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Report on the American Geophysical Union
Chapman Conference on Tectonics and Topography

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The Chapman Conference on Tectonics and Topography was held August 31September 4, 1992. The conveners for this conference were Michael Elliott at the Center for Earthquake Research in Memphis, Tennessee and Dorothy J. Merritts at the Department of Geophysics at Franklin and Marshall College in Lancaster, Pennsylvania.

The conference was designed to bring together disparate groups of earth scientists who increasingly found themselves working on similar problems but in relative isolation. Thus, process geomorphologists found themselves face-to-face with numerical modelers and field geomorphologists, hydrologists encountered geologists, and tectonophysicists found people with related data.

The keynote speakers represented a wide variety of disciplines, all of which were relevant to the interdisciplinary theme of the conference. One of the most surprising issues that surfaced was the relative dearth of data that exists about erosion - process and rates. This was exacerbated by Peter Molnar's reminder that erosion is critical to the evaluation of surface uplift.

Clem Chase presented his preliminary modeling on the development of topography using cellular automata, which inspired considerable and lively discussion from geomorphologists. Geomorphologists complained about Chases's lack of surface process rigor, while his advocates argued that the details were unimportant for the problem at hand. This type of face-off was symptomatic of the differences between the various scales of inspection practiced by participants; geomorphologists are more than often concerned with specific processes of erosion or transport, whereas tectonophysicists are integrating these effects into an average behaviour. Whether there is room or even a need for overlap between these extremes remains to be seen. The optimists among us, however, would regard any exposure to the extremes of the field to be valuable. To this extent, the Chapman Conference was considered to be a success.

To the thick of success, however lay, in the middle ground and, in particular, among the student participants. Students of geomorphology were listening to ideas on how to improve or follow-on some aspects of their research from geophysicists, and vice versa. Ultimately, there will be students who will be flexible enough to take the necessary collaboration to a productive end. Judging by the comments received from students, they were ready and anxious to continue their research having significant encouragement from all around.

One of the most valuable features of the conference was the ability to informally discuss some of the key issues of the Tectonics and Topography theme. This took the form of extended open discussion at the end of keynote lectures, discussion around extended poster sessions, and in organized groups during two evenings. The latter format was very successful. These organized groups allowed participants to expound on and be educated about topics such as erosion, long-river profiles, fractals and topography, putting surface processes into tectonic models, and the pros and cons of paleobotany in evaluating paleoelevations. All of this from only 98 participants, and all of it aimed at understanding the link between tectonics and topography.

(NASA-CR-193454) THE AMERICAN GEOPHYSICAL UNION CHAPMAN CONFERENCE ON TECTONICS AND TOPOGRAPHY (American Geophysical Union) 42 p

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In summary, the conference was a remarkable success. A handful of good 45-minute lectures left plenty of time for posters and there was ample time for informal discussions that usually languished into the early mornings. The field trip in the middle of the week was a wonderful break in the proceedings, so that people didn't get burn out on more than two straight days of lectures and posters.

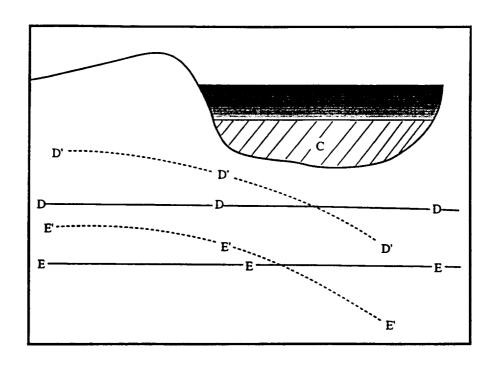
Many participants expressed an interest in publishing papers in a special section of the Journal of Geophysical Research, and plans are underway to do this. This special issue is scheduled to be published in the summer of 1994. When this publication becomes available copies will be forwarded to NASA. Attached is a copy of the at-meeting program which contains the abstracts that was presented at the conference.

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American Geophysical Union

Chapman Conference on

Tectonics and Topography



August 31 - September 4, 1992 Snowbird, Utah

Conveners: Dorothy Merritts
Michael Ellis



Chapman Conferences

- were originally inaugurated in 1976 in honor of Sydney Chapman.
- permit organized and in-depth exploration of specialized subjects.
- encourage interdisciplinary focus on special problems.
- give students a chance to interact with leaders in their field.
- have limited attendance (125) and can be held anywhere.
- can be proposed by any AGU member.
- about 5-8 conferences held each year.

Convening a Chapman can be as easy as 1, 2, 3.

- 1. You submit a written proposal to AGU.
- 2. AGU staff solicits approval of the proposal from AGU officers.
- 3. You handle the science; AGU staff handles the administrative duties.

For Further Information

To receive details on convening a Chapman Conference, contact

Brenda Weaver
American Geophysical Union
2000 Florida Avenue, N.W.
Washington, DC 20009
Telephone 202-939-3203
Fax 202-328-0566



COVER DIAGRAM: John Herschel's prescient view of the dynamic link between processes operating in the crust and on the surface is represented by his picture of the uplift of Scandinavia, and was conceived in 1834. According to Herschel, the weight of recent sediments (B) depresses the seabed (D) to D' and displaces the semifluid matter (E) to E', which elevates the shoreline and renews the erosion gradient. (After a drawing in Babbage, 1837.)



AGU Chapman Conference on Tectonics and Topography

MEETING AT A GLANCE

Sunday, August 30, 1992	Processes: A Case Study of the Andes and Himalaya
Golden Cliff Room	Mountains
Early Registration 5:30 p.m.	Dinner Break 5:30 p.m.
Opening Reception 6:00 p.m.	Session Begins 7:30 p.m.
Speakers/Chair Meeting 9:00 p.m.	
- Prince County	Wednesday, September 2, 1992
Monday, August 31, 1992	Wasatch Range
Ballroom 3	Field Trip to Wasatch Range 8:00 a.m.
Welcoming Address 8:00 a.m.	Thursday, September 3, 1992
Marning Cossion	Ballroom 3
Morning Session Clobal Climate Testanian and Temperature	Morning Session
Global Climate, Tectonics, and Topography	Geodynamics Deduced From Topography/Local to
Session Begins 8:30 a.m.	• • • • • • • • • • • • • • • • • • • •
Discussion 9:00 a.m.	Regional Scales Session Begins 8:30 a.m.
Poster Session 10:30 a.m.	Discussion 9:50 a.m.
Lunch Break 12:00 p.m.	
4 Pa C	Poster Session 10:30 a.m.
Afternoon Session	Lunch Break 12:00 p.m.
Dynamic Feedback Between Crustal and Surficial	A Staura on Section
Processes; Global to Regional Scales	Afternoon Session
Session Begins 1:30 p.m.	Geodynamics Deduced From Topography/Regional to
Discussion 2:50 p.m.	Global Scales
Poster Session 3:30 p.m.	Session Begins 1:30 p.m.
	Discussion 2:50 p.m.
Conference Center Terrace	Poster Session 3:30 p.m.
Western Barbecue 6:30 p.m.	m
	Evening Session
Tuesday, September 1, 1992	Topographic Database: Availability and Acquisition
Ballroom 3	Dinner Break 5:30 p.m.
Morning Session	Session Begins 7:30 p.m.
Fundamentals and Objectives of Geophysical and	m a
Geomorphological Modelling	Friday, September 4, 1992
Session Begins 8:30 a.m.	Ballroom 3
Discussion 10:00 a.m.	Morning Session
Summary 11:00 a.m.	Rates and Magnitude of Uplift and Exhumation
Poster Session 11:30 a.m.	Session Begins 8:30 a.m.
Lunch Break 12:15 p.m.	Discussion 9:50 a.m.
•	Poster Session 10:30 a.m.
Afternoon Session	Lunch Break 12:00 p.m.
Dynamic Feedback Between Crustal and Surficial	
Processes: Regional to Local Scales	Afternoon Session
Session Begins 1:30 p.m.	Kinematics Deduced From Topography
Discussion 2:50 p.m.	Session Begins 1:30 p.m.
Poster Session 3:30 p.m.	Discussion 2:50 p.m.
	Poster Session 3:30 p.m.
Evening Session	-
Dynamic Feedback Between Crustal and Surficial	Adjournment 5:00 p.m.
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AGU Chapman Conference on Tectonics and Topography

August 31 - September 4, 1992 • Snowbird, Utah

General Information

SITE

All scientific sessions will be held in the Cliff Lodge at the Snowbird Ski and Summer Resort, located in Snowbird, Utah. The oral sessions will be held in Ballroom 3, and poster sessions will take place in Ballroom 2. Activities in Snowbird extend from swimming and tennis, to tram rides and guided mountain hikes, rock climbing classes and mountain picnics. The new Spa at the Cliff Lodge surrounds you with the latest advances in fitness equipment and workout techniques - all surrounded by magnificent mountain and valley views. Cultural activities abound at Snowbird as well, with a summer-long repertoire of concerts and art and dance exhibitions. Contact the Concierge for more details.

REGISTRATION

Everyone attending this conference must register and pay the registration fee. The registration fee includes admission to all scientific sessions, the Opening Reception on Sunday, the Western Barbecue on Monday, and a copy of the final meeting program with abstracts.

The registration fee is \$200.00 for regular attendees and \$100.00 for students. Guests must purchase tickets to social functions they wish to attend.

ACTIVITIES

OPENING RECEPTION

• Opening Reception and Early Registration Sunday, August 30, 1992

Registration -

5:30 - 7:00 p.m. - Golden Cliff Room

Reception -

6:00 - 7:30 p.m. - Golden Cliff Room

CONFERENCE BANQUET

• Western Barbecue Monday, August 31, 1992

(Conference Center Terrace) 6:30 - 8:30 p.m.

COSPONSORSHIP

AGU gratefully acknowledges the National Aeronautics and Space Administration for their cosponsorship of this conference and providing travel support.



CHAPMAN CONFERENCE ON **TECTONICS AND TOPOGRAPHY**

Conveners: Dorothy Merritts, Franklin and Marshall College Michael Ellis, Memphis State University

AUGUST 31 - SEPTEMBER 4, 1992 • SNOWBIRD, UTAH

SCIENTIFIC SCHEDULE

(presenters are listed in bold)

SUNDAY, AUGUST 30, 1992

Early Registration Golden Cliff Room 5:30 p.m.

Opening Reception 6:00 p.m. Golden Cliff Room

Speaker's and Chairperson's Meeting Golden Cliff Room 9:00 p.m.

MONDAY, AUGUST 31, 1992

Welcoming and Introductions M. Ellis and D. Merritts 8:00 a.m.

M. Ellis Morning Session:

Global Climate, Tectonics, and Topography

Some Thoughts on the Signature of P. Molnar 8:30 a.m. Climate Change on Topography

Influence of Tectonics and Topography on 9:10 a.m. M. E. Raymo Global Climate

Discussion 9:50 a.m. M. Ellis

Poster Session I

The Geochemical and Stratigraphic Record L. A. Derry and C. France-10:30 a.m. of Himalayan Erosion in Sediments of the Lanord

Bengal Fan, ODP Leg 116

Sedimentary Response to Neogene 10:30 a.m. K. Flanagan

Regional Uplift in Wyoming

Paleobotanically Estimated Elevation of the K. M. Gregory 10:30 a.m.

Late Eocene Southern Rocky Mountains

10:30 a.m.	K. M. Menking and R. S. Anderson	Geomorphic Response to Climate Change Recorded in a Core of Owens Lake, Eastern California		
10:30 a.m.	N. Hovius	Sediment Flux From Source to Basin: A Global Overview Using a New Database		
10:30 a.m.	E. Evanoff			
10:30 a.m.	Y. Dilek and O. Tekeli	Cenozoic Tectonics and Geomorphology of the Inner Tauride Belt, Southern Turkey		
10:30 a.m.	P. Keller and A. U. Gehring	Tectonics and Weathering in the SE- Pyrenees (Spain): A Paleomagnetic Study		
10:30 a.m.	G. E. Tucker, R. Slingerland, and K. Furlong	Post-Rift Evolution of Passive Continental Margins: U.S. Atlantic Type vs. South African-Type; Part 2		
10:30 a.m.	T. G. Farr	Shapes of Desert Piedmonts		
BREAK FOR LU	NCH			
Afternoon Sessi Dynamic Feedbo Scales	ion: W. Dietrich ack Between Crustal and Surficial	l Processes; Global to Regional		
1:30 p.m.	C. G. Chase	Tectonics, Climate, and Topography: Fluvial Landsculpting Models of How the Colorado Rockies Weren't Uplifted in the Pliocene		
2:10 p.m.	J. Verges and D. W. Burbank	Subsurface Structures as a Control of the Topographic Relief During Thrusting: Southern Pyrenees		
2:50 p.m.	W. Dietrich	Discussion		
Poster Session II				
3:30 p.m.	H. Kooi, C. Beaumont, P. Fullsack, and A. Gilchrist	Escarpment Retreat on High-Elevation Rifted Margins; Insights Derived From a Surface Processes Model		
3:30 p.m.	T. F. Bullard and S. G. Wells	Fluvial and Tectonic Geomorphology Across a Forearc Region Impacted by the Subduction of the Aseismic Cocos Ridge, Southern Pacific Coast, Costa Rica		

3:30 p.m.	P. L. K. Knuepfer and J. H. Willemin	A Comparison of Response of Streams and Mountain Fronts to Different Modes of Uplift in Humid Regions: New Zealand and Taiwan
3:30 p.m.	M. T. Brandon	Late Cenozoic Uplift and Exhumation at the Cascadia Subduction Zone, NW Washington State
3:30 p.m.	F. J. Pazzaglia and T. W. Gardner	Post-Rift Evolution of Passive Continental Margins: U.S. Atlantic-Type vs. South African-Type; Part I
3:30 p.m.	D. W. Valentine	Adjacent Zones of Uplift and Subsidence Within a Fold and Thrust Belt, Southern End of the Cascadia Subduction Zone, Humboldt County, California

WESTERN BARBECUE Conference Center Terrace - 6:30 p.m. - 8:30 p.m.

TUESDAY, SEPTEMBER 1, 1992

Morning Session: R. Anderson
Fundamentals and Objectives of Geophysical and Geomorphological Modelling

8:30 a.m.	W. E. Dietrich	Geomorphological Modelling: An Experimentalist's Perspective
9:15 a.m.	S. Wdowinski	Techniques of Tectonophysical Modelling
10:00 a.m.	R. Anderson	Discussion Groups
11:00 a.m.	Summary by Discussion Groups	

Poster Session III

11:30 a.m.	S. Ellis, C. Beaumont, P. Fullsack, and J. Hamilton	Coupling of Surface Processes and Tectonics of Continental Collision Using Plane Strain and Thin Sheet Models
11:30 a.m.	J. C. Dohrenwend and C. F. Pain	Geomorphic Response to Cenozoic Uplift of the West Slope of the Cape York Peninsula, Northeast Queensland
11:30 a.m.	N. Okay	

11:30 a.m.	C. P. Stark	Cluster Growth Modelling of Erosion Patterns		
11:30 a.m.	S. Wdowinski			
11:30 a.m.	G. Willgoose	Geomorphologic Modeling and Interactions Between Active Tectonics and Topography		
11:30 a.m.	M. G. Foley, K. A. Hoover, P. G. Heasler, N. J. Rynes, and R. L. Thiessen	Semi-Automated Geomorphic Pattern- Recognition for Morphotectonic Analysis		
11:30 a.m.	A. Gilchrist, H. Kooi, and C. Beaumont	Escarpment Retreat on Passive Margins: Observations From Southern Africa		
11:30 a.m.	M. Perry	The Extraction of Stream System Geometry From Digital Databases		
11:30 a.m.	V. Sumin			
11:30 a.m.	D. U. Wise	Topographic Lineament Swarms: Indicators of Regional-Scale Paleo-stress Trajectories and Seismo-tectonic Domains		
11:30 a.m.	A. D. Howard, W. E. Dietrich, and M. A. Seidl	Modeling Fluvial Erosion on Regional or Continental Scales		
11:30 a.m.	K. L. Hanson, T. F. Bullard, and M. W. de Witt	Applications of Quaternary Stratigraphic, Soil-Geomorphic, and Quantitative Morphometric Analyses to the Evaluation of Tectonic Activity and Landscape Evolution in the Upper Coastal Plain, South Carolina		
DDEAN EOD I INCH				

BREAK FOR LUNCH

Afternoon Session: C. Chase

Dynamic Feedback Between Crustal and Surficial Processes: Regional to Local Scales

1:30 p.m.	P. O. Koons	Coupled Mechanical and Erosional Processes in 3d Collisional Mountain Belts
2:10 p.m.	M. A. Summerfield	Geomorphic Evidence in the Reconstruction of the Morphotectonic Evolution of Passive Margins: Possibilities and Limitations
2:50 p.m.	C. Chase	Discussion

BREAK FOR DINNER

Evening Session:

Dynamic Feedback Between Crustal and Surficial Processes: A Case Study of the Andes and Himalaya Mountains

7:30 p.m.

B. L. Isacks, J. Masek, T. Gubbels, and E. J. Fielding

Eroding Plateau Edges of the Andes and

the Himalayas

Poster Session IV

8:15 p.m.

E. Fielding

8:15 p.m.

T. Gubbel

8:15 p.m.

A. Moore

Coupled Extension and Uplift in the

Central Andes: Implications for Regional

Uplift History

8:15 p.m.

W. D. Cunningham

Strike-Slip Faults in the Southernmost

Andes and the Development of the

Patagonian Orocline

8:15 p.m.

J. W. Gephart

Spatial Order in the Topography of the

Central Andes and Its Relation to Nazca-

South American Plate Kinematics

8:15 p.m.

M. Jackson and R. Bilham

Trans-Himalayan Geodetic Leveling:

Constraints on Mountain Building

8:15 p.m.

J. Masek

8:15 p.m.

J. F. Shroder

Geomorphic Evolution of the Western

Himalaya

WEDNESDAY, SEPTEMBER 2, 1992

8:00 a.m.

R. Smith

Field trip to the Wasatch Range

THURSDAY, SEPTEMBER 3, 1992

Morning Session:

C. Vita-Finzi

Geodynamics Deduced From Topography/Local to Regional Scales

8:30 a.m.

W. B. Bull

Geodynamics Deduced From Landscapes

9:10 a.m.	R. S. Anderson	Tectonics Deduced From Topography: The General Challenge and Some Specific Examples From a Variety of Settings
9:50 a.m.	C. Vita-Finzi	Discussion
Poster Session	V	
10:30 a.m.	J. R. Arrowsmith	Diffusion-Erosion Analyses of Strike-Slip and Normal Fault Scarps Along the San Andreas Fault: Calibration and Application
10:30 a.m.	D. R. Currey	Limneotectonics and Buried Tectonic Topography Under Great Salt Lake, Utah
10:30 a.m.	D. R. Harden and D. Fox	Channel Adjustment in Fern Canyon Near Watsonville, California, Following the 1989 Loma Prieta Earthquake
10:30 a.m.	D. R. Montgomery	Uplift of the Central California Coast Ranges
10:30 a.m.	C. Schubert	The Boconó Fault, Western Venezuela
10:30 a.m.	K. R. Vincent and D. J. Merrits	The Nature of Faulting and Deformation Near the Mendocino Triple-Junction
10:30 a.m.	K. Grove and T. L. Niemi	Quaternary Terraces Near Point Reyes: Strain Gauges Along the San Andreas Fault Zone North of San Francisco, California
10:30 a.m.	O. A. Chadwick, J. E. Conel, and L. J. Onesti	River Terraces in Wind River Basin, Wyoming: Correlations, and Flexure From Yellowstone Uplift and Differential Basin Erosion
10:30 a.m.	N. T. Hall, M. Angell, M. W. De Wit, and R. R. Lettis	Late Quaternary Deformation of the Southern Santa Cruz Mountains, California
10:30 a.m.	H. M. Kelsey, D. C. Engebretsen, C. E. Mitchell, and R. J. Weldon II	Latitudinal Variation in Surface Uplift From Geodetic, Wave-Cut Platform and Topographic Data, Cascadia Margin
10:30 a.m.	M. Morisawa	
10:30 a.m.	K. A. Howard and W. D. Stuart	Compressive Origin of Topographic Waves in the Mojave Desert, California

.

