Integration of digital elevation models and satellite images to investigate geological processes

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Introduction

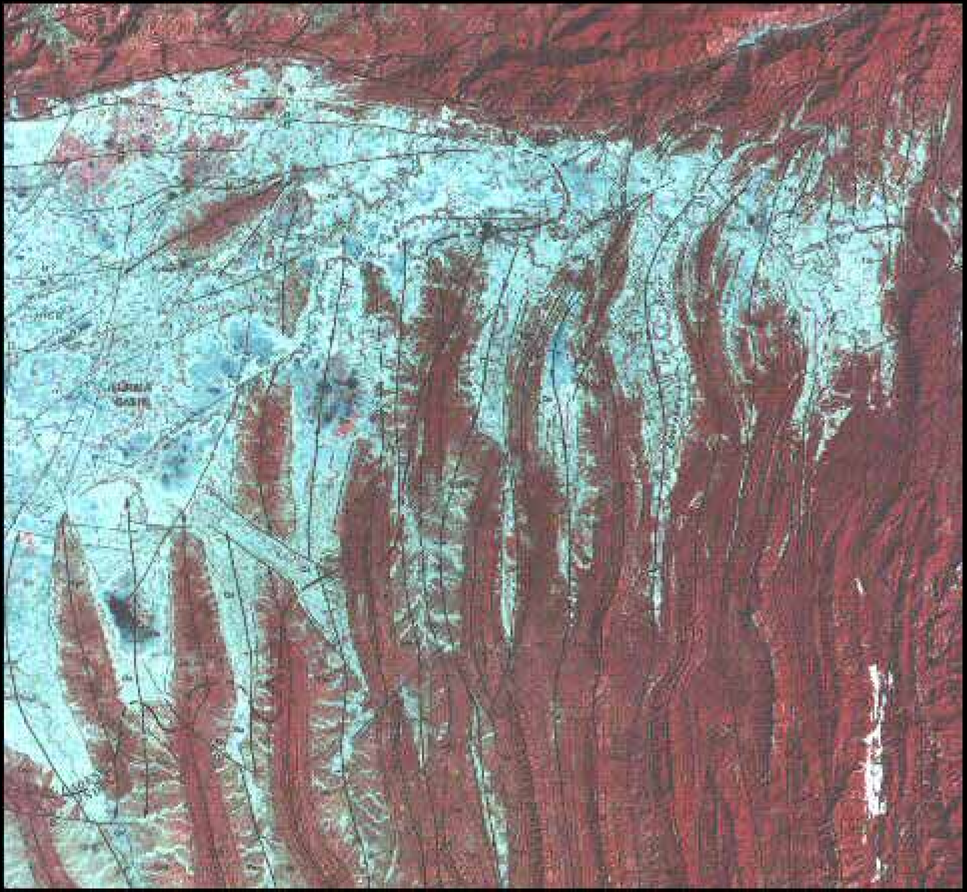
In order to better understand the geological boundary conditions for ongoing or past surface processes we face two important questions:

- How can we gain additional knowledge about geological processes by analyzing digital elevation models (DEM) and satellite images?
- Do these efforts present a viable approach for more efficient research?

- Classical geological approaches
- Case studies at a variety of scales and levels of resolution
  - Anticline geometry in the Western Escarpment of Northern Chile
  - Drainage patterns in the Coastal Cordillera of Southern Chile
  - Precipitation patterns derived from passive microwave data in the Himalayas
  - Volumes of landslides in the Swiss Alps
- Outlook: Quantification of geological processes with remote sensing techniques

Classical geological approaches 1

Lineament mapping (including simple pattern recognition)



Folds and faults of part of the Burma fold belt interpreted from a Landsat TM false color composite.

