth because of the rapid rates of erosion. Dr. Sheldon Judson of Princeton University suggested that geomorphologists may find that geophysical investigations provide the best means of discovering ancient landscapes as "palimpsests" within present features, using such techniques as radiometric dating. Dr. Dale Ritter, of Southern Illinois University, stated that the identification of process thresholds is a

most difficult task. Can we identify the conditions under which processes change by studying the landforms? How long does it take for landforms to repond to process changes, such as climate change? Dr. Ronald Greeley of Arizona State University spoke of the fundamental problems inherent in extrapolation from the Earth's surface to the surfaces of other planets with different environments. How can we relate terrestrial landforms to those which have developed in extremely low gravity environments and to non-earthly processes such as ice tectonism and sulfur volcanism? Dr. Baerbel Lucchitta of the U.S. Geological Survey, spoke of problems connected with studies of the Antarctic. Landsat data had been very useful in those regimes where most problems of mega-geomorphological scope are best considered over large areas using multiple data sets. Dr. Wilfred Bryan of Woods Hole Oceanographic Institute, pointed out that submarine geomorphology has always been on a mega- scale. New technology, including narrow beam sonar, deep sea photography and deep submersibles have only recently become available enabling oceanographers to study the sea floor in detail. Many landforms are new and rapidly changing. However, there are a significant number of landforms that are geologically quite old. Dr. C.R.Twidale of the University of Adelaide in Australia described three types of landforms of great antiquity found particularly in shield areas and in orogens, namely, exhumed landforms, epigene landforms and etch surfaces and forms. Widespread ancient landforms are particularly prevalent on the southern continents where the shield areas were never subjected to Pleistocene glaciation. Dr. Charles Rosenfeld of Oregon State University, spoke of the value of remote sensing techniques and products in the study of sudden geomorphic events such as volcanic eruptions. He illustrated this with examples of the methods he and others used before, during and after the great eruption of Mt. St. Helens in May 1980.

Dr. James Head of Brown University, outlined the basic approaches of planetary geomorphology and comparative planetology by posing several questions that form the basis for these investigations and he illustrated these approaches with examples from recent planetary exploration, particularly of Venus. The fundamental questions include: How do planets work? (What are the major factors in the formation and evolution of planetary bodies: what is the role of such major factors as planetary size, density, geochemistry, position in the solar system, etc.); What are the dominant processes that form and modify planetary surfaces? (These questions require global inventories of planetary landforms and topography.) How have these dominant processes changed with time? (For example, impact cratering is known to be a significant process in early solar system history.) How are these processes linked to internal thermal evolution? How do variations in bulk physical properties (such as size and density) and environment (incident sunlight, temperature and pressure characteristics of the atmosphere) influence basic geologic processes and the resulting landforms? (For example, the very high atmospheric pressure on Venus, about 100 bars, largely precludes explosive volcanic eruptions and large composite volcanoes.)

There has been a worldwide increase in geomorphological research due, in part, to the new information coming from spatial and planetary exploration. One manifestation of this is the First International Geomorphological Conference to be held in September 1985 in Manchester England under the sponsorship of the British Geomorphological Research Group. Dr. Ian Douglas of Manchester University, the conference chairman, urged members of the workshop to attend the conference.

Techniques valuable in mega-geomorphological research were considered by the workshop. Of particular interest were the uses of geomorphological mapping, the development and applications of quantitative methods, the use of radar and the availability and application of multiple data sets. Dr. Clifford Embleton of London University England, described the techniques of detailed geomorphological mapping with special reference to the IGU program of geomorphological mapping, an international cooperative effort to develop detailed maps of Europe west of the Urals on the scale of 1:2.5 million accompanied by a comprehensive text on "The Geomorphology of Europe". The first of 15 sheets of the map and the text have been published. The IGU maps were developed without use of space imagery because adequate space imagery of many parts of Europe was not available at the time the project was begun in the early 1970's. He pointed out a number of advantages to the use of remote sensing from orbit for future geomorphological mapping including a direct method for macro-geomorphological study, a uniform reliability and density of data over wide areas, access to remote areas, and records of complex patterns such as found in dune fields, karst regions and glaciated areas. Geomorphology has always had a strong qualitative bias in its research. Dr. Larry Mayer of Miami University spoke of need for a strong quantitative program in geomorphology. Modeling techniques and the use of various geophysical measures can be of assistance in providing the quantitative dimension. Dr. John Ford of Jet Propulsion Laboratory, described the uses and limitations of radar in geomorphic research. It is particularly useful in areas, such as Borneo, that are almost always cloud covered as radar will penetrate clouds. Radar can also penetrate some dry surfaces, such as hyper-arid desert areas, revealing features several meters below the surface. Dr. Jack MacCauley and Dr. Baerbel Lucchitta of the U.S. Geological Survey showed how multiple data sets for a given area of different types, such as Landsat and radar imagery and acquired at different times can be useful in geomorphological research, both for a better understanding of the Earth's surface and in the interplay between the Planetary Program and the Terrestrial Applications Program. An example of this is the comparison between Martian fretted terrain and Gilf Kibir, a hyper-arid region in the central Sahara.

Much of the workshop time was devoted to working groups where the workshop themes were discussed in depth along with the techniques and methodologies by which the themes might be explored. The results of these deliberations were brought back to the full body each day for further consideration, discussion and refinement. Summary reports from each of the working groups form one chapter of this volume.

A comprehensive study of "Regional Landforms from Space" is being prepared for publication by NASA under the editorship of Dr. Nicholas Short. It is co-authored by ten geomorphologists each of whom has written a chapter on one particular type of landform or landform process as the landforms and processes are seen from the perspective of Landsat. The book will be copiously illustrated with Landsat imagery and ancilliary photographs of landforms throughout the world. Part of the final day of the workshop was devoted to presentations by each of the authors present on the content and emphasis of his or her chapter.

At the final plenary session of the workshop there was a full discussion of conclusions reached by the group and recommendations for further action. The conclusions and recommendations are contained in the final chapter of this book.

On the first day of the workshop, Dr. Kathryn Sullivan, a geologist and astronaut and a mission specialist aboard the flight of the Space Shuttle Challenger in October 1984, spoke to the group on "A Geologist's View from Space". She suggested that a key word for the workshop should be "to say daring things." The daring thing she spoke of was that in the near future many more geologists, geomorphologists and other earth scientists should have her experience of direct observation of the earth from space as payload specialists on future shuttle flights. Hopefully, the future of geological and geomorphological research will be enhanced by this type of participation. Certainly, the perspective from space, with the ability to observe large regions of our planet, whether directly by shuttle flights or indirectly through satellite imagery, will be a very important factor in all future investigations of the Earth, the features of its surface, and the relationship of the Earth to the other planets with which it shares the Solar System.



CHAPTER I:  
Presentations  
by  
Workshop Participants



## A NEW GLOBAL GEOMORPHOLOGY?

Victor R. Baker  
University of Arizona  
Tucson, Arizona

Geomorphology is entering a new era of discovery and scientific excitement centered on expanding scales of concern in both time and space. The catalysts for this development include technological advances in global remote sensing systems, mathematical modeling, and the dating of geomorphic surfaces and processes. Even more important are new scientific questions centered on comparative planetary geomorphology, the interaction of tectonism with landscapes, the dynamics of late Cenozoic climatic changes, the influence of cataclysmic processes, the recognition of extremely ancient landforms, and the history of the world's hydrologic systems. These questions all involve feedback relationships with allied sciences that have recently yielded profound developments. Examples include climatology (climatic modeling); tectonics (plate tectonic theory); geophysics (high-resolution geodetic and gravity surveys, seismic stratigraphy); sedimentology (sedimentary basin analysis); hydrology (hydroclimatic modeling, systems analysis); geochemistry (isotopic indicators of environmental change, geochronological techniques); pedology (documentation of chrono-functions); oceanography (detailed mapping of the sea floor); and planetology (discovery of new landscapes on other planets). The intellectual feedback from these associations can generate profound tests of existing geomorphic theory. For example, what are the implications of ancient channel and valley forms on Mars for the early climatic history of that planet? Are regional rates of long-term degradation consistent with sediment accumulation in basins? What were global hydrologic conditions associated with full-glacial climates? What have been the magnitude and frequency of various cataclysmic geomorphic processes through time? Can the ancient terrains extant on the terrestrial planets elucidate the early Precambrian history of Earth? Finally, the most significant scientific questions in applied geomorphology also have a global or regional context. Relevant concerns include the following: (1) accelerated erosion induced by deforestation, (2) the paleogeomorphology of continental margins (the major frontier of petroleum exploration), (3) the hydro-geomorphic consequences of a Carbon Dioxide warming, (4) desertification, and (5) urban landscape metamorphosis. The emergence of a "New Global Geomorphology" will require increased work by large interdisciplinary research teams, greater international cooperation, and an expanded philosophical basis for the science of terrestrial planetary surfaces.

## GLOBAL MEGAGEOMORPHOLOGY

Ian Douglas  
University of Manchester  
Manchester, England

Any global view of landforms must include an evaluation of the link between plate tectonics and geomorphology. To explain the broad features of the continents and ocean floors, a basic distinction between the tectogene and cratogene part of the earth's surface must be made. The tectogene areas are those that are dominated by crustal movements, earthquakes and vulcanicity at the present time and are essentially those of the great mountain belts and mid-ocean ridges. Cratogene areas comprise the plate interiors, especially the old lands of Gondwanaland and Laurasia. Fundamental as this division between plate margin areas and plate interiors is, it cannot be said to be a simple case of a distinction between tectonically active and stable areas. Indeed, in terms of megageomorphology, former plate margins and tectonic activity up to 600 million years ago have to be considered.

The other major parameter in global geomorphology is climate, which again has to be considered in two parts, present and past climate. Much has been written about the relationship between process and climate. However, the fundamental factors seem to be the space-time-duration and magnitude-frequency characteristics of water flows, and whether or not the ground is vegetated. In a few areas the activity of ice, rather than meltwater, is significant, and in a few others, the work of wind, rather than rare rain and flood events, is important. The critical thresholds for process are those that determine when there is enough water, but insufficient protective vegetation, to permit erosion, and that where there is so much water that despite highly protective vegetation, high erosion rates occur. The former threshold is critical for process change in areas where vegetation survival is marginal, such as the Sahel zone of Africa. Here overgrazing may so reduce the vegetation that gullying becomes rapid and soil degradation extreme. Such well documented effects depend on the seasonal vegetation changes which can be detected on the continental scale using the AVHRR on NOAA satellites. In this case, a continental scale change in geomorphic process efficiency results from the combined effects of human activity and drought. Similarly the occurrence of severe erosion following Australian bush fires in 1983 may be related to the southern oscillation and the El Nino phenomenon in the Pacific. Both these examples relate to fluctuations within the present climate and thus suggest that the old notions of morphoclimatic zones may be largely irrelevant.

Nevertheless, the relationship between ecosystems and climate is close as is that between ecosystem dynamics and geomorphic process. Photogeology has led to great attention to the relatively sparsely vegetated zones of the earth's surface where the landforms are readily visible and their relationship to

geologic structures is easily assessed. The advent of SLAR and shuttle radar has widened the scope of landform remote sensing so that the ground beneath the forest may be better understood. Far from simplifying the relationship between climate and landform, such remote sensing data have reinforced the need for geomorphology to cope with climate change, even in the present-day humid tropics.

Yet, how far is this changing climate merely a superficial, Quaternary effect? Much evidence has been adduced to suggest that during the Tertiary, long periods of climatic stability occurred and landforms evolved under steady, unchanging conditions. However, as the details of deep-sea drilling projects become available, more Pliocene and Miocene climatic fluctuations are revealed. While the human mind seems to seek and therefore postulate stability and only infrequent change, nature seems to be characterised by irregular, uneven, but continuing changes. Many of the phenomena taken to indicate long-term stability may be created in a few tens of thousands of years, such as ferricrete profiles developed between dated early Tertiary basalt flows in the New England area of eastern Australia (Francis and Walker 1978). Climate is thus a difficult parameter for geomorphologists to use. The imprint of climatic change on landform is clear, but it is difficult to quantify relationships between present climate and process. Empirical data suggest that, given a similar tectonic setting, higher erosion rates and larger river channels for a given catchment size will be found in humid tropical rain forest areas experiencing the heavy downpour of tropical cyclones than in those equatorial rainforest areas devoid of such extremes. Yet, the highest rates of erosion in humid tropical areas are from the tectogene tropics of Indonesia and New Guinea, where volcanic and tectonic activity create steep unstable terrain supplying great quantities of sediment to rivers at times of heavy rain.

Not suprisingly, many schemes of morphoclimatic zones distinguish the mountain areas from the rest of the continents. Nevertheless, even in the cratogene areas, climatic zones tell us relatively little about landforms as such. As a first attempt at differentiation within one climatic zone, the humid tropics, geological history has to be considered (Table 1). The vast planation surfaces, argued by some to be the product of long periods of tropical landform evolution are characteristic only of the older land surfaces of Gondwanaland remnants.

### Plate Tectonics and megageomorphology

The southern hemisphere is the appropriate place to begin to analyse global megageomorphology for here can be seen great similarities from one continent to another and the existence of old land surfaces forming high level erosion surfaces. From the high ground of the plateaux of Africa, Australia or Brazil, the uniformity of the landscape is apparent in a way that cannot easily be recognised from aerial photographs or from the valley floors. However, it must not be assumed that all that is now at

the same level is of the same age. King (1983) argues that the features of a planation surface remain recognizably the same whether it remains close to sea level or is raised up by tectonic movements. Although a planation surface may be broken by faults or tilted by warpings, its surface characteristics should remain the same. Thus King recognises 6 global planation cycles (Table 2) remnants of which are to be found not only in the cratogene areas but also in such tectonically disturbed zones as the Andes and New Zealand Alps. The oldest cycle, the 'Gondwanaland' planation took place before the breakup of Gondwanaland and Laurasia. These platforms were largely destroyed by events on each continent as rivers drained to new base levels in the opening seas. The 'Kretacic' planation which followed is correlated with Jurassic to mid-Cretaceous oceanic sediments, and was terminated by vertical uplift in mid-Cretaceous time.

King (1983) sees the period of late Cretaceous to early Miocene time as one of tectonic quiet over large areas, outside the belt of Alpine, orogenesis. The 'Moorland' planation surface of this period can be found, he claims, over large areas of all the continents. Residual soils such as bauxite and ferricretes are widespread. For King, the 'Moorland' surface is the dominant landform feature from which most of the world's present scenery has been carved. At this stage it is unnecessary to go into detail on the other three planation surfaces, but it is important to look at their relationship to the break up of Gondwanaland and Laurasia.

While the breakup of Gondwanaland began about 200 million years ago, at the end of the Jurassic, 135 million years ago, the birth of the South Atlantic had only just begun by the opening of a rift and Madagascar was still joined to the east coast of Africa. Antarctica and Australia were still joined, and did not separate until the early Tertiary, the time at which the north Atlantic began to open between Rockall and Greenland in the final stage of the separation of Europe from America. On many of these land masses, great volumes of basaltic activity occurred, including that of the Deccan in India and in the British Isles from Antrim to Skye. However, such basalt flows were locally relatively shortlived, often spreading out over phenomena indicative of stable conditions, such as the erosion surfaces of the eastern highlands of Australia or the Cretaceous chalk of Antrim. All the evidence suggests that uparching, or cymatogeny (King 1983), possibly as continental plates pass over hot spots, may occur relatively quickly as the lithosphere becomes veined with magma. Thus the long period of 'Moorland' planation could easily be locally interrupted by doming, volcanicity and rifting as in the Rhine, Lake Baikal and Ethiopian rifts. (Bott 1982). The cracking-up of Gondwanaland and Laurasia is fundamental to much of the present day relief. The relationship of Britain to North America might have been closer if the North Sea rift had developed as fully as the mid-Atlantic rift did later. In fact the large-scale geomorphology of the British Isles has much in common with that of the Basin and Range province of the U.S. southwest.

## Re-assessment of global climatic geomorphology

The emphasis on the role of plate tectonic mechanisms continually disrupting the processes of erosion surface development finally forces geomorphologists to adopt a truly dynamic geomorphology which copes with both tectonic and climatic change. The old contrasts between tectonic activity and stability and between arid phases and wet phases have to be rejected as we move to a more critical event-based interpretation of the stratigraphy of the deposits which correlate with the development of our erosion landforms. The length of a climatic fluctuation required to produce a particular deposit or paleosoil is unknown. The last ten thousand years, studied in such detail, suggests that ecosystems can change quite rapidly, yet even in terms of Tertiary time, 10,000 years is very short. Given that the same thickness of sediments may be produced by both long, gradual deposition and a single rare, catastrophic event, the re-assessment of the principles of global climatic geomorphology becomes a challenging task. Since 1960 the mean annual sediment yields of the world's major rivers have been established. For many major rivers there are now several decades of records. In smaller basins long-term investigation such as the Coon Creek 1853-1975 study (Trimble 1981), have revealed how actual sediment yield has a temporal log often related to land use and river management changes. Yet with the data on vegetation conditions from AVHRR, the new WMO global studies of areas of unusually high or unusually low precipitation and the growing hydrologic and sediment yield data, it ought to be possible to link climatic variations to ecological change and seasonal and annual sediment yields. The duration and extent of ice, snow and wind-blown materials such as loess, could also be monitored in this way. The knowledge of the dynamics of the present day morphoclimate is an essential first step in the reassessment of global climatic geomorphology.

The second step is to look at the great synthesis of Julius Budel (1983) with his 10 present-day morphoclimatic zones (Table 3) and his emphasis on the great importance of the peritropical zone of excessive planation and the subpolar zones as the most effective morphoclimates. His approach to European landforms produces an elegant synthesis of successive phases of relief development, adequately emphasising changing geomorphic processes back to the late Cretaceous. Budel's tropical paleoearth would have existed over King's 'Moorland' planation period. Evidence of tropical conditions in relatively high latitudes in deposits such as the London Clay and the weathered interbasaltic bed in the Antrim basalts the stability of such climates and the magnitude of their short term variations is unknown. All that can be examined is the net result. Ocean areas indicate much more dramatic shifts of climate in the Miocene than once were expected. Similar detail for earlier periods may reveal comparable oscillations. Thus for megageomorphology the history of megadeltas and the details beneath desert sands become important. While the former depends on the drill bit, seismic and sonar records, the latter has been greatly helped by space shuttle radar.

The Magdalena Fan in the southern Caribbean Sea (Kolla et al. 1984), for example, provides a record of sedimentation since the late Cretaceous, with three late Cenozoic sequences associated with the uplift of the Andes. Analysis of the sediments in these areas can help reveal the timing and nature of changes in terrestrial ecosystems and denudation systems. Interpretation will only be improved if understanding of the variety of products of present-day morphogenesis is more closely analysed.

### Spatio-temporal thresholds

The critical state of a denudation system likely to produce a change in landform may depend on some major external factor, such as a succession of drought seasons, or on some internal condition, such as a massive random mass movement or the beginning of the undercutting of an unstable, weak material such as a dispersible mudstone. Any meaningful global geomorphology has to concentrate on the major continental fluctuations, probably best analysed in terms of seasonal changes. World climate data collection systems and weather satellite images will help in this. The studies of Saharan dust storms (Coude-Gausson and Rognon 1983) or the examination of climatic crises (Rognon 1983) indicate the way to go. Geomorphology is moving towards an event-based analysis. Progress will be made continuing to explore for the evidence of past changes and the analysis of present-day thresholds and major events. Only from the latter will the possibility of quantification emerge. However, unless these climatic events are coupled to tectonics, the full geomorphic significance of events like the El Chichon or Mt. St. Helens eruptions, or even the British earthquake of July 1984, will not be understood.

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TABLE 1 (after Douglas 1978)

Comparison of some pedological and geomorphological features of erosional landscapes  
Northern Australia, Sri Lanka, Peninsular-Malaysia, Borneo, New Guinea and Hawaii

Feature:	Australia	Sri Lanka	Malaysia	Borneo	New Guinea	Hawaii
Dominant age of landscape	Old	Old	Moderately old	Young	Very Young	Very Young
Proportion of fable rocks	Low	Low	Moderate	Moderate	High	Moderate
Recent Tectonism	Practically none	Practically none	Negligible	Some	Intense	Infrequent
Cainozoic vulcanism	Practically absent	Practically absent	Practically absent	Some	Abundant	Highly abundant
Tropical Karst	Practically absent	Virtually absent	Residuals only	Abundant	Abundant	None
Relief	Low to moderate	Moderate	Moderate	Moderate (save for Kmabulu)	Very High	High
Rate of Current soil development	Slow	Slow	Slow to moderate	Moderate	Rapid	Rapid
Rate of Current erosion and deposition	Low to moderate	Low to moderate	moderate	High	Very High	Very High
Depth of soil on slopes	Generally shallow	Generally shallow	Variable	Variable	Variable	Variable but usually high
Lateritic Crusts	Widespread	Widespread	Fragments	Possible	Absent	Absent
Palid zone of deep weathering	Widespread	Widespread	Few	Unknown	Rare	Rare

Note: The inspiration for this Table comes from Galloway and Laffler (1972) Table 2:1

TABLE 2 (after King 1983)

The several global planation cycles and their recognition

Planation Cycles:	Recognition:
I. The 'Gondwana; planation	Of Jurassic Age, only rarely preserved.
II. The 'Kretacic' planation	Early-Mid Cretaceous Age, on certain very high plateaux and ridges in Lesotho.
III. The 'Moorland' planation	Current from late Cretaceous till the mid-Cenozoic. Planed uplands, treeless and with poor soils. Often the oldest planation identifiable in Natal. Occurs below the Drakensburg escarpment. At the coast is overlain by marine Miocene strata.
IV. The 'Rolling' landsurface	Mostly of Miocene Age, forms undulating country above young incised valleys.
V. The 'Widespread' landscape	The most widespread global cycle, but more often in basins, lowlands and coastal plains than uplifted by recent tectonics to form mountain tops. Pliocene in age.
VI. The 'Youngest' cycle	Modern (Quaternary in age) represented by the deep valleys and gorges of the main rivers. Sometimes has glacial features.

TABLE 3

Budel's morpho-climatic zones of the present

1.	Glacial zone (and immediately adjacent area).
2.	Subpolar zone of excessive valley-cutting.
3.	Taiga valley-cutting zone, in the permafrost region.
4.	Etropic zone of retarded valley-cutting.
5.	Subtropic zone of mixed relief development, etesian region.
6.	Subtropic zone of mixed relief development, monsoonal region.
7.	Winter cold arid zone of surface transformation, largely through pediments and glacis.
8.	Warm arid zone of surface preservation and traditionally continued development, largely through fluvio-eolian sandplains.
9.	Peritropical zone of excessive planation.
10.	Inner tropical zone of partial planation.

## MEGAGEOMORPHOLOGY: MARS VIS A VIS EARTH

Robert O. Sharp  
California Institute of Technology  
Pasadena, California

The following comments are based largely on Mars vis-a-vis Earth. Personal knowledge of Moon, Venus, Mercury and other solar system bodies is too scanty for them to be included herein.

### Outrageous Hypotheses

One of the greatest benefits of the planetary exploration program could be to blast us out of intellectual ruts, forcing consideration or reconsideration of different, unusual, even seemingly outrageous explanations for puzzling natural phenomena.

The areas of chaotic terrain, the giant chasma of the Valles Marineris region, the complex linear and circular depressions of Labyrinthus Noctis on Mars all suggest the possibility of large-scale collapse of parts of the martian crust within equatorial and sub-equatorial latitudes. It seems generally accepted that the above features are fossil, being perhaps, more than a billion years old. Is it possible that parts of Earth's crust experienced similar episodes of large-scale collapse sometime early in the evolution of the planet?

We may have failed to recognize features created by regional collapse simply because of their scale or more likely because of alteration and obscuration by metamorphism, erosion, weathering, and burial, or any combination of those processes. It is difficult to find something if you don't know what you are looking for, lost car keys or trilobite fragments for example. What would a billion-year old area of chaotic terrain look like on Earth? Like the assemblage of rocks and structures constituting some terrestrial metamorphic complexes, for instance? Do some of our thick, multikilometer, localized accumulations of sedimentary rocks occupy ancient collapsed chasma? Does the seemingly nonsensical distribution of lithological units within some ancient complex rock terranes make sense if viewed in the pattern of martian labyrinth features?

An even more fundamental problem is the possible cause of large-scale regional collapse. On Mars deterioration of massive bodies of ground ice or the migration of magma from one area to another, to create gigantic volcanic constructs, have been proposed. Perhaps, it is time we looked again at the possibility of planetary expansion for both Mars and Earth. This old idea has not been generally welcomed to the banquet table by a majority of earth scientists, although vigorously sponsored by some, because of a seeming lack of adequate energy sources to produce significant expansion. Some of the discrediting calculations, however, have been made for an axial expansion of 1000 km, which seems an excessive requirement, or may not have looked far enough back into planetary history.

Planetary expansion might logically be expected to produce planet-wide manifestations. On Mars, visible surface features of collapse are located in equatorial and sub-equatorial areas, they are not planet-wide. Since both martian polar and subpolar regions, especially the north appear to have been sites of extensive deposition, collapse features there might be buried. It seems more likely, however, that martian collapse was actually equatorial in distribution. This makes one wonder if equatorial expansion of Mars may have involved a change in the figure of the planet rather than over-all expansion. An increase in oblateness of the spheroid, owing to an increase in rate of planetary rotation, could cause equatorial expansion in a latitudinal direction, a decrease in rotation rate would presumably result in longitudinal extension. An increase in rotational rate might have been caused by heavier elements settling to the core during planetary differentiation, but possible causes of a decrease are more speculative. Irregular distribution of martian collapse features within the equatorial region could reflect inhomogeneities of crustal and subcrustal materials. If Mars suffered a change in its spheroid because of a change in rotational rate, why not also Earth, albeit perhaps earlier in its history?

### Scale

The message from Mars in terms of surface features and relationships is "Think big." Many of the landslides, flood-scoured channels, valleys, chasms, labrinths, volcanoes, polygonal structures, collapse areas, rock streams, sand dunes, eolian deflated features, and other forms and relationships displayed on the martian surface are gigantic by Earth standards. This maybe, in part, a matter of viewing distance, commonly around 1000 km on Mars and only a fraction of that on Earth. More likely it is the result of the effective erasing and obscuring processes operating on Earth, weathering, erosion, and deposition, which allow us to see only the youngest features. By terrestrial temporal standards, much martian topography is fossil, the product of bygone processes and conditions. Could Earth once have had features of a size corresponding to those seen on Mars but now so modified by secondary surface processes to be overlooked?

If so, is it possible that relationships created by those features, mega-scars so to speak, could be identified or recognized by extreme remote sensing of Earth's surface? Further, are they worth looking for? The answer must assuredly be yes, for the unknown is always worth exploring. Mega-features of Earth's surface and crust already recognized and interpreted as the product of currently favored models, plate tectonics for example, might more satisfactorily be accounted for by some other model derived from the concept of large, fossil features developed perhaps by collapse of parts of the crust on a scale comparable to that seen on Mars.