10:30 a.m.	J. Zollweg				
10:30 a.m.	A. L. Reesman, D. R. Currey, and H. B. Haslam	Separation of Isostatic and Neotectonic Signals Recorded in Bonneville Stage Shorelines			
10:30 a.m.	R. G. Blom and R. E. Crippen	Interactive Terrane Visualizations, Steroscopic Landsat, Statistical Fault Detection, and Strain Field Maps Derived From Topographic Information			
Afternoon Sess Geodynamics D	ion W. Bull Deduced From Topography/Region	nal to Global Scales			
1:30 p.m.	R. S. Stein, P. Briole, JC. Ruegg, P. Tapponnier, and F. Gasse	In the Wake of Moses: Creation of Spreading Center Topography at the Asal Rift, Djibouti, Inferred From Comparison of Historical and Long-Term Deformation			
2:10 p.m.	M. Gurnis	Topography Driven by Mantle Convection- -From Regional to Global Scales			
2:50 p.m.	W. Bull	Discussion			
Poster Session	Poster Session VI				
3:30 p.m.	S. M. Agar and K. D. Klitgard	Evolving Border Fault Systems and Early Synrift Sedimentation: The Baikal Rift			
3:30 p.m.	C. J. Ebinger, D. C. Rex, and D. J. Harding	Rift Kinematics and Topography: Views From Afar			
3:30 p.m.	J. K. Weissel, G. D. Karner, A. Malinverno, and D. J. Harding	Tectonics and Erosion: Topographic Evolution of Rift Flanks and Rifted Continental Margins			
3:30 p.m.	W. J. Taylor and J. M. Bartley	Relationship Among Basin Formation, Upper Crustal Structures, and Isostasy: Examples From the Basin and Range Province			
3:30 p.m.	R. E. Arvidson	A Late Quaternary Landscape Evolution- Red Sea Coast, Egypt			
3:30 p.m.	C. Beaumont				
3:30 p.m.	M. S. Steckler and G. I. Omar	Controls on Erosional Retreat of the Uplifted Rift Flanks at the Gulf of Suez and Red Sea			

3:30 p.m.

S. Zhong and M. Gurnis

The Dynamics of Oceanic Trenches and Slabs Studied With a Finite Element Model of Viscous Flow With a Fault

BREAK FOR DINNER

Evening Session:

D. Harding

Digital Topographic Data: Availability and Acquisition

7:30 p.m.	D. J. Harding	Digital Topographic Data: Availability and Acquisition
7:45 p.m.	D. Hastings	On the Availability and Character of Digital Elevation Models
8:00 p.m.	S. Jenson	Defense Mapping Agency Digital Terrain Elevation Data and Digital Chart of the World
8:15 p.m.	D. Wingham	That Status of the World's Digital Elevation Models, and the Scope for Their Improvement With the ERS-1 Satellite
8:30 p.m.	B. Krabill	Mapping the Greenland Icesheet With Airborne Laser Altimetry and GPS
8:45 p.m.	H. Zebker and J. Martin	Topographic Mapping With Radar Interferometry
9:00 p.m.	J. P. Muller	Topography of Earth and Mars From Automated Stereomatching of Electo- Optical and Photographic Data Sources
9:15 p.m.	D. Smith	Expectations for the Mars Observer Laser Altimeter
9:30 p.m.	R. Arvidson	Global Topography of Venus From Magellan Radar and Altimetry Observations
9:45 p.m.	B. Isacks	EOS: the Earth Observing System
10:00 p.m.	T. Dixon and D. Harding	The NASA Global Topography Mission
10:15 p.m.	D. Harding	Discussion

FRIDAY, SEPTEMBER 4, 1992

Morning Session: D. Merritts

Rates and Magnitude of Uplift and Exhumation

8:30 a.m. M. T. Brandon Erosion Rates in Contractional Orogens

9:10 a.m. M. J. Pavich The Appalachian Piedmont as an Active

Planation Surface: Model and Methods of

Comparing Erosion and Uplift

9:50 a.m. D. Merritts Discussion

Poster Session VI

10:30 a.m. L. D. Abbott and J. Galewski Surface Uplift of the Finisterre Mountains,

Papua New Guinea

10:30 a.m. P. R. Bierman Use of In Situ Produced Cosmogenic

Isotopes to Determine Rates of

Geomorphic Processes

10:30 a.m. M. A. Seidl, W. E. Dietrich, Stream Power Dependent Erosion of

J. W. Kirchner, M. W. Bedrock Channels: Field Observations and

Caffee, R. C. Finkel, and G. Model Results

B. Hudson

10:30 a.m. S. P. Anderson, W. E. An Experimental Field Study of Chemical

Dietrich, G. H. Brimhall, R. Weathering Rates

Torres, and D. R.
Montgomery

10:30 a.m. M. Pubellier, B. Deffontaines, Morphological Signature of Arc/Continent

R. Quebral Collision: Geometric Application to

Kinematics of Deformation

10:30 a.m. S. Gupta Geomorphological Response to Tectonic

Uplift in Fold-Thrust Belts

BREAK FOR LUNCH

Afternoon Session: K. Furlong
Kinematics Deduced From Topography

1:30 p.m. G. King Plate Kinematics Deduced From Topography

2:10 p.m.	B. Hallet	Kinematics and Dynamics of Microtopography (Tentative Title)
2:50 p.m.	K. Furlong	Discussion
Poster Session VII		
3:30 p.m.	R. Bürgmann and R. Arrowsmith	Uplift of the Southern Santa Cruz Mountains Deduced From Fission Track Dating and Geomorphic Analyses
3:30 p.m.	C. M. Rubin and T. Dixon	Application of High Resolution Topography to the Kinematics of Fold-and- Thrust Belts
3:30 p.m.	A. R. Lowry and R. B. Smith	Strength and Stress of the Lithosphere From Gravity and Topography, With Focus on the Yellowstone Hotspot
3:30 p.m.	J. H. Willemin and P. L. K. Knuepfer	Kinematics of Arc-Continent Collision in the Eastern Central Range of Taiwan Inferred From Geomorphic Analysis
3:30 p.m.	W. R. Lettis and K. L. Kelson	Distribution of Geologic Slip Along Faults in the San Francisco Bay and Santa Maria Basin Regions
3:30 p.m.	W. W. Locke and G. A. Meyer	A 12,000-Year Record of Vertical Deformation Across the Yellowstone (Wyoming) Caldera Margin
3:30 p.m.	R. B. Smith and A. R. Lowry	The Yellowstone Hotspot: Topographic Signature, Structural Evolution, and Regional Geophysics
5:00 p.m.	Farewell and Concluding Remarks	



Monday, August 31, 1992

Morning Session:

Global Climate, Tectonics, and

Topography

Chairman: M. Ellis

Influence of Tectonics and Topography on Global Climate

M E Raymo (Department of Earth, Atmospheric, and Planetary Sciences, MIT, Cambridge, MA 02139; 617-253-7934)

It has been proposed that the uplift of the Tibetan Plateau in the late Cenozoic had a significant impact on global climate and may have led to the development of ice sheets at both poles [1-3]. The uplift of the Plateau, an area the size of France at a mean elevation of five kilometers, influenced climate in two major ways. First, through direct interaction between the area of high topography and atmospheric circulation. Not only are prevailing westerlies deflected around the area of high topography, but the strong heating of the plateau in summer drives a regional convection pattern which strongly influences the climatology of Africa, southern Europe, and Asia. In particular, this convection drives the southeast Asian monsoon which is responsible for the seasonally intense rainfall on the southern margin of the plateau.

Second, the uplift of the Tibetan Plateau may have led to global cooling through its influence on global chemical weathering rates. The monsoonal rainfall, concentrated on the slopes of the tectonically active Himalayas, results in extremely high rates of mechanical and chemical weathering. The ⁸⁷Sr/⁸⁶Sr record of marine carbonates suggests that a significant increase in global chemical weathering has occurred over the last 40 m.y. and we proposed that much of this increase was due to enhanced erosion in the Himalayan region. Because, the chemical weathering of a silicate rock results in the removal of CO₂ from the atmosphere, this increase in erosion could have led to a downdraw of atmospheric CO₂ and global cooling. By extension, it is suggested that surface air temperature is a relatively weak control on global chemical weathering rates.

¹Raymo, M.E., Ruddiman, W.F. and Froelich, P.N., 1988. Influence of late Cenozoic mountain building on ocean geochemical cycles. Geology, 16: 649-653

²Ruddiman, W.F. and Raymo, M.E., 1988. Northern hemisphere climate regimes during the past 3 Ma: possible tectonic connections. In: N.J. Shackleton, R.G. West, and D.Q. Bowen (Editors), The past three million years: evolution of climatic variability in the North Atlantic region, University Press, Cambridge, pp. 227-234.

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Poster Session:

The geochemical and stratigraphic record of Himalayan erosion in sediments of the Bengal Fan, ODP Leg 116

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We report Sr, Nd, O, and H isotopic data and clay mineral abundances for sediments recovered in ODP Leg 116 cores from the Bengal Fan The samples studied cover the period between ca. 17 Ma and the present. Before 6.8 Ma and after 0.8 Ma, the sediments are characterized by high deposition rates, coarse grain size and an illitechlorite rich clay assemblage (IC). Between 6.8 Ma and 0.8 Ma sediments are characterized by lower deposition rates, fine grain size and a smectite-kaolinite rich clay assemblage (SK). ENd(0) and 87Sr/86Sr values in the Bengal Fan sediments (all samples) define narrow range about -16.0 and 0.741. 318O values in quartz separates are +12.8%0.5%. Coarse biotite-chlorite separates give $\partial^{18}O = +3.6$ to +5.6‰. Combined 218O values of quartz and biotites, and the narrow range of the Sr values, indicate a source that underwent isotopic homogenization shortly before erosion. The High Himalayan Crystalline series (HHC), or a close analog, thus has been the dominant source of the Bengal Fan sediments at all times since the early Miocene. IC clay fractions ($<2\mu$) have $\partial^{18}O$ +11.5 to +15 ‰ and ca. 90 ppm Sr, while SK clays have $\partial^{18}O$ +18.2 to +22.6 ‰ and ca. 20 ppm Sr. The IC and SK clay fractions represent different alteration histories of the same source material. Increased chemical weathering of SK material results in the loss to solution of radiogenic Sr. Variations in sedimentation history of the Bengal Fan reflect a combination of tectonism, and the coupled effects of sea level and climactic changes. SK clays first become abundant at a time roughly coincident with evidence for increased monsoonal circulation in the region. The Bengal Fan does not show sedimentologic evidence of renewed uplift at this time. Rather, the Himalaya were an important topographic feature well before the onset of strong monsoonal circulation, probably since the early Miocene. The return of rapid IC sedimentation in the Pleistocene apparently is related to increased denudation in the hinterland. Perturbations of the carbon cycle due to burial of large amounts of organic C in Bengal and Indus Fan sediments, and of the phosphorous cycle due to high weathering fluxes from the Himalaya may be important factors influencing Neogene climate change.

Paleobotanically Estimated Elevation of the late Eocene Southern Rocky Mountains

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After Laramide thrusting in Colorado, erosion beveled the highlands and filled the basins, forming a late Eocene erosion surface of low relief. The elevation at which this surface formed is crucial to understanding the formation of the southern Rockies. Two schools of thought exist. Lowaltitude proponents argue that the Eocene surface formed at 300-900 m as erosion kept pace with uplift during orogeny, and that the present altitudes of over 2 km are mostly due to Pliocene epeirogeny. High-altitude proponents argue that the surface formed at near present elevations, with only local changes in relief during Pliocene extension. Neither fission track or geomorphologic methods resolve this controversy. Fission track dates indicate the surface rocks have not been buried by more than 3 km since the Paleozoic. Some cite Pliocene downcutting as evidence of regional uplift, but downcutting can also be caused by climate change, local base level change, or drainage integration. This study uses new paleobotanic climate analysis techniques to determine the paleoelevation of the Eocene surface by examining the overlying 34.9 Ma Florissant flora. I developed a multiple regression model explaining 93.3% of the variance in mean annual temperature of modern Northern Hemisphere floras using 5 leaf physiognomic characters. When I apply this model to the Florissant flora, I derive a paleotemperature of 10.7 ±1.5 °C. Combining this temperature with coeval sea level temperature and a terrestrial lapse rate implies a paleoelevation of 2.5 - 2.6 km. Pliocene uplift is thus not required to explain the present elevation of 2.5 km; instead, the low relief surface formed at high elevations, and Pliocene downcutting was a primarily a response to climate change.

Geomorphic Response to Climate Change Recorded in a Core of Owens Lake, Eastern California

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The Owens Valley in eastern California is a closed basin surrounded by the Sierra Nevada on the west and the White and Inyo Mountains on the east. The valley began opening 8-10 Ma (Bierman and others, 1991) and has since been receiving sediment from the mountains. Sediment produced by weathering is stored in a variety of reservoirs including alluvial fans, moraines, flood plains, and, ultimately, Owens Lake (a topographic low point at the southern end of the valley).

The Owens Lake core, drilled by the U.S. Geological Survey in the spring of 1992, affords an opportunity to determine the dependence of chemical and physical weathering rates in the surrounding mountains on changing climate. The core contains a sedimentation record spanning roughly 800ka to the present. During that time, the Sierra Nevada have experienced periodic glaciation while the westward-draining portions of the White and Inyo Mountains have remained unglaciated. XRD analysis of the clay-sized fraction of the core will distinguish between clays produced via physical weathering (i.e., glacial flour) and by chemical weathering. In addition, chemical tracers will be used to recognize sediment contributions from the east and west sides of the valley, and, therefore, to determine the dependence of weathering rates on the presence or absence of glaciation, a matter of much concern to those dealing with global climate change (i.e., Raymo and others, 1988).

In order to convert sedimentation rates to the rates of chemical and physical weathering of the mountains, they will be coupled to a sediment budget for the Owens Valley drainage basin. This budget will comprise the various sedimentary reservoirs and the fluxes between them, and will allow us to determine the time lag between weathering and sedimentation in the lake. We might expect this lag to be much shorter for dissolved constituents than for physical sediment.

Sediment Flux From Source to Basin: A Global Overview Using a new Database

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The development of stratigraphy in sedimentary basins is controlled at first order by subsidence, relative base level change and sediment supply to the depositional site. Whereas a great deal of work has been carried out on the first two of these controlling factors, the third has received relatively little attention. Over the past decade a limited number of datasets has been assembled, containing information on sediment transport by major rivers. These datasets, however, focus on the sediment output of rivers and contain little or no detail on the source areas of the material. Sediment liberation, denudation and transport processes within these source areas determine the sediment output of rivers. To be able to make valid assumptions about the role of variations in sediment supply in the development of basin fill, it is necessary to improve our knowledge of the factors governing sediment supply to depositional basins. With this in mind, a database containing information on large scale sediment fluxes from source to basin was constructed. In this database, over 70 parameters, characterising or influencing sediment liberation, transport and deposition are described for 150 major rivers througout the world.

The sediment routing system ideally consists of four parts: A sediment liberation area, normally an area of enhanced relief; a subaerial deposition area, eg. a floodplain; a shallow marine deposition area, the delta and (part of) the continental shelf; and a deep marine deposition area, the lower half of the continental rise and the abyssal plain. For each of these four subsystems a set of parameters was defined, thought to be characterising or influencing the sediment routing. These parameters include details on topography, geomorphology, geology, tectonics, climatology, hydrology, kinematics and land use. Furthermore, attention is being paid to the connection of the above mentioned subsystems, as it is likely that transfer of sediment from one subsystem into the next is of crucial importance to the output of the system. Statistical analysis of the data collected in the database enables distinction between factors that are characterising or influencing the functioning of large scale sediment routing systems in general, and factors that are only characteristic for individual systems and do not seem to play an important role in the functioning of sediment routing systems in general. In the modelling of basin fill, the database can be used as a tool to predict variations in time and space of sediment supply to depositional basins.

Cenozoic Tectonics and Geomorphology of the Inner Tauride Belt, Southern Turkey

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Okan Tekeli (Department of Geological Engineering, University of Ankara, Tandogan, Ankara, Turkey)

The Inner Tauride belt is part of the Taurus Mountains in southern Turkey (between the latitudes 37 and 38°N), and its elevation locally reaches 3500 metres, which is the highest in the entire mountain chain. The highly rugged and sharp topography of this part of the mountain chain is in sharp contrast with the steep slop to the south towards the Mediterranean Sea and with a subdued and much less elevated (~1000 metres) topography of the central "ova" system to the north. Glacial deposits of possible Pliocene age locally occupy the central part of the chain in the Aladag Mountains. The field evidence and structural data suggest that the pronounced topography of the Inner Tauride belt is a result of a significant and rather fast uplifting in the region around Miocene-Pliocene time. This timing partly corresponds to and mostly postdates the collision of the Arabian plate with Eurasia and hence is synchronous with the terminal obliteration of Neotethys in the eastern Mediterranean region. The localization of much higher and faster uplifting rates in the Inner Tauride belt to the west of the Arabian promontory is enigmatic, however, because one would expect to see it developing immediately north of and thus in front of the indenting Arabian plate. This paper will discuss the causes and effects of syn- and post-collisional uplifting, elevated topography, climatic changes, and adjustments in sedimentary patterns in this particular region of southern Turkey. If the current topography of the Inner Tauride belt was indeed acquired in Mio-Pliocene time, then it is inferred that much of this region occupied by extensive carbonate platforms had a subdued topography and low elevation prior to the Tertiary. Dismembered ophiolite complexes scattered throughout the belt on both the northern and southern flanks of the Taurus Mountains might have been then part of a single sheet of oceanic crust emplaced on top of platform carbonates in Late Cretaceous time suggesting a much more different paleogeography of the Neotethys than what is currently being envisioned.

Tectonics and Weathering in the SE-Pyrenees (Spain): A Paleomagnetic Study.

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The Pyrenees in SW-Europe are part of the Alpine orogenic belt. During the latest Cretaceous to early Oligocene, Mesozoic carbonate sequences were folded and thrust. Above these limestones conglomerates and sandstones discordantly overlie the structure of the main tectonic event. Since Oligocene times uplift led to erosion and incision of deep canyons exposing the Mesozoic limestones. Goethite and hematite are the main products formed during chemical weathering of limestones. These ferric oxides can carry a natural remanent magnetization (NRM) and therefore are important mineral phases for paleomagnetism. Near the late Eocene erosion surface the normally grey limestones appear reddish. The NRM of these reddish limestones is carried by two components, goethite and hematite. The goethite NRM has a direction (D=003°; I=56°; a95=5.0°) parallel to the present axial dipole field (ADF), whereas the hematite NRM shows a declination of 40° and an inclination of 56° (a95=5.9°). This direction can be attributed to a syntectonic magnetization during the early Oligocene. By contrast, in the grey limestones outcropping in the canyons only goethite NRM parallel to the present ADF was found. The absence of a pretectonic magnetization suggests that the NRM is a result of chemical weathering. Formation of goethite and hematite is indicative of climatic conditions. The difference of their NRM directions suggests that the chemical weathering of the limestone in the SE-Pyrenees is a multistage process. The first weathering stage, with hematite formation, infers a subtropical climate during the late Eocene and the second one, with goethite formation, suggests a cooler and more humid climate since the late Pleistocene.