Classical geological approaches 2

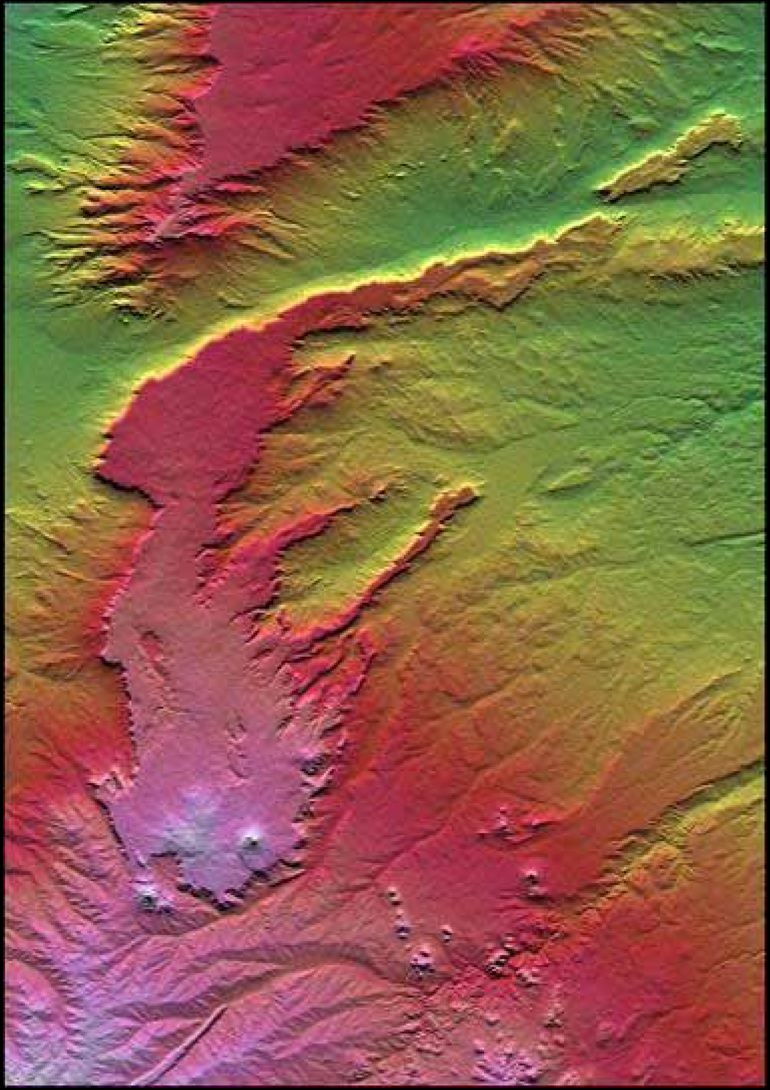
Geological unit mapping (based on visible contrasts)

This 10.5 by 11 km area in northern Chile was acquired by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on April 7, 2000. Dramatically displayed is a geological angular unconformity: a contact between layers of rock at different angles. On the right side of the image, Cretaceous sediments (146 to 65 million years old) were tilted upward to an angle of about 50 degrees, then eroded. On this surface volcanic pyroclastic deposits (rock composed of loose or fragmental material ejected from a volcano) were laid down as a flat sheet. The section of rocks has been eroding from the east, exposing the tilted and flat rock layers.

Credit
Image courtesy NASA/GSFC/MITI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team