## Genetic Processes

The processes of obscuration are so effective on Earth that we usually see or recognize only a part of the total work done by some particular genetic activity. This is a differential matter, and certain genetic processes are more suppressed or obscured than others. Features on the surface of Mars suggest that mass movements, wind, and ground-water (or ground-ice) sapping deserve more consideration than normally given in the creation of terrestrial landscapes. Wind is recognized as effective in local and special terrestrial settings, but it is possibly underrated in terrains of regional extent, except, in areas of extreme aridity. Features of the martian surface strongly suggest that wind is effective regionally, as well as locally, and should be factored into considerations of regional landscapes.

Many forms of mass movement are subtle and easily obscured by more vigorous and rapidly operating processes to the extent that the true contribution of mass movements is not recognized. On Mars, where the obscuring and competing processes are weaker, it is clear that mass movements of various types, including creep, slides, and collapse, have played a truly major role in landscape evolution.

Thanks to large and extensive features, widely distributed on the surface of Mars, that appear to have been created by sapping, this much neglected and overlooked process is now getting considerable well-deserved attention from terrestrial geomorphologists. The role of sapping in creating landforms merits further nourishment and cultivation.

## Catastrophies

Thanks, in part, to the opportunity for viewing of other planetary surfaces where fossil forms are preserved more fully than on Earth, terrestrial geomorphologists and planetary scientists have become more sensitive to the role and importance of catastrophies in creating landscape features. This is a healthy trend which deserves encouragement.

## Remote Sensing and Data Treatment

I suspect we have not yet succeeded in bringing into full play all the techniques, equipment, knowledge, and talents currently available for remote sensing of Earth's surface. Astronomers, astrophysicists, and planetary scientists may be doing a better job in that regard on distant planetary bodies. We should be able to measure more precisely and more fully the spectra of radiations emitted from Earth's surface.

Just as fruitful might be a more exhaustive processing of remote sensing data already on hand. Anyone who looked at the seemingly blank photos of Mars first returned by the Mariner 4 flyby, and then compared them with the final computer-enhanced product revealing a heavily cratered martian surface understands the potential of these methods. Are we perhaps sitting on a mine dump of valuable ore which has not been fully analysed?

## GEOMORPHOLOGICAL SIMILARITY AND UNIQUENESS

Robert S. Hayden  
George Mason University  
Fairfax, Virginia

The understanding of our planet and the dynamics operating at its surface has undergone a revolution in the past quarter of a century. Thanks to the development of new technologies, particularly in remote sensing of the environment, we are able to view the earth from a variety of perspectives and at a variety of scales. We can observe and directly study large regions of land by means of aerial photography and satellite imagery. We are rapidly gaining detailed knowledge of the over 70 percent of the planetary surface lying beneath the oceans which, until recently, had been terra incognita. The ability to study our planet or any specific region on its surface at multiple scales from large local scales to small regional scales has reordered our geomorphological perspectives and has given us the possibility of a fuller understanding of the dynamic complexity of the earth's surface.

At large local scales, the formation and development of the land surface tends to be dominated by a single process or several closely related geomorphic processes. Local landscapes can reasonably be labeled as landscapes of one or another geomorphic types such as volcanic, tectonic, coastal, deltaic or fluvial. The geomorphological investigation of local landscapes focuses on an in-depth study of the dominant process, as it operates in that location, comparing and contrasting its operation there with the same process operating at other locations. As study is expanded to larger regions dominant local processes come increasingly into competition with each other.

At smaller regional scales, geomorphological similarity gives way to difference and the unique character of each region becomes dominant, based on a regional geomorphic diversity. There appear to be thresholds of scale at which individual or closely related groups of geomorphic processes lose their dominance and diversity takes over. Identification of such thresholds is exceedingly difficult as they appear to vary from region to region. They probably also vary over time with changes in the mix of significant geomorphological processes operating on the regional landscape.

At smaller scales covering larger areas landscapes become regional geomorphological systems with a variety of processes interacting with one another to form the landscape. These regional systems are, in turn, sub-systems nested into one or more still larger regional systems of differing geomorphological character. For example, the Colorado River Delta Region in southwestern United States and northwestern Mexico is a highly complex geomorphological region located at the intersection of two larger geomorphological systems each controlled by different

complex of geomorphic processes. It is a sub-region of the Colorado River Drainage Basin, a fluvial geomorphic system in a predominantly mountainous setting, and, at the same time, a sub-region of the Gulf of California - Salton Trough, an active tectonic system in a largely marine environment. The delta region is a part of both and from the combination has inherited its unique geomorphic character.

Remote sensing technology, particularly the development of satellite imagery, has given geomorphology a valuable tool for the study of large area, regional landscapes. The small scale large area format of Landsat and other satellite imagery reduces the amount of detailed information provided for a given region. This can be an advantage for regional study as much of the local information that is filtered out tends to be detail which, while significant in small area studies, could mask regional patterns.

As resolution is improved and as new techniques, such as stereoscopic viewing become available, space imagery will provide more detailed information about particular locations. However, the primary value of space imagery for regional geomorphology lies not in the amount of detail it reveals but in the direct broad perspective of regions of the Earth's surface it provides. A regional geomorphology based on a broad perspective of the Earth is needed to compliment the detailed geomorphology focused on particular landforms and landform types, dominated by particular processes within relatively limited areas. Regional geomorphology should not be focused on detail but on the multiplicity of processes which, acting together over time, have given each landform region its character and uniqueness.

## REGIONAL LANDFORM THRESHOLDS

Dale F. Ritter  
Department of Geology  
Southern Illinois University  
Carbondale, IL 62901

One of the more significant trends in geomorphic thinking is the continuing development of the threshold concept. The importance of the concept stems from its premise that boundary conditions exist within geomorphic systems beyond which different processes will prevail or existing processes will change in magnitude or rate. Identification of the critical (threshold) conditions in terms of real parameters would allow geomorphologists to provide extremely valuable information to disciplines such as land management or environmental planning. In light of this, most studies involving thresholds have concentrated on establishing the conditions at which process change manifests itself through local erosion or deposition or by a change in the character of the process agent (rivers, glaciers, etc.). The emphasis on process thresholds seems to be prevalent regardless of whether the change is induced by internal or external factors. These studies are very important, but they require long and tedious collection of data.

The application of space technology to the understanding of process thresholds is an appealing goal of megageomorphology, but it may be extremely difficult to achieve because of spatial, magnitude and temporal problems. For example, changes in process attendant to the onset or decline of glaciation and the rise and fall of sea level are certainly large enough in magnitude to qualify as mega-thresholds. However, the time required to reach the threshold condition is probably well beyond the feasibility of continuous space monitoring. Other events such as the large dust storms viewed from space reveal processes that operate on a large scale. Clearly, these events represent the crossing of a threshold boundary of wind erosion, but whether they can be considered as a mega-threshold depends on factors such as recovery time. After the event has occurred the system may quickly revert to its original process condition of rate and magnitude. Thus, the threshold crossing may be only a minor aberration of process in a temporal sense, even though it was large in magnitude and affected a vast area.

Remote sensing technology allows us to recognize manifestations of regional thresholds, especially in the spatial characteristics of process agents. For example, a change in river channel pattern over a short distance reflects a threshold alteration in the physical controls of discharge and/or sediment. It is, therefore, a valuable indication of conditions as they exist. However, we probably will have difficulty determining whether the systemic parameters are now close to threshold conditions at which a different change will occur. This, of course, is a temporal and magnitude problem which is difficult to solve from the spatial characteristics. Certainly we can tell where threshold conditions

have been exceeded. Paleochannels and exhumed regional landscapes are testimony to mega-thresholds, and to the fact that part of the surficial environment is not adjusted to present conditions. However, it is difficult to ascertain from space when the mega-threshold was passed and at what parameter limits.

Despite these problems, the threshold concept should not be abandoned in megageomorphology. Another approach to the threshold concept might be to consider whether large geomorphic features also respond to external changes such as climatic variation or tectonic activity. In other words, do we have large scale landform thresholds whereby changes in external controls require significant adjustments in the character of the features themselves? Assuming that landform properties represent an accommodation between process and form, it might follow that process thresholds are forerunners of changes in the "equilibrium" character of landforms. If this scenario is viable, it suggests that continuous monitoring of landforms in regions experiencing climatic change or tectonic activity could yield important insights as to how and why landforms change. The converse may also be true. In addition, identification of the conditions that produce landform thresholds and the extent and nature of the response could also be important in disciplines concerned with the environment. Certainly the planned development of large communities in areas having landforms prone to threshold response would benefit by knowing what changes might be expected in the surface environment if external factors were altered.

It now seems certain that process thresholds can occur rapidly and often in response to relatively minor changes in controlling factors. It also seems clear that landforms are not permanent and, therefore, must change. The question, however, is whether they change within the temporal and spatial framework of the threshold concept. Thus, the suggestion of landform thresholds producing rapid adjustments to changing external factors is pure conjecture. Nonetheless, it is conjecture that can be tested. The reality of landform thresholds producing rapid response might be ascertained in areas that are presently experiencing climatic change or tectonic activity. Perhaps an excellent starting point would be to examine large alluvial fans and pediments in the extreme southern part of California. Recent acceleration of beach erosion and sea cliff retreat in this area has been attributed to a reasonably well-documented climatic change that began in the late 1970s. The suggested climate variation toward greater storminess and higher annual rainfall is based on long-term precipitation records and tree-ring analyses, in addition to varve thicknesses measured in Santa Barbara Basin. These data indicate that significant episodes of increased rainfall occur with a periodicity of about 30-40 years and last for about ten years. It is not certain how far inland this climatic shift penetrates, but parts of the Transverse Ranges are apparently being affected. Long-term weather records should be available farther inland to determine the areal extent of the climate change and its regional magnitude.

Assuming that a climatic variation has begun, what questions should we be asking about geomorphic features, and what information should we seek that might be provided by remote sensing technology? A few examples are offered using the climate change - fan adjustment as a model.

1) What geomorphic properties of large fans are best indicators of climatic change? In general it seems likely that morphometric parameters should be most fruitful in documenting any landform adjustment. Precisely which parameters should be employed will probably depend on the resolution of the sensing system. For example, the well known relationship between drainage basin area and fan area could easily be measured because the entire fluvial system can be viewed simultaneously. Depending on sensing resolution, it may also be possible to detect changes in drainage density in the source areas and the fan areas, and the ratio of the two. A change in fan shape might be determined by the relationship between perimeter length and fan area.

2) To what degree does human activity accelerate or depress the expected landform adjustments? Fans are commonly the locale of community development which may prevent adjustment. In contrast, various activities in the source areas may accelerate fan responses. Comparison of fans in sparsely inhabited areas, such as Baja, California, to those in highly developed regions could indicate the effect of human activity.

3) How long does it take for landforms to respond to climatic change? It may be that fans do not respond to climate variations having the cyclicity mentioned above; however, even that information would be significant.

4) What magnitude of climate change is needed to produce tangible modifications in fan character? Perhaps large fans are affected only by climatic variation having the magnitude of the glacial-interglacial cycle. If responses do occur, and it can be shown that the climate change is regional in extent, fans in different parts of the southwest U.S. may adjust in different ways and with a hierarchy of intensities. Some relationship might exist between the magnitude of climate change and the rate and degree of fan modification.

5) Are intrinsic fan thresholds real or do they represent responses to minor changes in external controls? Certain fan phenomena such as alternating fanhead trenching and filling are conceivably part of internal fan mechanics involving changes in channel slope at the fan apex. These reactions are logically controlled by an intrinsic threshold. It is also possible, however, that they represent adjustments to minor, periodic shifts in external controls. Simultaneous responses of the same type occurring on fans over a wide regional extent may indicate adjustment to external rather than internal controls.

6) Is there a size of fan threshold? It may be possible that the response or non-response of a fan to minor climatic variation is dependent on the fan size. Small fans may respond, but larger fans may require greater

magnitude of climate change or a longer time to reveal a tangible change.

The questions posed above are meant to be examples and are certainly not the only ones possible. It does seem, however, that modern sensing technology allows us to raise and possibly answer a variety of questions that would require enormous effort using more traditional geomorphic approaches.

## SOME OBSERVATIONS ON PALEOGEOMORPHOLOGY

Sheldon Judson  
Princeton University  
Princeton New Jersey

Reconstruction of ancient landscapes and landscape processes have long been attempted, and continue to be, with varying degrees of success. The process is not trivial and demands a wide variety of data collected over broad areas by students in many disciplines and sub-disciplines. The last two or three decades have seen a tremendous growth in the volume and quality of these data. As a result we now might very well try some paleogeomorphic studies on regional or larger scales.

The vast supply of new data available to us include (1) those attendant on the development of the theory of plate tectonics, (2) the information derived from an ever expanding volume of geologic and geophysical mapping, and (3) the greatly increased number and quality of geologic dates, particularly those radiometrically derived.

To an increasingly sound base for the examination of past geomorphologies we can begin to add some quantitative methods for the determination of past erosion rates. We have had but modest control over this aspect of the development of past landscapes. Most of our quantitative evaluations of erosion rates are focussed, understandably enough, on the Recent. There are some new techniques, however, that can be of help in measuring rates in the geologic past, well into Phanerozoic time.

We measure an erosion rate by (1) determining the amount of material accumulated from an area over time in a collecting basin, or (2) by measuring the material in transport from an area in a given time, or (3) establishing the distance a point or surface in the underground moves toward a subaerial position in a given length of time. It is this last method for which some new tools have become available during the last decade or so. Four are given below.

1. The color of a conodont changes with temperature. Temperature may be equated, via the geothermal gradient, with depth. The fossil provides a time line. Time and distance being known, a rate can be estimated. Anita Harris, et al., (1978) have contoured the color changes in conodonts in the Appalachian Basin. These can be converted into contours depicting lines of equal erosion.

2. Metamorphic assemblages have long been used to determine pressure and temperature conditions during their formation. Both P and T lead to estimates of depth. Using such information along with the information from fluid inclusions, radiometric ages, and general geology, Hollister (1982) has arrived at a rapid (2 mm/yr) uplift rate - by extension, an erosion rate - for a portion of the Coast in British Columbia.

3. The  $^{40}\text{Ar}/^{39}\text{Ar}$  incremental release technique can provide not only a primary age for a mineral but also, in some instances, the age and temperature of a subsequent thermal event which has affected the mineral. Dallmeyer (1978) combines the  $^{40}\text{Ar}/^{39}\text{Ar}$  method with other radiometric techniques, metamorphic assemblages, and geologic mapping to produce a thermal and tectonic history from which erosion rates are derived. For example, in the Stone Mountain area of Georgia's Inner Piedmont he deduces erosional rates of 0.162 mm/yr from 365 to 220 my ago and gives data for a rate of 0.02 mm/yr from 220 my to the present.

4. Fission track dating provides the age of the annealing process in such minerals as apatite, sphene, and zircon. Annealing occurs at different temperatures in different minerals. If we equate depth with temperature we again have time and distance from which to determine rate. Zeitler et al (1982) used such data, along with petrologic analyses, field relations, and radiometric ages, to outline the uplift history of a section of the Himalaya in Pakistan. Uplift rates, at different times and in different settings, were determined to range from a low of 0.07 to 0.7 mm/yr. We may equate these uplift rates roughly with erosion rates.

Turning to another subject, we have long recognized climate as a major geomorphic determinant. Climatic information is available to us from the paleontologic and sedimentologic records. But a number of workers are trying to develop computer models of past climate. Here the work on paleoclimate and ancient landscapes can be mutually supportive.

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ANCIENT LANDSCAPES  
THEIR NATURE AND SIGNIFICANCE FOR THE QUESTION OF INHERITANCE

C.R. Twidale  
University of Adelaide  
Australia

INTRODUCTION

It is still widely believed that much of the world's scenery is youthful. Thornbury's (1954, p 26) assertion that little of the world's scenery is older than Tertiary and that most of it is no older than Pleistocene dies hard. Yet there is ample evidence, long recognised, that very ancient forms and surfaces (here the term "surface" is used in the sense of a planation surface, surface d'aplanissement or Einebnungsfläche) are an integral part of the contemporary landscape, and that such features are not restricted to the low latitude regions, though they are well preserved there. Many of them were formed in environments very different from that in which they now occur and are thus inherited. Paleosurfaces of many age ranges have been recognised. They can conveniently be considered as of three types - exhumed, epigene and etch.

EXHUMED LAND SURFACES

These are forms and surfaces that have been buried and then re-exposed. They range in age from Archaean to Pleistocene. For example, part of a late Archaean inselberg landscape is locally exhumed where the headwaters of the Yule River extend into the Chichester Range of the northern Pilbara in the north of Western Australia. Some of the ancient landforms can also be observed in unconformity. Proterozoic landscapes, some in the form of plains, others involving inselberg landscapes, have been re-exposed in many parts of Arctic Canada and Greenland (Cowie, 1961; Ambrose, 1964) and in northwestern Scotland (e.g. Williams, 1969) where old inselbergs and pediments are both exposed and preserved in unconformity. Glaciated pavements of various Precambrian ages, once buried and now exhumed, have been reported from several of the world's cratons (see e.g. Harland, 1964; Perry and Roberts, 1968) and, of course, remnants of Late Palaeozoic glaciated pavements and related features of exhumed character are well known from various parts of Gondwanaland (see e.g. Crowell and Frakes, 1971). Watts (1903) long ago described fragments of a Triassic desert landscape from Charnwood in the English Midlands, and barchans of similar age are preserved beneath basalt flows in the Parana Basin of South America (Almeida, 1952).

Exhumed surfaces and assemblages of essentially Late Jurassic (or earliest Cretaceous) age are widely preserved. Such features are present, for example, at the margins of the Australian Craton - in northwest Queensland (the same surface has been traced into the western slopes and even into the higher areas of the Eastern

Uplands in north Queensland): the Tindal area of the northern N.T.; the Darwin area; the northern Flinders Ranges, South Australia; the northern Pilbara and Geraldton region of the central west coast of Western Australia (Twidale, 1956, 1984; Woodard, 1955; Twidale, 1981a; Jack, 1915; Wopfner, 1964; Playford et al, 1970). Exhumed and partially exhumed inselberg landscapes of this age can be seen east of Port Hedland in the north of Western Australia. Passarge (1895) argued that the Inselberglandschaft of Rovuma type is exhumed and of early Mesozoic age. Similarly, the famous inselberg landscapes of East Africa may in part be exhumed from beneath a Cretaceous cover (Willis, 1936). Various exhumed minor granite forms of Cretaceous age have been described from southern Sweden (e.g. Lidmar-Bergström and Rapp, 1978; Magnusson and Lidmar-Bergström, 1983). Exhumed inselberg landscapes or slightly younger age (pre Eocene) occur in northern Nigeria where bornhardts and nubbins have been exposed as the Benue Sandstone has been stripped away (Falconer, 1911).

Inselberg landscapes of pre Pliocene age are in process of re-exposure in the Murray Gorge in South Australia and pre (?late) Pleistocene inselbergs, including a suite of minor forms that are also being exhumed, from beneath Pleistocene dune calcarenite in northwestern Eyre Peninsula (Jack, 1912; Twidale and Bourne, 1976; Twidale and Campbell, 1984)

Clearly such exhumed features are especially significant in shield areas. The most important are related to major periods of world-wide marine transgressions of which the late Jurassic and early Cretaceous is a notable and geomorphologically significant example. The nature of the surfaces is frequently difficult to ascertain, for only rarely is there a saprolithic or sedimentary veneer preserved at the unconformity (but see Barbier, 1967). Most likely there has been marine trimming whatever the nature of earlier development. In places, the unconformity appears to be remarkable smooth, but elsewhere, as in the southern suburbs of Darwin, it is undulating. On the other hand, the preservation of such exhumed surfaces presents few difficulties, for they have been protected by the younger cover that has been eroded or is in process of erosion. Some exhumed features clearly evolved in environments different from those in which they now occur. This is most apparent in the case of those exhumed glacial forms now located in tropical or subtropical regions, but the observation applies equally where, for instance, marine features are exposed in continental areas.

#### EPIGENE PALAEOFORMS

These are surfaces that have apparently been exposed since their formation; they have not been buried, but survive despite their considerable antiquity. One of the oldest, if not the oldest, dated palaeosurfaces is preserved in the Gulfs region of South Australia. A laterite-capped high plain or plateau occurs on Fleurieu Peninsula, the Mount Lofty Ranges, the Lincoln Uplands (southern Eyre Peninsula), and on Kangaroo Island. On Fleurieu Peninsula and the Mount Lofty Ranges the lateritic high plain is

defined by faults. Marine sequences of Eocene-Miocene age occupy fault angle depressions marginal to the uplands, suggesting that the laterite and the surface on which it developed predates the Cainozoic. And lateritic fragments are reported from the basal Tertiary sequences (Campana, 1958; Glaessner and Wade, 1958).

On Kangaroo Island the laterite is developed on Precambrian, Cambrian and Permian strata. To the west of Kingscote the laterite was truncated and a basalt extruded onto the plain cut in mottled and pallid zone materials and standing lower than the main lateritised high plain. The basalt has been radiometrically dated as of Middle Jurassic age. Thus the laterite and the surface on which it developed postdates the Permian but predates the Middle Jurassic: other stratigraphic evidence suggests a Triassic age (Daily, Twidale and Milnes, 1974). Near Penneshaw a similar basalt rests on ferruginous zone laterite (Tilley, 1921; Daily, et al, 1979). The lateritised land surface has not been preserved by burial. Not only is there no evidence for such an event, but the sandy A-horizon is widely preserved and the mineralogy, granulometric characteristics and textures are consistent with its being a pedogenic feature; there is no possibility of introduction or transport. The lateritic and bauxitic high plains of the Darling Ranges, in the southwest of western Australia are, on the stratigraphic evidence and according to Fairbridge and Finkl (1978), of Cretaceous and Eocene age. Laterite-capped land surfaces of Jurassic age are reported from West Africa (Beaudet, 1978) and southern India (Demangeot, 1978).

The ancient surfaces described from the Drakensburg of southern Africa are of Mesozoic age, for they stand well above lateritised plains (African Surface) that are of early-middle Tertiary age (King, 1962; but see also de Swardt and Bennet, 1974).

Another ancient landscape is preserved in the southern Flinders Ranges of South Australia. The Flinders Ranges is a fold mountain belt of Appalachian type. An exhumed late Jurassic surface is preserved in the northern part of the upland, and remnants of a high plain interpreted as of similar age, but possibly graded to the Jurassic or Early Cretaceous shoreline, dominate parts of the central Flinders and are also recognised in the southern regions. Following recession of the Cretaceous sea, streams again dissected the folded sedimentary sequences and the present ridge and valley topography, determined by the pattern of the Palaeozoic folds, was formed. That pattern had evolved by the Eocene (Twidale, 1966, 1981a), for Cainozoic sediments laid down in a lake that during the Eocene extended over the northern Willochra Basin (an intermontane basin eroded in a faulted anticline) tongue up valleys eroded between the quartzitic ridges, showing that the framework of the present relief was already in existence during the Eocene; it has changed very little since. And extrapolating, there is no evidence to suggest that the pattern of ridge and valley developed throughout the Ranges is not of similar antiquity.

In the arid interior of western Australia the major drainage features now represented by strings of salinas date from the late Cretaceous and early Tertiary (Van de Graaf et al, 1977). In the southeast, for instance, the rivers drained to the Eocene shoreline at what is now the margin of the Eucla Basin (Nullarbor Plain).

Less dramatic (only because they are younger) but more extensive land surfaces preserved by ferruginous or siliceous duricrusts occur in many parts of the world. In Australia such lateritised and silcreted land surfaces, of essentially early-middle Tertiary age, occupy very large areas of the north and centre of the continent (see Twidale, 1983). Early Tertiary drainage channels preserved by silcrete deposits persist in the north of South Australia (Barnes and Pitt, 1976). The Ooldea and Barton ranges, at the northeastern margin of the Nullarbor Plain-Eucla Basin region are coastal foredunes of probably Miocene age developed in relation to a marine embayment and preserved by virtue of a calcrete capping (M. Bembow, pers. comm.).

(Many other ancient land surfaces have been recognised and dated, as, for example, in the Cleve Hills, Gwaler Ranges, and Arcoona Plateau in South Australia (see e.g. Twidale, Shepherd and Thomson, 1970; Twidale, Bourne and Smith, 1976; Twidale and Campbell, 1985a) and the MacDonnell and other fold ranges of central Australia (e.g. Twidale, 1980). Some granite inselbergs are thought to be of considerable antiquity from correlations between their stepped morphology and dated duricrusted remnants (Twidale and Bourne, 1975a; Twidale, 1982a, b, c). The basic forms of Ayers Rock and the Olgas are demonstrably of at least Eocene age (Twidale and Harris, 1977; Twidale, 1978a; Twidale and Bourne, 1978). But in these and other instances very little in the way of saprolith remains and it is almost certain that the forms are of etch character - see below).

These very old epigene forms present obvious problems, for their survival is difficult to explain (Twidale, 1976a). Positive feedback effects, protection in interior situations, compression of bedrock and unequal erosion all ease, but do not entirely resolve, the difficulty. Nevertheless, as ancient landforms exist, they must be possible.

Long survival has several results. Where escarpments, whether of structural or erosional origin, are being worn back only slowly, as in aridity or late in the dissection of plateaux (see e.g. Twidale, 1978b), scarp foot weathering causes a characteristic suite of minor forms to develop in the piedmont zone. On massive rocks flared slopes, platforms and enclosed linear or annular depressions are formed (see e.g. Clayton, 1976; Twidale, 1962, 1982a). In sedimentary environments scarp foot valleys, false cuestas and inverted channels develop. Gully gravure (Bryan, 1940; Twidale and Campbell, 1985b) and silcrete development take place, the latter a sure sign of slow landscape change (Hutton et al, 1972). More importantly, such scarp foot weathering and erosion ensure that scarps tend to a maximum steepness commen-

surate with stability (Twidale, 1960, 1967; Twidale and Milnes, 1983). On a regional scale long-continued deep and intense weathering mainly through the agency of water, though with significant contributions from microbial organisms (see Loughnan, 1969; Trudinger and Swaine, 1979), allows the saprolith to become thoroughly leached. It is no accident that the soils of ancient Australia and other old tropical landscapes are notoriously low in such solubles and phosphorus and various trace elements, and that they are readily eroded. The saprolith frequently becomes differentiated, and though most weathering can be regarded as geomorphologically negative or destructive, long-continued weathering allows the concentration of definite zones of horizons of minerals that, on desiccation, become remarkable tough. Such positive or constructional weathering effects are often overlooked, but they loom large in any consideration of the tropical lands. Geomorphologically such duricrusts not only form caprocks and so give rise to plateaux and in some areas lead to regional inversion, but they also form morphostratigraphic markers (see Twidale, 1981b, 1983). Another important geomorphological effect of deep, intense and long-continued weathering is the formation of a pronounced weathering front (Mabbutt, 1961a), an abrupt transition from friable weathered material to intrinsically fresh bedrock. This is the basis of an assemblage of forms, etch forms, that are increasingly recognised as of prime significance in the modern landscape.