Post-Rift Evolution of Passive Continental Margins: U.S. Atlantic Type vs. South African-type; Part 2

Gregory E. Tucker, Rudy Slingerland, and Kevin Furlong (All at: Department of Geosciences, Penn State University, University Park, PA 16802)

The physiography of Post-Gondwana rifted margins ranges from low-relief settings, such as the eastern margin of North America, to high-relief margins bounded by major escarpments. The Great Escarpment of southern Africa is one of the most impressive examples of the latter, and is widely believed to have existed since the Mesozoic. We examine the geomorphological and geophysical conditions necessary for the development and preservation of this remarkable feature by coupling a three-dimensional landscape evolution model with a geodynamic model. The landscape model treats drainage network development, fluvial and hillslope mass transport, and sediment production by mechanical and chemical weathering. The geodynamic model calculates the response of a continuous elastic lithosphere to vertically-applied, strike-averaged line loads.

Model results demonstrate that the stratigraphy and structure of a newly rifted margin exerts a major influence over its subsequent evolution. Development of a retreating escarpment or series of escarpments demands variably resistant, flat-lying or gently dipping strata in the window of erosion. By contrast, lithologically homogeneous settings of moderate erosional resistance, such as the Appalachian Piedmont, tend to undergo scarp degradation despite flexural isostatic uplift. The creation and maintenance of a retreating south Africantype escarpment also appears to require the initial creation and maintenance of a drainage divide close to the evolving scarp front. Maintenance of such a divide is promoted by a flexural uplift rate that exceeds thermal subsidence in the vicinity of the escarpment.

While such conditions are necessary, they may not be sufficient. Other necessary factors for the development of high-relief margins with great escarpments include: (1) thicker or hotter lithosphere, which promotes a higher average elevation, and (2) amplified denudational energy along the escarpment and coastal plain relative to the interior, such as would be provided by orographic precipitation.

Shapes of Desert Piedmonts

Tom G Farr (Jet Propulsion Lab, California Institute of Technology, Pasadena, CA 91109; 818-354-9057; SPAN BERLIN::FARR) (Sponsor: Diane L Evans)

The shapes of desert piedmonts are determined by the interplay between tectonic forces and climate. For alluvial fans, the relative rate of uplift vs. the rate of aggradation or channel cutting determines the slope of the fan, whether the fan is cut by a trench, the area of the fan relative to the drainage basin that formed it, and whether the piedmont is instead dominated by erosional processes, forming a pediment. Changes in uplift rate or climatic conditions can lead to the isolation of the currently forming fan surface through entrenchment and the construction of another fan further from the mountain front (decreased uplift or increased runoff) or closer (increased uplift or decreased runoff). Thus many alluvial fans are made up of a mosaic of fan units of different age, some up to early Pleistocene in age.

In order to separate the effects of the different exogenic and endogenic processes on the shapes of alluvial fan units, a modified conic equation is being fit to digital topographic data for alluvial fans in different arid areas. This will allow parameters for the apex position, slope, and slope curvature to be compared with unit age, drainage basin lithology, climate, uplift rate, and soil properties. Preliminary results indicate that: steep slopes are related to a higher proportion of debris flows vs. fluvial deposition; for a particular fan, apex position shifts with time due to segmentation or stream blockage; and fan-unit original area and volume may be estimated, even if the unit is buried by younger units or has been eroded.

Subtraction of the fit from the measured topography allows the amount of dissection to be estimated, previously done by counting contour crenulations. This is another measure of age and has also been used to distinguish fans from pediments, which are diagnostic of tectonically quiescent regions.

Afternoon Session:

Dynamic Feedback Between Crustal

and Surficial Processes: Global to

Regional Scales

Chairman: W. Dietrich

Tectonics, Climate, And Topography: Fluvial Landsculpting Models of How the Colorado Rockies Weren't Uplifted in the Pliocene

Clement G Chase (Department of Geosciences, University of Arizona, Tucson, AZ 85721; 602-621-6024)

The classic view of Southern Rockies tectonics is based on geomorphology. To W. M. Davis, the regional low-relief Eocene erosion surface deeply incised by young canyons meant that the post-Laramide Rockies had been reduced to low elevation as well as low relief, and that the canyons represented Pliocene rejuvenation of the landscape by uplift. This idea has stuck. Gregory's recent paleobotanical studies of Eocene flora on the erosion surface strongly imply, however, that the

Colorado Rockies and High Plains have stood at about their present elevation since Laramide thrusting, and the Eocene erosion surface was cut at high elevation. This makes better tectonic sense than the classic view, but what then of the geomorphology? A numerical model of fluvial landsculpting shows how climatic changes could have produced these differences between the Eocene and Pliocene Southern Rockies without uplift. At km-scale wavelengths, small storms have a smoothing effect on eroding terrain, while major floods are needed to roughen and incise the landscape. Simulations with the model show that humid conditions during Cretaceous-Paleocene would have allowed rapid erosion of the surface uplifts, though fission-track ages show that depth of exhumation was regionally no more than a few kilometers. During the Eocene, continued high precipitation but an absence of large storms would be capable of causing a relatively rapid smoothing of the landscape to a surface of low relief at high elevation. Monadnocks remaining above the Eocene surface require strong erodibility contrasts to survive. Post-Eocene conditions would require both much less humid conditions to allow a low erosion rate and persistence of the high topography, and the presence of large floods sufficient to incise the steep-walled young canyons into the erosion surface. The best independent test of this hypothesized climatic and geomorphic history is probably in the nature of the sediments derived from the uplifted area.

Subsurface Structures as a Control of the Topographic Relief During Thrusting: Southern Pyrenees.

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D W Burbank (Department of Geological Sciences, University of Southern California, Los Angeles, California 90089)

Relationships between tectonics and sedimentation in the external part of the Pyrenean fold-and-thrust belt permit the recognition of a large scale inversion of topography which strongly modified the distribution and drainage of terrestrial deposits. Paleogene tectonic inversion of previous Mesozoic extensional basin geometries controlled the location of frontal and lateral ramps of the thrust system. Distribution of Eocene foreland evaporitic levels controlled emergence to the synorogenic surface as well as blind thrust geometries. Alluvial and fluvial deposits associated with thrusts show progressive (wedgeshaped deposits) and angular unconformities which are related with rapid and localized uplift. These progressive unconformities can be either normal or parallel to the alluvial paleoflow directions depending on the distribution of regional and local emerging relief, and the alluvial drainage.

The construction of accurate geological cross-sections using these relationships between tectonics and sedimentation can closely constrain the geometry and timing of thrust motion. Despite the age of the Pyrenean orogeny, partially restored cross-sections may still be used to reconstruct paleorelief and distribution of synorogenic sediments. This is due to moderate long-term rates of uplift and erosion.

Complex tectonic regions along the frontal ramp system showed higher topographic relief than in oblique and lateral areas due to differences in footwall ramp angle. These oblique and lateral ramps were crossed by the rivers that pass from the internal parts of the chain into the foreland basin (e.g. both oblique ramps of the South Central Pyrenean Unit). The growth of structures at depth increased either regional or local topographic relief and deflected local drainage patterns (e.g. Oliana anticline). The differential distribution of décollement levels controlled the large-scale thrusting geometry, which evolved from one of low-tectonic-relief with widespread terrestrial overpassing and deposition, into a system of higher topographic relief (tectonic-inversion relief) which produced widespread diversion of regional alluvial drainage.

Poster Session:

Escarpment Retreat on High-elevation Rifted Margins; Insights Derived From a Surface Processes Model

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Major escarpments, located up to several hundreds of kilometers from the ocean on high-elevation rifted margins (e.g. Great Escarpment of SW Africa) may have formed by retreat inland from the rift hinge zone since continental breakup. We use a surface processes model to investigate physical conditions that are required to produce such long-distance escarpment retreat.

Erosional denudation is calculated by simultaneous solution of surface mass transport by: a) local linear diffusion (hillslope processes) b)long-range transport by surface water runoff which results from distributed precipitation and descends the topography via the steepest route. The water runoff reacts with the landscape by entraining and depositing material (bedrock/sediment) driven by a potential proportional to the local disequilibrium in sediment transport. Equilibrium sediment carrying capacity is proportional to the slope-discharge product. The reaction rate constant depends on the reactant (bedrock lithology/sediment). The equations are integrated on a planform cellular grid assuming that transport is constant during the timestep and that there is no net storage of mass in the water runoff network.

Diffusion causes slope decline. Water erosion causes steepening of slopes and narrowing of topography around drainage divides. The model behaviour consists of a competition between these components. Migration of divides occurs by diffusion only.

We demonstrate that:

a) long-distance escarpment retreat without significant slope decline in a uniform lithology can only occur if 1) the top of the escarpment acts as a drainage divide and 2) the lithosphere responds to the denudational unloading by regional isostasy.

b) an escarpment far inland from the rift hinge zone, can come into existence, not by escarpment retreat, but by steepening of slopes in the area of an inland drainage divide, or the seaward termination of an erosion resistant lithology, when the area seaward has been significantly degraded.

c) horizontally layered strata with differing erodibilities can produce stepped or 'staircase' escarpments retreating at different rates. They can also explain large-scale convex upward landsurfaces that are dominated by fluvial denudation as opposed to diffusion.

Fluvial and Tectonic Geomorphology Across a Forearc Region Impacted by the Subduction of the Aseismic Cocos Ridge, Southern Pacific Coast, Costa Rica

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- S G Wells (Department of Earth Sciences, University of California at Riverside, Riverside, CA 92521; 714-787-4367)

The tectonic framework and geomorphic responses to partial subduction of the Cocos Ridge are evaluated in the associated, 70 km-wide onshore portion of the forearc region using integrated Quaternary geologic, soils-geomorphic, and field-and office-based fluvial and tectonic geomorphology studies. Península de Osa (PO) in the outer forearc region (OFR) is oriented parallel to the trench and represents the vertical, isostatic block uplift of the OFR initiated in the latest Pliocene to Pleistocene in response to ridge subduction. PO is characterized by a high (>700 m) interior range block and an adjacent uplifting (2-6 m/ka) and deformed coastal piedmont that preserves late Pleistocene and Holocene beach ridges and fluvial terraces. The inner forearc region (IFR) contains the Fila Costeña (FC) fold and thrust belt with faulted mountain fronts and warped and faulted fluvial terraces across major structures in the FC. The middle forearc

region (MFR) is transitional to the OFR and IFR, contains tectonic and geomorphic elements of both regions, and is separated from the IFR and OFR by major structural discontinuities. Mountain front sinuosity (Smf) of discrete segments of the range fronts of the three regions are statistically different; Smf is high (1.1-2.6) in the OFR and MFR, and lowest across the ridge axis in the IFR (1.0-1.4); variability in Smf along the FC is greatest toward the margins of the onshore projection of the subducting ridge (1.1-1.9) and decreases away from the ridge axis (1.0-1.5). Range crest/piedmont-mountain front junction profiles indicate probable segmentation and deformation of the range block and piedmont in the OFR and IFR. The maximum range crest elevation corresponds closely with the broadest parts of ranges in the OFR, MFR, and IFR (and location of the subducting ridge).

The distribution of Quaternary deposits, location of tectonic activity, rates and styles of tectonic deformation, drainage basin morphometry, and tectonic geomorphic parameters indicate that changes in the tectonic framework and accompanying geomorphic expression are most pronounced inboard of the subduction zone along projection of the ridge, parallel to the fold and thrust belt, and along the margins of the subducting ridge. The segmentation of the tectonic framework is reflected in lower relative tectonic activity in the OFR and MFR with respect to the IFR; increased coupling between the subducting ridge and the overriding plate results in greater relative tectonic activity, magnitudes and rates of shortening, and crustal thickening in the IFR.

- A Comparison of Response of Streams and Mountain Fronts to Different Modes of Uplift in Humid Regions: New Zealand and Taiwan
- P. L. K. Knuepfer and J. H. Willemin (Dept. of Geological Sciences, State Univ. of New York at Binghamton, Binghamton, NY 13902-6000; 607-777-2389; knuepfer@sunquakes.geol.binghamton.edu)

The Southern Alps of New Zealand and the Central Range of Taiwan, both oblique collisional orogens, differ in the structural style that controls uplift. That, combined with effects of glaciation in New Zealand, produces differences in both mountain-front morphology and stream-terrace development, but stream longitudinal profiles are quite similar. The western margin of the Southern Alps is bounded by the Alpine fault, which produces uplift rates on the order of 5-10 m/ka that are greatest at or near the fault; precipitation in the mountains ranges from 2-3 m/yr at the base to ~10 m near the crest. In contrast, our studies of the eastern margin of the Central Range indicate that regional warping of the mountain block produces similar uplift rates, but the highest uplift rate is clearly displaced toward the interior of the range; precipitation is comparable to that in New Zealand. To first order, the Southern Alps and Central Range fronts are linear and abrupt. The stream long profiles are also similar, with numerous knickpoints. This implies the high potential geomorphic energy controls stream incision rather than the details of style of uplift. Footwall uplift west of the Alpine fault complicates the mountain-piedmont junction and alters alluvial fan development at the mountain front. In Taiwan, however, large canyon-mouth alluvial fans are deposited in subsiding portions of the piedmont Longitudinal Valley, and canyon-mouth embayments are extensively developed. Valley cross-sections in the Southern Alps reflect glacial modification. In contrast, rivers in the Central Range have strong valley-in-valley topography. Quantitative assessments of variations in mountainfront morphology show greater variations in relative uplift rate along the Central Range front than along the Southern Alps.

Late Cenozoic Uplift and Exhumation at the Cascadia Subduction Zone, NW Washington State

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The Olympic Mountains of NW Washington State represent a recently uplifted and denuded part of the Cascadia forearc. Coastal mountains to the north and south generally have summit elevations less than ~ 600 m, whereas the 45 highest summits in the Olympic Mountains range between 2134 to 2427 m. Recent work has shown that the highest part of the Olympics exposed the most deeply exhumed part of the accretionary wedge. Based on metamorphic assemblages and fission-track data, we have determined that subduction complex rocks in this area were initially accreted at a depth of ~ 12 km at ~ 17 Ma. They reached their thermal peak at ~ 14 Ma and cooled through 110° C at ~ 7.5 Ma. Stratigraphic evidence around the perimeter of the Olympics uplift show that erosional exhumation did not begin until ~ 12 Ma when the forearc first became subaerially exposed, indicating an average exhumation rate of 1 km/Myr.

Localized uplift in the Olympic Mountains appears to be driven by two processes: (1) continued accretion and thickening within the underlying subduction complex to account for the addition of 30 km of sediments beneath central Olympics over the last 17 Myr, and (2) the development of a 10 km-high arch in the underlying Juan de Fuca plate over about the last 15 Myr. During this time interval, convergence between the Juan de Fuca plate and North America has been relative steady and nearly orthogonal at the position of the Olympic Mountains. Accretion has been restricted to the sedimentary cover of the subducting plate. There is no evidence of collision of seamounts or oceanic plateaux. Thus, it is concluded that the subduction wedge evolved in a relatively steady fashion. The interrelationship of uplift, isostatic compensation, and the erosional response of a newly formed Olympic Mountains can be described by a simple one-dimensional model that assumes steady rates of accretion and

This study yields two important conclusions: (1) The generation of Late Cenozoic relief in the Olympic Mountains is a direct result of tectonic processes and not global climate change. (2) The emergence of the forearc region above erosional baseline causes an acceleration of tectonic deformation, even though other external processes may continue to remain steady. In an ancient subduction wedge, this transition might be taken as evidence of an episodic event, such as the collision of a seamount or plateau.

Post-Rift Evolution of Passive Continental Margins: U.S. Atlantic-Type vs. South African-Type; Part I

Frank J Pazzaglia and Thomas W Gardner (Both at: Department of Geosciences, Penn State University, University Park, PA 16802)

Passive continental margins exhibit diverse topographic expressions ranging from the relatively subdued relief of the U.S. Atlantic margin to the high-relief great cuestas of the South African margin. We hypothesize that 1) the U.S. Atlantic and South African margins have been similarly affected by flexural isostatic processes driven by continental denudation and offshore sediment deposition and 2) the contrasting topographic expression between the two margins must be attributed to other factors. We have constructed a simple geodynamic model to simulate isostatic processes of the U.S. Atlantic margin which treats the lithosphere underlying the margin as an infinite elastic plate of finite thickness that deforms flexurally under the stress

of strike-averaged vertically-applied line loads. The flexural response is constrained by three time lines reconstructed for the lower Susquehanna River basin from Coastal Plain stratigraphy, Piedmont fluvial terraces, Tertiary-Quaternary eustasy, and Pleistocene denudation rates.

Model results demonstrate a complex interaction between Atlantic margin topography, the isostatic response to denudational and depositional processes, and the modulating influence of exogenic forces such as eustasy and climate. Longitudinal profiles of fluvial terraces and their equivalent Coastal Plain deposits or unconformities can be reconstructed by isostatic flexure of the margin responding to a mass-flux caused by continental denudation and offshore loading in the Baltimore Canyon Trough. Overall isostatic continental uplift due to denudation and basin subsidence due to loading is accommodated primarily by a convex-up flexural hinge represented topographically by the Fall Zone.

Therefore, the fundamental surficial and lithospheric processes that shape low-relief U.S. Atlantic-type margins are virtually identical to those that shape the high-relief cuesta South African-type margins. Differences in topographic expression of the two margins are concluded to be a function of other factors including supracrustal stratigraphy and structure, lithospheric strength and climatic history.

Adjacent Zones of Uplift and Subsidence Within a Fold and Thrust Belt, Southern End of the Cascadia Subduction Zone, Humboldt County, California.

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The southern end of the Cascadia Subduction Zone bends eastward intersects the northern California coast forming a series of anticlines, synclines. Regions of uplift are found adjacent to regions of subsidence. Marine terraces constrain the rates of uplift to between 0.3 and 1.4 mm/yr, while an offset stratigraphic marker and late Holocene sedimentation rates estimate subsidence rates of between of 1.4 to 2.3 mm/yr. Isostatic adjustment and flexure of the underlying Gorda plate can explain the proximity of the zones of uplift and subsidence.

Crustal thickening due to slip along shallow thrust faults would be offset by isostatic adjustments and flexure of the underlying Gorda plate. For the Little Salmon Fault, near the front of the fold and thrust belt, the late Quaternary rates of horizontal convergence across the zone predict rates of total vertical offset equal to the sum of the uplift and subsidence rates. Isostatic adjustment of the crust in response to the faulting causes subsidence and reduces the rate of relative uplift. The apparent maximum subsidence is located towards the front of the fold and thrust belt, where there is no apparent uplift, and a maximum rate of sedimentation. I used a 2-d boundary element model to validate the crustal thickening model as one explanation for subsidence.

A simple 2-d boundary element model without isostacy can approximate the surficial deformation, but models incorporating isostacy place the maximum subsidence towards the center and not the front of the fold and thrust belt. This indicates that crustal thickening is not the only factor involved in the development of the zones of subsidence. Sedimentation rates are highest towards the front of the fold and thrust belt, therefore as proposed by King et al. (1), the sedimentation could control the topography, and location of the maximum subsidence. A majority of this sediment may accumulate following coseismic subsidence of the synclines during great earthquakes. Other explanations for the discrepancies could be changing crustal characteristics, fault dips at depth, or unrecognized blind thrust faults. Models incorporating sedimentation and other changing characteristics are being developed.