Classical geological approaches 3

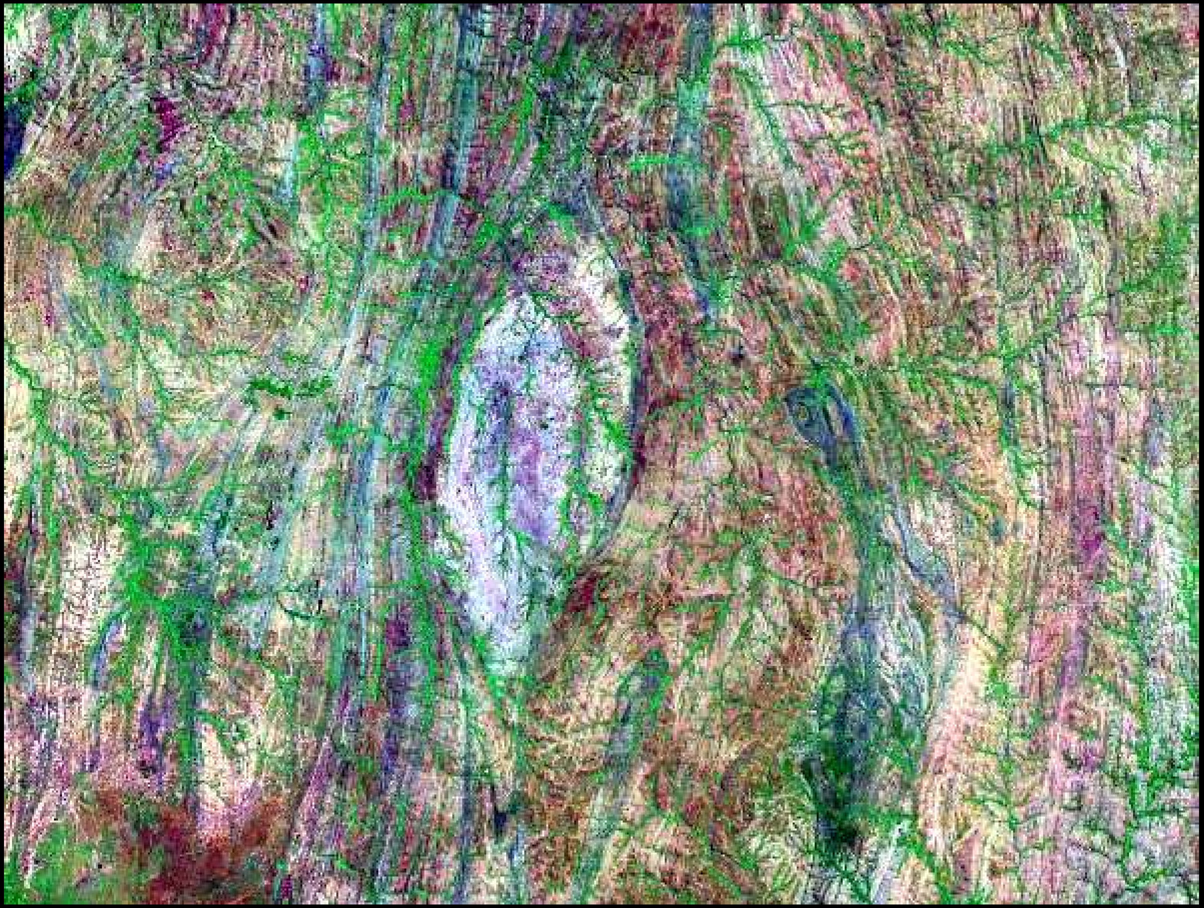
Surface analysis (3D views → structures)



All of the major landforms relate to volcanism and/or erosion in this Shuttle Radar Topography Mission scene of Patagonia, near La Esperanza, Argentina. The two prominent plateaus once formed a continuous surface that extended over much of this region. Younger volcanoes have grown through and atop the plateau, and one just south of this scene has sent a long, narrow flow down a stream channel (lower left).
Size: 62.4 by 88.8 kilometers (38.7 by 55.1 miles) Location: 40.0 deg. South lat., 68.6 deg. West lon. Orientation: North toward the top Image Data: Shaded and colored SRTM elevation model
Date Acquired: February 2000

Classical geological approaches 4

Visualization/Verification of structures (large scale)