#### ETCH SUBCUTANEOUS AND INTRACUTANEOUS FORMS

An etch surface or form is one that was initiated as part of a weathering front and has then been exposed through the stripping of the saprolith. Such features range in scale from boulders and minor forms like basins and Rillen to plains of regional extent. Their morphology reflects the exploitation of every structural nuance by weathering agents, and especially by moisture attack. The stripping of the saprolith, on the other hand, may be achieved by a variety of agencies - fluvial, glacial, marine.

The term "etch" originates with Wayland and Willis, but the essence of the idea was published much earlier. Thus, Hassenfratz (1791) and Logan (1849, 1851) recognised that minor granite forms had their origin in the subsurface at the weathering front (though they did not use the term). And Jutson (1914, see Brock and Twidale, 1984) was clearly aware that the New Plateau of the southwest of western Australia was an exposed weathering front, and that it is due to the erosional stripping of the lateritic saprolith that underlies the Old Plateau.

Though widely used (and etymologically apposite, for to etch is to engrave by means of a corrosive fluid), it is not certain that the term "etch" coined by Wayland (1934) and Willis (1936) is the most appropriate for describing the realities of nature. The saprolith is, in many areas, not a simple feature. In particular, resistant or potentially resistant horizons develop within the saprolith and are later exposed as surfaces or forms. For this reason alone it may be preferable to use Zwittkolvits'

(1966) evocative term "subcutaneous" for features that have evolved at the base of the saprolith (the true weathering front) and apply the term "intracutaneous" to those that are initiated within the saprolith. Thus, strictly speaking, many laterite-capped plateaux are etch or intracutaneous forms, for the A-horizon has most commonly been stripped to expose the ferruginous zone on which the land surface has stabilised. Intracutaneous forms originating deep in a lateritic saprolith occur in the Daly Basin, N.T. where the Bradbury Surface is coincident with the exposed ferruginous zone, but the Maranboy Surface, for instance, reflects the exposure of a silicified horizon within the profile (Wright 1963). But whatever terminology is used, the essence of etch/subcutaneous and intracutaneous forms is that they result from a structural contrast resulting from the weathering of the country rock: the saprolith is in whole or in part markedly less resistant than the fresh country rock.

Büdel (1957, 1977, 1982) has described etch surfaces from several parts of the world. Jutson's interpretation of the nature and relationship of the New and Old plateaux of Western Australia has been corroborated by later workers (Mabbutt, 1961b; Finkl and Churchward, 1973). The summit surface of the Mount Lofty Ranges is of similar type (Twidale and Bourne, 1975b; Twidale, 1976b), and various etch surfaces occur in the Mid North of South Australia (Alley, 1973). The prominent Hamersley Plateau is of etch type, though the surface is, in fact, morphologically so complex that it is best referred to as a Landscape (Twidale, Horwitz and Campbell, 1985). Pockets of pisolitic iron remain on the surface, but most of the weathered ironstone has been eroded. Some of the iron was re-precipitated in valley floor deposits (the Robe River Pisolite) that are of Eocene age. Thus, the earlier Hamersley Landscape is in one sense a Mesozoic feature: that is when the deep weathering occurred. The erosion of the saprolith, however, occurred in the early Tertiary. Etch forms have two ages: an age related to the period of deep preparatory weathering, when the weathering front was formed, and an age relating to the period of exposure, when the saprolith was stripped away to expose the front.

Several interpretations have been offered in explanation of granitic inselbergs of which the bornhardt is the basic form, and several have local applications, but most bornhardts are structural landforms that owe their resistance to weathering and erosion to the massive character of the compartments on which they are developed (Twidale, 1982 a and c). They originated in the subsurface as structurally determined projections of the weathering front (Falconer, 1911; Linton, 1955). It is no accident that the classical Inselberglandschaften are found in the interiors of the old supercontinents, where the rate of landscape change was slow, and there was ample time for deep differential subsurface weathering - first of the two stages involved in inselberg development. The inselbergs have been exposed by various agencies, including ocean waves and glaciers, though in this regard most are fluvial.

As might be expected in view of the origin of the host masses, many minor forms characteristic of granite outcrops are demonstrably initiated at the weathering front (Twidale, 1982; Boyé and Fritsch, 1973; Twidale and Bourne, 1975c, 1976).

Towerkarst may be of similar character. Certainly, minor features associated with limestone towers are suggestive of subsurface initiation and of the phased or episodic exposure of the major forms (see e.g. Sweeting, 1950; Lehmann, 1954; Jennings, 1976; Wilford and Wall, 1965; see also Twidale and Bourne, 1975a; Twidale, 1982a, b, and c).

Several features that are otherwise difficult of explanation may be of etch character. Thus, the Carnatic is an extraordinarily wide coastal plain in southeastern India. According to Cushing (1913) it averages some 60 Km width and is clearly of marine origin in an immediate sense, with spits and bars and what are construed as marine caves and stacks preserved near the inland margin (Cushing was not unduly influenced by the fact that the Ghats rise from the plain, and that the word "ghat" means water-steps - landing stairs from the body of water: there is apparently real evidence of the marine origin of the Carnatic). Yet the plain is altogether too wide to be due wholly and simply to marine planation. Very wide (up to 200 m from cliff base to outer edge) platforms in granite on northwestern Eyre Peninsula have been explained as etch forms, with the old saprolith stripped by wave action (Twidale, Bourne and Twidale, 1977). Could the Carnatic be of similar type, with marine agencies responsible for the erosion of a saprolith (under conditions of relative gradual rise of sealevel) and the retouching of the surface? Similarly, is the Labrador Plateau basically an etch surface due to the bulldozing (Boyé, 1950) of the preglacial saprolith by the Pleistocene ice sheets?

## DISCUSSION

Ancient land surfaces are an integral part of the modern scenery. From an economic point of view they imply leached soils or, in the case of etch surfaces, only thin soils, with all that such conditions imply for agriculture, soil erosion, and so on; and also the possibility of mineral concentrations. They pose problems for all the conventional models of landscape evolution (Twidale, 1976). The fact of inheritance also poses the question as to which morphogenetic system should be applied when explanations of landscapes are sought. Ancient surfaces and forms are especially well developed and preserved in the shield lands, but they are not restricted to them, for palaeoforms are well represented in orogenic and platform areas. Etch forms and surfaces are best developed in the protected interiors of continents or of former supercontinents. That regional drainage patterns may be inherited from such old planate surfaces is an importance consideration in the search for minerals (including water). Such palaeoforms frequently introduce an alien or exotic element to the landscape, for they developed in conditions different from those in which they are now found. Inherited glacier features

are an obvious example (though caution is necessary in interpretation in some instances (see e.g. Daily, Gostin and Nelson, 1973; and Agassiz, (1865) and Romanes (1912)). Torrid climatic conditions dominated the later Phanerozoic and many of the forms and surfaces reflect weathering and erosion under such warm humid conditions. Ayers Rock and the Olgas, for example, had their origins in the warm humid conditions of the Eocene, though they now stand in the desert plains of central Australia. Silcrete and laterite are also torrid forms, though silcrete especially is preserved in aridity (Hutton, et al, 1978; Wopfner, 1978).

Etch planation introduces another aspect to the question of inheritance, however. An etch, or subcutaneous, surface or form is an exposed weathering front, developed in the subsurface as a result of moisture (and biotic) attack. It develops regardless of the climate at the surface: the saprolite varies in thickness and character according to climate, but the nature of the front, it is suggested, basically reflects structure, and the effects of moisture and biotic action. It is largely independent of surface precipitation and temperature. Inselbergs, boulders, and minor basins, Rillen, etc. (see e.g. Boyè and Fritsch, 1973; Twidale and Bourne, 1975) are developed at the weathering front in a range of climatic conditions. The form of the front is retained regardless of the nature of the exposing agency. It is suggested that etch developments impose a significant commonality orazonality on the landscape. Together with structural control (which is in any case a prominent factor in subsurface weathering) it imposes a significant uniformity on landscapes, major elements of which persist from Tertiary and even earlier times, despite the effects of the ephemeral late Cainozoic glaciations.

Many landforms have their origins not at the land surface but at the weathering front. This is as true of gross morphology as of detailed sculpture. Not only hills and plains, but basins, gutters, elegant flares and linear depressions are initiated there. Alveolar weathering, which is of particular interest to students of Mars (Garvin, et al, 1981), also appears to be associated with iron concentrations at the weathering front.

The processes active at the weathering front are crucial to our understanding of the shape of much of the earth's surface. And whatever their precise character, water and microbial activities are prominent factors all over the world, so that the nature of the exposed fronts is similar over wide areas. This commonality adds another dimension to the question of inheritance.

Overall, then, the surface of the continents needs be viewed not as a simple feature comprehensible in terms of present or recent climatic conditions but rather as a mosaic comprising segments of different ages and origins, some of them of considerable antiquity. The events of the late Cainozoic loom large in our thinking, but the conditions then prevailing were ephemeral. Certainly lowerings of sealevel caused dissection and allowed dessiccation and hardening of some weathering horizons to produce duracrusts (though this would have occurred anyway though for dif-

ferent reasons). Otherwise landscapes were modified rather than drastically altered. The basics of much contemporary scenery date from earlier times and conditions.

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## GEOMORPHOLOGY, TECTONICS, AND EXPLORATION

Floyd F. Sabins  
Chevron Oil Field Research Co.  
La Habra, California

Explorationists interpret satellite images for tectonic features and patterns that may be clues to mineral and energy deposits. The tectonic features of interest range in scale from regional (sedimentary basins, fold belts) to local (faults, fractures) and are generally expressed as geomorphic features in remote sensing images. Explorationists (present writer included) typically employ classic concepts of geomorphology and landform analysis for their interpretations, which leads to the question - "Are there new and evolving concepts in geomorphology that may be applicable to tectonic analyses of images?" The NASA workshop is an opportunity for explorationists and geomorphologists to explore topics of mutual interest and application.

## MEGAGEOMORPHOLOGY AND NEOTECTONICS

Laurence H. Lattman  
New Mexico Institute of Mining and Technology  
Socorro, New Mexico

For several decades, subtle neotectonic effects involving several square kilometers have been studied in detail using remote sensing -- primarily various types of stereo-aerial photographs at scales of 1:10,000 to 1:80,000. These subtle effects, especially local uplifts associated with growing structures or differential compaction, have been detected by the effect on drainage patterns, changes in hydraulic geometry of individual channels or groups of channels, tonal halos (soil) and fracture patterns. The studies were extended with the advent of thermal IR imagery particularly in tonal analysis, and SLAR primarily in fracture pattern studies. Lately, quantitative efforts have begun attempting to link measured uplift over known structures with measured changes in hydraulic geometry and alluvial deposition. Thus, efforts are now underway attempting to quantify the relationship between neo- (micro-) tectonic changes and geomorphic parameters of drainage systems.

No published studies exist, to my knowledge, relating to regional neotectonic movement and geomorphic effects. Now, with thousands of square kilometers visible at once, and very recent stereoscopic imagery, mega-geomorphic effects of "mega-neotectonics" may be observable. For example, regional tilting or warping over an area tens or perhaps hundreds of kilometers long is known or suspected from repeated first-order level lines or cadastral surveys. No systematic studies of the large scale effects of such neotectonics exist.

Several Questions arise immediately:

1. Scale of effects: Streams are known to "slip off" or deflect around structural uplifts of small vertical extent. Such features generally cover 5 to 15 square kilometers. Do larger, fourth or higher order streams "slip off" or deflect due to subtle regional tilting or uplift? Are the many variations in lithologic resistance to stream erosion which would be encountered in a large area too great and therefore likely to mask such effects? In what large geomorphic provinces are such variations in resistance likely to be unimportant -- alluvial plains, deltas, glacial till plains?

2. Time scale: Are very large scale neotectonic effects likely to have mega-geomorphic expression as rapidly as studies have indicated local neotectonism does? It appears that small streams (second order) may show changes in hydraulic geometry due to neo-tectonism (or man-made, pseudo-neotectonic) effects within a few years. Is the same time enough for mega-geomorphic effects on drainage systems -- an intuitive, negative answer may be incorrect.

3. Non-drainage effects: Are there mega-geomorphic features other than those of large drainages to be seen resulting from large scale neotectonism? For example, subtle eolian effects, changes in features related to sheetwash, subtle changes in directions of erosional grain (smaller stream erosion seen only as a "grain" on small scale imagery), alluvial deposition changes, coastal features both erosional and deposition and far less obvious than the classical "shorelines of submergence or emergence."

In the United States and Europe, first and second order level lines have been established and resurveyed over many years. Regional neotectonism may be estimated from such data. Reasonably good repeated aerial photography now covers about 50 years in this country and systematic satellite imagery over a dozen years. Space photos, Landsat data, etc., provide a new format by which to study regional neotectonism involving uplift or tilting.

Neotectonic effects along larger faults -- those well expressed on regional imagery and particularly those on which recent movement has occurred -- are an area perhaps amenable to similar studies. An eventual aim here might be the systematic study of subtle mega-geomorphic features possibly associated with strain and incipient movement. This is again an area in which, to my knowledge, no concerted effort has been reported in the literature. A suggested approach would be first, to take the well-known geomorphic criteria for detection of local neotectonic effects which have been established by the oil explorationist (photogeologist-geomorphologist) and apply them over a much larger area to features such as the Palmdale "bulge" or the Wasatch fault system. In such a study the logical (and common) approach would be from the regional, small scale image to the detailed, large scale images of selected areas.

Several areas in the southwestern United States such as the Rio Grande Valley studied by Schumm and his associates, show measurable neotectonic uplift. These have not been studied by remote sensing, and should be.

Finally, the type of sensor or image best suited for such studies, if indeed a "best one" exists, is unknown. A review of mega-geomorphic effects related to the Palmdale "bulge" as seen by several types of remote sensor or after various types of enhancement, might shed light on this question.

## ANDEAN EXAMPLES OF MEGA-GEOMORPHOLOGY THEMES

Arthur L. Bloom  
Department of Geological Sciences  
2122 Snee Hall  
Cornell University  
Ithaca, New York 14853

### I. GEOMORPHIC PROVINCES

Geomorphic (or physiographic) provinces have been a well-known and useful method of regional landform classification for a century. Every earth scientist will recognize a phrase such as "Appalachian Plateau" or "Southern Rocky Mountains" as defining a discrete region of consistent geologic structure that has experienced a similar interval of erosion by a similar process or set of processes. The geomorphic provinces formalized in the United States by Fenneman in the 1920's continue to be highly satisfactory even though some boundaries were only vaguely drawn. Mosaics of Landsat images illustrate better than any earlier maps the validity and coherence of Fenneman's provinces (see Bloom, 1979). The concept of geomorphic provinces has been used subconsciously or intuitively, to describe the relief of the ocean floor and the topography of the moon and other planets.

A variant of the geomorphic province is the "morphotectonic region" in which relief is a direct expression of recent or ongoing tectonic and volcanic activity. The central Andes have apparently attained their present relief only in late Cenozoic time, and the landforms clearly show the regional tectonic patterns. A particularly interesting aspect of the morphotectonic subdivisions of the Andes is the repetition of "basin and range" morphologies in two tectonically different areas, the Puna and the Sierras Pampeanas. In spite of the geomorphic similarity to the extensional Basin and Range of the western United States, in both the Puna and the Sierras Pampeanas the ranges are bounded by reverse faults. This contradiction between the extensional Basin and Range of the western U.S. and the compressional "basins and ranges" of the Central Andes illustrates there is still much to be learned about the genesis of morphotectonic provinces.

Because relief elements are so easily seen and defined on TM and other space images, the central Andes is an excellent area in which to construct a complete morphotectonic classification of landforms from TM images. Suspected correlations between landforms and tectonic movements can be clarified by use of other space images such as side-looking radar and thermal images, and existing geologic maps and reports. Based on five years of previous research in the central Andes and on-going projects, including the anticipated receipt of SIR-B coverage, selected ancillary TM images and hand-held camera photographs, the Cornell Andes group will have built an extensive data base for the efficient and tectonically significant definition of that complex landscape.

## II. LANDSCAPE INHERITANCE

Bloom - 2

The Sierras Pampeanas are fault-bounded mountain massifs of crystalline basement rocks that reach elevations of 6 km on the eastern flank of the Andes between 28°S and 33°S. Tectonic uplift of the mountain blocks and subsidence of intervening basins has been active in Pliocene and Pleistocene time.

The uparched and tilted surfaces of the Precambrian and Paleozoic crystalline rocks in the Sierra Pampeanas are being stripped of younger sedimentary cover strata. Most of the covering rocks are of Cenozoic age, but some are of late Paleozoic and Cretaceous age. All are continental sediments except for a small area of Miocene marine sediments in the Valle de Santa Maria. Cemented to the basement gneisses and schists along some mountain fronts are red arkosic conglomerates of possible Mesozoic age. If so, then the basement surface under them is an exhumed Gondwana landscape.

The western flank of the Sierra Quilmes is a typical basement exposure with remnants of cemented conglomerate cover. The exhumed Gondwana surface, probably a pediment, dips westward at 11° to 16°, an angle that could be primary. LANDSAT and shuttle radar images of the Sierra Pampeanas show extensive areas of mountain fronts with similar rhombohedral fracture patterns and gentle slopes on crystalline rocks. Many or most of these surfaces are probably exhumed Gondwana pediments.

## III. PROCESS THRESHOLDS

Astronaut photographs taken during the STS-8 mission in September 1983 showed great plumes of red and white dust being blown out of dry lake beds in the southern Puna and transported southeastward across the Argentine Pampas, which were covered by low clouds at the time. This was the first demonstration that the Pampean loess is still actively accumulating, and provides a direct and obvious answer to the long-standing question of the origin of the Pampas and their soils. With an indication of the source of the wind-blown sediments, pedogenesis can now be studied in a much more direct and quantitative manner.

# SPACE IMAGERY AND SOME GEOMORPHOLOGICAL PROBLEMS OF THE GUIANA SHIELD, S.A.

Wilton N. Melhorn  
Purdue University

## Introduction

Like most academic geomorphologists, I know relatively little about planetary geomorphology, nor am I especially qualified to engage in constructive "megathink" about global geomorphology, though I have been guilty of some original considerations about the reality of ancient cyclic erosion surfaces in the global framework (Melhorn and Edgar, 1975).

For purposes of this workshop, I therefore will describe some ongoing involvement in regional geomorphologic research in South America. Because of association with LARS at Purdue University, there has been engagement, vicarious or advisory, in projects which led to Landsat 1-2 mapping of the natural resources of Bolivia (1:8,000,000 scale), and preparation of a geographic information system which mapped the general hydrology, geology, soils, and vegetation of Ecuador (1:4,000,000 scale). Currently we are involved more specifically in geological-geomorphological mapping of the Venezuelan portion of the Guiana Shield, and because of manuscript limitations only questions pertinent to this region are posed in the ensuing discussion.

The study of Venezuelan Guiana has evolved in the last few years from preliminary study of Landsat imagery (Fig. 1) into more localized and detailed geomorphologic analysis of the Roraima portion of the Guiana Shield, using a semi-controlled radar imagery mosaic (Fig. 2) and 4,000 black-and-white aerial photos, both available only at 1:250,000 scale. Gradually emerging is a geomorphological-geological map, at the same scale, intended for use in regional planning and economic development of a thinly populated, wild, inaccessible region of rich natural resource potential extremely important to a developing nation. As expected, each step forward has led to new questions about the geomorphic history and evolution of the region.

## Regional Setting

Some geological background is prerequisite to questioning and analysis. The Guiana Shield is of subcontinental magnitude. It consists of ancient 3.6-3.8 b.y. old, intensively deformed and metamorphosed Archean rocks. Scattered across the Shield are remnant outliers of the Roraima Group, a sedimentary sequence as much as 3300 m thick that lies unconformably on the older basement; presumably the Roraima is of Proterozoic age on the basis of radiometric dates obtained on dolerite dikes and sills which crosscut the Roraima in part. Apparently the Roraima formerly was a great prism of intra-cratonic sediments nested on and within the broad, bowl-shaped older pre-Cambrian basin. However, long-term erosion has removed most of this cover, leaving outliers marked by a series of near-vertical scarps, and a series of magnificent step-like cuestas, whose dip slopes incline 4°-6° inward towards the center of the Proterozoic depobasin. Because of lithologic variations, sloping stripped surfaces abound and are the most striking landform element. Gansser (1954) suggested that the Roraima formerly covered as much as 475,000 km<sup>2</sup> and extended from Surinam to the Sierra Macarena in Colombia. Present

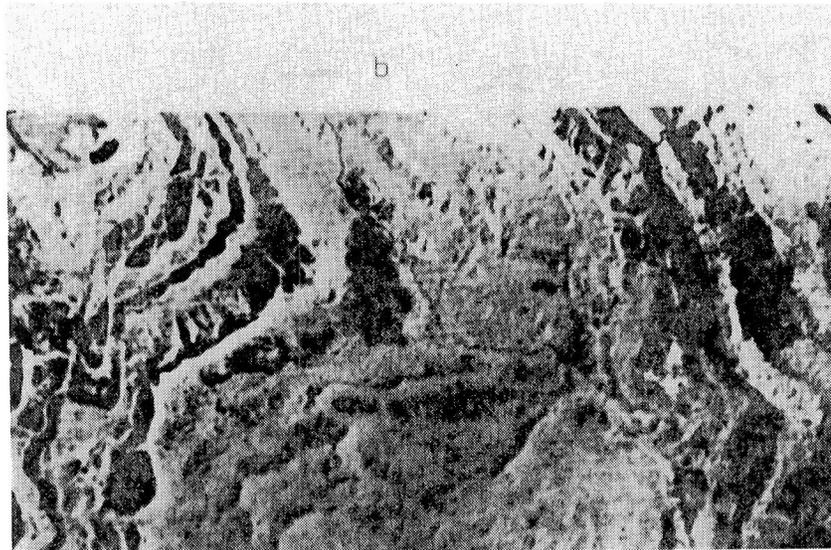
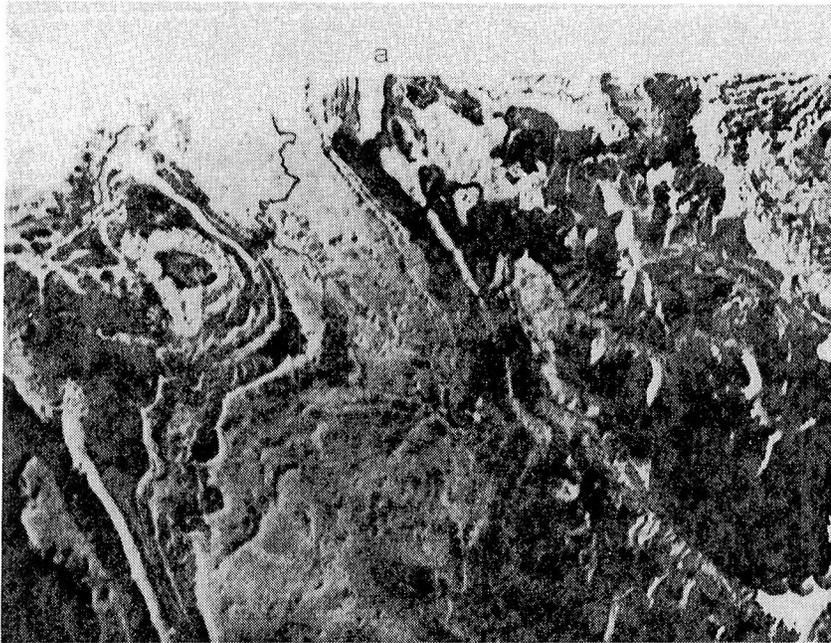


Fig. 1 - Examples of Landsat images. a) Chiguao River headwaters. Auyantepuí to the right. b) Detail of same area, showing sandstone "bridge" between Guiquinima and Auyantepuí.



exposure is limited to about 75,000 km<sup>2</sup>, mostly in southeastern Venezuela, and this is the area on which discussion focuses.

The Roraima Group divides upward into three formations -- Canaima, Guaiquinima, and Auyantepui -- each with a rather distinctive geomorphological signature or surface expression. The lower and upper formations are poorly cemented quartzose or feldspathic sandstones, arkoses, conglomeratic sandstones, and conglomerate lenses, all apparently deposited in a fluvio-deltaic environment. The Canaima is poorly exposed under dense rain forest and complete stratigraphic sections are few. The Auyantepui is a massive cliff-former, with nearly vertical 500 m high scarps that culminate in flat-topped or bowl-shaped, broad synclinal folds of the table mountains (tepuís) that rise precipitously above the Orinoco-Caróní lowlands (Fig. 3). Carbonate content of the rocks based on soil analysis is less than 4%, yet summits of some tepuis (Duida, Guaiquinima) are marked by 300 m deep, 2 km long, fluted karren "pseudokarst" shafts (cimas) developed in massive but poorly indurated quartzitic rocks. Local shale members apparently weather to hydromorphic clays and silts, which in the past were redeposited in alluvial flood plains, but do not constitute much of the sediment transported today.

The Guaiquinima is stratigraphically distinct because of the presence of volcanic tuffs, intercalated with hard beds of red or green jasper, and associated with intrusive dolerite or hornfel dikes or sills. Rb/Sr dating has yielded dates that range from 2100 m.y. to 1500 m.y., and are the only clue to relative age. Dikes where exposed surficially weather to positive relief elements of the landscape.

### Geomorphology

The geomorphology of Venezuelan Guiana is an almost classic case of landform evolution controlled by lithology and structure. Although there is some evidence of post-Roraima deformation into gentle, regional-scale anticline-syncline folds, and minor reactivation of basement block-faulting, nothing indicates that the region has been other than a stable craton of non-deposition for the last 1500 m.y. This requires speculation about the rate and magnitude of the long-term geomorphic evolution of the region. In the present climate, scarp retreat in tepuís clearly progresses rapidly. Surfaces are fresh and lack case-hardening, and large blocks weighing hundreds of tons are known to "peel" from tepuí-scarps with great regularity. Furthermore, radiocarbon dates from organics beneath a 15 m thick sand-gravel overburden in alluvial placer workings yield ages of only 3,000-10,000 yrs., indicating an enormous rate of denudation and flux during the Holocene, yet streams today are clear-flowing and sediment transport is minimal even during peak discharge. Furthermore, if stripping of the shield had occurred at the same magnitude and rate for 1500 m.y., clearly no Roraima rocks should remain! Unfortunately, we also have no hard evidence or even a "feel" about climates, landforms, and erosion rates for the greater span of Phanerozoic time.