(1) G. C. P. King, R. S. Stein, J. B. Rundle, *Journal Of Geophysical Research* 93, 13,307-13,318 (1988).

Tuesday, September 1, 1992

Morning Session:

Fundamentals and Objectives of

Geophysical and Geomorphological

Modelling

Chairman: R. Anderson

Geomorphological Modelling: an Experimentalist's Perspective

W E Dietrich (Department of Geology and Geophysics, University of California, Berkeley, CA 94720)

Geomorphological modelling should attempt to explain attributes of real landscapes. There are, however, two fundamental unresolved problems with this goal. One is the problem of quantitative description of landscape. What is it about actual landscapes that we wish to explain? Few would argue that we want to be able to predict the exact location of every channel and position of individual grains in a specific watershed. But what general, quantitative properties of actual landscapes could be defined and used to test model results? At present only relief, drainage density and slope appear to be distinctive attributes, yet these measures from real landscapes have not been used to evaluate model performance. In general, acceptance or rejection of a model has therefore been based more on model behavior and qualitative appearance of model results.

The other fundamental problem is the quantification of sediment transport laws that can be used in landscape modelling. Despite the general acceptance of the notion of slope dependent and slope-discharge dependent transport laws, there are no field-verified transport laws that have been shown to apply to long time and large spatial scales. Models lacking transport laws with parameters that can be calibrated from field measurements can not be validated, hence they represent untestable hypotheses. Most models are conceptual in that they show how a set of rules may operate to make a surface that looks like topography of landscapes.

These two problems may now be more tractable due to the development of digital elevation models to examine real landforms and due to the new surface age dating techniques involving cosmogenic radionuclides.

Poster Session:

Coupling of Surface Processes and Tectonics of Continental Collision Using Plane Strain and Thin Sheet Models

S Ellis, C Beaumont, P Fullsack and J Hamilton (All at: Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada, B3H4J1) We present results from plane strain (vertical section) and thin sheet (planform) finite element tectonic models of small to medium scale compressional and transpressional orogens in which the kinematic basal velocity boundary conditions correspond to detachment and subduction of lithospheric mantle below the orogen. The tectonic models are coupled to a planform surface processes model in which the topography is denuded by local diffusive (hillslope) and long-range advective (fluvial) mass transport (Kooi et al., this conference). The model rivers are charged by orographically controlled precipitation.

For the plane strain model we show results from the basic compression of a uniform crust, and the effects of isostasy and the negatively buoyant subducting lithosphere for strong and weak-based orogens. The effects of denudation are investigated for a windward prowedge (Taiwan-style orogen) and windward retrowedge (New Zealand Southern Alps-style orogen). Denudation is shown to modify the internal deformation and material trajectories within the orogen through the control of tectonics by the surface processes.

Within the restrictions of the thin sheet model, basal kinematic boundary conditions may also be applied, in order to investigate the transpressional features of weak-based orogens where significant basal detachment occurs. By applying boundary conditions such as an orogenic bend and/or oppositely vergent subduction zones, transpressional features (eg: horizontal shear zones and along-strike topographic variations) can be shown to develop. The effect of transpression on the geomorphic evolution of the model is investigated.

Geomorphic Response to Cenozoic Uplift of the West Slope of the Cape York Peninsula, Northeast Queensland

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C F Pain (Bureau of Mineral Resources, Geology & Geophysics, Canberra, ACT 2601, Australia; 06-2499469) (Sponsor: Micheal Ellis)

The western slope of the Cape York Peninsula is a broad (100-220 km wide), gently sloping (generally < 0.5 %) fluvial plain of very low relief. This erosional/depositional plain extends from the low (200 to 825 m) uplands of the peninsula's crest on the east to the shallow (67 m deep, 500 km wide) Gulf of Carpentaria on the west. It is underlain by a relatively thin (generally < 1000 m thick) sequence of shallow marine and fluvial deposits of late Mesozoic and Cenozoic age; onshore, the Cenozoic part of the section is typically less than 200 m thick.

This continuously evolving plain has formed in response to one or more episodes of broad regional uplift during latest Cretaceous and Cenozoic time. Total uplift during this period is estimated at about 400 - 500 m within the crestal uplands but generally less than 100 m across the presently degrading proximal to medial portion of the fluvial plain. A physiographically distinct, NW-SE trending transitional zone extends obliquely across the central part of the peninsula. This zone separates a predominantly degradational terrain to the northeast from a predominantly aggradational terrain on the southwest; most areas southwest of this zone have undergone net subsidence.

Relicts of a gently warped fluvial terrain of early to middle Tertiary age attest to the slow degradational response of the region. These include: (1) isolated buttes and broad, gently sloping cuestas underlain by late Cretaceous and (or) early Tertiary fluvial deposits and capped by thick bauxitic and ferrigenous deep-weathering profiles, (2) deflected principal streams in the vicinity of these surface remnants, (3) a predominance of subparallel to subdendritic consequent drainage across degradational areas of the plain, and (4) evidence of paleodrainage including low curvilinear ridges capped by silcrete. Average Cenozoic denudation rates are estimated at 3 - 4 m/m.y. within the crestal uplands and 0.5 - 1.5 m/m.y. across proximal areas of the fluvial plain.

CLUSTER GROWTH MODELLING OF EROSION PATTERNS

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Fractal cluster growth models have become popular recently as analogues of erosion processes. For example, phenomena such as diffusion-limited aggregation and invasion percolation have been suggested as rival models for drainage network evolution. I propose to unify some of these models and to establish the morphology and scaling of the spectrum of resulting erosion patterns. The erosion of the margin of a flat plateau can be modelled as the combination of three disordered growth processes:-

- Pseudo-viscous fingering, which is the result of fluctuations in the groundwater pressure field and hence the subsurface outflow rate and sapping rate. Such erosion patterns are either Laplacian fractals, where groundwater is sourced from a distant aquifer, or Poissonian fractals, where groundwater is recharged over the whole plateau.
- Invasion percolation, which is the result of variations in the erosion rate controlled solely by fluctuations in the strength of the local substrate. This end-member process produces fractal streams consistent with the Hack length-area relation.
- Quasi-uniform retreat, which is the result of processes acting at the erosion front which are uncorrelated with either the substrate strength or the groundwater pressure field. The cluster growth analogue is Eden growth, where particles are added randomly to a cluster perimeter.

The fractal scaling of each pattern, its erosion front, and its model streams are all well constrained in each case. Complicating factors such as fluctuation damping (noise reduction) and aquifer heterogeneity have also been explored.

Geomorphologic Modeling and Interactions Between Active Tectonics and Topography.

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The author and coworkers have in recent years developed a computer model (SIBERIA) for investigating, in a controlled environment, the interactions between the climatic, geologic and topography. The latest enhancements of this model and their motivations will be discussed. The importance of the interaction between channel and hillslope processes will be stressed. Using SIBERIA the author has previously published relationships between catchment area, slope and elevation for two cases constant and zero tectonic uplift - the so called "dynamic" and "declining" equilibrium cases. Recent work extending these relationships to the cases of time varying tectonic uplift and climate will be discussed and it will be shown that the geomorphology of these transient catchments can be described similarly. Using SIBERIA numerical experiments were used to investigate the timescales of change of elevations in the landscape; different parts of the catchment respond at different rates and these effects are

quantified. The results of an analysis of elevation response to stochastic tectonic uplift will be discussed as will the effect on geomorphology of incorporating simple but realistic feedbacks between uplift, landscape form and surficial processes.

Semi-Automated Geomorphic Pattern-recognition for Morphotectonic Analysis

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We have developed a semi-automated geomorphic pattern-recognition method for identifying buried geologic structures manifested in erosional topography. Using only a digital elevation model (DEM), we can identify linear segments of valley bottoms and fit planes to those segments that are coplanar. Our algorithms find all points in the DEM that are lower in elevation than their neighbors, string these low points together into continuous valley bottoms, and fit vectors to colinear segments of the valleys. The analysis then compares valley-segment vectors to find those that are coplanar and calculates the locations and orientations of the resulting planes. Statistical clustering of the planes allows us to spatially locate zones of anomalously high density for comparison with mapped geologic features. Implicit in this approach is the assumption that segments of erosional valleys lying along approximately planar faults or fracture zones are coplanar. Coplanar analysis detects planar correlations in any three-dimensional orientation, from vertical to horizontal; however, because they are not expected to control the erosional development of drainages, we do not look for shallowly dipping planes.

We analyzed the Yucca Flat area of the Nevada Test Site to test our approach in an area where subsurface geology and geologic structures are relatively well known. The coplanar pattern-recognition analysis identified 26,473 individual planes in a 30-m resolution DEM for a 33-km x 42-km area. In the 21 most significant clusters of planes, we compared the surface traces with the following: topographic features, mapped geology and geologic structures, fractures activated during nuclear tests, litho-stratigraphic isopach and structural contour maps, gravity anomaly plots, a plot of basin-fill thickness modelied on gravity anomalies, and a magnetic anomaly map of the northern part of Yucca Flat. We found strong correlations between plane clusters, segments of surficial faults, and apparent structures in the subsurface. The automated analysis apparently detects associations of subparallel fractures in the upper few kilometers of the earth's crust that we infer are upward-diverging fault or fracture splays reflecting faults or folds at greater depth.

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Escarpment Retreat on Passive Margins: Observations From Southern Africa

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The 'Great' escarpment of southern Africa is a high relief feature that is sub parallel to the present coastline. It is located more than 100 km inland of the rift hinge and it has been suggested that it is genetically related to rifting in the South Atlantic and has undergone retreat from the rift hinge to its current position.

Empirical studies that have attempted to quantify modern catchment denudation rates have emphasized the role of slope and climatic variables on a global scale. The application of such relationships to southern Africa implicitly suggests that the Great escarpment is actively evolving over geological time scales. However, the onshore stratigraphic record indicates that this feature has essentially maintained its current position relative to the coastline throughout the Cenozoic. It is suggested, on the basis of geomorphic evidence and insights from a surface processes model, that lithological/structural variations in the substrate have played a major role in controlling the denudation rates and landscape evolution of this region since rifting.

Topographic Lineament Swarms: Indicators of Regional-scale Paleo-stress Trajectories and Seismo-tectonic Domains

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More nonsense and psuedoscience may have been written about lineaments than almost any other area of geology. In many geologic minds, the subject is slightly more respectable than water-witching, but not by much. However, this may be a case of "throwing out the baby with the bath water." (1) Improved methodology can greatly aid the reliability of the basic data sets. Use of highly redundant observations and careful reproducibility tests can identify domains of development of individual swarms of topographic lineaments with considerable reliability. Domains of individual swarms commonly have dimensions of a few 100's to 1000 or more km. (2) Map domain limits of these regional-scale topographic swarms can be correlated with other, better known geologic features to obtain clues to the age and tectonic environments in which they formed. Such an analysis for Italy (Wise, et al, GSA, 1985) shows a strong correlation of individual swarms with broad flexures and regional extensile environments. Individual members of the swarms may be extensile faults or merely zones of more intense fracturing. The swarms are apparently formed by extremely minor brittle crustal extension above a slightly more ductile, extending crust. Two of these domains seem to correlate with present day seismo-tectonic provinces in Italy and another seems to define an ancient zone of weakness along the axis of the Appalachians, a zone which is still the site of concentrated seismic activity. The thesis of this paper is that domain analysis of topographic lineament swarms is a generally overlooked but extremely useful tool for a wide range of structural and geomorphic problems.

Modeling Fluvial Erosion on Regional or Continental Scales

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Modeling of erosion, landform development and sediment yields in response to tectonics has often focused on hillslope development with rudimentary attention to the fluvial network. We suggest that this emphasis should be inverted, with sediment yield from slopes being modeled as a convolution function of past rates of fluvial erosion, climate and lithology.

Modeling of stream network tectonic response has generally assumed fine-bed alluvial channels, so that profile response can be modeled using bedload transport models assuming high sediment rates. This is appropriate for channels on sedimentary aprons and lowlands, but in the high-relief portions of uplift belts channels are likely to be either bedrock or gravel.

Mechanisms and rates of erosion of bedrock channels are poorly characterized. Current models relate erosion rates to bed shear stress or to stream power, although solution and abrasion may also be important. Exposure of bedrock greatly slows headward propagation of baselevel control relative to alluvial channels, (e.g. the Appalachian Fall Line and Hawaiian channels).

Coarse-bed alluvial channels are often close to threshold and their gradients are controlled by a minor component of total sediment load. Profile evolution depends upon coarse sediment supply, abrasion, weathering and sorting. As an example, most of the fall of the Colorado River in the Grand Canyon is controlled by local rapids through tributary fan boulders.

Much remains to be learned about distribution of bed types, erosion rates, and processes determining profile evolution, particularly in bedrock and coarse-bed channels.

Applications of Quaternary Stratigraphic, Soil-Geomorphic, and Quantitative Morphometric Analyses to the Evaluation of Tectonic Activity and Landscape Evolution in the Upper Coastal Plain, South Carolina

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In the Atlantic Coastal Plain region where rates of erosion (10 to 40 m/Ma) and uplift (10 to 30 m/Ma) are an order of magnitude greater than the slip rates of recognized Cenozoic faults (0.3 to 1.5 m/Ma, Prowell, 1988), any tectonic signal that may be recorded in the landscape is easily masked by geomorphic processes in response to climatic, eustatic, and isostatic changes. Morphometric analyses combined with detailed mapping of fluvial terraces and upland geomorphic surfaces provide new approaches and data for evaluating the Quaternary behavior of Tertiary-active faults that are recognized in subsurface data in the Upper Coastal Plain of southwestern South Carolina.

Analyses of longitudinal stream and terrace profiles, regional slope maps, and drainage basin morphometry were implemented to detect evidence for long term tectonic uplift and/or tilting of the landscape. Relationships of basin shape, relief ratio, stream frequency, and drainage density developed from detailed characterization of 16 tributary basins and 200 subbasins were compared in a spatial sense across the updip-projected surface traces of the Pen Branch fault (a Tertiary reactivated reverse fault that initiated as a basin-margin normal fault along the northern boundary of the Triassic Dunbarton Basin) and other faults imaged in the subsurface. Preliminary results show that drainage density for basins developed along the trace of the Pen Branch fault is significantly higher (a=0.05) than drainage density for basins that lie northwest or southeast of the fault. Convex-upward longitudinal profiles in the upper reaches of these basins suggest added local relief. Additional field and morphometric studies will evaluate if apparent rejuvenation of drainages along the trace of the Pen Branch fault is the result of nontectonic geomorphic processes or local tectonic uplift and tilting within a framework of regional uplift.

Fluvial terraces along the Savannah River that cross the Pen Branch fault are critical strain gauges that can be used to constrain rates of deformation (due to either faulting or folding). Two prominent, laterally continuous terraces, the Bush Field (Qtb) and the Ellenton (Qte) at 11 ± 2 and 24 ± 2 above local base level, are estimated to be 100--250 ka and 350 ka-1 Ma, respectively. Age estimates are based on comparison of soil profile development and weathering characteristics to a regional soil chronosequence and comparison of rates of incision and regional uplift. Longitudinal profiles of these terraces across the fault show no obvious evidence of warping or faulting within a resolution of ~ 3 m. Additional drilling and detailed structure contour mapping of the erosional surfaces associated with each of these terraces will better constrain maximum possible amounts of Quaternary deformation. Application of rigorous sedimentary petrologic and mineralogic analyses (QFL ratios, heavy mineral suites, and clay mineralogy) and detailed soils investigations will help to refine age estimates.

Afternoon Session:

Dynamic Feedback Between Crustal

and Surficial Processes: Regional to

Local Scales

Chairman: C. Chase

Coupled Mechanical and Erosional Processes in 3d Collisional Mountain Belts

PO Koons (Geology Department, University of Otago, Box 56, Dunedin, New Zealand.)

An image of mountain building in collision of continental plates with roughly equal dimensions has emerged from field observations, numerical and analytical modelling of erosional and mechanical processes in the Southern Alps. Perturbation of moist prevailing winds by growing topography results in a marked asymmetry in the amount and intensity of precipitation with consequent concentration of deformation in the windward plate through erosion and thermal weakening. An asymmetric orogen consisting of a high strain inboard wedge adjacent to the indentor and a low strain outboard wedge is a consequence of the rain forest- rain shadow pattern. The coupled wedges have very different, but predictable erosion-uplift-elevation relations. Within a single orogen, erosion rates are inversely related to elevation and high mountains form where uplift rates are low. Nonlinearities in both slope and stream processes accentuate the inverse relationship of elevation and erosion rates.

Although the gross characteristics of the Southern Alps can be modelled by the 2d continuum approximations, the fabric and some fundamental features of oblique orogens are poorly represented unless 3d deformation and mechanical heterogeneities are considered. The theory and implications of a 3d critical orogen, deforming under oblique collision, are introduced and solutions are presented relating increasing horizontal shear stress to reduction in the outboard topographic slope. The inboard slope remains steep under the influence of the indentor orientation and erosion conditions. Strain partitioning and mechanical-stream coupling in the inboard produces major river valleys along σ_2 -vertical structures which run at high angles to the plate boundary. The net effect is that the 3d oblique orogen is characteristically narrower and more abrupt than the 2d orogen and contains a better defined drainage fabric within the inboard wedge.

Geomorphic Evidence in the Reconstruction of the Morphotectonic Evolution of Passive Margins: Possibilities and Limitations

M A Summerfield (Department of Geography, University of Edinburgh, Edinburgh EH8 9XP)

Interest in the morphological evolution of what are now recognized as passive continental margins extends back at least to Jessen's Randschwellen concept and the chronological schemes of workers such as Dixey and King. Only recently, however, have morphological, as opposed to stratigraphic and structural, data begun to be seriously incorporated into tectonic models of passive margin evolution. Potentially such evidence can provide valuable constraints on tectonic models, especially when combined with quantitative estimates of denudation using thermochronologic techniques and sediment volume data. Nevertheless, there are a

number of problems involved with the use of morphological data, including uncertainties as to the age and origin of erosion surfaces and the climatic and neotectonic disruption of drainage patterns previously established by major tectonic events. The primary difficulty, however, arises from the problem of establishing absolute as opposed to relative changes in landsurface elevation in the absence of paleodatum information from marine deposits or paleoshorelines. Modeling approaches to landscape evolution in passive margin settings are problematic as a result of the apparent discrepancy between some process rate estimates based on contemporary field measurements and estimates of long-term denudation rates. It seems likely that these discrepancies are due to an underestimation of the importance of lithological controls in long-term landscape evolution in such tectonic environments.

Evening Session:

Dynamic Feedback Between Crustal
and Surficial Processes: A Case Study
of the Andes and Himalaya Mountains

Chairman: B. Isacks

Eroding Plateau Edges of the Andes and the Himalayas

B. L. Isacks, J. Masek, T. Gubbels, and E. J. Fielding (INSTOC, Cornell University, Ithaca, NY 14853; Isacks@Geology.Cornell.Edu)

Climatically driven erosion of the narrow mountain belts in Taiwan and New Zealand can produce a balance between erosional outflow and tectonic inflow of crustal mass because high erosion rates can be maintained across much of the mountain mass. In contrast, the erosion of the large Andean and Tibetan plateaus is concentrated mainly in narrow belts along the windward plateau edges. The erosion rates in these belts, although among the highest on earth, were not high enough to balance the large tectonic influxes that built the plateaus. The orographic concentration of erosion along the edges, however, may have played a major role in the evolution of the plateaulike physiography characteristic of these two most outstanding continental uplifts. In both regions an earlier phase of crustal shortening and thickening distributed throughout the areas of the present plateaus preceded a later phase where shallow shortening became concentrated along the presently active Himalayan and eastern Andean thrust belts. Late Cenozoic climatic change acting on the rising topography may have initiated or encouraged those transitions. We test these ideas in two ways: (1) through an examination of three transects across the Andean and Himalayan thrust fronts showing topographic, climatic and tectonic characteristics that affect rates of erosion; and (2) 3-D forward modeling of the topography with the effects of orographic precipitation, kinematic uplift history, mass transport, and isostasy. A critical consideration is the different roles of the lower altitude fluvial system and the higher altitude glacial system. We find evidence that the storage and pulse-like release of melt water associated with Quaternary climate oscillations produce short periods of greatly enhanced erosion.