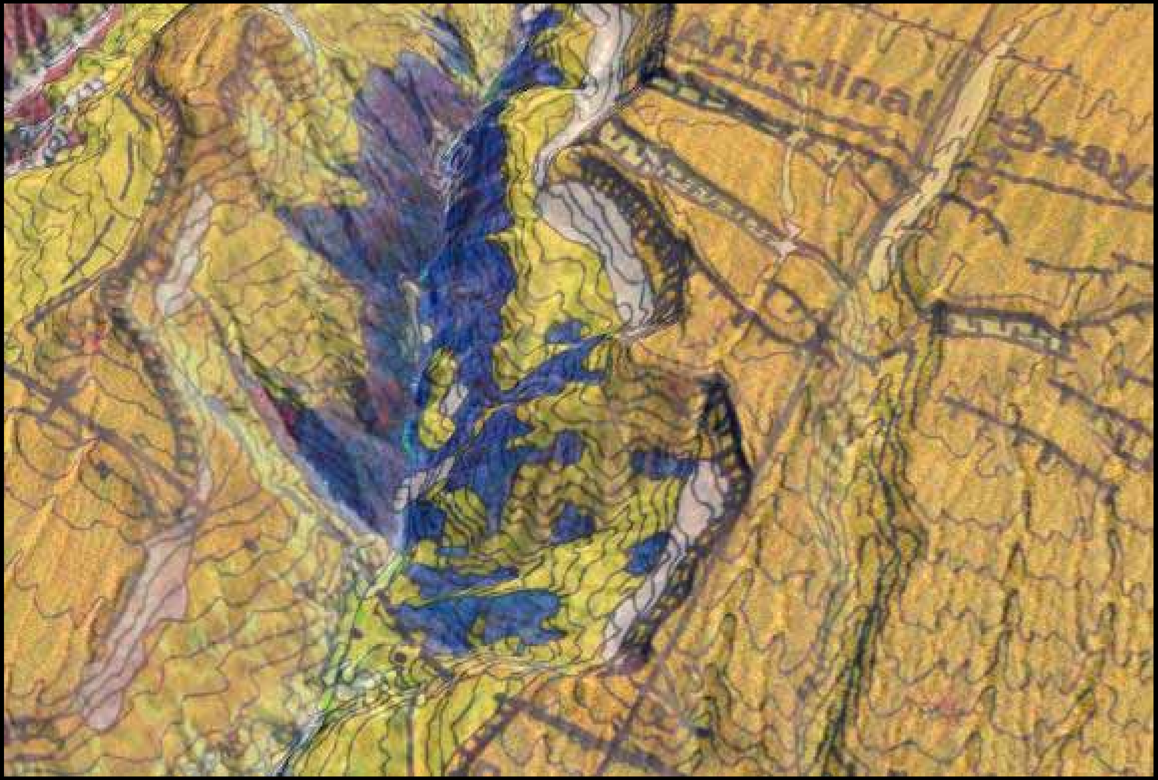
Plutonic dome structure (~ 15 km long) in a N-S striking strike-slip faultzone, Madagascar.

Three Landsat ETM+ bands, each sharpened with the panchromatic band.