Other evidence of changing climate comes from extensive alluvial fans, such as those near the Indian mission at Kamarata in the Chiguao River valley southeast of Auyantepui (Fig. 4). These densely jungle-covered surfaces, as much as 6 km broad, clearly did not form under the present climate or cover. Elsewhere, as near Kavanayen Mission, are flat-topped sloping surfaces which may be true pediments rather than the ubiquitous, stripped surfaces characteristic elsewhere. Are all these, along with broad alluvial floodplains such as mark the Kukenan River valley farther east, relicts of a Pleistocene, or earlier, semiarid to arid climatic regime? The concept of global climatic

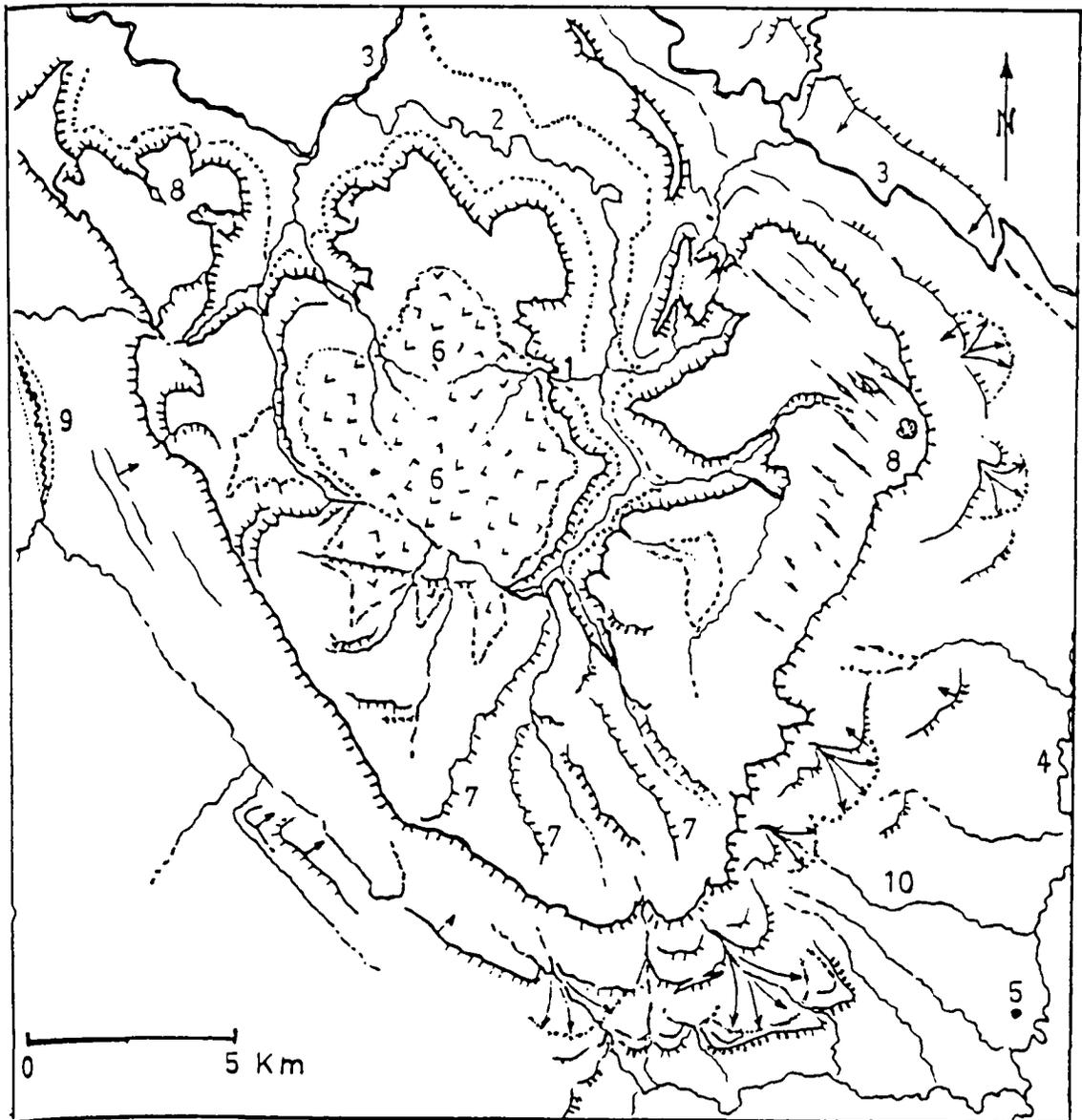


Fig. 3 - Geomorphological map of Auyantepuí, 1 - Angel waterfall. 2 - Churun River. 3 - Carrao River. 4 - Akanan River. 5 - Kamarata. 6 - Probable sill of basic rocks. 7 - Scarps, 100-150 m high, on Auyantepuí. 8 - Pseudokarst landforms. 9 - Kukurital River flood-plain. 10 - Alluvial fans and apron near Kamarata. Hachured borders are major scarps around Auyantepuí.



Fig. 4 - Alluvial fans west of Kamarata. Hachured borders show scarps; stipples are alluvial fans.

change and an arid episode at low latitudes has been proposed, on equally tenuous evidence, by Damuth and Fairbridge (1970), Tricart (1974), and Wallace et al (1960).

The region is located about 4° to 6° North, 59° to 64° West in the moisture-laden subtropics. There is no pronounced dry season, and annual rainfall on higher tepuis may exceed 5000 mm. More than three-quarters of the region is tropical rain forest (bosque), the remainder tropical grassland and brush savanna (selva). The latter apparently is natural in part (as on some positive-relief dikes), but much is clearly anthropic, owing to clearing and burning. Once vegetation is removed and a thin surface ferricrete-silcrete layer breached, "instant badlands" form, carving canyons 30 m deep in a few years. These rapid changes in landscape need repetitive monitoring regionally to determine the variations in hydrology, erosion, and sediment flux that result from changing landuse in a region which has considerable mineral, soil, and water resources but is very fragile under human impacts. For example, under enhanced development sediment flux to streams may rapidly increase and substantially impair the hydrologic regime. The world's highest waterfall (Salto Angel) with direct free-fall in excess of 1000 m is fed by a stream only 4 km long that originates in rain forest atop Auyantepuí. Removal of this forest assuredly would decrease or greatly vary flow, and inasmuch as the region has important hydroelectric potential, any cumulation of flow changes is an important economic consideration. Likewise, what would happen to agriculturally attractive floodplains, such as along Kukenan and Kukurital rivers, under strong flooding and regular overbank discharge and renewed deposition of coarse-grained clastic debris, an event that does not now occur?

#### Role of Space Imagery

The foregoing recital lists only a few examples of how geomorphic change has and continues to modify a major region of South America. But how does all this relate to the value of sequential acquisition and analysis of high-altitude and space imagery? Population explosion in South America inevitably is leading to the opening of virgin interior lands; thus continuous monitoring of landscape change clearly is of great interest. Space imagery, perhaps even for several decades, accompanied by repetitive radar imaging and high-altitude color-IR photography will tell much about such important matters as the gross magnitude of denudation and erosion, actual rates and mode of scarp retreat, the role of sediment flux and flooding, and continuing vegetative change under the present climatic regime. The resolitional capability of the new Large Format Camera System seems to offer much potential for monitoring important site-specific changes and problems.

In a purely scientific sense, sensor products may help identify sites of reasonable access that can be studied to provide better documentary evidence of an earlier arid climate regional pedimentation episode or cycle and long-term changes in landscape evolution.

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## DEEP SEA MEGA-GEOMORPHOLOGY: PROGRESS AND PROBLEMS

Wilfred B. Bryan  
Woods Hole Oceanographic Institution  
Woods Hole, Massachusetts

Historically, marine geologists have always worked with mega-scale morphology. This is a consequence both of the scale of the ocean basins and of the low resolution of the observational remote sensing tools available until very recently. In fact, studies of deep sea morphology have suffered from a serious gap in observational scale. Traditional wide-beam echo sounding gave images on a scale of miles, while deep sea photography has been limited to scales of a few tens of meters. Recent development of modern narrow-beam echo sounding coupled with computer-controlled swath mapping systems, and development of high-resolution deep-towed side-scan sonar, are rapidly filling in the scale gap. These technologies also can resolve morphologic detail on a scale of a few meters or less. As has also been true in planetary imaging projects, the ability to observe phenomena over a range of scales has proved very effective in both defining processes and in placing them in proper context.

At the same time, the new technology has placed new demands on researchers trained in remote sensing rather than in observational field geology. In some cases this leads to "rediscovery" of phenomena familiar to land geologists. Indeed, as more detail becomes available, many of the supposed differences between subaerial and submarine morphologic development have disappeared.

The discovery of unique deep sea life forms associated with active hot springs on the sea floor was a completely unexpected by-product of the increased emphasis on deep sea imaging programs. Such discoveries provide hope for similar discoveries in the alien environments of other planets. Feedback between observation of seafloor morphology and comparable features on land has stimulated much new research on ophiolite complexes and ancient Archean basalt terrains; some of this in turn suggests analogies with volcanic events on other planets. Important inter-relationships are emerging between morphologic and tectonic features on the seafloor, and the geochemistry of associated volcanic rocks. These discoveries point to the need for more inter-disciplinary communication between morphologists, petrologists, and geophysicists.

Studies in comparative planetology require a reasonable consistency in scales and quality of imagery used for comparison, for maximum success. This must include vertical feedback among observations at different scales for best understanding of processes within a given environment, and horizontal feedback between comparable types of images, at similar scales, in different environments. Deep sea imaging technology has benefitted from many of the lessons learned in space, and we are just now becoming able to observe more than two-thirds of the surface of the Earth, on the same scale and in the same detail with which we have already observed the Moon, Mercury, Mars, and the moons of several distant planets. Clearly, a major challenge remains to observe the details of volcanic, tectonic, and erosional features of our own planet's "inner space", and to understand the processes operating there.

## ONE APPLICATION OF MEGA-GEOMORPHOLOGY IN EDUCATION

Robert W. Blair Jr.  
Fort Lewis College  
Durango, Colorado

It has been said that those who do not learn from history are condemned to repeat it. The same can be said about people's understanding of geologic history. One advantage of a synoptic view displaying landform assemblages provided by imagery is that one can often identify geomorphic processes which have shaped the region and which may affect the habitability of the area over a human life time. Considering the continued growth of the world population and the resultant pressure and the exploitation of land, usually without any consideration given to geologic processes, it is imperative that we attempt to educate as large a segment of the population as we can about geologic processes and how they influence land use. I believe that space platform imagery which exhibits regional landscapes can be used 1) to show students the impact of geologic processes over relatively short periods of time (e.g. the Mount St. Helens lateral blast) 2) to display the effects of poor planning because of a lack of knowledge of the local geologic processes (e.g. the 1973 image of the Mississippi River flood around St. Louis MO) and 3) to show the association of certain types of landforms with building materials and other resources (e.g. drumlins and gravel deposits).

One way to initiate an understanding of geomorphology and landscape evolution is to introduce students to geomorphic concepts. I have taken the liberty to reproduce the 10 fundamental concepts as given by Thornbury (1969, chapt. 2) and have attempted to illustrate these concepts through the use of landform suites from space platform imagery.

1) THE SAME PHYSICAL PROCESSES AND LAWS THAT OPERATE TODAY OPERATED THROUGHOUT GEOLOGIC TIME, ALTHOUGH NOT NECESSARILY ALWAYS WITH THE SAME INTENSITY AS NOW. This statement, of course, represents a classic interpretation of uniformitarianism. The concept of uniformitarianism has come under considerable criticism over the last several years because many of the interpretations, when examined critically, are not totally valid (Shea, 1982). The statement above, for example, uses the word "laws" as though nature abides by someone's laws. Whose laws are they? And what are they? The uniformitarian concept, according to Shea, is simply the application of Occam's Razor or choosing the simplest solution. For example, to account for a given landform assemblage, the investigator should select the simplest explanation which works under our observed constraints of nature.

Landsat and other space platform imagery, which displays the broad synoptic view of the landscape, nicely illustrates the concept of uniformitarianism when applied to landform analysis.

Take, for instance, an Algerian desert scene displaying longitudinal dunes. For an exercise, have students determine what is the simplest explanation for the presence of these linear, and in places, bifurcating landforms.

2) GEOLOGIC STRUCTURE IS A DOMINANT CONTROL IN THE EVOLUTION OF LANDFORMS AND IS REFLECTED IN THEM. Virtually any image in the vicinity of a plate boundary can verify the dominant influence of geologic structure. The term "structure", however, is used by Thornbury to include variations in lithology; thus, buttes and mesas capped with a horizontal resistant unit can also illustrate this concept.

3) TO A LARGE DEGREE THE EARTH'S SURFACE POSSESSES RELIEF BECAUSE THE GEOMORPHIC PROCESSES OPERATE AT DIFFERENTIAL RATES. In homogeneous flat lying rocks, such as a thick shale formation, downcutting is dependent, in part, on the concentration of energy by the downcutting stream. The rate of downcutting will be greatest where the concentration of energy is greatest. The mere presence of a dendritic drainage pattern indicates relief. The fact that entire drainage basins can easily be shown on many Landsat images adds validity to the synoptic view approach to the study of landforms.

4) GEOMORPHIC PROCESSES LEAVE THEIR DISTINCTIVE IMPRINT UPON LANDFORMS, AND EACH GEOMORPHIC PROCESS DEVELOPS ITS OWN CHARACTERISTIC ASSEMBLAGE OF LANDFORMS. This possibly, more than any other concept, can be best substantiated with the use of space platform imagery and large landform assemblages. For example, compare the nature of drainage patterns and valley development in a fluvial-dominated system with that of a glacial-dominated system. The glacial valleys tend to be broad and stubby compared to the fluvial valleys, thus, reflecting the nature of glacial erosion.

5) AS THE DIFFERENT EROSIONAL AGENTS ACT UPON THE EARTH'S SURFACE, THERE IS PRODUCED AN ORDERLY SEQUENCE OF LANDFORMS. This concept is most applicable over cyclic time as defined by Schumm and Lichth (1965); however, the orderly or systematic change from one type of landform to another can be shown in Landsat images which display pediments and inselbergs from the Basin and Range Province.

6) COMPLEXITY OF GEOMORPHIC EVOLUTION IS MORE COMMON THAN SIMPLICITY. This concept can be easily exhibited with space imagery in mountainous regions such as the Zagros Mountains of Iran, where structure, lithology, salt diapirs, weathering, mass wasting and fluvial processes meld to produce a complex topography.

7) LITTLE OF THE EARTH'S TOPOGRAPHY IS OLDER THAN TERTIARY AND MOST OF IT IS NO OLDER THAN PLEISTOCENE. Of all the concepts listed by Thornbury, this one is probably the most difficult to demonstrate through the study of mace-landforms as viewed on space imagery. If students have a good grasp of geomorphic

processes and variations in their intensity as they alter the landscape, then the concept is not difficult to visualize. Images which show sand seas, deltas or expanding drainage basins can be used to demonstrate this concept.

8) PROPER INTERPRETATION OF PRESENT-DAY LANDSCAPES IS IMPOSSIBLE WITHOUT A FULL APPRECIATION OF THE MANIFOLD INFLUENCES OF THE GEOLOGIC AND CLIMATIC CHANGES DURING THE PLEISTOCENE. This concept can be appreciated when one is confronted with accounting for glacial valleys, horns and cirques in an area now dominated by fluvial, weathering and mass wasting processes. Scenes from the Southern Rocky Mountains can illustrate this concept.

9) AN APPRECIATION OF WORLD CLIMATES IS NECESSARY TO A PROPER UNDERSTANDING OF THE VARYING IMPORTANCE OF THE DIFFERENT GEOMORPHIC PROCESSES. The Niger River in central Mali and the associated vegetated sand dunes indicate clearly that there has been a climatic change in the not so distant past.

10) GEOMORPHOLOGY, ALTHOUGH CONCERNED PRIMARILY WITH PRESENT DAY LANDSCAPES, ATTAINS ITS MAXIMUM USEFULNESS BY HISTORICAL EXTENSION. A comparative study of the earth with other planets can be a fruitful exercise when one realizes that the early earth's crust must have resembled the present day moon about 4.2 billion years ago.

This is not an all inclusive list of important geomorphic concepts nor is the importance of the above concepts equal, but with the use of space imagery and the analysis of mega-landform suites included within the imagery, a fruitful and lively discussion can ensue. If students can appreciate and understand these and other concepts of geomorphology and then apply them positively so as to avert some natural disaster when dealing with man's seemingly endless focus to dominate nature, then at least modern space technology has not been developed in vain.

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## Use of the Synoptic View: Examples from Earth and Other Planets

B. K. Lucchitta

U.S. Geological Survey, 2255 North Gemini Dr., Flagstaff, AZ 86001

### Introduction

Space technology has added the synoptic view to other techniques used in geomorphology. Synoptic views are provided by spacecraft images or by application of space technology to time-honored information systems. Examples of spacecraft images of Earth are Landsat, Seasat, and the SIR (Shuttle Imaging Radar) series. Examples of applied space technologies include the digital conversion of topographic maps to shaded relief maps and digital correlation methods. From the study of other planets we have learned that synoptic views enable the deciphering of a planet's history: large features are identified and mapped before small ones; studies proceed from the general to the specific. On Earth, we generally recognize smaller features and study specific processes first, then extrapolate toward larger features and a general synthesis. With the advent of space images of Earth, perhaps the time is ripe to employ the methods used for other planets to the study of terrestrial geology and geomorphology. The following examples illustrate the use of regional-scale studies on Earth: the application of synoptic-view images in Antarctica, the use of digital methods and correlations of multiple data sets in regional studies, and some benefits to our understanding of terrestrial geology that have been obtained from analyses of other planets.

### Antarctica

Because of the remoteness of its vast regions, Antarctica has more to gain from exploration by space-age methods than do the other continents. The synoptic view of images from space is helpful in preparing planimetric maps, in monitoring coastlines and ice streams, and in identifying blue-ice areas. Maps are essential base materials for the interpretation of geologic, geomorphic, and geophysical features. In Antarctica, where little ground control is available, the Landsat digital satellite images of the multispectral scanner (pixel size about 80 m) and of the Thematic Mapper (pixel size about 30 m), and the photographs of the large-format camera carried by the shuttle (resolution about 20 m) can increase the accuracy of maps at medium scales. NOAA-AVHRR (advanced very high resolution radiometer) images obtained by weather satellites (resolution about 1 km) can facilitate the preparation of maps at small scales.

Images from space obtained at different times also help in the monitoring of changes in coastlines and ice sheets. Repeated coverage by aerial photographs is much more costly. Advances and retreats of glaciers, ice streams, and ice shelves may reflect changes in climate. Monitoring of the west antarctic ice sheet is particularly important, as it rests on bedrock that is largely below sea level (Drewry and Jordan, 1983); invasion of sub-ice sea water could cause rapid disintegration of the ice sheet and a world-wide rise in sea level.

Flow-lines in ice streams are exceptionally clear on Landsat images, especially on those taken at low sun angles. The location of ice-intake areas can thus be determined; this information, when combined with depths to bedrock

from radio-echo sounding, may lead to an understanding of the mass balance of the ice sheets. Radar images of the ice sheets from anticipated missions in polar orbit would have the advantage of cloud penetration and would further elucidate the detailed surface structure of the ice sheets; acquisition of such radar images is highly recommended.

Synoptic views over Antarctica also aid in the rapid recognition and location of blue-ice areas, which have recently acquired importance because they contain lag deposits of meteorites (Williams et al., 1983). Digital methods applied to Landsat multispectral images can highlight blue-ice areas, and thus locate them with a minimum of effort.

### Digital Methods and Correlations

Digital methods that were first developed for space images can be applied to terrestrial topographic, geologic, or geophysical data. If of regional scale, these data can produce synoptic images and permit computer correlation of superposed data sets. Computer transformation of topographic maps into shaded relief maps yields images that are not marred by varied albedoes of the scene or cultural overprints; therefore, these images are ideal for regional analysis of structure and geomorphology. Megalineations that bound major physiographic provinces are easily recognized, and variations in regional drainage patterns permit delineation of distinctive rock types, structure, and geomorphology. Careful mapping of geomorphic provinces and structural lineations on these images, combined with studies of the geologic literature, may contribute significantly to an understanding of landform development.

Small-scale digital shaded relief maps or other synoptic-view images are ideal for superposition of other data sets to provide visual displays or to furnish computer correlations. Computers can produce two-dimensional histograms that correlate color, albedo, numerical identifiers of drainage patterns, elevations, gradients, digitized geologic units, and geophysical data such as gravity, aeromagnetism, and heatflow. These correlation techniques have been successfully applied to data from other planets, but their use on Earth has only begun. Worldwide digital maps of topographic and geologic data and their correlations may point toward relations on a large scale that are as yet unknown.

### The Planetary Experience

The synoptic view has helped us to understand the history of other planets. Some of these insights may contribute to a better knowledge of the history of Earth:

Geologic mapping of the Moon taught us that early accretion leaves planetary surfaces scarred by craters. Intense meteorite bombardment and its consequences probably also profoundly influenced the development of the early Earth.

The cratering record on the Moon and other bodies shows that some impact bombardment extends into recent times and that impacts on Earth may have occurred periodically. From this and other observations stems the hypothesis that links the extinction of some terrestrial species to impacts. Also, we are beginning to acknowledge the importance of other

catastrophic events, and we are realizing that perhaps the principle of uniformitarianism as commonly interpreted has restricted our thinking: geologic processes operating on Earth may indeed have changed with time.

One-plate planets with thin atmospheres lack pronounced endogenic or exogenic destructive forces; landforms consequently develop fully. On Earth, landforms are obliterated nearly as fast as they form, and features tend to remain small. On Mars we see huge volcanoes, landslides, debris flows, possible rock glaciers, and landforms carved by floods or ice. We see tectonic features such as grabens, rifts, and folds (wrinkle ridges) in their original constructive forms. Studies of these features are elucidating or refining our appreciation of processes on Earth.

Wind features on Earth are rarely preserved because they are quickly destroyed, mostly by fluvial activity. Mars, however, is a natural laboratory where wind features, especially those carved by erosion, are observed in pristine form. We have come to interpret some desert landforms on Earth in the light of what we have learned from Mars (Breed et al., 1982). Antarctica is a cold dry desert region; its ice sheets locally display sweeping sinuous scarps and ridges that are similar to wind-formed features on Mars; perhaps the Martian analogs will aid in the interpretation of these Antarctic features.

## Conclusions

The synoptic views afforded by spacecraft images, the application of digital methods to terrestrial data, the approach to problem-solving used on other planets, and the relevancy of extraterrestrial experiences to terrestrial geomorphology all contribute to a new awareness in the study of terrestrial landforms and processes. Many uses can easily be added to the brief list given above, as the potential of geomorphologic studies on a global scale is only beginning to be realized.

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GEOMORPHIC CLASSIFICATION OF ICELANDIC AND MARTIAN VOLCANOES:  
LIMITATIONS OF COMPARATIVE PLANETOLOGY RESEARCH FROM  
LANDSAT AND VIKING ORBITER IMAGES\*

Richard S. Williams, Jr.  
U.S. Geological Survey  
Reston, Virginia 22092

Summary

As a result of collaborative research by Elliot C. Morris (U.S. Geological Survey's Branch of Astrogeology), the late Sigurdur Thorarinsson (University of Iceland), and me to develop a comprehensive geomorphic classification of Icelandic and Martian volcanoes, we identified some limitations in using orbital images of planetary surfaces for comparative landform analyses. In our study the principal orbital images used were Landsat MSS images of Earth and nominal Viking Orbiter images of Mars. Both are roughly comparable in having a pixel size which corresponds to about 100 m on the planetary surface. A volcanic landform on either planet must have a horizontal dimension of at least 200 m to be discernible on orbital images. A twofold bias is directly introduced into any comparative analysis of volcanic landforms on Mars versus those in Iceland because of this scale limitation. First, the 200-m cutoff of landforms may "delete" more types of volcanic landforms on Earth than on Mars or vice versa. Second, volcanic landforms in Iceland, too small to be resolved on orbital images, may be represented by larger counterparts on Mars or vice versa.

Iceland was selected as the best region on Earth for comparing volcanic landforms with those on Mars because of the tremendous variety of types of volcanoes in Iceland. The previous geomorphic research by Sigurdur Thorarinsson in developing a classification of Iceland's volcanoes, the enormous body of geologic literature on Iceland's volcanoes, and the wealth of thematic maps, aerial photographs, and various types of satellite images of Iceland provided comprehensive source material. The classification scheme divides Iceland's volcanoes into 3 compositional groups: basalt, rhyolite, and central (mixed), and further subdivides them on the basis of nature of volcanic activity (explosive or effusive), environment during formation (subaerial or subglacial), and form of feeder conduit (central or linear). Pseudocraters were also included as a special "volcano" landform that formed under unusual conditions. Only 8 of the 25 discrete types of subaerial and(or) subglacial Icelandic volcanoes could be unambiguously identified on Landsat MSS images: lava shield, table mountain, subglacial ridge, mixed cone row, tephra ring, flow dome, composite cone, and composite volcano massif. Five other volcano types could be identified only because their location was found on other source material (e.g., aerial photographs, maps, etc.). The other 12 types had dimensions too small to be recorded.

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\*Discussion commentary for Theme IV, Planetary Geomorphology Perspectives, Workshop-Conference on Global Mega-Geomorphology, Oracle Conference Center, Arizona, 13-17 January 1985, which was sponsored by the National Aeronautics and Space Administration and the International Union of Geological Sciences.

A number of geomorphologists have used Viking Orbiter images of the Martian surface to classify volcanoes on the basis of their morphologic similarity to volcanoes on Earth. Elliot Morris found that the classification scheme used for Icelandic volcanoes cannot be directly applied to Martian volcanoes because the criteria, which are used to classify the former, either are not known or must be inferred for the latter. Five principal types of volcanoes have been recognized on Viking Orbiter images of the Martian surface: lava shields, domes, composite cones, highland paterae, and volcano-tectonic depressions. The highland paterae apparently have no known counterpart volcano landform on Earth, but the other 4 Martian volcano types are represented by 4 counterpart volcano landforms recognized on Landsat MSS images of Iceland. Two of the 8 volcano types discernible on Landsat MSS images of Iceland are subglacial and may not have a counterpart landform on Mars. The other two types, mixed cone row and tephra ring, are barely discernible on Landsat MSS images of Iceland; if their counterparts on Mars are smaller, then they may not be recorded on nominal Viking Orbiter images of Mars.

## AEOLIAN GEOMORPHOLOGY FROM THE GLOBAL PERSPECTIVE

Ronald Greeley, Department of Geology, Arizona State University, Tempe, Arizona 85287

Any planet or satellite having a dynamic atmosphere and a solid surface has the potential for experiencing aeolian (wind) processes. A survey of the Solar System shows at least four planetary objects which potentially meet these criteria: Earth, Mars, Venus, and possibly Titan, the largest satellite of Saturn. While the basic process is the same among these four objects--the movement of particles by the atmosphere--the aeolian environment is drastically different (Table 1). It ranges from the hot (730 K), dense atmosphere of Venus to the extremely cold desert (218 K) environment of Mars where the atmospheric surface pressure is only  $\sim 7.5$  mb.