Poster Session:

Coupled extension and uplift in the central Andes: Implications for regional uplift history

Alexandra Moore (Harvard University, now at Hartwick College, Dept. of Geology, Oneonta NY, 13820)

Crustal kinematics and potential energy considerations applied to thickened continental crust may be used to constrain the uplift history of orogenic belts. Normal faulting at high altitudes, contemporaneous with and parallel to thrust faults in flanking lowlands areas, implies that the mountain belt has reached its strength-limited maximum elevation. Crustal extension documented within the Peruvian Altiplano places constraints on the uplift history of the central Andes. NW-SE striking low-angle normal faults parallel the axes of the Peru -Chile trench and active thrusts in the Subandean zone. These structures dismember Tertiary continental foredeep basin deposits. 40Ar/39Ar ages from biotite and sanidine in interbedded tuffs date the basin sediments at 13-19 Ma. These strata are exposed in the hanging wall of a low-angle normal fault system, dating the initiation of extension as post-13 Ma. Younger, more steeply-dipping normal faults offset the low-angle structures and offset 6 Ma igneous rocks, further constraining the initiation of extension to 6-13 Ma. Fissiontrack dating in the adjacent Cordillera Oriental (Benjamin et al., 1987) suggests that erosional denudation in that area accelerated significantly at 9 Ma. The time-coincidence of extension and rapid denudation suggest that the two processes are related, and that accelerated uplift of the mountains is a spatially limited phenomenon balanced by the subsidence of the adjacent basin. In this case of coupled subsidence and uplift there is no change in the average elevation of the orogen and no change in average crustal thickness. Crustal extension on the Altiplano implies that the Andes were a region of very thick crust prior to ca. 13 Ma, and that regional uplift has not accelerated through the Neogene, but rather that high elevations have been maintained at or near present levels for the last 13 Ma.

Strike-Slip Faults in the Southernmost Andes and the Development of the Patagonian Orocline

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The Patagonian orocline is the 90° bend in the southernmost Andes extending for over 1000 kilometers between 50°S and 56°S. Paleomagnetic data indicate that the orocline is, at least in part, the product of tectonic rotation. Recent field work in the Beagle Channel region of southernmost Chile provides evidence for widespread leftlateral strike-slip faulting in the internal zones of the mountain belt. Although much of the structural evidence indicates Cenozoic brittle strike-slip faulting, ductile fabric data suggest that Mesozoic ductile strike-slip or oblique-slip shearing also occurred. The implication is that the mid-Cretaceous Andean orogeny involved the transpressional inversion of the Rocas Verdes marginal basin and that transpression has been the dominant deformational regime in the region for the last 120 Ma. Regional left-lateral strike-slip faults are now recognized in all lithotectonic provinces of the southernmost Andes. A statistical study of regional lineament trends using aerial photographs and satellite imagery suggests that many unstudied lineaments are also strike-slip faults. A new model is proposed that integrates the development of strike-slip faulting and the structural evolution and uplift of the southernmost Andes with the rotational development of the orocline. The Patagonian orocline appears to be the product of broad interplate shearing accommodated by strike-slip faulting, block rotation and contraction and is probably continuing to evolve today.

Strike-slip faulting has played a major role in the topographic development of the southernmost Andes. Many of the linear fiords that cut through the orogen, including the western arm of the Straits of Magellan are strike-slip faults. The highest elevations in the region are found in the Cordillera Darwin massif, a basement-cored uplift that averages 1000 meters higher in elevation than surrounding sectors and that exposes the highest grade metamorphic rocks in the Andes south of Peru. The uplift history of Cordillera Darwin is controversial however, its location at the western termination of the left-lateral South American-Scotia plate boundary and the fact that it is locally bounded to the north and south by strike-slip faults suggests that strike-slip faulting was an important component to Cordillera Darwin orogenesis

Spatial Order in the Topography of the Central Andes and its Relation to Nazca-South American Plate Kinematics

lohn W. Gephart (INSTOC, Snee Hall, Cornell University, Ithaca, NY 14853; 607-255-5552; gephart@geology.cornell.edu)

The topography of the Andes around the Altiplano-Puna plateau, 12°-32°S latitude, exhibits a high degree of "spatial order," or a non-random shape, that must reflect the physical mechanisms of mountain building in this non-collisional orogen. The mountain belt in this region has a distinct bilateral symmetry about an ENE-trending vertical plane that crosses the Chilean coastline near 21°S. This appears to reflect the stable plate kinematics of the mid-Tertiary, during which the Nazca-South American relative rotation pole persisted for >15 Ma in an orientation perpendicular to the present symmetry plane (i.e., with convergence along a great circle path)—a geometry that shares its bilateral symmetry with the orogen. The central Andes also exhibit a significant (though imperfect) radial symmetry about a point at approximately 23°S, 79°W, an expression of the arcuate shape of the mountain belt. This may depend on the flexural behavior of the subducting slab, as is typical of oceanic island arcs, though of opposite sense of curvature in this case.

The relatively minor antisymmetric component of topography is itself ordered—concentrated in the forearc and of a well-defined wavelength. This may reflect small opposing rotations of the two plates relative to the symmetry coordinates (at different length scales for the two plates): clockwise for South America (~500 km wavelength) and counterclockwise for Nazca (-1000 km). That these are inferred only in the central Andes requires that the plates be non-rigid. Such relative rotations are consistent in sense with an inferred late-Tertiary change in plate kinematics, as the relative rotation pole migrated southward toward the Andes (with convergence along small circle paths) from its earlier stable position at 90°. That this effect is localized (of large amplitude) in the central Andes, and is consistent with the direction of changing plate kinematics, suggests that the region encompasses a perturbation that is forcing the change in plate motions; i.e., the torque may be induced locally. One possible source of the perturbation is the interaction of an originally symmetric mountain belt with an extreme latitudinal climate variation on the east side—with high precipitation on the north limb versus low on the south. The resulting differential erosion may induce a dynamic response of the orogen that disrupts the original symmetry. This effect would not occur until the mountains were uplifted, perhaps in midto late-Miocene, generally consistent with the timing of changing plate Thus, atmospheric circulation may affect plate tectonic processes. That relatively subtle effects in the central Andes may significantly perturb plate kinematics is consistent with the notion that the predominant forces of plate tectonics act at subduction zones, rather than at ridges and transforms, which comprise virtually all of the other boundaries of the Nazca and South American plates.

Trans-Himalayan geodetic leveling: Constraints on mountain building

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Precise leveling networks in India and Tibet are linked through the Kingdom of Nepal. Profiles in Tibet and Nepal have been measured at least twice in the past 15 years. Although the data are of high quality, systematic errors limit the accuracy with which deformation may be resolved. The leveling line through Nepal, which traverses all the principal structural components of the Himalaya, is ~ 250 km long and is associated with random errors (in mm) of $1.1\sqrt{L}$ (L in km). Random errors in the Tibet level lines are believed to be similar. Combined random errors result in an uncertainty in monitoring the elevation of the Tibetan plateau relative to the plains of India (a distance of ~ 350 km) to better than ± 2 cm. Slope dependent errors increase the combined uncertainty to ± 4 cm.

In Nepal a sequence of local uplift and subsidence features with wavelengths between 20 and 50 km emerge above the random and systematic error in the data at rates of 2-4 mm/yr. Neither large earthquakes nor substantial ground water withdrawal projects are coincident with the leveling line and tests for significant slope dependent errors in the leveling data are negative. Although the lack of seismicity precludes the identification of a discrete dislocation surface, we use elastic dislocation modeling to determine a range of possible fault geometries that satisfy the uplift features. In southern Nepal, uplift rates of 2 ± 0.3 mm/yr with a wavelength of 30 km coincide with active folding of an anticline on the southern flank of the Lesser Himalaya. Based on elastic dislocation models, a range of detachment geometries satisfy the deformation field but geologically realistic models fall into a group of horizontal to shallow dipping, sub-horizontal faults between 12 and 6 km in depth. Although the wavelength of the observed deformation field permits models with significant slip closer than 4 km to the surface to be excluded, no unique solution exists. To the north, in line with the great Himalayan peaks, an 80 km wavelength uplift feature with vertical velocity of 4 mm/year may correspond to the increase in dip of the Moho proposed by Molnar and Lyon-Caen.

A limited number of height differences provided by Chinese colleagues suggest a general northward tilt of the Tibetan plateau. A more detailed geologic interpretation awaits release of the full

data set.

Geomorphic Evolution of the Western Himalaya

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Geomorphic evolution of the Karakoram, Nanga Parbat, Kohistan, and Swat Himalaya during Quaternary has involved pronounced differential uplift, coupled primarily with antecedent incision by the Indus River and tributaries down from gently rolling erosion surfaces, together with extensive multiple glaciations. The Deosai Plateau erosion surface at ~4000 m altitude may correlate with the Silver Saddle surface at ~7000m on Nanga Parbat (8125m) and the Kohistan surface at ~4500m. The Patundas surface in Hunza and other similar high-level surfaces are scattered Plio-Pleistocene remnants throughout the western Himalaya but their dating is a problem. The Indus River maintains a trench along the active Raikot Fault at the base of Nanga Parbat down to 1160 m. The Indus channel across the Nanga Parbat massif has been deflected by ~Tertiary left lateral and ~Quaternary right lateral motion on the fault. Three main glacial stages are recognized by most workers. The earliest or Shanoz stage includes glaciated high-level erosion surfaces, and perhaps the reversely magnetized Bunthang till deep in Skardu valley. The Jalipur tillite in the

Indus Valley bottom along Raikot Fault is indurated, tectonically deformed, and perhaps Shanoz age but British workers consider it young lodgement till only. The middlemost Yunz stage had two major stades, was an ice cap on Deosai Plateau, involved major valley incision, and advanced farthest down Indus Valley. The last, or Borit Jheel glaciation had several stades that produced massive recessional and cross valley moraines below extensive Holocene moraines and modern glacier ice. Erosion of at least 6700m vertically downward appears to have occurred through the Nanga Parbat massif during the Quaternary.

Thursday, September 3, 1992

Morning Session:

Geodynamics Deduced from

Topography/Local to Regional Scales

Chairman: C. Vita-Finzi

Geodynamics Deduced From Landscapes

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Streams are concentrated avenues of erosional power and deposition. Adjustment to long term geodynamic controls depends on available stream power and rock resistance. Response times to climate change are short. Study of climatic and tectonic influences on geomorphic processes and landforms allows deduction of tectonic styles and rates from fluvial landscapes. Landscape assemblages provide information about uplift of mountains relative to basins when defined in terms of tectonic, erosional, and depositional base-level processes. Streams tend to degrade and maintain a dynamic equilibrium longitudinal profile through the process of tectonically induced downcutting. Lateral erosion then bevels major bedrock straths; the fundamental tectonic stream-terrace landform. Climatically controlled aggradation followed by degradation leaves an aggradation surface; the fundamental climatic stream-terrace landform. Elevation of streambeds by either aggradation or tectonic uplift provides provides the vertical space for flights of minor complex-response degradation terraces to form. Two shapes of alluvial fans--segments of cones and planar sheets--are geodynamic end members. Fan aggradation associated with normal faulting tends to build a cone, but horizontal tectonic translocation tends to spread aggradation and deposit a tabular sheet.

Tectonics Deduced from Topography: The General Challenge and Some Specific Examples from a Variety of Settings

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Solution of the general problem of the evolution of large scale landscapes requires a knowledge of both the tectonic and geomorphic processes and their rates. The mismatch between the scales at which uplift and erosional processes act makes the problem both complex and interesting in that it raises the possibility of feedbacks.

I will first discuss several instances in which we have considerable constraint on the tectonics, through use of paleo-benchmarks in the landscape. These must be both documented in space and in time in order to be useful; the most promising will be those whose initial geometry is deducible through modern analogues. Digitial topography greatly aids in these endeavors; determination of the ages of these surfaces is both crucial and more problematic. The Santa Cruz marine terraces are one such example. Not only can the deformation pattern due to tectonic forcing be documented, but the rates at which these remnant surfaces are degrading can be used to constrain the geomorphic efficiency in the same locality. I will briefly discuss other settings in which remnants of paleo-surfaces may be used to determine total tectonic forcing, including the Sierra Nevadas, the Finisterre Range, Papua New Guinea, and the Upper Blue Hills badlands, Utah.

The more general problem involves a landscape with no remaining benchmarks. The effort becomes much more model dependent, and the assessment of the quality of the model more difficult. Tectonic forcing includes both the earthquake cycle, with its coseismic, interseismic components, and such aseismic processes as underplating in accretionary wedge settings. Major problems facing the geomorphic modeler include assignment of initial conditions, and the changing efficiencies of geomorphic processes through major climatic cycles. The entire system responds to the evolving topographic load flexurally, leading to debates about the proper choice of elastic plate parameters and the necessary geophysical data sets to make these choices.

Poster Session:

Diffusion-erosion Analyses of Strike-slip and Normal Fault Scarps Along the San Andreas Fault: Calibration and Application

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Quaternary deformation and subsequent geomorphic responses along the San Andreas fault in the Carrizo Plain (San Luis Obispo County, California) present an unusual opportunity to develop and apply coupled tectonic and geomorphic models. We have begun by calibrating diffusionerosion models for fault scarps at the Wallace Creek offset stream complex, and modified diffusion-erosion models for gullies developed on those scarps. Southeast of the offset channel at Wallace Creek, horizontal offset and localized uplift have created a 15 m high southwest facing scarp. Radio-carbon dates from an alluvial fan deposited in front of the original scarp indicate that the scarp was first exposed about 13 ka (Sieh and Jahns, 1984, GSAB, v. 95, p. 883 - 896). The mass diffusivity (the parameter summarizing the erosive processes) could be calculated from this well documented age. Using a 35 mm/yr strikeslip rate, the distance from a reference point on Wallace Creek to any location on the scarp can be used to infer the time since the exposure of that part of the scarp. These ages constrain the diffusion analysis and aid in the determination of mass diffusivity for the hillslopes along the scarp: ~10 m²/ka. To determine a bulk mass diffusivity, the volume of the alluvial fan was compared to that of material removed from the scarp by hillslope processes and gully formation. The volume of eroded and deposited material was divided by the average width of the inferred source to yield a cross-sectional diffusivity for comparison with the scarp analyses: ~15 to 80 m²/ka. Gullies cutting the scarp face initiate as rills and develop as predicted by a diffusion erosion analysis. However, gully profiles develop faster than the scarp profiles, implying a higher relative mass diffusivity: consistent with the larger values for bulk mass diffusivity determined from the fan and total scarp volumes.

The method used in this study evaluates erosive processes that are generally ignored in diffusion-erosion analyses through detailed morphometric, instrumental, and stratigraphic investigation. Work has begun to apply these methods to normal fault scarps in the Elkhorn Hills (an uplifted and deformed block 30 km southeast of Wallace Creek near the northern end of the Big Bend in the San Andreas Fault), in order to determine the temporal development of the structures there.

Limneotectonics and Buried Tectonic Topography Under Great Salt Lake, Utah

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Limneotectonics uses distinctive lakeshore levels (LSLs) and lakebed horizons (LBHs) of known isotopic age as strain gauges—isostatic-deflection tiltmeters, seismotectonic-displacement slipmeters, and basin-fill depometers—to constrain mainly the vertical component of neotectonic kinematics in lake basins.

Late Quaternary vertical kinematics of the Great Salt Lake basin floor can be gauged by several LSLs and LBHs—e.g., top of lower salt (TLS = 107 ka), pre-Bonneville radiocarbon horizon (PRH = 30 ka), top of middle salt (TMS = 21-20 ka), Bonneville higheststand level (BHL = 15 ka), Bonneville Flood horizon (BFH = 14.5 ka), base of upper salt (BUS = 13 ka), Gilbert highstand level (GHL = 11-10 ka), top of upper salt (TUS = 9 ka), Farmington Bay ooid horizon (FOH = 7 ka), and Mazama ash horizon (MAH = 6.8 ka).

Examples—TLS, hanging-wall burial along east Great Salt Lake fault = >0.57 mm/yr; PRH, down-to-the-west net vertical slip on east Great Salt Lake fault = 1.4 mm/yr; PRH, down-to-the-east net vertical slip in Farmington Bay graben = 0.2 mm/yr; TMS, hanging-wall burial along east Great Salt Lake fault = 2.0 mm/yr; BHL, total hydro-isostatic deflection at basin centroid = 90 m (post-higheststand mean rate = 6 mm/yr; maximum rate = 73 mm/yr; post-2.6-ka-highstand mean rate = <0.4 mm/yr); BFH, hanging-wall burial along east Great Salt Lake fault = 2.3 mm/yr; BUS, hanging-wall burial along east Great Salt Lake fault = 3.9 mm/yr; GHL, down-tothe-east net vertical slip in Farmington Bay graben = 0.38 mm/yr; TUS, down-to-the-west net vertical slip on east Great Salt Lake fault = 1.1 mm/yr; FOH, down-tothe-east net vertical slip in Farmington Bay graben = 0.3 mm/yr; and MAH, down-to-the-west net vertical slip on east Great Salt Lake fault = 0.60 mm/yr.

Channel Adjustment in Fern Canyon Near Watsonville, California, Following the 1989 Loma Prieta Earthquake

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Fern Canyon, a small stream crossing the San Andreas Fault 8 km northeast of Watsonville, has formed a broad floodplain upstream of two compressional ridges that deflect the present channel in a right-lateral sense and that have at least partly dammed it during late Holocene time. Linear cracks formed during the Loma Prieta earthquake follow the fault trace just upstream of these ridges; these cracks showed 1-2 cm of ridge-side-up displacement. Between March, 1990 and June, 1991, repeated surveys along the Fern Canyon channel revealed an increase in the thalweg elevation along 30 m of the channel upstream of the fault. The middle 17 m of this reach showed an average of 28 cm of aggradation. We infer that the aggradation occurred during the March, 1991 storms that produced the only significant post-earthquake runoff that winter. Between March, 1991, and June, 1992, a period of near-normal runoff, about half of the total 1990-91 increase in bed elevation persisted. Aggradation, which resulted from the infilling of the streambed alluvium with fine-grained, organic-rich sediment, appears to reflect a decrease in the gradient upstream of the fault. Results to date suggest that earthquakes without significant surface rupture induce changes in stream channels that, over geologic time, can produce the characteristic offset streams of the San Andreas Fault zone.