- Band 7 red
- Band 4 green
- Band 2 blue

Classical geological approaches 5

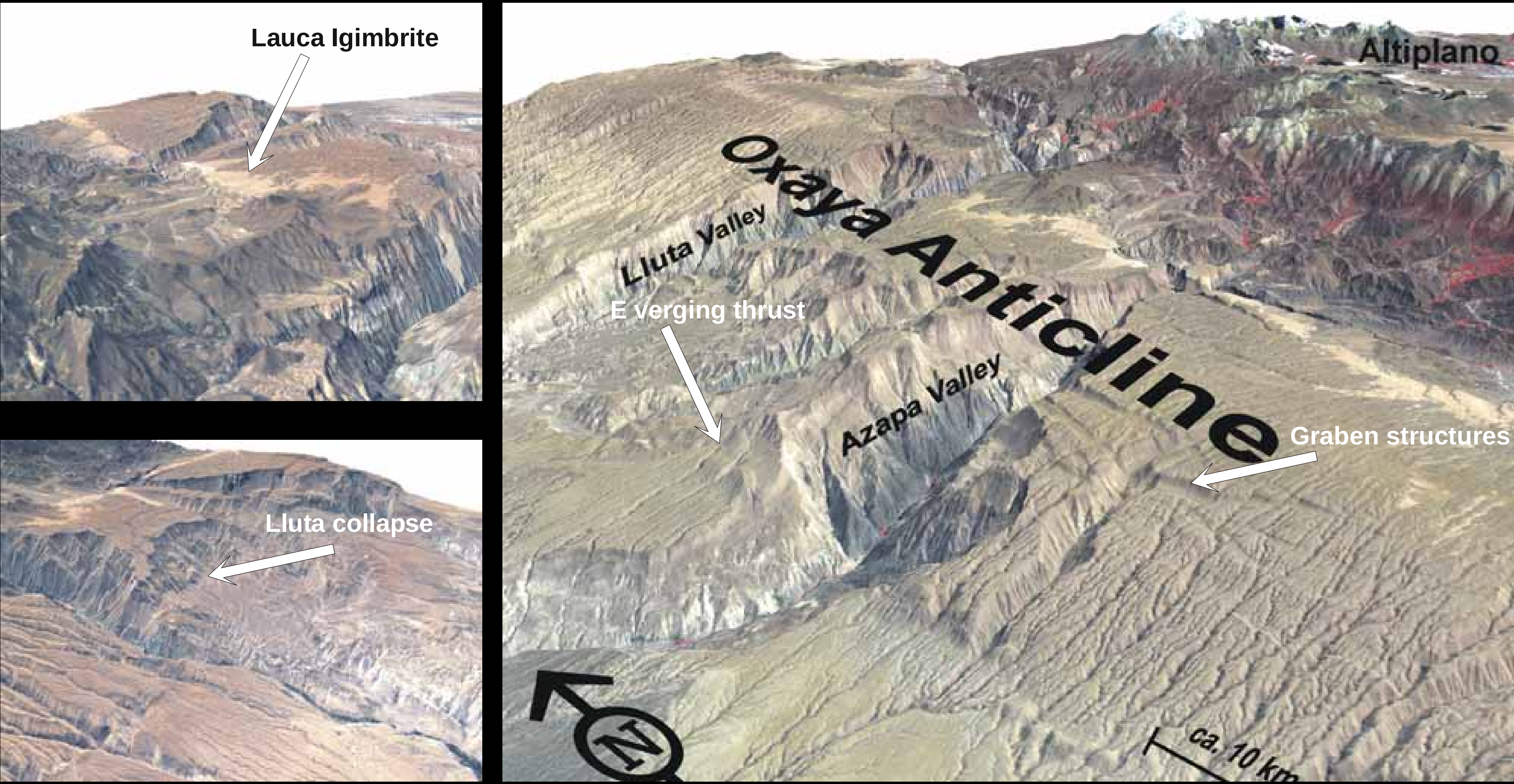
Control of mapping (Maps draped on DEM’s for quality control)