On Earth most aeolian processes occur in deserts, coastal areas, and periglacial regions. Deserts occupy more than 30% of Earth's land surface. In recent years, considerable attention has been given to desertification--the conversion of useful land to desert terrains. The process has been particularly acute in Africa where the consequences of desertification are having a severe impact on food production. Dust storms figure prominently in desertification, not only by removal of agricultural soils, but also by the burial of useful land. It is estimated that agricultural land damaged by wind erosion in the United States alone varies from 400 to 6,000 km<sup>2</sup> per year.

On Mars, telescopic observations for the last 100 years have shown that dust storms are frequent and can be global in extent. The Mariner 9 spacecraft, put into orbit around Mars in 1971, revealed a wide variety of features directly attributable to aeolian processes, including dunes, yardangs, active dust storms, and the formation of "variable" features. "Variable" features are albedo patterns on the surface which change their size, shape, and position as a function of time and in response to near-surface winds. Most variable features act as "wind vanes" and maps showing their orientation have been used to model the patterns of near-surface winds. Spacecraft observations of the martian surface also show widespread sedimentary mantles which may be of aeolian origin. Understanding the timing and distribution of these deposits is critical in understanding the evolution of the martian surface.

Prior to spacecraft observations, speculation for cloud-shrouded Venus included environments ranging from humid swamps to hot, dry deserts. Results from the Venera and Pioneer Venus missions showed the latter to be true and revealed both the existence of small particles on the surface and near-surface wind velocities well above saltation threshold for sand. Experiments simulating the venusian environment show that small-scale aeolian-bedforms are in some ways analogous to features formed by water on Earth, a result that might be expected, given the high fluid density of the venusian atmosphere. However, questions remain about the efficacy of aeolian processes on Venus, especially in regard to widespread aeolian erosion and deposition. Some of these questions may be addressed with the return of high resolution radar images from Venera and the Venus Radar Mapper missions.

In considering aeolian processes in the planetary perspective, all three terrestrial planets share some common areas of attention for research,

especially in regard to wind erosion and dust storms. Although rates of wind erosion have been estimated for small-scale features such as ventifacts, there are few valid methods for determining rates of wind erosion regionally or for large landforms such as hills. This is particularly critical for understanding the evolution of the surfaces of Mars and Venus. Similarly, knowledge of the processes and rates of soil erosion on Earth have a direct social and economic impact. In addition to wind erosion, the generation of dust storms figures prominently in global aeolian processes on Earth, Mars, and perhaps Venus, yet the general processes involved in dust-raising by wind are very poorly understood.

Space technology may provide the opportunity to address some aspects of the problems outlined above. The martian experience has shown that the global inventory of aeolian features and their relationship to current processes can provide direct information on atmospheric circulation. On Earth, remote sensing instruments placed on orbiting spacecraft may provide new data for the investigation of local and regional dust storms. The combination of multi-spectral imaging, infrared sensors, and radar systems may provide an unparalleled opportunity to study the initiation and growth of dust storms in remote regions and provide information on particle sizes, rates of transport, and local environmental factors involved in the formation of dust storms. Such monitoring would enable a much better assessment of the global effects of dust storms and the development of predictive models.

Since the pioneering work of Bagnold, laboratory experiments dealing with various aspects of aeolian processes have shed light on the movement of windblown particles. The ability to conduct similar experiments in Earth-orbital environments may provide unique opportunities (hitherto unavailable on Earth) for assessing aspects of aeolian processes. Threshold curves relating wind speeds required to move particles of different sizes show that dust is as difficult to move as coarse sand. The reasons for this have been attributed to a combination of aerodynamic effects and to interparticle forces which become more important with decreasing particle size. Unfortunately, in experiments conducted on Earth, interparticle force terms are intimately linked with gravity terms. If threshold experiments were conducted in a gravity-free environment, it would be possible to remove the gravity term and thus allow assessment of various interparticle forces. This would enable a much better understanding of the factors involved in raising dust on Earth and other planets as well.

The Mars Geoscience/Climatological Observer mission planned for early 1990's will provide global surveys of surface compositions and may have the ability to monitor dust storms and other aeolian events on a daily basis. The forthcoming Venus Radar Mapping mission may provide a global inventory of aeolian features. Like Mars, the detection and mapping of variable features such as wind streaks could provide the opportunity to map near-surface atmospheric circulation. The detection of wind streaks on Earth via shuttle imaging radar (SIR-A) demonstrates the ability of radar to detect these features.

In summary, exploration of the Solar System has shown that aeolian processes are important on planets other than the Earth. By necessity, planetary exploration began with global perspectives and then focused on local

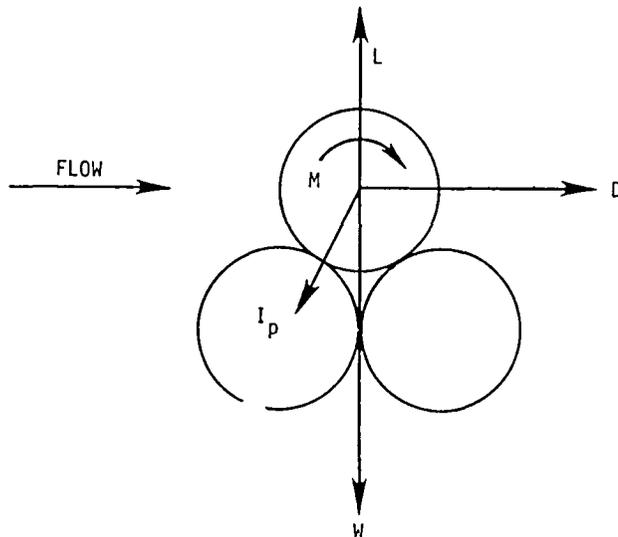
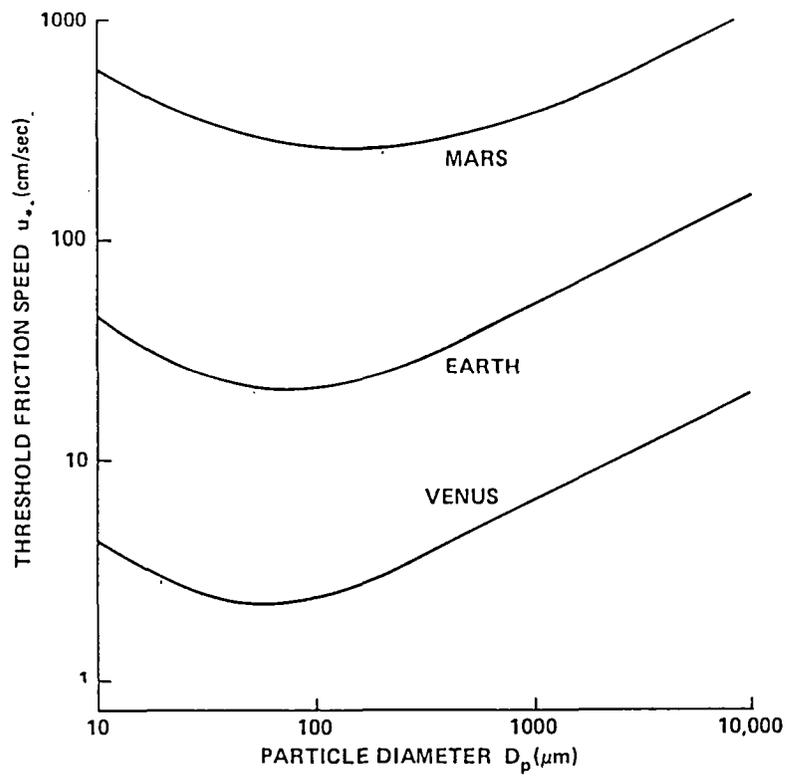
processes and features. It is this global perspective that has been largely lacking in studies of aeolian processes on Earth and which may provide potential for future research.

Table 1. Relevant properties of planetary objects potentially subject to aeolian processes

	VENUS	EARTH	MARS	TITAN
Mass (Earth = 1)	0.815	1	0.108	0.02
Density (water = 1)	5.2	5.5	3.9	1.4
Surface gravity (Earth = 1)	0.88	1	0.38	.11
Surface gravity (cm/s <sup>2</sup> )	888	981	373	136
Atmosphere (main components)	CO <sub>2</sub>	N <sub>2</sub> O	CO <sub>2</sub>	N
Atmospheric pressure at surface (millibars)	9 x 10 <sup>4</sup>	10 <sup>3</sup>	7.5	1.6 x 10 <sup>3</sup>
Mean temperature at surface (°C)	480°	22°	-23°	-200°
Minimum U <sub>*t</sub> (cm/s)	2.5	20	200	3.5
Optimum particle size (μm)	75	75	115	180

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$$\text{Lift} + \text{Drag} + \text{Moment} = \text{Weight} + \text{Interparticle Force}$$

## GOMORPHIC ANALYSES FROM SPACE IMAGERY

Marie Morisawa  
State University of New York  
Binghamton, New York

One of the most obvious applications of space imagery to geomorphological analyses is in the study of drainage patterns and channel networks. Landsat, high altitude photography and other types of remote sensing imagery are excellent for depicting stream networks on a regional scale because of their broad coverage in a single image. They give us a valuable tool for comparing and analysing drainage patterns and channel networks all over the world.

There are three aspects to be considered in such a geomorphological study: (1) Origin, evolution and rates of development of drainage systems, (2) Topological studies of network and channel arrangements, and (3) the adjustment of streams to tectonic events and geologic structure (i.e., the mode and rate of adjustment).

### (1) Origin and rates of evolution of a drainage system.

The origin and early development of stream channels has not often been documented. Glock (1931) outlined a theory on the stages of drainage evolution as a network is established, elaborated and integrated. Research by Schumm (1956) and Hack (1965) have given some insight into the changes made in a network as drainage patterns grow. A study by Ruhe (1952) gave a handle on the time scale involved in stream development on tills of different ages in Iowa. Numerous papers by Abrahams (e.g., 1975, 1977) have tried to ascribe changes in drainage networks to factors such as relief and available space. It should be pointed out that, with the exception of Glock's theoretical paper, all these (and other) studies have been done on the basis of detailed, "on the ground" or topographic map analyses.

With space imagery covering the world, we can find drainage nets in all stages of development. Using space as a substitute for time, we can work out the evolution of a typical network. In addition, the patterns can be related on a regional scale to physical and geologic characteristics. Moreover, with continuous coverage, changes over time can be documented to produce rates and actual manner of evolution.

### (2) Topological studies of network and channel arrangements.

Smart and Moruzzi (1972) gave geomorphologists a basis for the analysis of drainage network topology. Fig. 1. Their study and that of Morisawa (in press) dealt with distributary drainage patterns on deltas, Fig. 2. The Smart and Moruzzi system of topologic analysis has more recently been applied to braided stream channel configurations (Morisawa and Ginzler, in preparation), Fig. 3. Krumbein and Orme (1972) applied the Smart and Moruzzi technique of analysis to a braided channel net that they

had mapped in the field. All of these studies have been done from networks derived from topographic maps or in the field where the patterns were "frozen" in time. However, each of these types of distributary nets are known to be ephemeral, i.e., in a state of constant flux. Space imagery and high altitude photography will allow such patterns to be followed as they change over time. Research of this type may provide valuable information of stable (and unstable) components of the channel systems and insight into long term characteristics of the patterns.

(3) The adjustment of streams to tectonic events and geologic structure.

It is a well-known axiom in geomorphology that structure has a great influence on drainage patterns (Zernitz, 1932). Many detailed studies have related drainage networks to the underlying geologic structures. Morisawa (1963) indicated the expected frequencies of flow directions in dendritic drainage patterns and showed the influence of foliation on skewing the observed frequencies. Judson and Andrews (1955) and Cox and Harrison (1979) gave evidence that joints can influence direction of stream flow. Orientation of streams in the Piedmont of Georgia was ascribed to various structural controls by Woodruff and Parizek (1956). Hack (1966) described circular stream patterns guided by exfoliation in the underlying rocks in an area of North Carolina. Many other papers in addition to those cited have shown how rivers are influenced in their flows by geologic structure.

The use of such knowledge can be instructive when viewing remote imagery on a global scale. Analysis of drainage networks can allow determination of many structural elements in regions we are unable to visit. Such imagery can enable us to examine large regions to determine geomorphic similarities and differences on a global scale. The availability of world-wide coverage of space imagery may allow us to trace the rate and manner of stream adjustment to the underlying structure and thus solve many longstanding problems of drainage evolution. And with successive imagery over time, we may be able to see the actual adjustments as they take place. In this way we may be able to peer back into the geomorphic past.

Moreover, studies have shown that fossil drainage systems, now buried beneath the surface are revealed by shuttle radar imagery. McCauley and others (1982) thus discovered ancient buried channels under the Sahara sands. Various kinds of space imagery may, hence, enable us to unravel not only the evolution of drainage and paleolandscapes but also to determine former climatic regimes.

Associated with this aspect of applications of space imagery, but with a broader implication, is its use in the study of tectonic geomorphology. Although plate tectonics has dominated geologic thought and research for many years now, it is only recently that this idea has purposefully been related to the concomitant landforms and processes well-known in geomorphology

(Ota, 1980). Thus a new setting has appeared for geomorphological analyses where continental surfaces are studied to provide evidence in their landforms of the nature of their tectonic history (Ollier, 1981).

Geomorphology cannot be isolated from other geologic phenomena and it must be integrated with our modern knowledge of tectonics. Subduction, uplift and plate movements have an effect on landforms and geomorphic processes, hence configuration of landforms can be used to interpret tectonic history (Kennedy, 1962 and Morisawa, 1975). The interplay of tectonic forces and geomorphic processes of denudation on the rocks of the earth results in characteristic landforms depending on the dominance of any of the involved factors of tectonism, denudation and earth materials.

At the 1984 Binghamton Geomorphology Symposium on Tectonic Geomorphology ample evidence was given that tectonic history can be read from geomorphology of the surface (Morisawa and Hack, in press). Landsat, Seasat and other types of space imagery will be most helpful in studies which seek to interpret tectonic events from drainage nets and other surface features. For example, Lowman (1976) used lineaments and drainage anomalies shown on Seasat imagery to delineate faults in California. Morisawa (1975) used ERTS imagery to trace lineaments and drainage patterns in the Adirondacks in an effort to document faulting and neotectonic movements in relation to soft sediment deformation.

The large size of some structures can be more easily recognized from space imagery which gives broad areal coverage, yet even minor details can be seen. Both aspects provide information for interpreting and integrating regional geology and tectonic events from landforms. A whole new world has opened up before the geomorphologists of the future.

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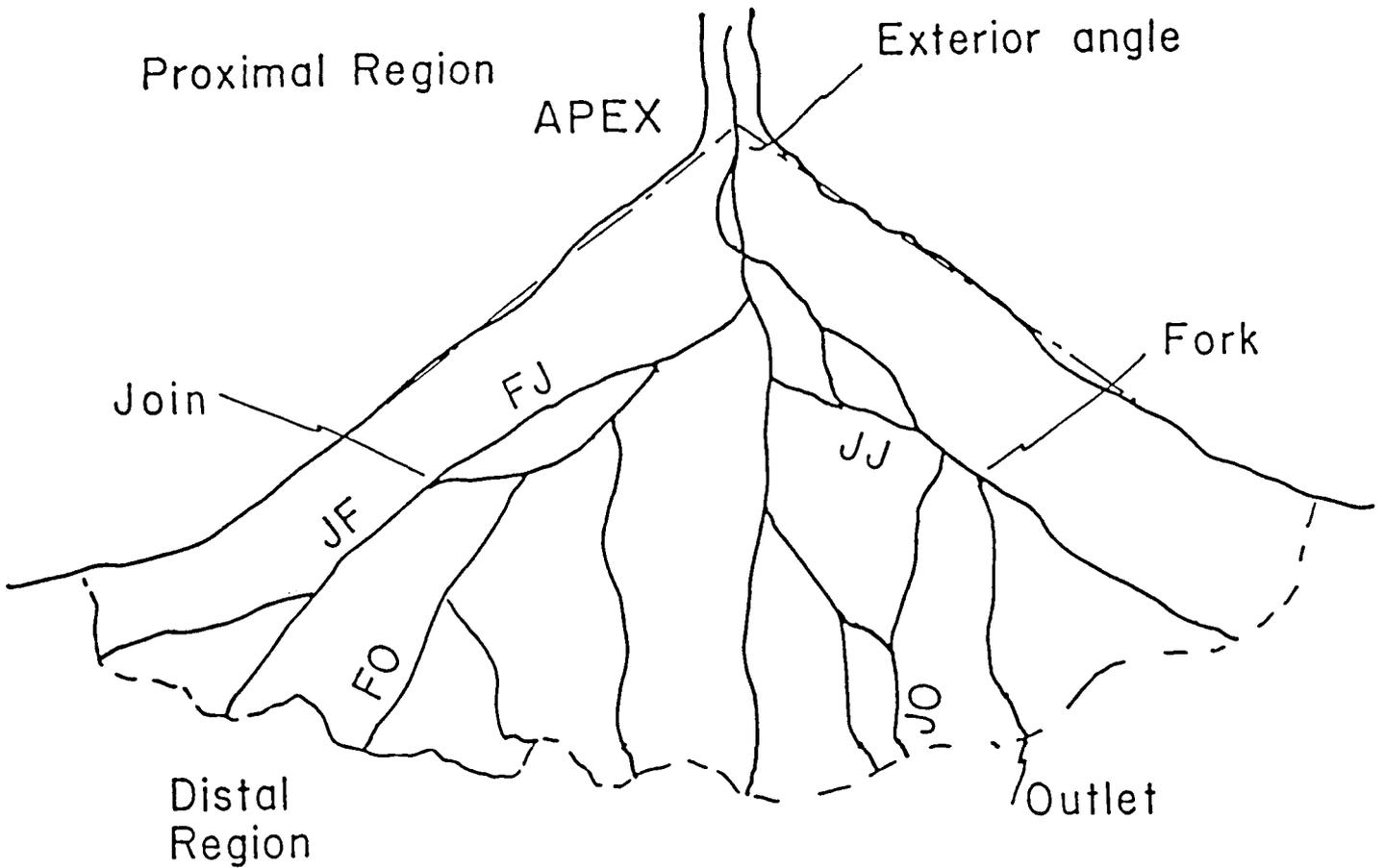


Figure 1. Nomenclature for topologic analysis of distributary networks. FF = link between two forks, FJ = link between fork and join, FO = link between fork and outlet, JF = link between a join and fork, JJ = links between two joins, JO = link between a join and outlet. After Smart and Moruzzi, 1972.

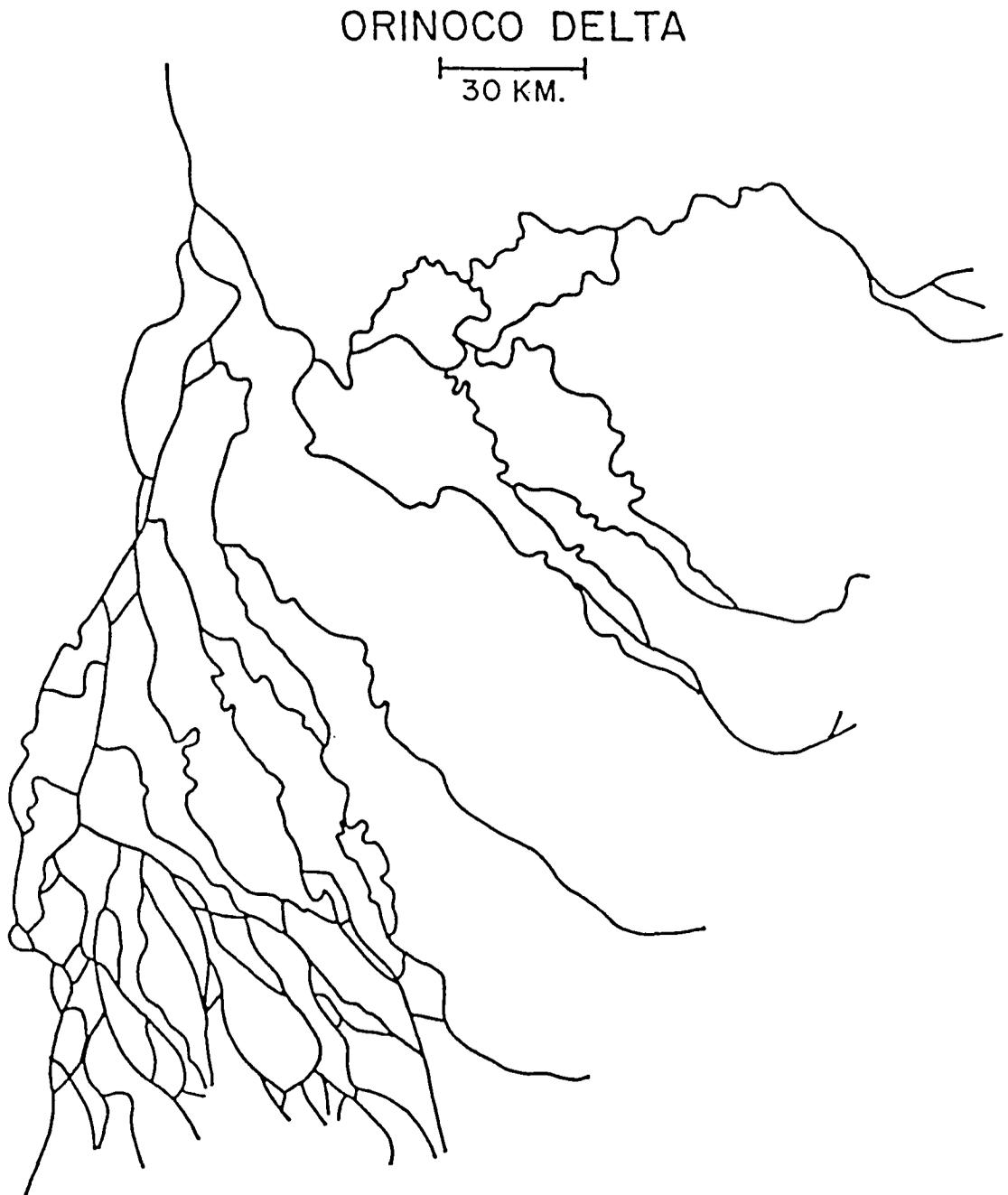


Figure 2. Distributary network of the Orinoco delta.

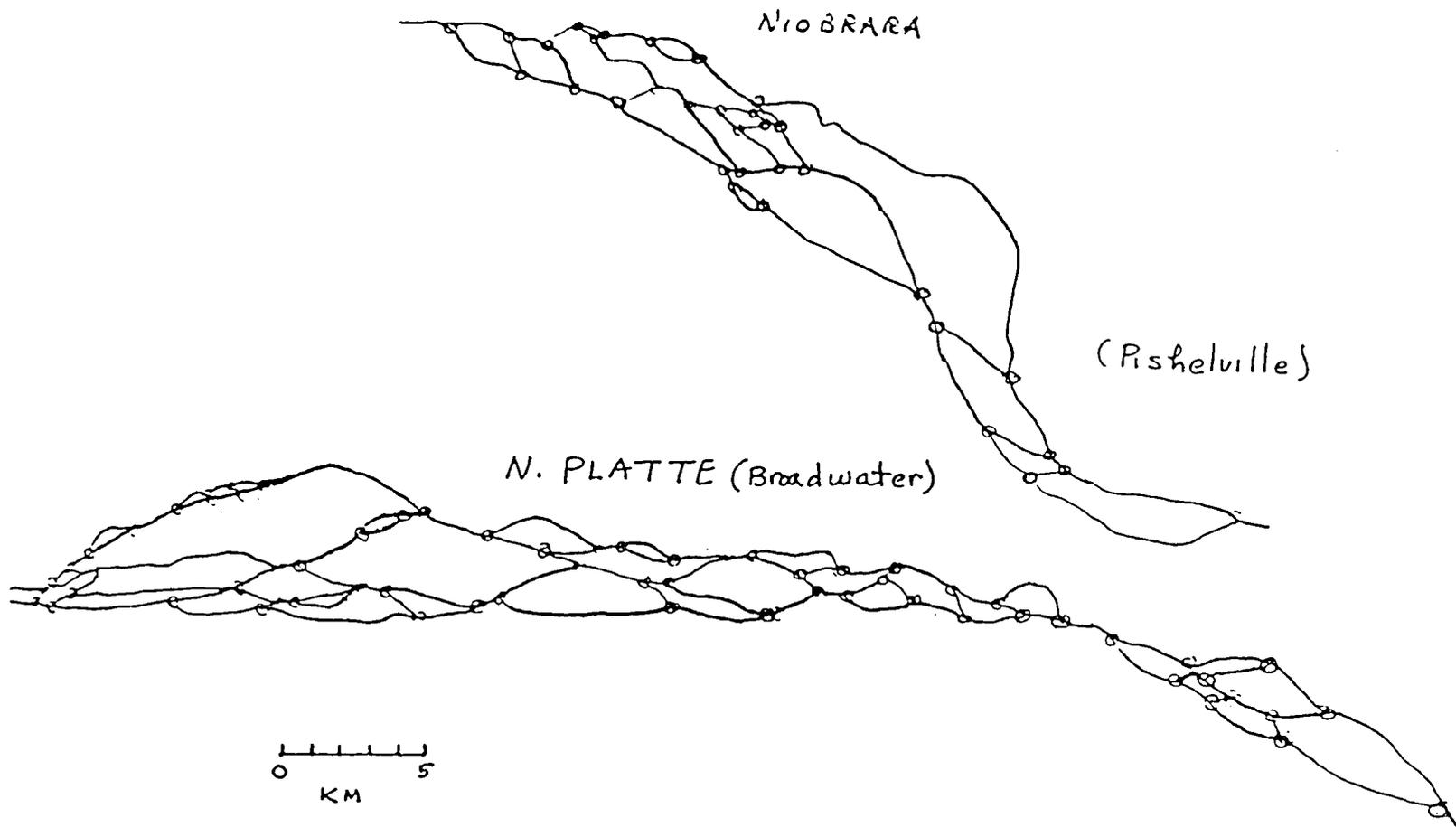


Figure 3. Braided channel networks.

## THE PROBLEM OF SCALE IN PLANETARY GEOMORPHOLOGY

Lisa A. Rossbacher  
Earth Sciences Department  
California State Polytechnic University  
Pomona, CA 91768

Recent planetary exploration has shown that specific landforms exhibit a significant range in size between planets. Similar features on Earth and Mars offer some of the best examples of this scale difference. The difference in heights of volcanic features between the 2 planets has been cited often; the Martian volcano Olympus Mons stands approximately 26 km high, but Mauna Loa rises only 11 km above the Pacific Ocean floor. Polygonally fractured ground in the northern plains of Mars has diameters up to 20 km across; the largest terrestrial polygons are only 500 m in diameter. Mars also has landslides, aeolian features, and apparent rift valleys larger than any known on Earth.