Uplift of the Central California Coast Ranges

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A simple model for tectonic uplift due to compression of a crustal wedge is used together with geologic and geomorphic contraints on tectonic uplift and erosion rates to address the question of whether compression of a crustal wedge could account for the geologically well-constrained post-Pliocene surface uplift of the central California Coast Ranges. In conjuction with reported erosion rates, the critical taper model of accretionary wedge deformation (e.g., Dahlen, 1990) estimates that the width of the Coast Ranges requires a minimum Pacific-North America plate convergence rate of 0.5 to 2.0 mm/yr to sustain their present elevation. Compression of a wedge with fixed lateral boundaries provides another simple model for deformation in the California Coast Ranges. Assuming that compression across the wedge is sufficient to cause shortening, and material can not cross either the basal or lateral boundaries of the wedge, then compression must be accomodated by uplift. Seismic refraction studies and other evidence suggests that the accretionary wedge supporting the California Coast Ranges is approximately 100 km wide and 10 km Using this geometry, published plate-margin-normal convergence rates for the Pacific and North American plates predict tectonic uplift rates in close agreement with those independently derived from dating and/or correlation of marine terrace deposits, fission track studies, leveling and subsidence measurements, and extrapolations from uplift associated with the Loma Prieta earthquake. Reasonable estimates of the long-term erosion rates for the central California Coast Ranges are probably on the order of 0.05 to 0.20 mm/yr. Expected post-Pliocene surface uplift for a variety of tectonic uplift rates can be determined by combining isostatically-compensated tectonic uplift and erosion rates over the 3.5 m.a. period since the change in plate motion hypothesized to have resulted in Coast Range uplift. This simple model of Coast Range deformation predicts that plate convergence rates on the order of 4 to 8 mm/yr are compatible with reconstructed post-Pliocene surface uplift of 300 to 600 meters, suggesting that a small convergent component to relative plate motion across the Pacific-North American plate boundary is sufficient to account for significant post-Pliocene uplift in the central California Coast Ranges.

The Boconó Fault, Western Venezuela

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The Boconó Fault consists of aligned valleys, linear depressions, pull-apart basins and other morphological features, which extend for

about 500 km in a N45°E direction between the Táchira depression (Venezuela-Colombia border) and the Caribbean Sea. It crosses obliquely the Cordillera de Mérida and cuts across the Caribbean Mountains, two different geologic provinces of Late Tertiary-Quaternary and Late Cretaceous-Early Tertiary age, respectively. Other minor morphological features include ponded alluvium, push-ups, pressure ridges, alighed and offset drainages, fault trenches and depressions (open and closed), sag ponds and swamps, shutterridges, fault saddles, scarps, fault planes, fumaroles, and hot-water springs. Many of these features are enhanced due to the steep topography of the Cordillera. Radiocarbon dated glacial sediments suggest a Holocene right-lateral offset rate of 3.3 mm/ a. The age of the sedimentary fill of the La Conzélez pull-apart basin suggests that the 7 to 9 km right-lateral offset necessary to produce it took place in Middle to Late Pleistocene time. Late Pliocene-Early Pleistocene (?) alluvial sediments vertically offset by the basin formation suggest a subsidence rate or up to 1 mm/a. The majority of seismic events are well aligned with the main fault trace. Focal depth is typically 15 km. Geodetic studies of several sites along the fault suggest a right-lateral rate of displacement of about 1 mm every 5 months (15 a of observations).

The Nature of Faulting and Deformation Near the Mendocino Triple-Junction

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The Mendocino triple-junction region (MTJ), of coastal CA, is perhaps the most studied structure of its kind in the world, but confusion persists regarding several aspects of the feature. Principally, both the nature and location of the San Andreas fault (SAF) are poorly understood, as is the cause of rapid rates (≤ 4 mm/yr) of surface uplift of the King Range just to the south of the MTJ. We address these two issues by combining current geological thinking on the northern section of the SAF with new evidence of late Quaternary tectonism in and near the King Range. Geologists working in the region have abandoned the traditional location of a single SAF along the coast line in favor of faults, probably including the Mattole shear zone, located east of the King Range (Clarke, 1992; McLaughlin et al, in press). This implies the King Range is riding on the Pacific plate not the North American plate as previously thought. Evidence of Quaternary deformation in the region include: 1) Holocene marine terraces are uplifted, faulted and deformed along the coast. 2) Terraces along two rivers have been disrupted and deformed apparently by faulting. 3) A Holocene thrust fault has been discovered in the Mattole valley sub-parallel to nearby lineaments that are suggestive of strike-slip faulting. 4) Geological young shear zones (probably Quaternary) have been identified and are near vertical strike-slip shears or near horizontal faults. Taken together the evidence of latest Quaternary tectonism indicates a coexistence of thrust faults and strike-slip faults with strike orientations of N. NW and W. We evoke a model of an on-land, wide, multiple strand, transpressive San Andreas termination, and in addition suggest the King Range on the Pacific Plate is uplifting in mechanical response to compression with both the North American plate and the subducted Juan de Fuca (Gorda) plate.

Quaternary Terraces Near Point Reyes: Strain Gauges Along the San Andreas Fault Zone North of San Francisco, California

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Surface elevations and deposit characteristics of terraces exposed along the San Andreas fault zone provide a record of Quaternary deformation associated with movement along the boundary between the Pacific and North American lithospheric plates. A marine terrace along the Pacific coastline may correlate to the youngest terrace in the Santa Cruz Mountains south of San Francisco (about 70--100 k.y. The terrace surface is folded; elevations range from over 50 meters above sea level to below sea level in a synclinal axis. The youngest terrace surface along the eastern edge of Tomales Bay attains an elevation of 24 m and is also synclinally folded. Fold axis orientations are subparallel to the San Andreas fault (trending about N35W). Compressional structures parallel to the principal shear direction (implying contraction perpendicular to the San Andreas fault) have been observed throughout the San Francisco Bay Area (Aydin and Page, 1984, GSA Bull.), but they are not well accounted for by theoretical "wrench tectonic" models.

Pleistocene deposits of the Millerton Formation, exposed in terraces along the eastern edge of Tomales Bay, attest to continued contraction of the region. The formation consists of fining-upward packages, formed when the fault valley was inundated during sea-level highstands, separated by erosional unconformities, formed during sea-level lowstands. The syntectonic influence manifests itself in angular discordances between beds and as deformational features within beds. Age resolution is not yet adequate to tell whether the cycles correspond to substage sea-level fluctuations of marine isotope stage 5 or to stage 5 plus older stage fluctuations.

River Terraces in Wind River Basin, Wyoming; Correlations, and Flexure From Yellowstone Uplift and Differential Basin Erosion

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Strath river terraces along Wind River and tributary streams throughout Wind River Basin, Wyoming, have been mapped to evaluate roles of isostatic rebound from differential basin erosion, and mantle plume-driven Yellowstone uplift in terrace generation and flexure. A suite of 15 terraces and terrace remnants has been identified along 160 km of Wind River between Dinwoody Creek and Wind River Canyon that span a vertical interval above the modern channel of more than 300 m. Longitudinal profiles along the river segment between Dinwoody Creek and Riverton converge downstream to the east, whereas the opposite relationship is found for terraces along Badwater Creek, which drains from the east. At Riverton, downcutting of Wind River has also been accompanied by its eastward migration over a time period spanning generation of at least the last 13 members of the terrace sequence. Three terraces, designated WR3 (Upper Bull Lake), WR7 (Sacajawea Ridge), and WR9 in order of increasing age, have good continuity over a 95 km northwest-southeast leg of the river. A new find by C. Jawaroski of Lava Creek ash in WR7 near Kinnear, together with a previous ash locality above and east of Red Creek (Izett and Wilcox, 1982), formerly assigned to WR9, and now both dated at 670 ky by K. Pierce et al. (1992), force reinterpretation of our previous longitudinal profile correlations. The new interpretation gives an average gradient of 5.1 m/km for WR7 compared to 4.5 m/km for the original interpretation. WR3 has an average gradient of 4.6 m/km

compared to 4.2 m/km for the modern channel. Straightforward profile extrapolations that originally suggested separate assignments to the affected WR7 and (formerly) WR9 segments produce a vertical height difference between the two at Bull Lake Creek of nearly 40 m. The discrepancy between mapping and ash correlations has yet to be resolved. Elastic calculations using a floating place crustal model suggest the observed downstream terrace convergence is compatible with progressive regional tilting from uplift in the Yellowstone region. Flexure from differential basin erosion, also evaluated using an elastic plate model, does not contribute recognizable terrace deformation probably because of high crustal flexural rigidity.

Late Quaternary Deformation of the Southern Santa Cruz Mountains, California

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Remnants of six distinct Quaternary fluvial terraces are preserved along the Pajaro River where it crosses the San Andreas fault zone and the southern Santa Cruz Mountains between the southern Santa Clara Valley and the Watsonville Basin. The three lower terraces formed after the late Wisconsinan-Holocene rise in sea level. The three higher terraces developed on deformed sediments that contain the 400,000-year-old Rockland Ash; these terraces are correlated with sea level highstands represented by marine oxygen isotope stages 9 (320 ka), 7 (214 ka), and 5 (80-125 ka). The ages and relative elevations of the terraces across a transverse profile yield a uniform uplift rate of 0.3 mm/yr, consistent with the uplift rate derived from elevated marine terraces near Santa Cruz. Longitudinal profiles and laterally offset back edges of the terraces indicate an up-on-the-west vertical separation of 0.05 to 0.1 mm/yr for the Castro fault and right-lateral slip rates of about 14 to 15 mm/yr and 1.5 mm/yr for the San Andreas and Sargent faults, respectively.

These late Quaternary strain rates calibrate a crustal-scale kinematic model of the southern Santa Cruz Mountains developed by integrating surface geology with seismicity, gravity, and seismic refraction data. The model reveals a southwest-dipping, reverse-right oblique slip fault that intersects the San Andreas fault at a depth of about 8 km. The Sargent, Castro, and Carnadero faults are splays that root into this oblique-slip fault at depths of about 3 to 5 km. This model suggests that transpression across the plate margin is accommodated by oblique slip at depths greater than about 5 km that this oblique slip is partitioned in the shallow crust into nearly pure strike slip on the San Andreas and Sargent faults and nearly pure dip slip on the Carnadero fault. Reverse slip on this complex system of faults east of the San Andreas, and not movement on the San Andreas fault is responsible for uplift of the Pajaro River terraces.

Latitudinal Variation in Surface Uplift from Geodetic, Wave-cut Platform and Topographic data, Cascadia Margin

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We present latitudinal variations in net surface uplift for the Cascadia margin for two different time periods: geodetic surveys (last 70 years) and wave-cut platform deformation (average rate for last 80,000-125,000 years). We also present data on the magnitude of surface uplift of the Coast Ranges. The first two data sets represent uplift rates of rock relative to the geoid. The latter data set is an appproximation of net uplift of rock above sea level, minus the amount of rock eroded, during the last several million years. These data sets allow us to compare interseismic uplift with long term surface uplift, and long term surface uplift with spatial variables that may influence surface uplift, such as the age of the underlying subducted slab. The latitudinal variation in topography is derived from digital terrain data available in a 5' grid. The geodetic and topographic data span latitudes 40°-49°. Wave-cut platform data span latitudes 42°-45°. Geodetic data show the greatest amplitude in surface uplift rates, --0.25-4 mm/yr. Wave-cut platform uplift rates are for the most part < 0.25 mm/yr. Spikes in uplift rate occur at several localities along the Cascadia margin where a distinct structure - a fault or a fold - displaces the wave-cut platform. In a gross sense, the topographic trends mimic the marine terrace trends in uplift. For instance, topography and wave-cut platforms are relatively high from latitude 42°-43.4° and relatively low from latitude 43.4°-44.2°. The topographic and marine terrace data sets show differences both in the along-coast trend of values and in magnitude of uplift rate. At least for latitudes 43°-46°, the trend of the geodetic data is anticorrelated with the topographic and wave-cut platform data trend. In terms of interseismic strain accumulation in Cascadia, the contrasting magnitudes of surface uplift between the last 70 years and the last 100,000 years suggest strain is accumulating as transient surface uplift. Comparing latitudinal topographic trends to the age of the underlying subducted slab, the most distinctive change in average topography corresponds to a major change in the age of the underlying slab, implying magnitude of surface uplift may in part be controlled by contrasting bouyancy of the underlying subducted oceanic crust.

Compressive Origin of Topographic Waves in the Mojave Desert, California?

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Two pairs of broad topographic troughs and swells 200- to 250-km long formed adjacent to and along the big bend of the San Andreas fault in the Mojave Desert. On the California 1:750,000-scale geologic map the two WNW-striking, 45-km-wavelength troughs (Bristol-Danby and Lucerne-Dale troughs) appear as mostly Quaternary deposits, while the crests appear as mostly older bedrock units.

We propose that the topographic waves are regional neotectonic buckle folds induced by horizontal NNE compression of the Mojave block. Thrust and reverse faulting accentuates structural relief of the waves.

Previous neotectonic analyses of the Mojave desert have focused largely on sets of strike-slip faults that segment the Mojave block like a sliced loaf of bread. We contend that the buckled waves and oblique shear of these smaller slices both represent manifestations of the regional stress and strain regime in the Mojave block. The historic Palmdale bulge is even broader.

The 45-km wavelength may be controlled by thickness of a folded layer of granitic continental crust. The folded layer may be 7-10 km thick if analogy can be made to scale modeling of buckled oceanic lithosphere in the Indian Ocean (Bull et al., 1992, <u>Tectonics 11</u>, 537-548). This thickness matches that of the seismically active brittle upper crust in the Mojave block.

Separation of Isostatic and Neotectonic Signals Recorded in Bonneville Stage Shorelines

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Least squares linear regression (LSLR) was used to evaluate 22 load-simulating, averaged water depths at 181 Bonneville Stage shoreline sites. A flexually weighted "load" with a 130 km radius provided the best Airy-like relationship. The "raw" results, all 181 sites, contain both isostatic and neotectonic signals and yield: a paleo-lake level 1549.5 m, cor. coef. of 0.985, a slope of 3.10, and residuals of ± 3.44 m.

Most larger residuals are associated with: 1) a Northeastern Low (22 sites with -3 to -8 m) probably related to Snake River Plain, 2) a WSW trending residual high (40 sites with +8 m max.), 3) subsidence at volcanic Pavant Butte (-16 m, erupted just prior to Bonn. Stage), 4) up to 10 m of possible magmatic swelling at Cove Creek dome, and 5) about 6 + and - sites related to Wasatch fault zone.

Refinement of data into an isostatic component suggests a paleo-lake level of 1552.5 m, slope of 3.42, residuals of <± 1.3 m, and cor. coef. in the 0.9975 to 0.9983 range, depending on where certain boundaries are drawn. After refinement, it appears reasonable to suspect about 2 to 3 m of subsidence associated with sediment loading from the Sevier and Bear Rivers. Also, there appears to be a subtle 1.5 m difference between the sites in the northern main body of the lake and its shallower southern end. This difference may be inherent in the modeling technique or related to lithospheric or asthenospheric differences.

Interactive Terrane Visualizations, Stereoscopic Landsat, Statistical Fault Detection, and Strain Field Maps Derived from Topographic Information

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Here we describe four methods of using topographic information that we are developing and applying in our studies of the tectonics of the southwest United States.

- (1) Work is underway to network several supercomputers, controlled from a single workstation, in order to interactively enhance and explore Landsat imagery, seismic profiles, and topographic information as three-dimensional crustal blocks for the visualization of detachment fault terranes.
- (2) Through the use of digital elevation data, we have produced stereoscopic Landsat displays from single Landsat images. The result is a fully synergistic merger of the information provided by each data type, similar to stereo color aerial photographs, but with far superior lithologic discrimination.
- (3) With the increased availability of high resolution DTMs from the USGS and now from JPL's TOPSAR, we are working to refine a geomorphometric method of revealing obscure fault traces across broad alluvial terrains (Crippen, 1983, GSA Abs. with Progs., v. 15(5), p. 401). The method detects deviations from normal fluvial concavity by testing correlations of elevation versus local relief.
- (4) We expect to be able to map in comprehensive geographic detail the horizontal strain field of the Landers, California (28 June 1992) earthquake (M=7.4, maximum offsets > 6 m) with a precision of one meter or better using SPOT 10 m imagery. The method uses subresolution pattern matching (primarily of topographic shading) for images taken before and after the earthquake.

Afternoon Session:

Geodynamics Deduced from

Topography/Regional to Global Scales

Chairman: W. Bull

IN THE WAKE OF MOSES: CREATION OF SPREADING CENTER TOPOGRAPHY AT THE ASAL RIFT, DJIBOUTI, INFERRED FROM COMPARISON OF HISTORICAL AND LONG-TERM DEFORMATION

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 P. Briole, J.-C. Ruegg, and P. Tapponnier (Institut de Physique du Globe de Paris), and F. Gasse (Université de Paris-Sud).

The Asal rift provides the world's best subaerial analogue for young slow-spreading mid-ocean ridges. Seismic and geodetic observations of a 1978 seismo-volcanic crisis supply deformation associated with an individual event, and show that that dike inflation and fault slip

extended to <5 km depth. An extensively-dated 8-kyr-old Lake Asal shoreline has been downwarped 70 m, yielding the Holocene fault slip and broadscale deformation across the rift. The 1978 fault slip + Holocene slip rate gives a mean repeat time of 200-300 yr per fault, or 100-200 yr between tectonic events on groups of faults. Independent support for this repeat time comes from the 1978 rift opening + Quaternary spreading rate (~16 mm/yr), which gives ~150 yr. The rift topography furnishes a gage of long-term deformation that we infer to be 34±6 kyr old, using the Holocene deformation rate. Comparison of the vertical deformation on the 3 time-scales reveals that all faults within the rift valley dip steeply and display similar slip rates, irrespective of their distance from the rift axis. Observations of uniform fault throws on mid-ocean rifts have encouraged the hypothesis that faults form at the rift axis, slip until they are translated outside the 2-km-wide neovolcanic zone, and then become inactive. At Asal we instead find that faults throughout the 8-km-wide rift valley are active. Given its width and spreading rate, the mean age of rift valley basalts should be an order of magnitude older than the inferred age of the rift topography and limited radiometric dating. The net subsidence rate at the rift axis during the past 35 kyr is $\tilde{8}$ mm/yr, which could not be sustained for much longer periods without voluminous infilling by lavas. These findings suggest that the long-term vertical deformation of the rift is cyclic: Rifting takes place by steady, self-similar stretching with scant volcanic effusion, interrupted by episodes of rapid volcanic filling of the rift valley, which erase evidence of former faulting. Such an outpouring last took place at Asal about 35 kyr ago.



Rift Valley Shape Maintained as the Rift Thins, Accompanied by Modest Volcanism



Much of Rift Valley Rapidly Filled by Lava, Surface Evidence of Faulting Masked

Topography Driven by Mantle Convection -- From Regional to Global Scales.

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Mantle convection is an important control on topography through the viscous coupling of buoyancy forces to the Earth's surface. Rearrangement of mantle buoyancy forces will lead to active subsidence and uplift. It follows that any constraints which can be placed on the time evolution of topography (especially from stratigraphy) can be used to better understand the time evolution of mantle convection. Mantle convection can effect topography on scales from regional to global. These effects will be illustrated through finite element modeling of plates and convection.

At the largest global scales, horizontal temperature gradients can develop through continental insulation or through differential cooling of different ocean basins. For example, if heat is added under a supercontinent at the same rate heat is being lost from the mantle, then the overlaying supercontinent would have an uplift rate of ~ 5 to 10 m/Myr. A global pattern of dynamic topography with an amplitude of 500 meters to 1 km could be generated in about 100 Myr. The physical plausibility of insulation through a non-subducting continental plate (or raft) has been explored in fully dynamic models. Seismic tomography of the upper and lower mantle shows a dominance of low order structure (degrees 1-3). Global residual topography of the oceans have a strong degree two pattern with an amplitude of 500 to 1,000 m.