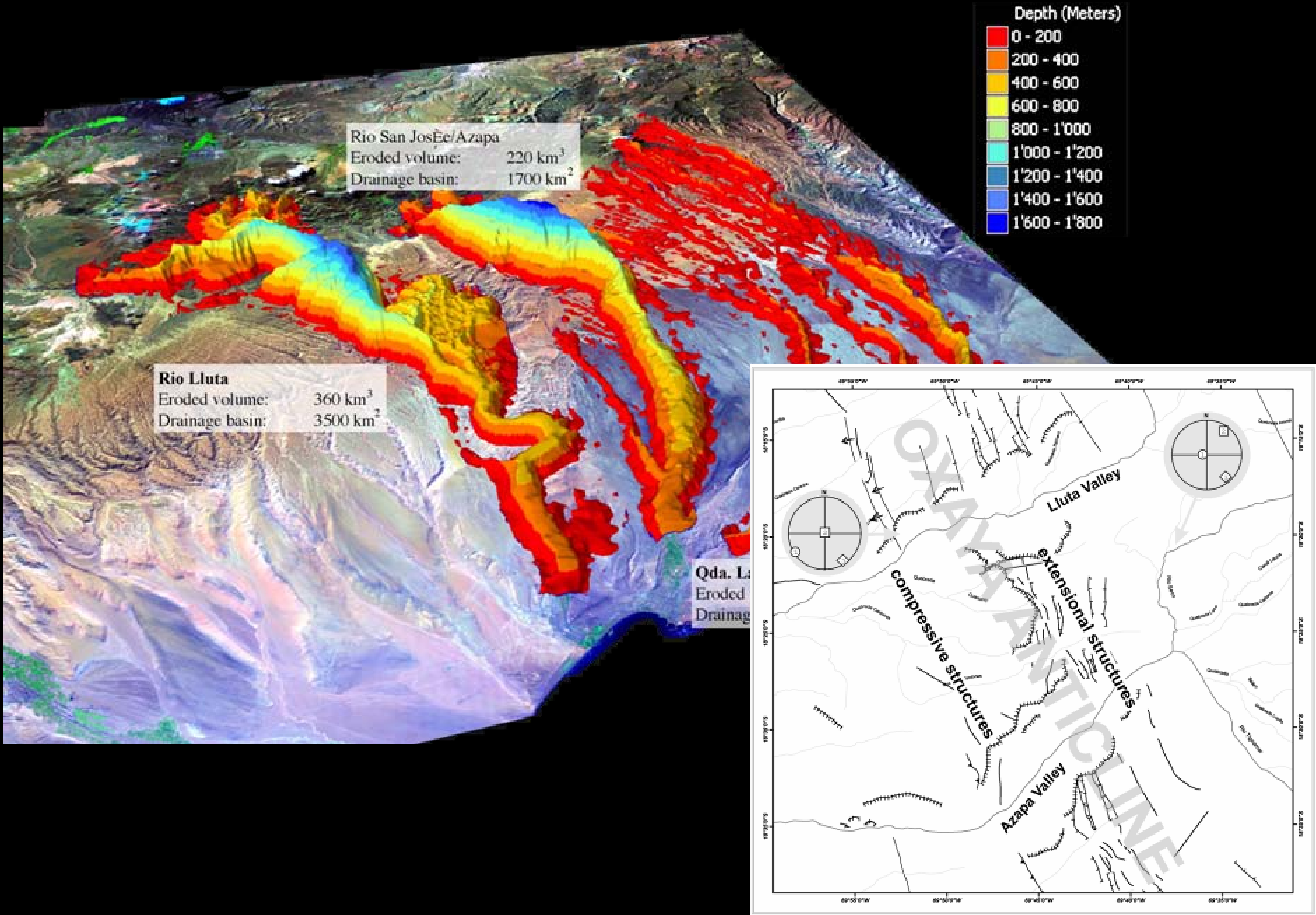
Geological map of Northern Chile (Garcia et al., 2003) Draped on SRTM 90 together with Landsat 7 ETM.