No single factor can explain the variations in landform size between planets. Controls on variations on Earth, related to climate, lithology, or elevation, have seldom been considered in detail. The size differences between features on Earth and other planets seem to be caused by a complex group of interacting relationships.

The major planetary parameters that may affect landform size include the following:

Gravitational acceleration is a driving force in geomorphic activity, especially in mass movement and fluvial processes.

Radius of the planetary body seems to influence plate tectonics, which causes mountain building, rifting, and volcanism.

Lithospheric thickness affects the isostatic compensation of large-scale features, including the heights to which mountains and volcanoes can grow.

Atmospheric density influences the intensity of degradational processes at a planetary surface, and particularly the effectiveness of wind.

The presence of water contributes to both chemical and physical weathering; in solid and liquid form, it is an effective geomorphic agent.

Ambient temperature range, particularly the frequency

with which the temperature crosses 0°C in the presence of water, influences the effectiveness of numerous processes.

Observing resolution has proven to be a factor in the observed sizes of Martian landforms. High-resolution Viking images collected late in the mission reveal polygonal patterns with diameters similar to those of terrestrial polygons.

The control listed above that is most conducive to experimental testing is gravitational acceleration ( $g$ ). Remotely sensed data about the surfaces of other planetary bodies offer a passive way of studying the possible effect of variations in  $g$ , but the influences of other parameters are impossible to eliminate. The establishment of a permanent space station later in this decade should make it possible to study the role of gravity in geomorphic processes further. The importance of time in most geomorphic processes makes long-term studies on a space station more desirable than short-term experiments in high-altitude aircraft like the KC-135.

Plate tectonics has a major effect on the geomorphology of a planetary body, by recycling crust and producing volcanoes and mountain chains. Mercury and the Moon are probably too small to have plate tectonics; Mars may have had tectonism earlier in its history. Whether Venus has had tectonic activity is unclear. For the inner planets, the energy source for tectonism is primarily radioactive decay.

Several of the Galilean satellites also have a form of tectonism, as with the "sulfur volcanism" on Io and the "ice tectonics" on Ganymede. In both of these cases, the energy seems to come from tidal heating caused by gravitational interaction between the satellite and Jupiter. Both size and composition seem to play a role in tectonics. A minimum size for plate tectonics may be somewhere between the radius of Earth and that of Mars. A logical extension is whether there is an upper limit to the size of a planet that can support plate tectonics.

The atmosphere plays a multiple role in geomorphology, and it might be possible to generalize about the geomorphology of a planet based on its atmospheric density. The absence of an atmosphere seems to result in a surface characterized almost exclusively by impact craters. If an atmosphere exists, its density, the wind speed, and the availability of loose material will control the formation of aeolian landforms.

Freezing and thawing of water is an important mechanism in mechanical weathering; its significance depends on both the availability of water and the temperature range on a planetary surface. Presumably other ices could do the same type of geomorphic work. The length and magnitude of these temperature cycles may also play a role in the size of resulting geomorphic features. This possibility has been

suggested to explain the large size of polygonal-fracture patterns on Mars.

Explaining the relative sizes of landforms is just one problem in planetary geomorphology, and several other aspects of the subject that have received little attention lately may offer valuable insights into global mega-geomorphology. These include (1) physiographic provinces as a large-scale subdivision of the Earth's surface, (2) the use of an index correlating the size of a feature with the planetary radius, and (3) the consideration of relatively rare or poorly understood landforms. Division of the Earth's surface into large-scale sub-units, by physiography or climate, may provide new insights into how to subdivide the surfaces of other planets.

Attempting to understand the size differences in landforms among the terrestrial planets and some satellites of the outer planets prompts a further question: Is there an upper limit to how big a certain geomorphic feature can be? For example, if polygonally patterned ground ranges up to 500 m in diameter on Earth and 20 km across on Mars, could even larger polygons occur elsewhere - and, if so, under what conditions? Investigation of these questions may lead to a broader understanding of the physics underlying geomorphic processes.

## QUANTITATIVE ANALYSIS IN MEGAGEOMORPHOLOGY

Larry Mayer  
Miami University  
Oxford, Ohio

Megageomorphology is the study of regional topographic features and their relations to independent geomorphic variables that operate at the regional scale. These independent variables can be classified as either tectonic or climatic in nature. Quantitative megageomorphology stresses the causal relations between plate tectonic factors and landscape features or correlations between climatic factors and geomorphic processes. In addition, the cumulative effects of tectonics and climate on landscape evolution that simultaneously operate in a complex system of energy transfer is of interest.

Regional topographic differentiation, say between continents and ocean floors, is largely the result of the different densities and density contrasts within the oceanic and continental lithosphere and their isostatic consequences. Regional tectonic processes that alter these lithospheric characteristics include rifting, collision, subduction, transpression and transtension. The magnitude of topographic change that results from these processes may in the first approximation be described by isostatic responses to lithospheric thickening, thinning, or heating. For example, rooted topographic highs are related to crustal thickness while rootless topographic highs may be supported by thermal incursions into the lithosphere.

Theoretical models that relate topographic response to changing lithospheric characteristics are essential tools in quantitative megageomorphology. The well known McKenzie model for the evolution of passive margins is an excellent example of a model that in many cases is well constrained by stratigraphic data and predicts the sinking of passive margins as a function of a cooling lithosphere in isostatic equilibrium. The modeling of foreland basins as a flexural downwarping in response to thrust-induced loading is another simple model that relates tectonics and topographic evolution.

Larger scale geomorphic studies also have direct application to megageomorphology. The impact of tectonism on geomorphic systems, where measurable, provides vital information and empirical constraints on the rates at which tectonic processes operate. For example, morphometric data gathered in areas where the tectonic history is known may ultimately be useful as multivariate training sets for classifying areas where the tectonic history is unknown. Too, the evolution of fault scarps and consanguine features, has provided data on the ages of prehistoric faulting events and resulted in a totally new field of study referred to as paleoseismology.

Climatic impacts on regional geomorphic systems have direct significance on the rates at which processes operate. Regional climatic differentiation with regard to geomorphic process (as opposed to form) is an understudied field within megageomorphology. There should be a focus on the physical constraints that climate and climatic changes places on the operation of geomorphic systems and clear understanding of the importance of time series and hysteresis in climatic geomorphology. Climate geomorphic systems that are simple and can be inverted, or have unique solutions, are those that hold most promise for helping us understand climatic variation in space and time.

## Use of Spaceborne Imaging Radar in Regional Geomorphic Studies

J. P. Ford

Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, CA 91109

In the past two decades, the use of both photographic and non-photographic remote sensing from satellite platforms has provided a unique capability for the observation and study of earth and planetary surfaces. A wide range of imaging sensors that operate in different portions of the electromagnetic spectrum have yielded images of large areas that formerly were unknown, or that had not previously been observed at a simultaneous instant in time. In addition, remote sensors equipped with multispectral or multiband capabilities are capable of taking data at different wavelengths simultaneously. Notable examples include the Landsat series of multispectral scanners, thematic mappers, and return beam vidicons.

Landsat images of the earth have found wide application in regional reconnaissance mapping programs. They serve especially well in mapping remote inaccessible terrains, in areas where conventional aerial photographs and topographic maps are not available. However, the quality of Landsat images, and of all images or photographs that are acquired at optical and infrared wavelengths, depends on solar illumination conditions. The utility of such images is limited in areas that are cloud covered.

Large areas of the earth are perennially cloud covered, particularly in the humid intertropical belt and in polar regions. As exploratory and exploitive activities are extended further into such regions, there is an increasing need to understand the geomorphic processes that are peculiar to the respective environments, and to assess the impact of cultural activities on these processes. The task of observing and evaluating the geomorphic processes that operate over large areas is facilitated with the utilization of spaceborne images.

Microwave radar energy is capable of penetrating cloud cover, and synthetic-aperture radar (SAR) systems are active sensors that provide their own illumination. Thus, SAR sensors can be effectively operated independently of weather conditions or time-of-day, and they are well suited to the acquisition of images over cloud-covered terrains.

Brightness levels on a radar image are representations of surface backscatter. They are determined by the interaction of surface physical properties with imaging parameters, notably including incidence angle, polarization and wavelength. For any given set of imaging parameters, the backscatter is mostly a function of surface slope and surface roughness at the scale of the radar wavelength. The sensitivity of the backscatter to topography is very high. A change in slope of a few degrees can change the radar backscatter by a factor of 2 or more at incidence angles below  $30^{\circ}$ . At larger incidence angles, the backscattered energy is proportional mostly to surface roughness. Thus, SAR images are most useful in studying patterns and features that are expressed as changes in slope or roughness. For this

reason, airborne SAR images have been successfully used in geomorphic and structural mapping.

Airborne radar images have been acquired for geological exploration and for inventorying natural resources by exploration companies and government agencies, notably in extensively cloud-covered tropical regions such as Brazil, Venezuela, Panama, Nigeria, Togo, etc. Airborne radar images are acquired in the form of narrow linear swaths, with a wide range of incidence angles across the swath. Large-area coverage is obtained by mosaicing adjacent image swaths.

The Seasat SAR (1978), Shuttle Imaging Radar SIR-A (1981), and SIR-B (1984) experiments have successfully demonstrated that spaceborne SAR's provide high-resolution coverage of land and ocean surfaces. The spaceborne SAR's have the capability to acquire large-area coverage across a wide swath through a small range of incidence angles. Both Seasat SAR and SIR-A operated at a single frequency (L-band, 23.5 cm wavelength), single polarization (HH), and fixed incidence angles (20 for Seasat SAR; 50 for SIR-A). Interpretations of Seasat SAR and SIR-A images for geologic mapping purposes have demonstrated that the images contain a predominance of useful geomorphic information (see references for examples). Distinctive terrain textures are highlighted on the images and serve to discriminate broad lithologic associations. The SAR's enhance subtle topographic features to provide important geomorphic and structural data. The potential exists for future operational SAR systems to monitor dynamic geomorphic processes, such as shoreline erosion, delta formation, stream channel flooding, glacier movement, etc.

During the present decade, the main thrust of spaceborne radar research is to understand the basic properties of surface features that relate to the radar illumination geometry (incidence angle), polarization and radar signal frequency (wavelength). SIR-B was equipped with a stepwise movable antenna to provide multiple incidence capability. Multiple incidence coverage yields a capability for radar stereo measurement and topographic mapping. The role of SIR-C (1988) is to provide unique information about surficial units and processes that can be obtained through its multipolarization and multifrequency capabilities. Existing and future spaceborne imaging radar data sets will provide an excellent tool for application to regional geomorphic studies.

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## TECHNIQUES, PROBLEMS AND USES OF MEGA-GEOMORPHOLOGICAL MAPPING

Clifford Embleton  
King's College  
University of London  
United Kingdom

At the closing session of a conference organized by the British Geomorphological Research Group (BGRG) in London in 1976 (Embleton et al., 1978), G.H. Dury attempted to look into the future of geomorphology. His final argument was, essentially, that projections of current trends and rates of growth are, in the longer term, meaningless, because scientific advance does not occur as a smooth curve of progression but as a step function, a series of revolutions. Looking back on the last 150 years or so of scientific geomorphology, it is possible to identify the principal revolutions that have marked its advance - the uniformitarianism of Lyell, the glacial theory of Agassiz, the cyclic theories of Davis and Penck, the climatic geomorphology of Büdel, and so on. The effects and significance of three other 'revolutions' are still being evaluated: the revolution in the measurement of geological time, the technological revolution in global remote sensing, and the concept of plate tectonics in geology.

In the early decades of the twentieth century, geomorphology was dominated by theories of cyclic landform evolution and by an historical approach. The emphasis was on landforms, especially at medium to large spatial scales; the ergodic hypothesis, with its substitution of space for time, was usually assumed. Long time-scales were employed, and relict elements, sometimes of great age, were commonly recognised in present landscapes.

Dissatisfaction with the speculative and unscientific nature of much of this type of geomorphology, an increasing desire to place geomorphology on a more rigorous and quantitative foundation, and the advent of the computer, caused a swing away from historical geomorphology in the 1950's. The emphasis of geomorphology shifted to studies of processes, both in the field and in the laboratory, and to theoretical modelling of these processes. In order to make the investigations manageable, geomorphologists concentrated more and more on smaller spatial scales and short temporal scales. Many became obsessed with micro-geomorphology, with first-order drainage basins, beach profiles, single hillslopes.

The great changes that were then taking place in geology passed almost unnoticed, or were regarded as rather irrelevant. After all, the radiometric dating revolution was hardly of interest to those studying contemporary hillslope processes, and plate tectonics and sea-floor spreading were worlds away from stream channel processes. The advent of satellite surveys and the development of remote sensing techniques were of no importance to such objects of geomorphological study. At last, however, the 1980's are beginning to show a response by geomorphologists to these new concepts and techniques, and a re-awakening of interest in historical geomorphology, large-scale geomorphology and the study of landforms. To quote Ollier (1981), "over

the next few decades, geomorphologists must forget their trivial catchments and see megaforests instead of trees."

The term mega-geomorphology itself is quite new - we used it in 1981 for the title of another conference in London organised by the BGRG (Gardner and Scoging, 1983). Mega-geomorphology is on the same scale as plate tectonics, biological evolution and macro-climatic change. It is not concerned, as Ollier says, "merely with a little bit of sculpturing on the top of the geological column". Its time scales are measured in millions of years, its forms are studied as continental or macro-regional assemblages. Techniques of radiometric dating and remote sensing are essential to its study.

#### Mega-geomorphology and remote sensing

The most important techniques for the study of mega-geomorphology are without doubt those that fall under the heading of remote sensing, utilising surveillance from artificial satellites and employing sensors that range across a large part of the electro-magnetic spectrum. For the first time in the history of geomorphology we have a direct method for identifying global or macro-scale morphostructures. Remote sensing has many advantages over traditional ground survey (Verstappen, 1977a, 1977b) - unprecedented speed and accuracy, a uniform density of information over the whole mapping area and uniform reliability. Problems of ground access or difficulty of terrain are side-stepped, and there is an unrivalled capability for recording complex geomorphological patterns such as those of dune fields, tropical karst, ocean waves, glacier surfaces or thawing permafrost. It completely obviates the need for the traditional procedures of scale reduction, cartographic generalisation and data selection that are responsible for introducing inaccurate or biased depictions of landforms. Additionally, remote sensing from frequently orbiting satellites is ideally suited to studies of landform dynamics: sequential imagery gives instantaneous and repeated views of such rapidly changing phenomena as flooded areas, depositional coastlines, snow cover or proglacial areas.

At the same time there are problems. The most important is that a completely new basis for interpretation is needed. For any successful geomorphological interpretation of remote sensing data, it is essential that the analysis be carried out by a geomorphologist, preferably someone with field experience of at least parts of the area being investigated, with an understanding of the geomorphological process systems operating in the area at present, and if possible with background knowledge of the paleo-geomorphological evolution of the area. These needs cannot be too highly stressed. If the area is largely unknown in terms of its geomorphology, mapping by remote sensing must be accompanied by an adequate programme of fieldwork, at least sampling parts of the terrain, and if necessary also analysing soil and rock samples in the laboratory.

## The geomorphology of Europe

Before satellite remote-sensing data became widely available, a project was commenced for the geomorphological mapping of Europe. The Commission for Geomorphological Survey and Mapping (see Embleton, 1981) was set up by the International Geographical Union in 1968, under the chairmanship of Professor J. Demek, then of the Institute of Geography in Brno, Czechoslovakia. The Commission included representatives from nearly all countries of Europe, as well as the Soviet Union, and a few from other areas. The Commission has now been in existence for 16 years, Professor H. Th. Verstappen succeeded to the chairmanship in 1980, while I have recently taken over as chairman from Verstappen. Two main projects have been organized by the Commission, one completed in 1984. the second planned for completion by 1986-87. The first was to compile a systematic text on the geomorphology of Europe, now published (Embleton 1984). The second was to prepare and publish a geomorphological map of Europe, as far east as the Ural Mountains, in 15 sheets at a scale of 1:2.5 million, to complement the existing geological and Quaternary maps of Europe at the same scale. A detailed legend for the mapping was established and subsequently revised (Embleton, Maresova and Matousek, 1983, 6th revision), and careful coordination between some 30 geomorphologists in various countries including the Soviet Union was achieved. The first sheet (number 10) was published in 1976; after various delays due to political and financial difficulties, the publication of further sheets is now proceeding. All the geomorphological information is now complete, and all the cartographic work finished. Four more sheets are to be published by the Czechoslovak Academy of Sciences, in conjunction with UNESCO, in 1985. and the remainder will follow in 1986-87. The Commission has, at the same time, published several manuals of geomorphological mapping at various scales to explain the procedures of data collection and compilation (Demek, 1972; Demek and Embleton, 1978; Kugler, 1982; Russian and Chinese editions have also been printed - Bashenina et al., 1976, and Chen Zhi-ming, 1984).

The Geomorphological Map of Europe is based wholly on ground survey. The original data were compiled on larger scales, and there was then a process of successive generalisation and scale reduction to 1:2.5 million. Because of cartographic limitations, some data were selected and other data discarded. All these procedures inevitably introduce a subjective element, coloured by individual perception or particular geomorphological theories. There were many problems of correlation, such as the disagreements on the locations of Quaternary moraine systems running across East and West Germany, whose first mapping showed some remarkable displacements at the actual frontier!

## Remote sensing and the geomorphology of Europe

When the project to compile a geomorphological map of Europe was first formulated, remote sensing data were either unavailable or the resources for their analysis were not available (i.e. in eastern Europe). The authors of the map of Europe are fully aware of its imperfections - variations in accuracy, level of detail and cartographic deficiencies. However, an immense amount of field experience lies behind it, and it is this experience that

could be utilised if a project to re-map the continent were undertaken, based on remote sensing from satellite data. It was noted earlier that perhaps the single most important problem in compiling a new map from remote sensing is that of checking the data against ground truth. In the case of Europe, however, at least an approximation to the ground truth is already available. To make progress in any aspect of global mega-geomorphology, we need an information store on global landforms, which must include the geomorphological mapping of whole continents (as well as submarine areas). The most logical starting point would be Europe, which would then provide the necessary further experience for mapping other areas. It may be noted in passing that, in recent contacts with Chinese geomorphologists, great interest has been expressed in the mega-geomorphological mapping of their country, which their Academy of Sciences is keen to promote.

To undertake a new map of the mega-geomorphology of Europe will require considerable financial backing, access to satellite data and expertise in analysis.

#### The uses of mega-geomorphological mapping

The prime function of all types of geomorphological mapping is as a visual information store. At the smaller mapping scales, say 1:2.5 million or less, it has the ability to display the spatial relationships of mega-morphostructures. Broad patterns and distributions, sometimes not previously apparent, can be perceived, from which inferences can be made about the locations of major geomorphological boundaries and about the regionalisation of forms. In turn, this provokes questions about the origins of these phenomena and the setting-up of hypotheses.

A second important function is in the field of research coordination, as became readily apparent during construction of the geomorphological map of Europe. Not only do geomorphological phenomena have to be viewed in a wider spatial context, but the discipline of mapping within an agreed international framework and the need for agreeing temporal and spatial correlations often forces the geomorphologists concerned to re-examine their basic concepts and approaches.

Thirdly, small-scale geomorphological maps can play a useful educational role. Comparisons with other physical maps (geology, soils, vegetation, etc.) show the complex integration of all elements of the natural environment. For geographical teaching purposes, the landform map is superior to a simple topographic map, provided it is well designed.

Finally, the importance of geomorphology to the interpretation of remote sensing data needs to be stated. Much traditional geological photo-interpretation, for instance, is based on analysis of landforms and drainage patterns, prior to field checking. The experienced geomorphologist with his training in the perception of spatial elements in the landscape and his conceptual appreciation of process and landscape evolution through time, can much more easily and reliably appreciate terrain types depicted on remote-sensing imagery than the analyst without such a background.

## Conclusion

This paper is in the nature of a plea for a programme of global geomorphological mapping based on remote sensing data. This is a necessary step in bringing together the rapidly evolving concepts of plate tectonics with the science of geomorphology. Geomorphologists must bring back the broader spatial and temporal scales into their subject, and abandon their recent isolation (at least in western countries) from tectonics and geological history before the Quaternary. It is suggested that a start be made with a new geomorphological map of Europe, utilising the latest space technology.

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LARGE FORMAT CAMERA PHOTOGRAPHS  
A NEW TOOL FOR UNDERSTANDING ARID ENVIRONMENTS

Alta Walker  
U.S. Geological Survey  
Reston Virginia

The Large Format Camera (LFC) was developed by NASA to produce high resolution stereo photographs from space with maximum photogrammetric fidelity. The camera has a 30.5 cm focal length lens and an f/6.0 aperture. The optics are corrected to permit operation with black and white (b/w), natural color (col) and color infrared (cir) film. Interchangeable minus-haze and minus-blue filters are located near the aperture stop, and an anti-vignetting filter is provided on the front element of the lens. The field-of-view of the LFC along track is 73.7 degrees (ratio 1.5 x H) and across track is 41.1 degrees (ratio 0.75 x H)

The frame format of the LFC is 23x46 cm with the long dimension in the direction of flight. The camera can be operated to produce 10, 60, 70, or 80 percent forward overlap for stereoscopic coverage. With 80 percent forward overlap, the stereo model base height ratio is 0.3 for successive frames and 1.2 if every fourth frame is used. The LFC magazine has a capacity of 2400 frames.

Two horizon-looking stellar cameras, one directed 45 degrees forward and the other 45 degrees aft were used to photograph the star field in synchronism with exposures of the LFC. Post flight mensuration and calculation of the stellar photographs will provide altitude information for the LFC.

The initial flight of the LFC was on shuttle mission STS-41-G in October, 1984. This mission was at 57 degrees inclination and operated at three different altitudes: 352 km, 272 km and 225 km. Four Kodak film types were used: 3412 b/w Panatomic-X Aerocon II, 3414 b/w High Definition Aerial; 50-242 Aerial Color Positive, and 50-131 High Definition Aerochrom Infrared Positive. The four films were spliced together to provide a continuous roll in the magazine. The ground resolution of the photographs is better than 10 meters. Extensive coverage was obtained on all continents except Antarctica.

Approximately 150 LFC photographs of the world's arid lands are available from this mission. Most of the photographs are high definition black and white, some are color infrared, and a few are natural color positives. The photograph scale ranges from approximately 1:1,000,000 at the high altitude to 1:740,000 at the low altitude. Coverage varies from 190,000 square kilometers to 57,000 square kilometers.

Accurate large-scale topographic data in arid lands is difficult to obtain due to their general remoteness. Because the parameters of the LFC camera, the exposure position and the altitude

are well known, topography can be determined for each stereo model with high precision. Using the stereo capacity of the LFC, relief has been calculated for several dunes in select sand seas. Additionally, profiles of dunes indicate the morphometry of simple, compound and complex types, important in determining the present and past eolian regime. With the LFC photographs, the positions of dunes with respect to each other and the relief differences of adjacent interdunal areas are determined photogrammetrically.

Sand seas are less than 20 percent of the world's arid areas. In eolian deflation zones, subtle color differences may indicate changes in the underlying geology or in the desert varnish. Land-use patterns and water resources in the borders of arid lands are mapped.

Because of geometric fidelity, high resolution and stereoscopic coverage, the LFC is far superior to Landsat or any previously used Earth-orbiting photographic system for understanding arid land environments.

# QUANTITATIVE ANALYSIS OF GEOMORPHIC PROCESSES USING SATELLITE IMAGE DATA AT DIFFERENT SCALES

Richard S. Williams, Jr.  
U.S. Geological Survey  
Reston, Virginia 22092

## Summary

Aerial and satellite images and photographs of the Earth and satellite images of other planets and moons in our solar system are a rich new source of information about the landforms on these planetary bodies. The availability of this material has triggered a renewed scientific interest in regional and global geomorphic investigations and comparative studies of landforms on different planets and moons.

In addition to Landsat images, Large Format Camera (LFC) photographs, and other types of satellite imagery, such as satellite imaging radar (SIR) images, side-scan sonar (SSS) images of the seafloor are also providing new data about the geomorphic, structural, and tectonic character of the 75 percent of the Earth's surface obscured from satellite (or aerial) view. Comprehensive knowledge about the geomorphology of landforms on the seafloor is vitally important for comparative planetologic studies. In the near future, the Venus Radar Mapper (VRM) system will provide important image and other data about the geomorphic, structural, and tectonic character of Venus. Side-looking airborne radar (SLAR) images, SIR images, and SSS images of our own planet will be important in the analysis of the VRM images. Viking Orbiter images of Mars and Voyager images of Jupiter's Galilean moons and the moons of Saturn have provided unexpected information about active and dormant geomorphic processes that have shaped or are still shaping these planetary surfaces.

When aerial and satellite photographs and images are used in the quantitative analysis of geomorphic processes, either through direct observation of active processes or by analysis of landforms resulting from inferred active or dormant processes, a number of limitations in the use of such data must be considered. Active geomorphic processes work at different scales and rates. Therefore, the capability of imaging an active or dormant process depends primarily on the scale of the process and the spatial-resolution characteristic of the imaging system. Scale is an important factor in recording continuous and discontinuous active geomorphic processes, because what is not recorded will not be considered or even suspected in the analysis of orbital images. If the geomorphic process or landform change caused by the process is less than 200 m in x-y dimension, then it will not be recorded. Although the scale factor is critical, in the recording of discontinuous active geomorphic processes, the repeat interval of orbital-image acquisition of a planetary surface also is a consideration in order to capture a recurring short-lived geomorphic process or to record changes caused by either a continuous or a discontinuous geomorphic process.

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\*Discussion commentary for Theme III, Process Thresholds, Workshop-Conference on Global Mega-Geomorphology, Oracle Conference Center, Arizona, 13-17 January 1985, which was sponsored by the National Aeronautics and Space Administration and the International Union of Geological Sciences.

The experience with Landsat multispectral scanner (MSS) images of our own planet is instructive. For many types of landforms, Landsat MSS images have inadequate spatial resolution to be able to record them. In other words, a particular geomorphic process or the change caused by the process must reach a certain size threshold before it can be recorded by an imaging system. Also, the maximum repeat interval of Landsat 1, 2, and 3 for any given area was 18 days, 16 days for Landsat 4 and 5. Because of cloud cover the actual repeat interval is often considerably longer, several months or even years in some terrestrial locations. Few volcanic eruptions among many, for example, have been recorded by Landsat since 1972. The NOAA satellite, with its 12-hour repeat interval, albeit at lower resolution, has been far more successful in recording volcanic eruptions.