On a regional scale subducting slabs effect vertical motion. Constrained dynamic models of subduction zones have been set up wherein internal buoyancy forces have been imposed apriori in a finite element analysis of viscous flow. Time evolution is simulated by imposing a sequence of different slab configurations. Dynamic topography resulting from initiation of slab subduction at an ocean-continent margin causes the continental lithosphere to subside rapidly. As subduction continues and the slab shallows a basin depocenter and forebulge migrate in toward the continental interior. Finally, closure of the ocean basin leads to regional uplift. The dynamic subsidence rates (including sediment loading) associated with changing the characteristics of slabs can exceed 100 m/Myr.

Poster Session:

Evolving Border Fault Systems and Early Synrift Sedimentation: The Baikal Rift.

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K.D. Klitgord (U.S. Geological Survey, Woods Hole, MA 02543)

In the Ol'khon region of the Central Baikal Rift, splaying of the western border fault has generated several fault-parellel structural domains bounded to the west by the Primorskiy Fault. The Morskiy Fault forms the eastern edge of this splay, separating the Ol'khon region from the deep Central Baikal Basin. We have proposed that rift broadening is accomplished by the progressive westwards migration of the western border fault at the Baikal Rift. The migration transfers footwall units to hanging-wall domains, initiates fragmentation of hanging wall domains and modifies the locus of local Flexural response to extension. Relief in the Ol'khon region has not been significantly modified by glaciation and therefore directly reflects neotectonic processes which we have studied using combined field, Landsat TM and topographic data.

The Primorskiy Fault hanging-wall and footwall regions display various stages of dismemberment which are intimately linked to patterns of erosion, transport and deposition. The along-strike segmented character of both hanging-wall and footwall morphology has direct control on the location and nature of sediment dispersal. The Primorskiy Footwall elevation increases stepwise to the north with major transport through the Primorskiy Range localized at these steps. The Primorskiy Graben, along the base of the Primorskiy Fault, broadens to the north (from 1 to 7 km wide) and deepens in a stepwise Range. The Graben not only controls along-strike sediment transport throughout synrift sedimentation. Mass wasting occurs locally within Graben footwall regions where material is being transerred to the hanging wall. Major sediment traps occur at the overlap between main border faults and are migrating with fault propagation. Reactivation of steeply-dipping basement fabrics also restrict sediment dispersed. The Ol'khon region has fragmented into several fault bound domains with low but distinctively different relief. Shift in local flexural uplift of the Primorskiy and Morskiy footwalls in response to this fragmentation and local changes in surface tilt arise. Locally high standing regions may preserve a residual topography from earlier faulting or reflect present deformation partitioning within the hanging wall. The consistent inter relationships between sedimentation and neotectonics which we have documented suggest that it is possible to predict the next stages in synrift deposition patterns and their potential feedback on patterns of local flexure.

Rift Kinematics and Topography: Views from Afar

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The seismically and volcanically active Afar rift system marks the transition between oceanic and continental rifting above a mantle plume. The 300 km-wide Afar Depression is ideally suited for remote sensing studies of fault kinematics: There is little vegetation or soil cover; normal faults expose thick piles of datable volcanic flows, volcaniclastics, and fluvio-lacustrine sediments; and field studies indicate that topographic surfaces throughout much of the region represent bedding planes and fault scarps. Thus, bedding and fault kinematics can be determined directly from the high-resolution digital topography (90 m grid) and Landsat Thematic Mapper imagery (30 m resolution). We have used the digital topography, Landsat imagery calibrated by field observations, and results of K-Ar dating to study the kinematics of Quaternary extension in the Afar Depression. The results of field and remote sensing studies in southern Afar, where rates of extension are ~ 1 mm/yr (Asfaw et al., 1992) and central Afar, where geologically determined rates of extension are 5-10 mm/yr, are compared in light of recent seismicity to evaluate the spatial and temporal distribution of strain across the Afar Depression.

Inverse and forward models of short and intermediate wavelength topography and gravity data are used to estimate the plate strength and to predict topographic relief resulting from extension of a finite strength lithosphere. Both the fault kinematic and modelling studies indicate that extension/magmatism is distributed across a broad region, with extension accommodated both by faulting along the western boundary of Afar and along faults bounding narrow basins within the 300 km-wide Afar Depression. Further studies of topographic relief associated with the "soft" and broad plate boundary in Afar should improve our understanding of processes leading to the onset of true seafloor spreading.

Tectonics and Erosion: Topographic Evolution of Rift Flanks and Rifted Continental Margins

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 D J Harding (NASA/Goddard Space Flight Center, Greenbelt, MD, 20771; 301-286-4849)

The topography of the Earth's surface at any particular time represents the combined effects of tectonism on one hand, and erosion/depositional processes on the other. It therefore makes sense to study erosion in settings where we can estimate the tectonic component of the topography. Rift flanks and rifted continental margins are well-suited to the study of erosion processes for two reasons. First, the tectonic component of the topography, which results from the rifting process, can be predicted from simple geodynamic models. In a sense, the rift-related tectonic topography provides "initial conditions" from which the evolution of topography, primarily through erosional processes, can be studied. Second, many rifted continental margins around the world feature a conspicuous erosional escarpment which demarcates broad interior uplands, where local relief is subdued and erosion rates appear relatively low, from generally lower areas seaward of the escarpment showing much greater relief and apparently higher rates of erosion. The prominence of erosional escarpments in the geomorphology of rifted continental margins worldwide suggests to us that a common process of erosion has been active despite differences in climate, lithologies, and ages of rifting among those margins. We have analyzed high-resolution gridded topography data from eroding rifted margins by fractal methods to learn how erosion processes modify the wavelength components of the topography. We assume that we can use the spatially separated upland and coastal regions of rifted margins as a proxy for a time evolutionary sequence. We find that erosion systematically and significantly roughens components of the topography over the range in length scales considered in these analyses (typically, from about 500 m to 10 km). The most intriguing scientific insight stemming from the work thus far concerns the form and therefore the inferred behavior of erosional escarpments at rift flanks and passive continental margins. These escarpments exhibit two basic forms, depending on the direction of surface water flow in the upland region relative to the escarpment. Where flow is directed away from the escarpment (i.e., it is a drainage divide), the escarpment takes the form of subdued embayments and promontories, such that the overall trend of the escarpment remains fairly straight as it evolves with time. On the other hand, where streams from the upland flow across the escarpment, it takes the form of deeply-incised, elongated gorges whose heads appear to propagate up the drainage system of the upland surface.

Relationship Among Basin Formation, Upper Crustal Structures, and Isostasy: Examples From the Basin and Range Province

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At least three types of continental basins can be defined based on width, depth and nature of the bounding structures. They are: (1) deep (up to several km) rift basins bounded by steeply to moderately dipping normal faults, for example the modern Basin-Range basins; (2) elongate, narrow and shallow (<1 km) extensional basins that form in the hangingwalls of low-angle normal faults such as Duck Creek (Young, 1960) and Rattlesnake Spring basins, NV (Taylor, 1990); and (3) broad, mainly shallow successor basins formed along the front of a contractile orogenic belt (e.g., Claron Formation basin, SW UT). The smallness of

the narrow and shallow basins does not indicate insignificance, rather when compared with the other basin types, it suggests differences in lithospheric behavior associated with basin development.

New geodynamic models indicate that the style of upper crustal structures can be related not only to crustal thickness and strain rate, but also to Moho temperature and the function of the mantle in isostasy. Narrow, shallow basins form in concert with metamorphic core complex or detachment-style extension. In this case, the Moho temperature is relatively high, flow in the lower crust is rapid, and the mantle is not involved in isostasy. Isostatic balance is maintained by flow in the lower crust. Rift-type or deep Basin and Range basins form where the mantle is involved to some degree in isostatic compensation. The Moho temperature is high, but can be lower than during the formation of the metamorphic core complex type basins given the same initial crustal thickness and strain rate. The broad, shallow successor basins form where the crust has relaxed after deformation, the Moho has returned to an approximately equilibrium temperature, and the mantle is fully involved in isostatic compensation. The mantle-involved isostasy imposes a wavelength of >100 km on a basin.

A Late Quaternary Landscape Evolution-Red Sea Coast, Egypt

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Fieldwork, combined with analysis of Landsat thematic mapper data and samples, shows several coral reef terraces exposed along the Red Sea Coast that are interbedded with fluvial deposits from the late Proterozoic rocks in the Red Sea Hills. Marine terraces associated with the coral deposits can be traced to a series of fluvial terraces that extend to the Red Sea Hills. A major coral terrace between Quesir and Marsa Alam is interpreted to correspond to the 124 Ka SL high stand, when SL is interpreted from Barbados and New Guinea data to be ~6 m above the current value. Further, this major marine terrace correlates with a prominent fluvial terrace found in each of the half dozen wadis examined in detail. The terrace is typically 10 m above the current wadi floor levels and probably formed by: (1) accumulation of alluvium in the wadi valleys during the 124 Ka high stand, including progradation of fluvial deposits over the coral reef, and (2) dissection of the deposits to the current wadi floor elevation during subsequent low stands as streams attempted to adjust to lower base levels. Detailed topographic mapping is being pursued using GPS and SPOT stereo data. When combined with new U-Th disequilibrium dating of coral samples, the rate of uplift and erosion and the timescale for landform evolution will be derived.

Controls on Erosional Retreat of the Uplifted Rift Flanks at the Gulf of Suez and Red Sea

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The Gulf of Suez and Red Sea rifts are presently bordered by large asymmetric flanking uplifts that have been denuded by scarp retreat. Prior to rifting the Gulf of Suez was a shallow marine platform and the Red Sea was a low relief peneplane. Thus all of the tectonic uplift that generated the 1-1.5 km high rift flanks is the result of extension. Along most of the Red Sea, the sedimentary cover has been stripped off resulting in broad exposure of the basement along the rift. At the Gulf of Suez, the prerift sediments form a southward thinning coastal plain wedge. The section thins from over 2000 m at the northern end of the rift to less than 400 m at its junction with the Red Sea. The strata are composed of cliffforming Eocene-Cretaceous carbonates overlying the easily eroded Cretacous-Cambrian "Nubian" sandstone. At the northern part of the Gulf of Suez where the Nubian sandstone is not exposed, the carbonates form a scarp at the rift border fault. Further south, undercutting of the carbonates has resulted in scarp retreat at a rate inversely proportional to the sedimentary thicknesses. At the southernmost Gulf of Suez, the scarp is located ~100 km inland from the border fault. Fission-track analyses of basement samples indicate that uplift commenced synchronously with the beginning of the main phase of extension at ~20 Ma. Thus scarp retreat has progressed at rates of up to 5 km/Ma. The basement exposure along the border fault forms a rugged terrain dissected by wadis that the fission-track data shows has been increasingly eroded to the south. Although there is considerable local scatter, the basement samples show an overall increase in exhumation from just below the sediment-basement interface to the north to over 5 km to the south.

The Dynamics of oceanic trenches and slabs studied with a finite element model of viscous flow with a fault.

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Dynamic topography driven by mantle buoyancy forces is strongly influenced by vertical and horizontal variations in viscosity and by faults at plate boundaries. We are now developing an Eulerian finite element model of thermal convection with faults which are treated as free interfaces. We have now utilized this new approach in "constrained" dynamic models: buoyancy forces have been added to the interior of the system and internal flow and total surface stress have been computed. Gravity and geoid anomalies, made up of a sum of boundary deflections and internal mass anomalies, are also computed. The models are intended to simulate a single oceanic plate and attached slab at a single instant in time. When ever a fault is present in models with a high viscosity lithosphere, a well developed high amplitude but narrow depression forms sea-ward of the fault -- almost identical in shape to observed oceanic trenches. Without a fault, the dynamic depression is simply distributed over a broad zone more than a 1,000 km across. With faults, there is still a broad dynamic depression over the back arc region but an amplitude reduced by about 30% from cases without faults. For a 100 Ma oceanic plate subducting at 45°, the trench is about 4 km deep (with a water load) and about 150 km wide. Trench depth increases with both plate age and the length of the slab, but decreases with the angle of subduction. Trench depth increases with increasing horizontal viscosity contrast between the slab and mantle. Modeled trenches are associated with short wavelength free-air and geoid lows. With a model with a high viscosity lower mantle ($\eta_{LM}/\eta_{UM} = 100$), we can explain all relevant topography and gravity signatures in the subduction environment: trench topography (~4 km), depression of the back-arc region (~1km), free-air anomalies over trenches (-200 mgals), geoid lows over trenches (-10 m), and long wavelength geoid highs over slabs (~30 m over a 10^4 km scale). These signals are close to observed signals in the Western Pacific.

Evening Session:

Topographic Database: Availability and

Acquisition

Chairman: D. Harding

Digital Topographic Data: Availability and Acquisition

D J Harding (NASA/Goddard Space Flight Center, Code 921, Greenbelt, MD 20771; ph. 301-286-4849; fax. 301-286-1616; Internet harding@denali.gsfc.nasa.gov)

Analysis of the relationships between tectonic processes and topography is often hindered by limited access to digital topographic data of sufficient resolution and accuracy. In this session, ten oral papers will be presented that describe the current state of digital topography data sets, and advanced methods for acquisition of improved topographic data. The availability, on a global basis, of public-domain digital topographic data will be described, and prospects for public release of classified holdings, such as Digital Terrain Elevation Data produced by the Defense Mapping Agency, will be considered. The capabilities and performance of methods for acquisition of improved topographic data will be evaluated, including satellite radar altimetry, aircraft laser altimetry, interferometric synthetic aperture radar, and automated photogrammetry via correlation of digital stereoscopic images. Operational versions of these techniques are currently being used to obtain local to regional scale topographic data of high accuracy. Examples of application of several of these techniques to global planetary mapping will also be discussed, including the nearly complete topographic mapping of Venus by Magellan radar altimetry and SAR stereoscopy, and the upcoming mission of Mars Observer which will provide global Martian topography by 1995 via laser altimetry. Ironically, these planetary missions are providing knowledge of the topography of Venus and Mars that, on a global basis, exceeds our knowledge of the Earth's topography. Plans for acquisition of improved global topography for the Earth's land surfaces and ice sheets will be described, including stereoscopic imaging sensors and altimeters aboard the Earth Observing System, and prospects for a dedicated Earth Probe Global Topography Mission under study by

Friday, September 4, 1992

Morning Session:

Rates and Magnitude of Uplift and

Exhumation

Chairman: D. Merritts

Erosion Rates in Contractional Orogens

M T Brandon (Department of Geology and Geophysics, Yale University, P.O. Box 6666, New Haven CT 06511; 203-432-3135; Internet: Brandon%Geoxrd@Venus.YCC.Yale.edu) Regional-scale erosion represents an important and poorly understood process affecting contractional orogens. Metamorphic and geochronologic data can be used to determine the amount of denudation that has occurred in an ancient mountain belt or subduction complex, but these data usually cannot distinguish the mode of denudation, whether by erosion or by tectonic processes such as extensional faulting. The relative contribution of erosion must be determined by other independent means.

One method is to use measured modern rates. However, average modern rates have been shown to vary as a function of the time scale and length scale used for the measurement, with rates decreasing for longer time and length scales (e.g., Gardner and others, 1987). This problem may be the result of biases associated with sampling a lognormal distribution. Scaling relationships should be used if data from different types of studies are to be compared.

The sedimentary fill in a foreland basin provides a minimum estimate of the amount of erosional denudation in the adjacent orogenic highland, but, as noted by England (1981), a foreland basin has a relatively limited capacity. For instance, England (1981) estimates that >50% of the denuded overburden from the Alps was transported into deep marine basins in the Mediterranean.

Various arguments have been made for higher rates of erosion during the Late Cenozoic in association with global cooling and continental glaciation. Supporting evidence includes a marked increase in the flux of continent-derived sediment into the deep oceans and an increase in radiogenic Sr in seawater over the last 15 Myr. However, much of the increased sediment flux could be due to cannibalization during sealevel low stands of sediments stored in low elevation continental basins. Furthermore, there is no direct link between seawater Sr and physical denudation, as indicated by the lack of correlation between chemical and physical denudation rates determined from sediment load data from the major rivers of the world.

The global compilation of Pinet and Souriau (1988) clearly show that in active orogenic belts, the average rate of physical

denudation is primarily a function of mean elevation above an erosional baseline. Climatic factors such as mean temperature and annual precipitation are not important factors. This study, along with others, support the diffusion model for erosion and sediment transport at a regional scale. This type of model implies that average surface slope or average local relief probably would represent a more useful independent variable in the study of regional-scale physical denudation using sediment load data.

The Appalachian Piedmont as an Active Planation Surface: Model and Methods of Comparing Erosion and Uplift

M J Pavich (U.S. Geological Survey, Reston, VA 22092; 703-648-6963)

The planation surface or peneplain is still a prevalent concept in geomorphic thought. Large areas of the terrestrial surface are low relief, erosional systems that fi: the concept of a planation surface. These surfaces often cut diverse parent lithologies, dominantly meta-sedimentary, Igneous bodies, such as massive granites, often form monadnocks or inselbergs above these surfaces.

Measurements of rates of regolith production and erosion on the Appalachian Piedmont, the "type section" of the Davisian peneplain illustrate that the Piedmont upland regolith is a dynamic, not static system over the time scale of post-orogenic uplift (e.g. the past 70 Ma).

Study of baseflow dissolved solids draining Piedmont basins indicates a minimum rate of saprolite production of about 4 m Ma⁻¹. This minimum rate or production near the Fall Line is less than the estimated rate of surface lowering and saprolite consumption during the late Tertiary and Quaternary periods of topographic inversion. Measurement of cosmogenic ¹⁹Be inventories in two 15-20 m cores of Piedmont upland regolith indicate a minimum residence time of residual soil and saprolite of about 1 Ma. This indicates a possible maximum rate of saprolite production and erosion of about 20 m Ma⁻¹.

Using the best available evidence, therefore, the typical Piedmont upland regolith has a residence time of between 1 and 5 Ma. Residence times may not be the same everywhere and ages may vary systematically across the surface. The geomorphic evidence of topographic inversion, and similar regolith profiles in other humid temperate and tropical regions, strongly suggests that production and removal of Piedmont saprolite has been an ongoing Quaternary process and that most of the Piedmont regolith is significantly younger than 5 Ma.

Independent geophysical evidence suggests that the rate of uplift, probably involving tilting, of parts of the Piedmont, Blue Ridge, and Valley and Ridge has averaged between 5 and 20 m Ma⁻¹ through the Cenozoic. Fission track and paleontological data suggest that the Piedmont and Coastal Plain are part of a larger monoclinal "tilt" plane with increasing rates of uplift and subsidence away from the "fulcrum" of the Fall Zone contact between crystalline basement and sedimentary cover. These data provide a model of geomorphic evolution that can be tested by a varied of methods: K/Ar, Fission Track, and coamogenic isotopes.

Poster Session:

Surface Uplift of the Finisterre Mountains, Papua New Guinea

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A full understanding of the dynamics of mountain building requires measurement of the rate at which the topographic surfaces of mountain belts rise. A quantitative knowledge of surface uplift rate provides insights into processes of lithospheric dynamics and the relative effects of uplift versus erosion in shaping mountain topography. Most studies of mountain uplift employ geodetic measurementss, dating of uplifted marine terraces, or thermobarometry on exhumed crustal rocks. England and Molnar recently noted that none of these techniques measures the true rate of surface uplift on the scale of an entire mountain range.