Analysis of Landsat MSS images (79-m picture element or pixel), Landsat RBV or TM images (30-m pixel), and the space shuttle LFC photographs (10 m per line pair) indicates that the LFC photograph probably has spatial resolution adequate for most regional quantitative studies of landforms and for comparative global studies of various types and classes of landforms. Landsat MSS images are an important source of image data for similar studies, but the scale of the landforms being analyzed must be 20 times larger than those discernible on LFC photographs: 200-m minimum dimensions (x,y) for the MSS image versus 10-m minimum dimensions (x,y, and z) for the LFC photograph. This means that all classes of landforms that have x and y dimensions less than 200 m will not be discernible on MSS images.

Landsat MSS images can best be used in quantitative studies of large-scale geomorphic processes, or in the changes produced by such processes, in a time-lapse manner. The changes recorded on an image may be the result of indirect influence rather than the direct influence of a specific geomorphic process or processes. Even the effects of very subtle geomorphic processes, such as small-scale stream captures, tectonic changes, land subsidence caused by groundwater withdrawals, etc., especially when reinforced by regional variations in climate, may produce local or regional changes in vegetative cover and drainage patterns. Successful quantitative geomorphic studies with Landsat MSS images completed so far include: changes in fluvial landforms caused by major floods, measurement of glacier advance (including surging glaciers) or recession, measurement of average velocity of outlet glaciers from two or more images, delineation of coastal changes caused by the passage of severe storms, areal measurements of new lava flows and tephra falls.

The scale factor is so critical in regional or global quantitative geomorphic studies that an important first step for geomorphologists is to obtain complete image data sets of all land areas of the Earth at the largest scale feasible with existing technology. This has now been nearly achieved with Landsat MSS images (79-m pixel size or about 200 m equivalent spatial resolution). This existing Landsat image data set allows geomorphologists to conduct comparative global studies for the first time, some of which were enumerated in the preceding paragraph. The next step is to acquire a Landsat TM image data set of the land areas of the Earth. The 30-m pixel of the TM image (or about 75 m equivalent spatial resolution) lowers the threshold of detectability and, therefore makes many more landforms of the Earth's land areas available for geomorphic analysis.

Another image data set of considerable value to regional geomorphologic studies, especially in regions of persistent cloud cover and low relief, is the SIR imagery acquired during two space shuttle missions. Satellite radar images of the Earth's surface are also important to have for comparative planetologic studies of Venus. The Earth's volcanic regions should have a special priority in the continuing program to acquire SIR images of our planet.

The newly available LFC photographs, all in stereo and some with a spatial resolution of 8 m per line pair (equivalent to a digital imaging system with 3-m pixels), represent a quantum leap in satellite imagery available for scientific analysis. The stereophotogrammetric characteristics of the LFC photograph would essentially open all the land areas of the world for quantitative geomorphic analysis, if complete coverage existed, and open a "golden age" for regional and global geomorphic studies of our planet.

# QUANTITATIVE GEOMORPHOLOGIC STUDIES FROM SPACEBORNE PLATFORMS\*

Richard S. Williams, Jr.  
U.S. Geological Survey  
Reston, Virginia 22092

## Summary

The five spacecraft in the Landsat series, the first of which was launched on 23 July 1972, provided geomorphologists with their first access to a complete set of medium-resolution, multispectral images of most of the land and shallow-sea areas of the Earth. These revolutionary new data about our planet provide a valuable source of information on landforms and geomorphic processes to those scientists involved in comparative geomorphic studies of landforms on a global basis. One of the first geologists to take advantage of this new data source was Ed McKee and his colleagues in U.S. Geological Survey (USGS) Professional Paper 1052 (1979), entitled "A study of global sand seas." Another global study, entitled "Satellite image atlas of glaciers," in which Landsat images are the principal source of data, is in preparation by the author and more than 50 other scientists.

An important aspect of the Landsat image to geomorphologists is the fact that many areas of Earth now have multiple sets of coverage spanning a 13-year interval. For those geomorphic processes that produce areal changes resolvable on Landsat images, quantitative, two-dimensional measurements can be made. Sequential Landsat images have been used to determine the velocity of outlet glaciers, calculate changes in area of ice caps, delineate changes in areal extent of barrier beaches and islands following severe storms, determine the areal extent of new lava flows and deposits of tephra, and so on.

Although Landsat images of our planet represent a quantum improvement in the availability of a global image-data set for independent or comparative regional geomorphic studies of landforms, such images have several limitations which restrict their suitability for quantitative geomorphic investigations. The three most serious deficiencies are: (1) photogrammetric inaccuracies, (2) two-dimensional nature of the data, and (3) spatial resolution.

Landsat is not a mapping system in the strict sense, although Landsat images have been used to produce maps of many areas, either as a single image or as image-mosaic maps. Landsat image-maps significantly improve in our knowledge of poorly mapped regions. To serve as a true map, however, Landsat images must be related to the figure of the Earth, either by geometrically correcting the data or by fitting a recognized geomorphic grid to the data. Such a grid uses identifiable features on the image, whose geographic locations are known from independent geodetic surveys, for geometric and geographic control. Even with independent geodetic control, most Landsat image maps have inaccuracies in position of 100 m or more in well mapped areas and 1 km or more in poorly mapped areas. Although some geomorphological studies only require measurements of relative change, such as measurement of the fluctuation in termini of a glacier, many studies require precise geographic location ( $x, y$  or  $\phi, \lambda$ ).

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\*Discussion commentary for Theme V, Other Themes in Mega-Geomorphology, Workshop-Conference on Global Mega-Geomorphology, Oracle Conference Center, Arizona, 13-17 January 1985, which was sponsored by the National Aeronautics and Space Administration and the International Union of Geological Sciences.

Most landforms have a unique three-dimensional character. However, Landsat images (and most other space images and photographs available to the scientific community) can only be used in geomorphic studies of a two-dimensional (x,y) nature, and then only in a relative sense because of a lack of precise geographic position. Future geomorphic studies of the Earth's subaerial landforms will require satellite data that can be analyzed stereoscopically. The third dimension, z, is the missing element in quantitative regional and global geomorphic studies.

The other limiting factor of Landsat images, and most other satellite images and photographs, is the inadequate spatial resolution for many types of geomorphic studies. The Landsat 1-5 multispectral scanner (MSS) and Landsat 1 and 2 return beam vidicon (RBV) images have a picture element (pixel) size of 79 m; the Landsat 3 RBV and Landsat 4 and 5 thematic mapper (TM) images have a pixel size of about 30 m. The standard photogrammetric definition of resolution is "the minimum distance between adjacent features, or the minimum size of a feature, which can be detected by remote sensing. For photography, this distance is usually expressed in lines (line pairs) per millimeter recorded on a particular film under specified conditions" (Manual of Photogrammetry, American Society of Photogrammetry, fourth edition, 1980). An approximate way to convert from pixel size to photographic resolution is to multiply the pixel dimension by 2.8; hence Landsat MSS and RBV (Landsat 1 and 2) images have a theoretical photographic resolution of 221 m; Landsat 3 RBV and Landsat 4 and 5 TM images have a resolution of 84 m. This means that only large landforms and geomorphic processes that produce significant change will be recorded on Landsat images. Unless a geomorphologist knows an area well through field work or analysis of large-scale aerial photographs s/he may not be aware, or even suspect, that important geomorphic features are present or that geomorphic processes have left their mark. Astrogeologists have a similar problem in their analysis of landforms on other planets and moons. My geomorphic studies of Icelandic volcanoes, for example, provide an insight into the problem. Of the 25 discrete types of subaerial volcanoes in Iceland, only 7 types of volcanoes can be unambiguously identified on Landsat MSS images. The other 18 are "missing", either because of the lack of stereoscopy (third dimension) or because of inadequate spatial resolution or a combination of both. Except in a gross sense, Landsat MSS images cannot be used to study Iceland's volcanoes. Although the increase in resolution of the Landsat 3 RBV image adds three more types of volcanoes, the combination of still inadequate spatial resolution and non-stereoscopic nature of the data still limits the usefulness of the Landsat image for such geomorphic studies. Ed McKee's research on sand seas was successful, because dunes or dune groups had areal and(or) linear dimensions large enough to be resolved spatially on the Landsat image. The third dimension was not that critical; the x-y geometric configuration of dunes and dune groups was more important. This is one of the reasons that we have been analyzing Landsat images of glaciers. Although the third dimension (z) is very important to glaciological studies, information on the x-y geometric configuration of ice sheets, ice caps, and tidal, valley, and outlet glaciers is also valuable. Measurements of area, changes in area, and fluctuations of glacier termini can also be determined from two-dimensional satellite images, such as Landsat.

To effectively carry out regional and global quantitative geomorphologic studies of the landforms of the Earth, it is necessary to develop specialized satellites which will carry optimum instrumentation. The two most important systems needed are: (1) an imaging instrument capable of acquiring photogrammetrically accurate stereoscopic images of the Earth's surface, with a ground resolution of  $\leq 10$  m per line pair, adequate for 1:50,000-scale topographic mapping (at a scale of 1:50,000),

and (2) a laser altimeter capable of measuring elevation differences of  $\leq 10$  cm. Both satellite systems will need the type of positional accuracy achievable with the Global Positioning System (GPS) (projected to be a few meters in x, y, or z) and with accurate attitude control of the spacecraft achievable with stellar sensors. Both the stereoscopic imager and the laser altimeter need to be operated for at least 10 years to build up a basic global set of cloudfree data. After 10 years the stereoscopic imager should be operated repetitively to acquire new data sets for comparative studies of changes in landforms. The laser altimeter should also be operated after 10 years to support similar types of studies, such as studies of ground subsidence caused by groundwater withdrawal, ground subsidence or elevation caused by tectonic forces, inflation and deflation of volcanic calderas caused by intrusive and extrusive volcanic activity, changes in elevation of ice sheets and ice caps, and so on.

The new black-and-white, color, and color-infrared photographs from the Large Format Camera (LFC), which was flown in October 1984 on the Space Shuttle (STS Mission 41-G), provide superb examples to geomorphologists of the type of satellite data that can satisfy their needs. Frederick J. Doyle of the U.S. Geological Survey (written communication, 1985), stated that a stereo model of LFC photographs covers about 170 by 170 km with a ground resolution of  $< 10$  m (high resolution black and white film) and has an internal photogrammetric precision of  $\leq 5$  m in x, y, and z coordinates. By orienting the stereo model to 3 or 4 ground control points (GCP's) an accuracy of about 8 m can be obtained in geographic position and terrain elevation. For comparison, the internal geometric accuracy of the thematic mapper (TM) image is 30 m, using about 20 GCP's. In future operations of the LFC with the Global Positioning System (GPS) and an electro-optical, stellar-attitude sensor, the stereo model would have the same internal accuracy, and the absolute position and elevation anywhere in the world could be determined with an accuracy of about 20 m without any GCP's. Although the LFC is capable of producing adequate image data, it is not likely to be flown on the Space Shuttle very often and also, because of orbital limitations of the Space Shuttle, coverage is not likely to be obtained on a systematic basis. What is needed is a dedicated free-flyer spacecraft, in near-polar orbit, to acquire global data on a systematic basis. Our experience with using Landsat images in glacier studies is that about 150 data sets (acquisition for about 10 years at 22 orbits per year over the same location) are necessary in some glacierized regions to obtain optimum, cloudfree images under the right seasonal conditions.

The U.S. Geological Survey has proposed a mapping satellite, Mapsat (also called the Orbital Mapping System (OMS) by the International Society for Photogrammetry and Remote Sensing, which has carefully studied and accepted the Mapsat concept), to acquire multispectral stereoscopic images of the Earth on a long term, systematic basis. With a stellar sensor for attitude control and the GPS for positional control, Mapsat or OMS would provide the needed image data. A NASA scientific panel has proposed a Laser Atmospheric Sounder and Altimeter (LASA) which would acquire the needed data on landform elevation. Unless LASA were carried on Mapsat or OMS, it, too, would need to be carried on a satellite with a good stellar sensor and use of GPS.

Both the stereoscopic images and the laser altimeter would provide important new sources of data to geomorphologists involved in landform studies. Stereoscopic images would provide the areal coverage and accurate x, y, and z geometry of landforms. The laser altimeter would provide detailed elevation information

which, at  $\leq 10$  cm, would revolutionize comparative regional and global landform studies. Even our best topographic maps rarely show contours of 1 m and usually provide data ranging from 5- to 100-m contour intervals. Space data of this kind would permit not only the study of megageomorphology but would also be useful in microgeomorphological studies.



CHAPTER II  
Working Group  
Reports



GLOBAL GEOMORPHOLOGY  
Report of Working Group Number 1:

Leader: Dr. Ian Douglas

First Meeting:

Remote sensing was considered invaluable for seeing landforms in their regional context and in relationship to each other. Sequential images, such as those available from Landsat orbits provide a means of detecting landform change and the operation of large scale processes, such as major floods in semi-arid regions. The use of remote sensing falls into two broad stages:

1. The characterization or accurate description of the features of the earth's surface.
2. The study of landform evolution.

Stage 2 can only deal on the human time scale with relatively small scale changes, but can be invaluable for the study of short-lived phenomena, such as earthquakes, tidal waves and floods. The particularly severe land degradation caused by human activity, such as over-grazing in the Sahel or forest clearance in the Amazon and Himalayan foothills, and its impact on denudation systems can be monitored and assessed. Many of the most serious impacts of such changes are off-site, downwind and downstream.

The multiple data sets now available for many areas provide an opportunity to examine a series of attributes of a given region. It would be useful to prepare a series of maps of an area like the Appalachians to show landform attributes, such as structure, fluvial erosion, evidence of glaciation and karst, and to develop a history of tectonics and denudation. Alternatively the whole American Plate could be examined in detail, looking at patterns to establish geomorphic provinces. Such a study need not be confined to the subaerially exposed parts of the plate but should include the submarine morphology. Information from radar, sonar and radar sea surface altimetry should be incorporated into such a study.

These studies could be regarded as a trial for a system of comparative global geomorphology studies. A global geomorphology working party could be set up to evaluate the pilot investigations and pursue an extended program. However it is essential to insure that geomorphologists are asking the right questions. The working group agreed on the following major questions.

1. How does the surface of the whole earth look at the planetary scale?

2. What are the significant major units at which to look in terms of megageomorphology?
3. Do landforms converge to some (one or more) common types?
4. How do the units identified in question 2 relate to geodynamics? (exogenetic/endogenetic)?
5. What is the global extent of exogenetic landforms?
6. What is the global extent of endogenetic landforms?
7.
  - a. How can we distinguish the changes in geomorphic processes stemming from the modification of ground cover by human action?
  - b. What is the relationship between climatic fluctuations and land surface changes?
  - c. What will be the geomorphic effects if half the world's population is living in cities by the year 2000?

Questions 1 to 6 relate to extensive static coverage of the earth's surface while question 7 requires sequential imaging of changes at the present time. The first question takes the study of landforms of the earth to the scale of studies of the surface features of the planets. From this fundamental, planetary scale, examination of the earth, the answer to question 2 will emerge. The appropriate units may be the continental and oceanic plates or geomorphic provinces within them. The unit boundaries do not have to conform with the present coastline.

Remote sensing techniques assume that a particular distinctive pattern, tone, hue, or signature is made by a single unique feature. However geomorphologists recognize the principle of equifinality, that the same landform may be produced by more than one cause. The extent to which such convergence forms occur at scales at which satellite and space vehicle sensors are used needs to be detected.

Questions 4, 5, and 6 stem from the answers to question 2. Some landforms directly reflect tectonics, while others are direct expressions of the work of running water, wind, ice, or waves. However the extent of such direct relationships is unknown, yet can be readily observed from space imagery.

The influence of climatic fluctuations and human activity over the period since Landsat data became available have locally been great, especially in terms of droughts, floods, forest clearance and over-grazing. Question 7 tackles these changes and endeavors to make the important separation between people-induced effects and natural change. The effects of urbanization are emphasized because of both the growth of urban areas and the demands these place on the surrounding countryside.

## Second Meeting:

The group was concerned to tackle scientific questions and to specify some challenging tasks for geomorphological investigations using space imagery. The following questions were identified.

1. The use of space imagery, especially new improved radar sensors, to investigate geomorphic changes during the Quaternary in low latitudes, particularly in forested areas.
2. The investigation of the construction and destruction of volcanoes by collecting a series of images of volcanic cones at different stages of evolution and bringing them together to show the pattern of landform evolution.  
Volcanoes were chosen as the most clear-cut features to use for a pilot study of this type. Similar comparative investigations of other landforms could follow.
3. Tests of the two major concepts of evolution of the earth's surface features, the theory of climatogenetic geomorphology advanced by Büdel and his co-workers, and the relationship between plate tectonics and landforms.
4. The use of space imagery to detect relict features indicative of paleogeomorphology and paleohydrology. The use of SIR-B radar has been particularly significant in this respect.
5. The analysis of the impact of human action on geomorphic processes and their effects on societies through such phenomena as:  
forest clearance  
water diversion  
over-grazing  
urbanization  
together with the effects of climatic variability on societies.

Question 1 tackles the fundamental issue of how can features caused by Pleistocene aridity in the tropics be recognized. SIR-B data from areas such as Borneo indicates that landforms beneath tropical rainforest can be recognized but the sensors need further improvement. It would be useful to have sensors capable of revealing information about the depth of weathering and the presence of bauxitic, ferruginous or siliceous duracrusts. Work using SLAR 10 years ago enabled the Quaternary landform history of part of the Amazon basin to be revealed. However, shuttle radar imaging systems would greatly speed up this work in other forested tropical areas. Such work is of economic significance, stratigraphic work in S.E. Asia, for example, indicates important alluvial ore deposits in buried braided stream channels which formed under seasonally dry climates at times of Quaternary low sea level.

Question 2 is a modeling exercise using empirical data from actual landform examples which can easily be measured or digitized from space images. Development of such technology would enable far better predictions to be made of the changes in landform evolution likely to occur as a result of large scale engineering or land development works.

The third question turns to fundamentals of theory in geomorphology. Büdel argued that etchplanation processes under seasonally wet climates prevailed over much of the earth in the early Tertiary and that remnants of the erosion surfaces so created are to be found in many areas. The signatures of the features could be recognized on appropriate images, their extent mapped and the evidence evaluated against the results of conventional field studies. Similar tasks could be undertaken with tectonic features to come closer to the problem of the relative roles of climate and tectonics in landform evolution.

Question 4 extends the use of imagery to detect traces of relict landforms and inherited features. It recognizes that much of the character of the earth's surface was determined under different combinations of geomorphic processes from those at present operating. By examining the consequences of past changes, the likely effects of future changes, such as global cooling or global warming, become more easily predictable.

Question 5 returns to the issues discussed in relation to the seventh question at the first meeting of the working group. The role of sequential images in seeing the consequences of both short-lived extreme events and the slower, more insidious degradation of the land by human action cannot be over emphasized.

Overall, the working group was enthusiastic about the prospects for global geomorphology and urged a continuing effort to develop concepts, scientific ideas, methods, instrumentation and means of access to and use of remote sensing data.

LANDSCAPE INHERITANCE  
Report of Working Group Number 2:

Leader: C.R. Twidale

The group concerned with Landscape Inheritance did not consider the obvious and widely recognized assemblages related to late Cainozoic climatic changes, with glaciated terrains, with former lakes now abandoned or much reduced, with fields of sand dunes now stabilized by vegetation. We were concerned more with inheritance in the longer time perspective.

The conventional wisdom is, or until recently has been, that the earth's scenery is essentially youthful, much of it being of Pleistocene age. The validity of this assertion was questioned, surfaces and forms of much greater antiquity being cited from several cratonic regions, and also from the older orogens. Exhumed forms, some of them of great age (one inselberg landscape of Archaean age was noted), are more common and extensive than has previously been supposed. Epigene forms of Mesozoic age are increasingly being demonstrated from the world's cratons and orogens. Etch features also are more widely developed than has been realized.

Plains dominate the continental areas. Some are located at or close to present base level. Others stand high in the relief. Many are complex and include exhumed, older epigene and etch components. The world's plainlands are worthy of close examination. Analyses of the denudation chronology of the continents (and plains are surely the end product of long-continued weathering and erosion) complement basin studies, the chronology of deposition. Denudation chronology provides a framework for process studies. The age and nature of surfaces also bears on questions of soil fertility and susceptibility to erosion.

It was recommended that studies of denudation chronology be undertaken, possibly in relation to contrasted cratonic regions. The Westralian, Canadian and Baltic shields were mentioned as possibilities (subsequently it occurred to one of us that the East African Shield might provide a contrasting example of a tectonically active craton). The nature and age range of surfaces that make up the shields ought to be analysed, the processes responsible for shaping the surfaces, and, in the case of the ancient epigene forms, the reasons for their survival.

Once several major areas had been treated in this way (and that in itself would be a major contribution to geomorphological knowledge), it would be possible to analyse the signatures obtained by various satellite sensors in order to ascertain whether the signatures are consistently characteristic and hence whether extrapolation and further mapping by satellite are feasible.

PROCESS THRESHOLDS  
Report of Working Group Number 3:

Leader - Richard S. Williams Jr.

The Process Thresholds Working Group concerned itself with the same issue that we had previously wrestled with during earlier meetings of the group: that is, whether a geomorphic process to be monitored on satellite imagery must be global, regional, or local in its effect on the landscape. As Prof. Dale Ritter pointed out, major changes in types and magnitudes of processes operating in an area are needed to be detectable on a global scale. One thing the group concluded from review of geomorphic studies which have used satellite images is that they do record change in landscape over time (on a time-lapse basis) that is the result of one or more processes. In fact, this may be one of the most important attributes of space imagery, in that one can document landform changes in the form of a permanent historical record.

The group also discussed the important subject of the acquisition of basic data sets by different satellite imaging systems. Geomorphologists already have available one near-global basic data set resulting from the early Landsat program, especially images acquired by Landsats 1 and 2. Such historic basic data sets can serve as a benchmarks for comparison with landscape changes that take place in the future. They can also serve as a benchmarks for comparison with landscape changes that have occurred in the past (as recorded by images, photography, maps). For instance, we have had reasonably good plane-table maps available of many areas dating back to the early 1900's and modern photogrammetric maps since the 1930's. Therefore, we have a means of using space images to look at certain types of landscape changes; for instance, coastal changes, variations in area and position of glaciers, areas covered by lava flows or tephra falls, etc. Geomorphologists have, for many regions, excellent data sets in the form of maps, aerial photographs, and satellite images. The number and diversity of data sets is expected to multiply in the future, affording more opportunities to monitor and to measure some of the geomorphic changes that have affected the planetary surface. The newly available Large Format Camera photography, although still limited in coverage, is an example of an important new data set to be exploited by geomorphologists.

Prof. Robert Sharp recommended, and the working group members all concurred, that perhaps what should be done is to design a series of natural experiments, dealing with landform changes resulting from desertification, sea level fluctuation, alluvial fan deposition, for example, in which field measurements could be combined with measurements on satellite images. One specific example Prof. Sharp suggested is the measurement of wave refraction along a coast from radar images, looking at the major attack points of erosion. One important recommendation

that could result from this workshop is, with the basic data sets that are already archived, to have NASA put together a series of funded research opportunities (A.O.'s), so that we can broaden the opportunities for research in global geomorphology beyond this group to the larger scientific community.

The members of the working group also discussed whether satellite images can be used to detect evidence of regional tilting of the terrain. Prof. Sharp noted that lakes are excellent tiltmeters, so that using time-lapse measurements of changes in lake basins are a possibility. It was also discussed by working group members that the availability of data from satellite-borne laser altimeters, when combined with the Global Positioning System, will permit precise ( $\pm$  a few centimeters) monitoring of regional tilt caused by tectonic and volcanic processes.

We examined the concept of rates of change in geomorphic processes. Can we detect rates of change? Are they fast or are they slow? How far do they deviate from equilibrium conditions? Can we see some of these processes and the effects they produce on satellite images; for example, the effect of climatic change on regional lake levels, on the distribution of vegetation, on glacier advance and recession? What about human interaction with the landscape? One experiment that was discussed repeatedly involved the region of Africa known as the Sahel, especially man's interaction with changes caused by a prolonged period of subnormal rainfall. Is there a feedback function between man and the natural environment that is making conditions worse? There was a recognition that the many natural and cultural variables are very complex, but it was still considered to be the type of geomorphic experiment in regional habitability that could be done with satellite images in which changes in landforms and vegetative cover are related to man's activities.

We also discussed a number of other topics amenable to study with satellite images, including desertification such as in the Sahel, and the effect of rising sea level on coastal landforms, barrier beaches, deltas, etc. Deltas are of special interest, because they are so sensitive to changes in volume of fluvial discharge, in sea level, and in sediment load. The reduction in the area of glacier ice also suggests loss in volume of glacier ice, which is probably the primary contributor to the 15 cm. secular rise in sea level during the past century. There was an extensive discussion concerning alluvial fans. Prof. Sharp recommended another experiment in which the change in morphology of alluvial fans over time can be compared between those in the American Southwest and those in Baja California. In the latter case the regional impact of man's activities is considered to be far less than in the southwest, where road building, dam construction, alteration of vegetative cover, water-reclamation projects, groundwater withdrawal and urbanization have severely impacted the natural environment.

Prof. Sharp also recommended the novel idea of initiating experiments that were not likely to come to fruition for one hundred years or more. He referred to the idea as the "Century Project" - sort of a time-capsule approach to scientific experimentation. Can we design experiments in which the geomorphic process has a recurrence interval which is so long that a long period of observation by satellite imaging or laser-altimeter systems would be required?

Three questions were posed by conference attendees following the presentation of Process Thresholds:

1. What about the need for indefinite archiving of data?

To monitor and to measure landscape changes on the Earth's surface, it is extremely important that all basic data sets of image data (and eventually laser altimetry data) be permanently archived for comparative studies.

2. What about the geomorphic significance of short-lived phenomena and rare events?

Within the resolution and spectral limitations of imaging sensors on satellites many types of short-lived phenomena and rare events can be documented; for example, surges of glaciers, landslides and other mass movements, products from explosive and effusive volcanic eruptions, accelerated erosion, dust plumes, extreme meteorological events, such as floods, tornado tracks, coastal erosion caused by severe cyclonic storms, etc.

3. What about the potential use of satellite-borne laser altimeters?

The ability to measure profiles of "static" and "dynamic" landforms on a global basis to accuracies of a few centimeters would open a golden age in quantitative geomorphology, including important applications to comparative planetology. Geomorphologists would have a tool to conduct worldwide comparative quantitative studies of all classes of "static" and "dynamic" landforms. In the latter case are included measurements of inflation and deflation of volcanic calderas caused by upwelling and lateral movement of magma, tilt caused by volcanic and tectonic processes, changes in geometry of coastal landforms, etc. In conjunction with satellite images to give areas, laser altimeter data could also be used to determine volumetric measurements of regions covered by new lava flows or tephra falls, changes in relative volume of glaciers (area times change in thickness), etc. Laser altimeters are currently being used on aircraft in support of experiments associated with the crustal dynamics program.

PLANETARY PERSPECTIVES  
Report of Working Group Number 4:

Leader: Lisa Roszbacher

The study of global megageomorphology from a planetary perspective requires that, philosophically, we view the Earth as a planet like any other; one among a number of bodies of varied size and composition which, together with the Sun, form the Solar System.

A first step in the study of the Earth from the planetary perspective is the development of global distribution maps of such factors as landforms, tectonics, and of key processes operating on Earth. Data of other types, such as gravity and magnetism, should also be included and, so far as possible, multiple data sets should be developed. The mapping is not an end in itself but must be followed by good science. The compilation of maps would serve as a catalyst for research and a basis for interpretation. They could be used scientifically to document changes such as glacial variations and their relationships to climate, volcanic eruptions and their effects, and coastal alterations. Slow and rapid changes should be studied together with the relationships between scale and the rapidity of change.

Investigations of global tectonics looking at plate edges and particularly plate interiors should be increased with investigations of such things as river cutting and the development of recent grabens. A study of the relationship of geomorphology (ie: surficial processes) to lithology and structure is needed. The planetary perspective can also help in the identification and investigation of exotic features such as suspect terrains. We need a global synoptic view to study many topics, such as glacial mass balance, through monitoring of the West Antarctic Ice Sheet and its relationship to world climate. We also need to investigate the relationship between major geological events and the biosphere.

Exploration of the Moon and other planets of the Solar System has provided us with images showing large areas of these bodies and the variety of landform features and processes found on their surfaces. The identification of terrestrial analogs is a major tool in studying the features we see on other bodies, although we should beware of applying a strict uniformitarianism in this context. Just as we must use caution in saying "The present is the key to the past", we now need to test the hypothesis that the Earth is the key to the Solar System. For example, can we really use such things as the observations of Earth from SIR-B to interpret the landforms of Venus?

On the other hand, our understanding of terrestrial features, particularly those of the geologic past which have been obliterated by subsequent processes, can be enhanced by the identification of analogs to these features on other planetary bodies. They can help us deal with such questions as the importance of cratering in the early history of the Earth, the significance of chaotic events, the character and importance of early volcanism and the distribution of landforms through time and space.

Global geomorphology, from the planetary perspective, involves all of geology, including the lithology and structure of the whole earth. At the global scale, geomorphology is the starting point of geology.

CHAPTER III  
Conclusions  
and  
Recommendations



# GLOBAL MEGAGEOMORPHOLOGY

## Workshop Summary, Conclusions, and Recommendations

Victor R. Baker  
University of Arizona  
Tucson, Arizona

James W. Head, III  
Brown University  
Providence, Rhode Island

At the beginning of the Tucson workshop a question was posed: Given the recent elimination of geomorphology from the programs of some academic institutions, was it appropriate to conclude that this branch of earth science had lost its intellectual excitement and perhaps should slowly fade into the shadows of more visible disciplines such as geophysics. The thirty workshop participants were stimulated to pursue the antithesis of such a view.

Probably the most general realization achieved by the attendees was that they all indeed have considerable scientific interest in common. The specialties represented at the meeting included oceanography, glacial geology, coastal studies, resource exploration, physical geography, remote sensing, eolian processes, landscape evolution, fluvial processes, tectonic geomorphology, and planetary geology. After a few days of open exchange of views and information, what had at first seemed an overwhelming diversity of interests was found to be a complementary range of talents. The causes for this realization were several. First, all concluded that geomorphology has recently been presented with exciting new techniques, most notably the rapidly developing technology of remote sensing. Second, these tools have arrived at a time when geomorphology is reassessing its role by defining or rediscovering important research thrusts. Third, geomorphologists are increasingly leaving their specialty niches to pursue broad interdisciplinary concerns with tectonic, paleoclimatologic, and even extraterrestrial ramifications. In essence, we are seeing the beginnings of a "New Global Geomorphology" built on expanded scales of concern in both space and time.

By the end of the proceedings the question posed at the beginning of this report was answered with a resounding "no". Instead, all expressed the view that geomorphology was poised on the verge of very exciting developments. Many of the major new discoveries will concern global-scale features and their origins. To retain the necessary cooperative spirit for this hopeful future it was concluded that similar workshops on global megageomorphology should be held on a regular basis. The rest of this report will explore the detailed conclusions and recommendations that emerged from the workshop.

## SUMMARY OF WRITTEN COMMENTARIES

Perhaps the best way to convey the views of individual conference participants is to summarize their written commentaries which appear in this volume. The organization of this summary reflects themes that emerged from the workshop.

While many geomorphologists might question the meaning of megageomorphology, Clifford Embleton made it clear that the term conveys, not so much a particular scale of landscape, but a particular scale of thinking about landscapes. Robert Sharp made a more succinct statement: "think big". Rather than considering the details of single hillslopes, first order drainages, or micro-processes, geomorphologists need to concentrate on large spatial scales and long time scales. Embleton views the thinking scale as comparable to that utilized in studying plate tectonics, biological evolution, and macro-climatic change. As with these other mega-scientific exercises, geomorphology can be renewed and revitalized by revolutionary advancement. The catalysts for change are technological advance, including remote sensing systems, mathematical modeling, and radiometric dating. Embleton observes that the new tools can be combined to enhance the traditional role of geomorphological mapping in integrating geomorphology with its sister disciplines of tectonics and historical geology.

The concept of thresholds has proven quite useful in modern geomorphology. A threshold is a critical condition that must be achieved for geomorphic systems to undergo significant change. Dale F. Ritter notes the difficulties in evaluating process thresholds on a regional basis using remote sensing technology. However, he suggests that landform thresholds might be evaluated over large areas by continuous monitoring. Regions subject to profound climatic change or tectonic activity would be ideal study areas. Ritter uses the relationship of alluvial fans to climatic adjustment as an example of key scientific questions that would arise from such a study.

The antiquity of many landscapes and the inheritance of ancient landform elements in modern landscapes are themes that have, until recently, been neglected in modern geomorphology. The terrestrial planets of the solar system are dominated by ancient landscapes, so it is refreshing to have an in-depth review of these themes for Earth by C.R. Twidale. He notes three major types of ancient planation surfaces: exhumed, epigene, and etch. It has only recently been appreciated that there are major exceptions to the view that all terrestrial landscape is late Tertiary or younger in age. Such anomalies are central to healthy scientific progress.

Sheldon Judson also sees an opportunity for geomorphology in the reconstruction of ancient landscapes and landscape processes. New geophysical techniques are providing novel approaches to the measurement rates. However, Ian Douglas points out that the complexities of climate and tectonism must be confronted in

interpreting denudation. Douglas, like Twidale, sees profound megageomorphological similarities in the ancient Gondwana landscapes of the southern hemisphere. In the Pampeanas of the central Andes, Arthur L. Bloom utilizes a variety of satellite imagery to find additional Gondwana remnants. In these studies geophysics has become a tool to study scientific problems of a geomorphological nature.

The topic of tectonic geomorphology is one of growing interest. Laurence H. Lattman proposes a study of regional neotectonic movement and megageomorphic effects of that movement. Such effects might include stream "slip off", variations in erosional resistance, coastal effects, and subtle eolian effects. Marie Morisawa also sees a fascinating role for space imagery in the study of drainage patterns and channel networks. Using a global sampling, changes in time and space can be observed to understand drainage evolution. The relationship of drainage to tectonism is of particular concern. Larry Mayer proposes the use of quantitative theoretical models to relate such megageomorphic features to global tectonism.

Ian Douglas also observes that climatic geomorphology is posed for a reawakening, similar to that of tectonic geomorphology. The old schools of morphoclimatic zonation now need reassessment on an Earth that is being globally sensed and modeled. The topics provide an appropriate test area for this new climatic geomorphology, and W.N. Melhorn describes some applications in the unusual landscapes of the Guiana Shield.

The feedback between planetary and terrestrial geomorphic studies heretofore had not been realized by many conference participants. B.K. Lucchitta notes that planetary exploration proceeds in a logical fashion: large features are identified and mapped before small ones. On Earth the usual geomorphic procedure has worked in reverse. The time has now come to use the techniques applied to the study of other planets for the study of the Earth. Wilford Bryan reminds us that such techniques have long been applied to the study of the 70% of Earth that is covered by water. Marine geologists have always used remote sensing to study mega-scale morphology. Interestingly, as new technology has elucidated smaller ocean-bed landforms, marine geologists have found that they were studying phenomena of great similarity to that already documented by land-based geomorphologists.

Mars is an ocean-less planet that has approximately the same surface area as Earth's land area. Robert P. Sharp observes that Mars geomorphology can teach us much about Earth geomorphology. The biggest lesson is one of considering or reconsidering different, unusual, or even outrageous explanations for puzzling geomorphic features. Are there "mega-scars" on Earth from ancient collapse phenomena, such as the chaotic terrain of Mars? What has been the role of catastrophes in geomorphic history? Already the question of sapping phenomena on Mars has led to a reawakening of interest in sapping as an agent of terrestrial morphogenesis.

The opportunity to study geomorphic processes on several planets has great potential for elucidating the fundamental nature of those processes. Ronald Greeley shows that aeolian geomorphology can be pursued on four planetary objects with a range of gravity, atmospheric pressure, surface temperature, and other parameters. The variation in aeolian landforms in these different settings can be used as a type of natural experiment to document the complex operation of aeolian geomorphic systems. Similarly, Richard S. Williams, Jr., finds that many Icelandic and Martian volcanoes have remarkable morphologic similarity. However, there are also some striking differences, and these raise basic questions about volcanic processes.

Perhaps the most obvious puzzle posed by Mars geomorphology is why geomorphic features, otherwise analogous to those on Earth, are so large on Mars. Lisa A. Rossbacher lists the planetary parameters that might account for the size disparity, but no firm conclusions are yet available. Have geomorphologists yet answered the simple question: How large can a certain geomorphic feature be?

The problem of scale in geomorphology is a concern raised in several other presentations. Robert S. Hayden finds major differences between the synoptic view provided by space imagery and the detailed view of landscapes used in conventional geomorphology. Hayden notes that local scales are dominated by specific processes such as volcanism, fluvial, or coastal. However, regional scales take on a unique character related to geomorphic diversity. Richard S. Williams, Jr., provides a detailed analysis of various satellite image scales that are useful in studying active geomorphic processes. He predicts a "golden age" for regional and global geomorphic studies if one can achieve high-resolution stereophotogrammetric coverage of the land areas of the world.

A final area of megageomorphological concern is that of applications. Because the focus of the conference was on basic scientific issues, applied geomorphology was not a major discussion item. However, the profound benefit to mankind of applied geomorphic research could certainly be the focus of another workshop. Floyd Sabins does note the fundamental input of geomorphic knowledge to natural-resource exploration utilizing satellite imagery. Explorationists and megageomorphologists can benefit from an interchange of ideas. Finally, Robert Blair reminds us of the educational application. Using W.D. Thornbury's classic fundamental concepts of geomorphology, he shows how space platform imagery easily illustrates the principles of the science.

Although most of the workshop was devoted to science issues, some discussion inevitably turned to the exciting technology that prompted our reassessment of geomorphology. J.P. Ford writes of the profound advances made in the use of spaceborne imaging radar. This system produces remarkable images of cloud-covered tropical regions. It also has the useful ability to highlight distinctive terrain textures and topographic features. Another

recent development is the Large Format Camera. Alta Walker describes this instrument and its results from the October, 1984, shuttle mission. The geometric fidelity, high resolution, and stereoscopic coverage of the Large Format Camera makes it an ideal geomorphological mapping instrument.

Of course, not all the technology ideal for megageomorphology yet exists. In the spirit of encouraging appropriate future trends, Richard S. Williams, Jr., proposes the optimum instrumentation for global quantitative geomorphic studies. The following systems are envisioned: (1) an imaging system capable of acquiring photogrammetrically accurate stereoscopic images with a resolution of at least 10 m, adequate for 1:50,000 - scale topographic mapping; (2) a laser altimeter capable of measuring elevation differences of at least 10 cm, and (3) a global positioning system for defining accurate positional accuracy. These systems should be operated for at least a decade in order to study the changing surface of the planet.

### SOME MAJOR THEMES

Considerable workshop discussion resulted in the tentative identification of several megageomorphologic themes. The list and discussion are not meant to be complete. They merely illustrate some possible research thrusts.

#### Global Geomorphic Provinces and Mapping

Remote sensing has a phenomenal capability for the characterization of features on the earth's surface. At the regional scale it has been useful to divide features into regions of similarity. The classic geomorphic concept of physiographic provinces should be resurrected for use with new technology for geomorphic mapping. A global Earth geomorphologic province map, analogous to global maps of other planetary bodies was deemed to be of extreme importance. Such analysis over the whole globe will stimulate a variety of research questions. What is the global distribution of volcanoes in relation to the earth's heat budget? What are the details of terrain at convergent plate boundaries? What are the geomorphic signatures of suspect terrain? Can those signatures be used to correlate to other regions? Can we recognize geomorphic palimpsests that include relicts of ancient crustal processes?

#### Continental Denudation

Geomorphologists at the turn of the century enjoyed a mutually beneficial collaboration with sedimentary geologists through their studies of erosion surfaces and nearby sedimentary basins. Remarkable recent advances have been made in the analysis of sedimentary basins on the continental shelves and on the land areas of the globe. Moreover, the related geomorphic erosion surfaces can now be dated, mapped, and measured with great accuracy. The time is ripe to resurrect the global study of planation surfaces as a part of a new quantitative approach to continental denudation. It would be of significant benefit to various basic research questions.

### Geomorphology and Tectonics

The "New Global Tectonics" has stimulated various branches of geology since its inception 20 years ago. Geomorphology is now playing an important role in this revolution for the earth sciences. Neotectonic studies of tectonically deformed landscapes are establishing the rates of plate and intra-plate movements. Regional studies are showing tectonic interaction through the structural expression of landforms.

### Environmental Change Related to Global Processes

Sequential imaging of the planet has phenomenal potential for documenting both landform change and the operation of large-scale processes. Short-lived phenomena, such as various natural hazards, can be studied in remote areas of the globe. Chronic problems such as desertification and deforestation can be placed in a regional and long-term context. It may prove possible to establish regional landform thresholds that will allow the prediction of future environmental change based on studies of existing and past change. The role of thresholds in change is extremely significant because there is a major lack of understanding concerning the influence of geologic processes on the habitability of Earth. Most people think that geologic/geomorphologic processes operate on scales of millions of years, not years, and therefore not consequential to short-term human habitation. Process rates, thresholds, and environmental change operate on all time scales. A significant challenge to geomorphologists is to document their short-term significance. This whole topic relates directly to the emerging international concern of global habitability.

### Planetary Geomorphology

The study of megageomorphology ultimately leads to the planetary scale. Both submarine and planetary geomorphology have much to gain from and much to give to the experience of Earth-land geomorphologists. The surfaces of other planets, and the ocean-covered surface of Earth, allow the study of a broad range of controlling parameters for the basic geomorphic processes. Moreover, the discoveries made in other planetary environments have already lead to important questions about the interpretation of our own. The tools and intellectual methodology of planetary exploration are directly applicable to terrestrial exploration. As Robert Sharp points out in his commentary, we may be sitting on a mine dump of valuable ore that has not yet been adequately analyzed.

## RECOMMENDATIONS FOR IMPLEMENTATION

The workshop generated a partial list of recommendations. The list has not been prioritized, nor is it complete. It is proposed that future workshops will focus attention on developing a specific and inclusive list.

## Case Studies

The conference themes might well be approached by endorsing specific case studies that would demonstrate the utility of advocated techniques and approaches. For example, detailed megageomorphic studies might be made of two stable cratonic areas, such as a comparison of Australia and the Canadian Shield. Similarly, attention could be focused on a area of active tectonism, such as the Andes or Himalayas. A comparative study might be done of geomorphic expression in the Appalachians versus the Caledonides. Alternatively there could be a global focus on a specific issue, such as the distribution of volcanoes, or an inventory of paleoclimatic indicators in the landscape.

## Instrumentation

Both radar and the Large Format Camera were found to be of tremendous use in global geomorphological studies. Radar has the ability to image through cloud cover, to penetrate sand cover in extremely arid regions, and to enhance subtle terrain or ice features. The Large Format Camera provides stereo capability and high resolution. We recommend that future space missions, including shuttle flights, give a high priority to imaging with these systems in order to acquire global data sets.

## Data Availability

A consensus of the workshop was that Terrestrial Data Centers be established in a manner analogous to NASA's Planetary Data Centers. Such centers would devote their attention to the cataloging and archiving of Earth remote sensing data, particularly older Landsat data. The centers should employ laser disc technology for this data to aid in its wide and economical distribution to geomorphologists and interested scientists. The centers should also provide user training in data access.

## Multiple Data Sets

Planetary experience has shown that multiple data sets of various remote sensing products are of great use in global studies. Such data sets need to be assembled for terrestrial work and made available to the scientific community.

## Global Habitability Studies

Mega-geomorphology and regional landforms analysis can play a potentially major role in NASA's developing Global Habitability Studies and the International Geosphere - Biosphere Program of the National Academy of Sciences. This follows from the premise that soils, vegetation distribution, demography, land use practices, environmental conditions, characteristics of the oceans and some aspects of climate are all intimately tied to the solid Earth and its landscape interface with man's varied habitats. The geomorphic community should be ready to demonstrate the applications of regional to world-scale geomorphology to the efforts of NASA and the IGBP as these develop further.

### Future Meetings

It was agreed that the workshop had been immensely successful and that a follow-on meeting should be held in a year or so. The same workshop-sized meeting format should be employed for future gatherings. The next scheduled discussion of the workshop issues will occur at the First International Conference on Geomorphology sponsored by the British Geomorphological Research Group, September 15-21, 1985, in Manchester, England. An appropriate step might be to propose a NATO-sponsored conference. It would also be useful to work with a variety of national and international scientific societies including AAAS, NAS, GSA, AAG, IUGS, IGU, BGRG etc. on the sponsorship of megageomorphological symposia, sessions, etc. Clearly, global megageomorphology is a topic of accelerating scientific interest. The momentum established in Tucson must be continued.

## FIELD TRIP

### Geomorphic Surfaces in the Tucson Basin, Arizona

Victor R. Baker  
University of Arizona  
Tucson, Arizona

At the conclusion of the conference sessions on January 17, 1985, a one-day field trip introduced the participants to large-scale geomorphic features in the vicinity of Tucson, Arizona. The trip route began at the Conference Center at the northwestern end of the Santa Catalina Mountains (Figure 1). A guidebook (Ely and Baker, 1985) describes the one-day itinerary, which includes a diversity of desert and mountain scenery typical of the southwestern United States.

The major purpose of the field trip was to view prominent geomorphic phenomena that can be interpreted from LANDSAT Thematic Mapper images and other remote sensing of the Tucson Basin. Features investigated in the field included the following: (1) A sequence of terraces, pediments, and fans in the Cañada del Oro drainage (McFadden, 1978). (2) A series of pediments and alluvial fans flanking the Tucson Mountains (Katzner and Schuster, 1984). (3) The effects of a recent, large flood on the Santa Cruz River (Baker, 1984). (4) Alluvial fan surfaces and Pleistocene faulting in the Madera Canyon area of the Santa Rita Mountains (Pearthree and Calvo, 1982).

In each of the various field areas, geomorphic surfaces were characterized by their age, genesis, soils, lithology, and vegetative cover. These factors all result in varying appearance on the remote sensing imagery. The oldest surfaces investigated were Early to Mid-Pleistocene fans present on the piedmonts of the Santa Catalina, Tucson, and Santa Rita Mountains. Differing lithologies of mountain source areas produced a variety of soils and vegetative responses on the ancient fans and younger surfaces. Considerable discussion on the field trip centered on the origin of the various geomorphic surfaces and their relationship to climatic change and tectonism.

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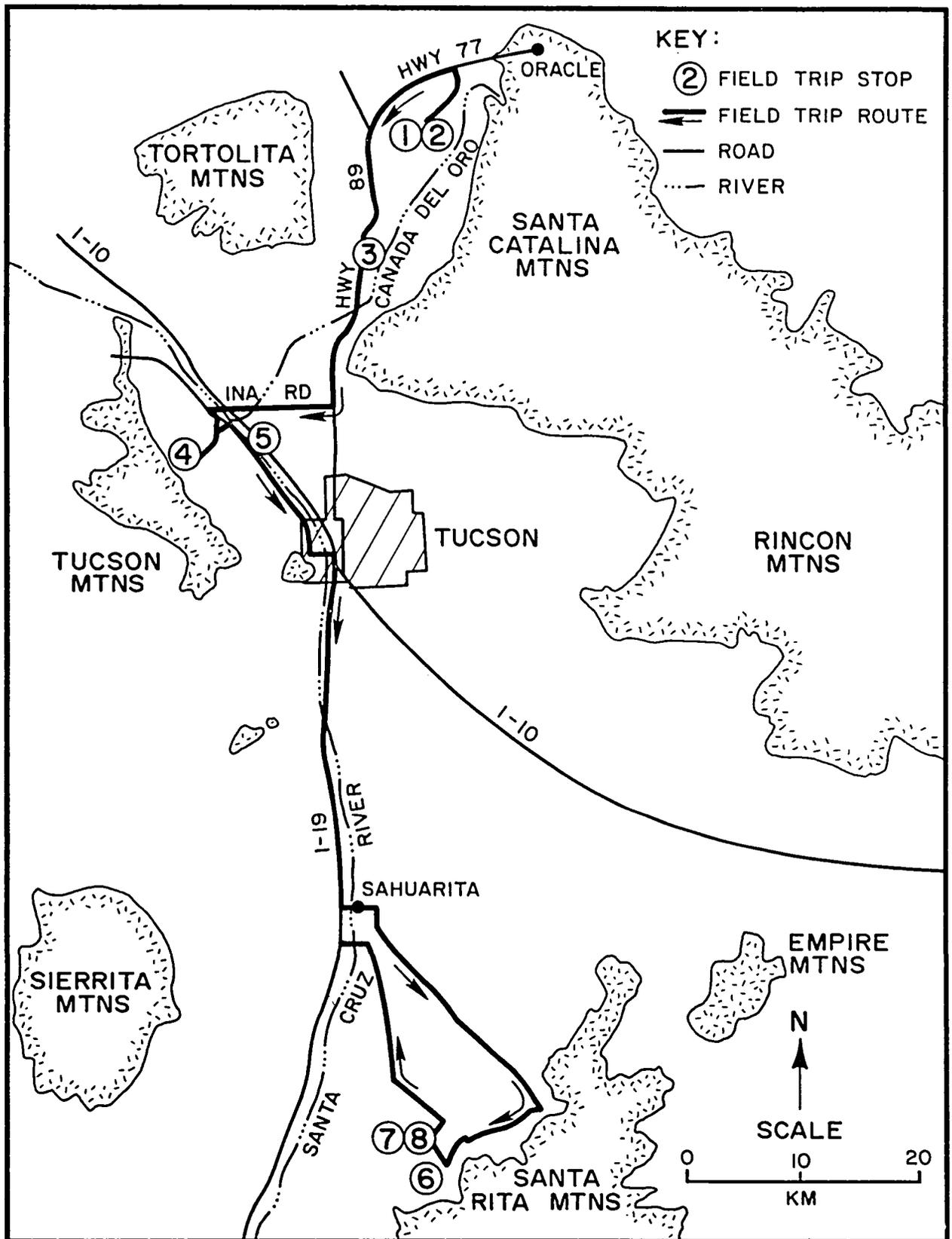


Figure 1. Map of field trip route.

LIST OF  
WORKSHOP PARTICIPANTS

## WORKSHOP PARTICIPANTS

<u>NAME:</u>	<u>AFFILIATION:</u>
Prof. Victor R. Baker	Department of Geosciences University of Arizona Tucson, AZ 85721
Prof. Robert W. Blair Jr.	Department of Geology Fort Lewis College Durango, CO 81301
Prof. Arthur L. Bloom	Department of Geological Sciences Cornell University Ithaca, NY 14853
Dr. Wilford Bryan	Department of Geology & Geophysics Woods Hole Oceanographic Institute Woods Hole MA 02543
Prof. Ian Douglas	Faculty of Arts(Physical Geography) Victoria University of Manchester Manchester M13 9PL, ENGLAND
Prof. Clifford Embleton	Faculty of Science(Geography) University of London(Kings College) Strand, London, WC2R 2LS, ENGLAND
Dr. John R. Everett	Earth Satellite Corporation 7222 47th Street Bethesda, MD 120815
Dr. John Ford	Jet Propulsion Laboratory Pasadena, CA 91109
Prof. Ronald Greeley	Department of Geology Arizona State University Tempe, AZ 85281
Prof. Robert S. Hayden	Dept. of Public Affairs(Geography) George Mason University Fairfax, VA 22030
Prof. James W. Head III	Department of Geological Sciences Brown University Providence, RI 02912
Dr. Oscar Huh	Coastal Studies Institute Louisiana State University Baton Rouge, LA 70803

## WORKSHOP PARTICIPANTS

<u>NAME:</u>	<u>AFFILIATION:</u>
Prof. Sheldon Judson	Department of Geological and Geophysical Sciences Princeton University Princeton, NJ 08540
Ms. Catherine Kitcho	NASA Headquarters Code EE Washington, DC 20546
Dr. Laurence H. Lattman	President's Office New Mexico Institute of Mining and Technology Socorro, NM 87801
Dr. Baerbel Luchitta	U.S. Geological Survey Flagstaff, AZ 86001
Prof. Larry Mayer	Department of Geology Miami University] Oxford, OH 45056
Dr. John S. McCauley	U.S. Geological Survey Flagstaff, AZ 86001
Prof. Wilton N. Melhorn	Department of Geosciences Purdue University West Lafayette, IN 74907
Prof. Marie Morisawa	Department of Geological Sciences State Univ. of New York-Binghamton Binghamton, NY 13901
Prof. Dale F. Ritter	Department of Geology Southern Illinois University Carbondale, IL 62901
Prof. Charles Rosenfeld	Department of Geography Oregon State University Corvallis, OR 97331
Prof. Lisa A. Rossbacher	Department of Earth Sciences California State Polytechnic Univ. Pomona, CA 91768
Dr. Floyd F. Sabins	Chevron Oil Field Research Co. Box 446 LaHabre, CA 90631

WORKSHOP PARTICIPANTS

<u>NAME:</u>	<u>AFFILIATION:</u>
Prof. Robert P. Sharp	Division of Geological and Planetary Sciences Cal. Inst. of Technology(Geology) Pasadena, CA 91125
Dr. Nicholas Short	NASA/Goddard Space Flight Center Code 622 Greenbelt, MD 20771
Dr. Kathryn D. Sullivan	NASA/Johnson Space Center Code CB Houston, TX 77058
Prof. C.R. Twidale	Department of Geography University of Adelaide Box 498 GPO Adelaide, South Australia 5001 AUSTRALIA
Dr. Alta S. Walker	U.S. Geological Survey Code 591 National Center Reston, VA 22092
Dr. Richard S. Williams, Jr.	U.S. Geological Survey Code 927 National Center Reston, VA 22092







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