The Finisterre Mountains of northern Papua New Guinea are a plateau capped by Miocene-Pleistocene limestone that provides a unique opportunity to calculate the rate of surface uplift. The range has been built in the last 3 My by collision of the Australian continent and the Bismarck volcanic arc. The limestone crops out in numerous 200-1000 m high cliffs at elevations up to 4000 m. During the fall of 1992 we will collect data to document the uplift rate of several cliff sections. Total uplift will be derived from present elevation and initial depth data from benthic foraminifera. Age data will be derived from planktonic foraminifera, nannoplankton, and Sr isotope stratigraphy. Our uplift data will extend over an area of approximately 6x103 km², large enough to calculate a surface uplift rate, sensu England and Molnar.

The removal of mass by erosion leads to isostatic compensation that can drive uplift, even in the absence of tectonic forcing. The plateau of the Finisterre Range has been incised by several major, amphitheatre-headed canyons, which represent the only substantial areas of erosion on the north flank of the range. This geometry makes it an easy matter to calculate the missing volume and mass. Modelling of the isostatic response to such a negative load, assuming a reasonable range of crustal thicknesses and flexural rigidities, will allow us to estimate the amount of uplift that is driven by erosion rather than tectonics.

Use of In Situ Produced Cosmogenic Isotopes to Determine Rates of Geomorphic Processes

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The abundance of in situ produced "cosmogenic" isotopes can be used, in specific geologic situations, to constrain the rate of geomorphic processes. Cosmogenic isotopes, including ¹⁰Be, ²⁶Al, ³⁶Cl, and ²¹Ne, are produced predominately by cosmic-ray interactions in the uppermost meter of soil and rock. Their abundance, once geologic and radiogenic backgrounds have been considered, reflects the integrated cosmicray dose as determined by exposure time and/or erosion rate.

Lal¹ presents simple models that can be used to interpret isotope abundances measured in samples collected from bedrock surfaces. In exceptional circumstances, where preservation of an original surface can be demonstrated, iso-

tope abundance can be used to calculate exposure ages. However, in most geologic situations, interpretive models provide only minimum ages and maximum erosion rates.

Recently, we have developed a model for interpreting the abundance of cosmogenic isotopes measured in fluvial sediments. In specific geomorphic terrains, this interpretive model can be used to estimate basin-scale erosion rates from measured isotope abundances.

In order to illustrate the potential and limitations of cosmogenic isotope measurements, I present measurements made on both rock and sediment samples collected from granite landforms in the southern United States. These measurements suggest that some landscape elements are eroding slowly, < 5m/My.

¹Lal, D. (1991) EPSL <u>104</u>, 424-439.

Stream Power Dependent Erosion of Bedrock Channels: Field Observations and Model Results

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River incision into bedrock generates valleys in mountainous landscapes, hence it is a key process linking landscape evolution with tectonics and climate change. We combine field observations with modelling results to provide a new understanding of the processes causing river incision into bedrock in mountainous terrain. Field observations suggest that both vertical wearing of the channel bed due to stream flow, by such processes as abrasion by transported particles and dissolution, and step-wise lowering caused by knickpoint propagation, play a role in Hawaiian channel downcutting. Surface exposure dating analyses in progress may provide further evidence of the relative role abrasion and knickpoint propagation play in channel incision. Germane results will be presented at the conference.

Topographic map analyses of rivers incised into well-dated Hawaiian lava flows show that long term average erosion along certain reaches is linearly related to stream power. However, modelling results indicate that application of a simple stream power dependent erosion law, in combination with varying boundary conditions, is insufficient to predict the propagation of knickpoints. Consequently, application of a single erosion law to the entire bedrock channel network may be inappropriate.

An Experimental Field Study of Chemical Weathering Rates

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Chemical weathering transfers CO₂ from the atmosphere to limestone on the sea floor on a geologic time scale, and therefore may play an important role in global climate change. To date, carbon cycle models have used very simple, untested characterizations of the controls on chemical weathering. To remedy this situation a series of catchment-scale sprinkler experiments were performed to determine empirically a "chemical erosion law". An 860 m² hillslope hollow in the Coast Range of Oregon was instrumented with 200+ piezometers and 100+ tensiometers for hydrologic modeling and 33 soil solution samplers for geochemical modeling. Water was also collected from two weirs on the site.

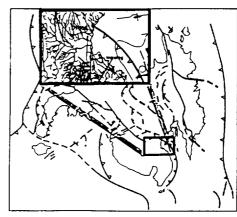
Steady rainfall applied with sprinklers to the hollow yielded quasisteady runoff and solute production. The steady conditions of the sprinkling experiments allow straight-forward characterization of the hydrology, and hence the weathering rates as a function of water flux. Solute concentrations decrease with increasing discharge. However, as water discharge dominates solute flux calculations, the mass loss in solution increases with discharge. Water emerging from the soil has lower solute concentrations than water from the weathered bedrock. Thus solute flux also depends strongly on the details of the water flow paths operating during a storm.

In addition to simulated rainfall studies, we are analyzing the temporally integrated weathering record found in the greywacke sandstone bedrock itself. Samples from a 35 m core and two soil pits have been analyzed for physical and chemical composition. By assuming that Zr and Ti are immobile during chemical weathering, we calculate physical strain and chemical losses accompanying the weathering process. Comparison of the calculated elemental losses in the weathered rock with the water chemistry observations will test the reliability of each of these methods, one spatially averaged, one temporally averaged, as indicators of chemical weathering rates.

Morphological Signature of Arc/Continent Collision: Geometric Application to Kinematics of Deformation

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Mindanao (southern Philippines) is the present loci of late Pliocene, Pleistocene and active arc/continent collision. However, most of the island is covered with Quaternary volcaniclastic aprons and alluvium. Topography and range geometry were carefully studied and compared with drainage patterns and anomalies that were used to correlate distant seismic lines. After integrating radar, SPOT, and Landsat MSS data, the tectonic pattern inferred from this study, after being checked in the field where pre-Pleistocene formations crop out, was compared with the deformation pattern observed offshore from geophysical and seismotectonic data. The interpretation integrates extentional areas within the fold-and thrust collisional belt, which are pull apart basins along strike-slip faults or piggy-back basin rotation voids. These features reflect the global geometry of the entire Philippine archipelago which shows wrench and collision fronts where the arc faces continental blocks



and subductional reentrants between the blocks. These observations were plotted on a neotectonic man which highlights the relative importance of the faults. This neotectonic map serves as a supporting document for natural hazards studies which are of primary importance in such areas.

Geomorphological Response to Tectonic Uplift in Fold-Thrust Belts

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Preliminary work will be presented on the response of fluvial systems to tectonic uplift from the frontal part of the Himalayan fold-thrust belt.

A major alluvial fan occurs in the Dehra Doon valley, Uttar Pradesh, northern India, adjacent to the very distinctive mountain front of the Main Boundary Thrust. Present day drainage arising from the mountain front is deeply incised into the fan surface and a series of cut-and-fill terraces are preserved on the valley sides. Such terraces represent former elevations of the active channel which indicates that the mountain front drainage has downcut through the fan deposits and into the underlying bedrock. Incision is probably a response to tectonic tilting and uplift. The existence of several levels of terraces suggests that tectonically-induced downcutting occurred in several phases punctuated by episodes of fluvial aggradation.

This poster explores the consequences of tectonic uplift on the incision history of mountain front drainage.

An ancient example of incised valleys developed ahead of basement thrusts from the upper Eocene of the South West Alpine Foreland Basin will also be presented.

Afternoon Session:

Kinematics Deduced from Topography

Chairman: K. Furlong

Poster Session:

Uplift of the Southern Santa Cruz Mountains Deduced From Fission Track Dating and Geomorphic Analyses

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The Santa Cruz Mountains (SCM) are closely associated with a restraining left bend of the San Andreas Fault (SAF). Especially since the 1989 Loma Prieta earthquake, attention has focused on the seismotectonics of the area and the relationship between youthful uplift and seismically active structures. A comparison of the coseismic uplift pattern during the Loma Prieta earthquake with marine terrace elevations and the topography of the northern SCM suggests that the uplift southwest of the SAF may be caused by Loma Prieta-type events. In contrast, Loma Prieta, the highest mountain in the SCM and located northeast of the SAF, was down-dropped in the Loma Prieta earthquake by about 15 cm. Clearly other structures, such as underlying reverse faults of the Lomita-Sargent-Berrocal fault zones (including the Soda Spring, Sierra Azul, and Shannon faults) must be active to explain the high uplift rates inferred from the youthful geomorphology of the southern SCM and its high topography.

Samples from an east-west transect across the Loma Prieta area yield -4 Ma apatite fission track ages. These ages give the time since cooling below about 110 °C, suggesting that uplift rates northeast of the SAF around Loma Prieta mountain have been on the order of 0.8 mm/yr (samples from southwest of the fault have much older ages--unrelated to recent SAF tectonics). By combining these data points with morphometric analyses of the youthful topography of the area, we will further determine the extent and distribution of uplift. Regional residual maps (contour map of ridge crest elevations minus stream elevations) indicate zones of high incision rates that, accounting for differential climate and rock type, reflect high uplift-rate zones. Detailed drainage network maps and longitudinal river profiles allow us to further evaluate the uplift pattern and the activity of the faults that cause the rise of the mountains. Whereas the region to the southwest of the SAF is characterized by a broad upwarp and folding (with uplift rates about 0.1 - 0.4 mm/yr), the southern SCM (northeast of the SAF) are dominated by deeply rooted, active reverse and obliquely slipping faults forming a well defined, wedge-shaped uplift zone (rising at about 0.8 mm/yr). The asymmetry in the deformation is related to the different lithology of the fault-bounding blocks, the existence of preexisting structures, and interaction with neighboring faults of the SAF system.

Application of High Resolution Topography to the Kinematics of Fold-and-Thrust Belts.

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The transpressional fold-and-thrust belt in the Temblor Range of California and the subduction-related fold-and-thrust belt of the central Andes provide ideal settings for the application of high accuracy and resolution topographic data to neotectonic studies. In the Temblor Range, strain accumulating due to oblique convergence between the North American-Pacific plates is presently accommodated in part along this active fold-and-thrust belt. Slip between the two plates occurs along a broad zone of deformation and is locally partitioned into both transcurrent and

compressive displacements; however, the overall mechanics of the active fold-and-thrust belt are poorly known. In the central Andes, an active fold-and-thrust belt is forming due to the convergence between the Nazca and South American plates, however, the transfer of slip across the belt and the role of specific faults and kinematics remain poorly understood. In both regions, neotectonic processes have well defined topographic expressions. High accuracy and resolution topographic data can be inverted to yield important constraints on neotectonic processes related to convergence. Topographic data is particularly important for investigating fault geometry and determining uplift and shortening rates in remote parts of the central Andes.

We are beginning to use high resolution topographic data coupled with high resolution imagery to address the neotectonic and kinematic development of active fold-and-thrust belts. These studies will (1) provide constraints on the kinematic development and overall mechanics of tectonically active compressional mountain belts; (2) constrain the geometry of active faults; (3) provide independent slip rate estimates, for comparison with geodetic estimates and models.

An overview of the experiment objectives and design, together with initial topographic results from the Temblor Ranges and San Gabriel Mountains, California will be presented.

Strength and Stress of the Lithosphere from Gravity and Topography, With Focus on the Yellowstone Hotspot

A R Lowry and R B Smith (Department of Geology and Geophysics, University of Utah, Salt Lake City, UT 84112)

Analyses of the relationship between topography and gravity are commonly used to determine the flexural response of the lithosphere, characterized by the effective elastic thickness T_e. One methodology involves modeling the isostatic response to a well-constrained loading process, but use of this approach is limited to areas where such processes are known to occur. Signal processing techniques can be applied to most gravity/topography data sets but require spatial averaging within windows of dimension 400 to 1000+ km, precluding their use for assessment of tectonic features of smaller scale than the window width. We have developed a method for the analysis of coherency of topography and Bouguer gravity using a maximum entropy spectral estimation technique, allowing estimation of T_c at scales of resolution of ~200 km. Use of this method in the northeast Basin-Range and Yellowstone-Snake River Plain regions indicates a minimum T_c of 1.5 km over the volcanically active Yellowstone caldera and maximum 60 km over the stable Middle Rocky Mountains. Given the state of stress in regions of extensional tectonism, i.e. $\sigma_v > \sigma_{hmax} > \sigma_{hmin}$, a directional anisotropy is predicted with T_e largest in the direction of σ_{hmax} . Previous investigators noted such an anisotropy in the Basin-Range but attributed it to local compensation on faults extending through the brittle portion of the lithosphere. However, directional determinations of T_c in areas for which $\sigma_v > \sigma_{hmax} > \sigma_{hmin}$ exhibit the expected relationship between anisotropy and principal stress direction whether or not there is associated normal faulting (e.g., the Basin-Range and Colorado Plateau, respectively). Lateral variations in T_e offer additional insights into the relationships of various tectonic regimes. For example, the >2000 Ma Archean Wyoming craton is characterized by 20-60 km T_c abutting the <6 km T. northeast Basin-Range. The Yellowstone hotspot appears to have thermally eroded the older, colder cratonic lithosphere from beneath as evidenced by an indentation of small T_e (< 2 km) to the Precambriancored Beartooth Range. Hence the arrival of the hotspot at the edge of the craton might be expected to coincide with a slowing of the northeastward migration of silicic volcanic centers while the hotspot heats and melts the cold cratonic lithosphere. This concept is supported by the current location of the mantle plume as much as 80 km in advance of the center of the 0.6 Ma Yellowstone caldera, as inferred from long wavelength topography and geoid anomaly data.

Kinematics of Arc-Continent Collision in the Eastern Central Range of Taiwan Inferred From Geomorphic Analysis

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Quantitative analysis of morphologic variations along the eastern margin of the Central Range of Taiwan and geomorphic analysis of river terrace profiles provide two dimensions of insight into the kinematics of an active arc-continent collision. We have developed new methods to obtain rigorous and robust maximum likelihood estimates of boundaries between distinct geomorphic domains of more-or-less uniform landscape character along the mountain front. The technique uses independent interpretations of different mountain-front characteristics, such as sinuosity and drainage density, to identify domains. Three to five geomorphic domains are consistently defined by a variety of parameters, and domain boundaries are unrelated to lithology. To the extent that the geomorphic domains reflect differences in the rate and/or style of tectonic driving force (as is commonly assumed), frontal uplift rates are spatially discontinuous. There is no clear progression in uplift age or rate along the front suggested by the different frontal parameters used.

Stream long profiles and terrace tread and strath profiles provide information on uplift history in the interior of the range. In most cases, terrace treads and straths of probable Holocene age diverge upstream from the modern river channel. These profiles are consistent with uplift rate increasing away from the mountain front. Uplift along a major range-bounding fault is not consistent with the stream and terrace data.

Distribution of Geologic Slip Along Faults in the San Francisco Bay and Santa Maria Basin Regions

W.R. Lettis and K.I. Kelson (Both at: William Lettis & Associates, 1000 Broadway, Suite 612, Oakland, CA 94607)

Slip rate data on faults in the San Francisco Bay area and the Santa Maria Basin are compiled to compare observed rates of geologic deformation with those predicted from plate motion studies, geodetic data, and structural modeling. In the San Francisco Bay region, we resolve available geologic slip rate data into components parallel and perpendicular to predicted motion between the Pacific plate and Sierra Nevada block. We select four paths across the Bay region between the Farallon Islands and Stockton, and sum resolved components of slip along each of the paths. This analysis shows that cumulative long-term deformation parallel to plate motion for all of the paths ranges from about 40 to 43 mm/yr, which is comparable to the predicted rate of plate motion of 39 \pm 2 mm/yr along N30°W \pm 2°. Calculated geologic discrepancy vectors range from 2 to 6 mm/yr, generally perpendicular to the predicted plate motion direction (N60°E). In the Santa Maria Basin, we use uplift rates determined from elevated marine terraces to estimate fault slip rates. The basin consists of a series of northwest-trending ranges and intervening valleys. Ranges are uplifting at rates of 0.1 to 0.2 Within the San Luis Range, uplift is occuring along northwest-trending reverse faults, which is consistent with northeastdirected crustal shortening reflected by geodetic data and structural modeling. An important result from these two regions is that very low rates of convergence can produce significant topographic expression. In both study areas, convergence, uplift, and topographic expression appear to be largely a result of localized fault kinematic processes (restraining fault bends or stepovers, reverse faulting), rather than regional plate convergence.

- A 12,000-year Record of Vertical Deformation Across the Yellowstone (Wyoming) Caldera Margin
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- G A Meyer (Dept of Geology, University of New Mexico, Albuquerque, NM 87131; 505-277-5261)

The 600 ka Yellowstone caldera shows several signs of unrest, the most evident of which is historic ground deformation. We document the spatial and temporal variability in calderarelated deformation across the ca. 12,000 yr since deglaciation by surveying, correlating, and dating the raised shorelines of Yellowstone Lake.

Correlatable remnants of about twelve terraces are preserved around the lake. Elevations of the five most continuous terraces clearly show deformation patterns. Each terrace is interpreted as representing an episode of uplift (ca. 1 per ka) of the caldera interior and subsequent subsidence, with little net volume change. This cyclic behavior may result from magma emplacement and subsequent withdrawal or cooling and crystallization, and/or episodic trapping and release of magmatic fluids.

Early postglacial movement was relatively down toward the caldera axis, possibly reflecting cooling, loss of trapped fluids, and/or glacioisostatic compensation. Net deformation over the past 5000 yr has been dominantly up within the caldera interior and slightly down along the rim. This is similar to and perhaps dominated by the effects of historic inflation. Subtraction of the inferred volume of this episode suggests net subsidence, perhaps as a result of regional extension and long-term cooling of the Yellowstone caldera.

The Yellowstone Hotspot: Topographic Signature, Structural Evolution, and Regional Geophysics

Smith, R.B. and A. R. Lowry, Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah, 84112 Quaternary caldera-forming volcanism, high rates of crustal deformation, high heat flow and widespread earthquakes reflect the contemporary dynamics of the Yellowstone Plateau, now the active element of the Yellowstone hotspot. Yellowstone also coincides with a 400 km-wide topographic bulge that rises an average of more than 300 m above the surrounding terrain that is thought to be related to thermal buoyancy of the lithosphere. In contrast, the track of the hotspot, the bimodal rhyolitic-basaltic Snake River Plain (SRP) shows a progression of silicic volcanic centers decreasing in age by -4 cm/yr northeasterly to Yellowstone commensurate with southwesterly intraplate motion of the North American plate, computed at 4.5 cm/yr. A systematic topographic decrease of 800 m extends southwesterly for 700 km along the SRP depression and fits the decay curve for the instantaneous passage of a crustal heat source. Also, the drainage basin of the Snake River represents a 500+ km-wide depression that encompasses the SRP volcanic system and a surrounding subsidence shoulder that we believe reflects lateral flexure into the SRP. The aseismic SRP is surrounded by a shaped pattern of moderate to large earthquakes, M_s ≤ 7.5, with a vertex at Yellowstone a extending SW like a bow wave and similar shaped zones of Quaternary normal faulting adjacent to the SRP that lack significant Holocene faulting. The crustal seismic velocity model for the YSRP is characterized by a high velocity mid-crustal core and a silicic uppermost crust overlain by surficial deposits of mantle-derived basaltic magmas. These systematic variations of topography and crustal properties are consistent with such mechanisms as thermal contraction resulting from lithospheric cooling, removal of roof support due to explosive volcanism, and flexure and strengthening of the crust associated with emplacement of a stiff and dense mafic layer. Intraplate tectonic reconstructions to ~25 Ma place the projected location of the Yellowstone hotspot coincident with the Mendocino triple junction at the edge of the North American plate, 200 km further SW than the oldest mapped silicic centers. This suggest an 900 km-long track for the Yellowstone hotspot that has influenced a much greater area of the western U.S. than previously thought.

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