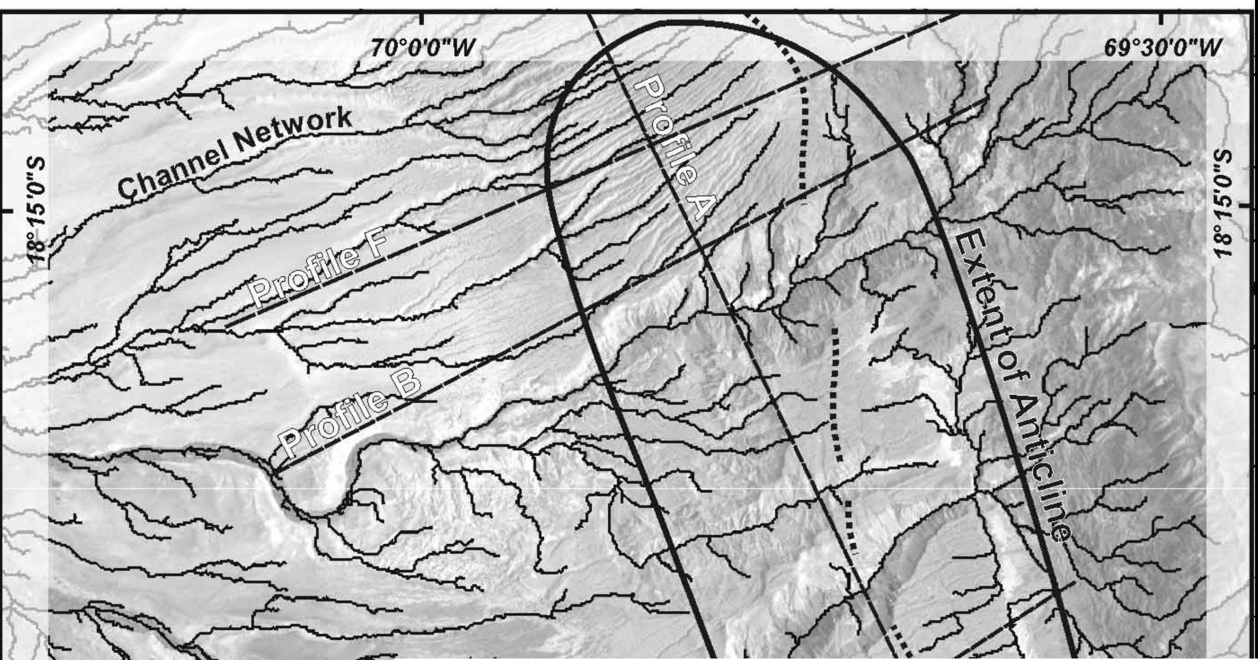
Case studies 1

Oxaya Anticline Geometry

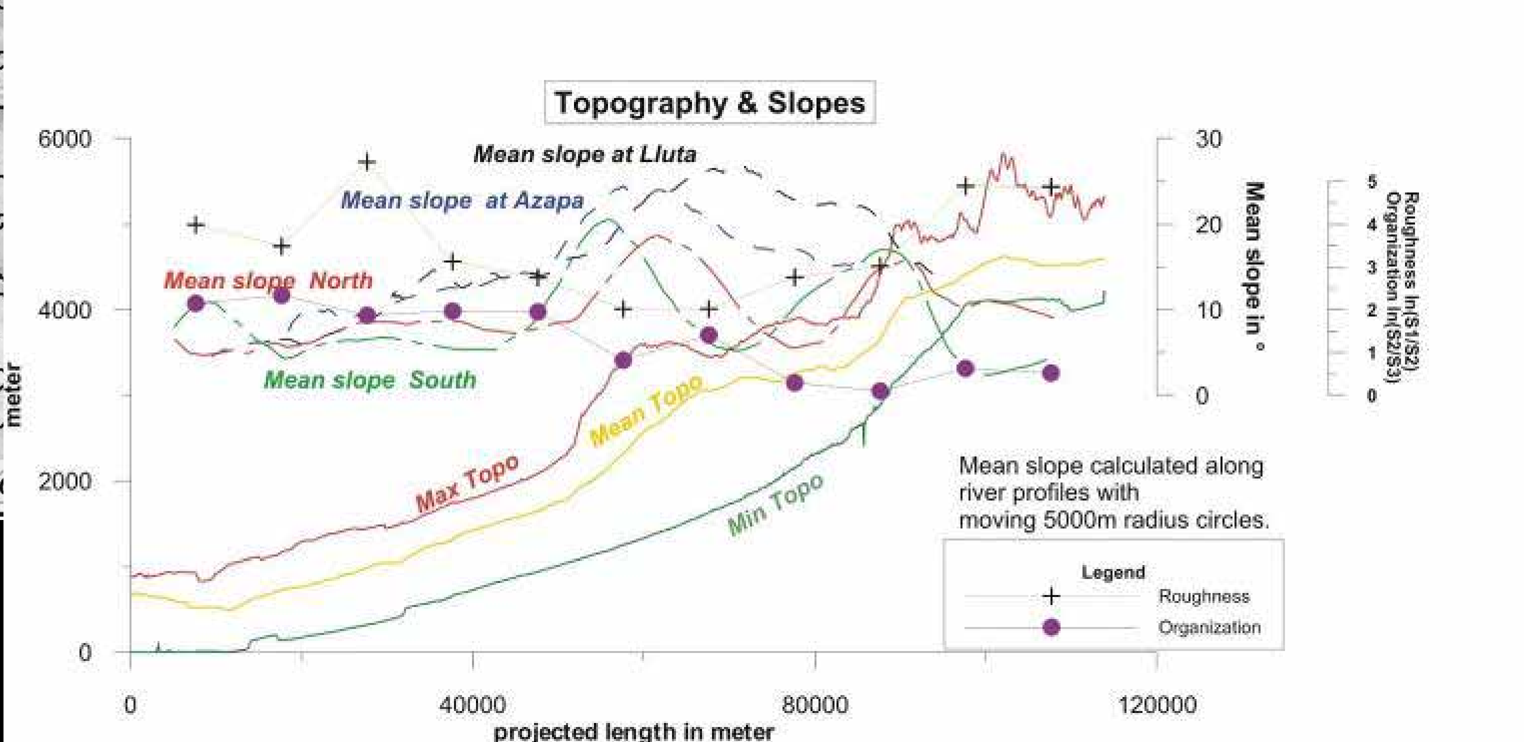


3D views of the Oxaya Anticline (Landsat 5, band 3, 2, 1, draped on SRTM 90 DEM).
a) The Lluta collapse at the western limb, b) the onlap of the Lauca Ignimbrite (bright lithology) and
c) the extensional and compressive structures can be clearly recognized.

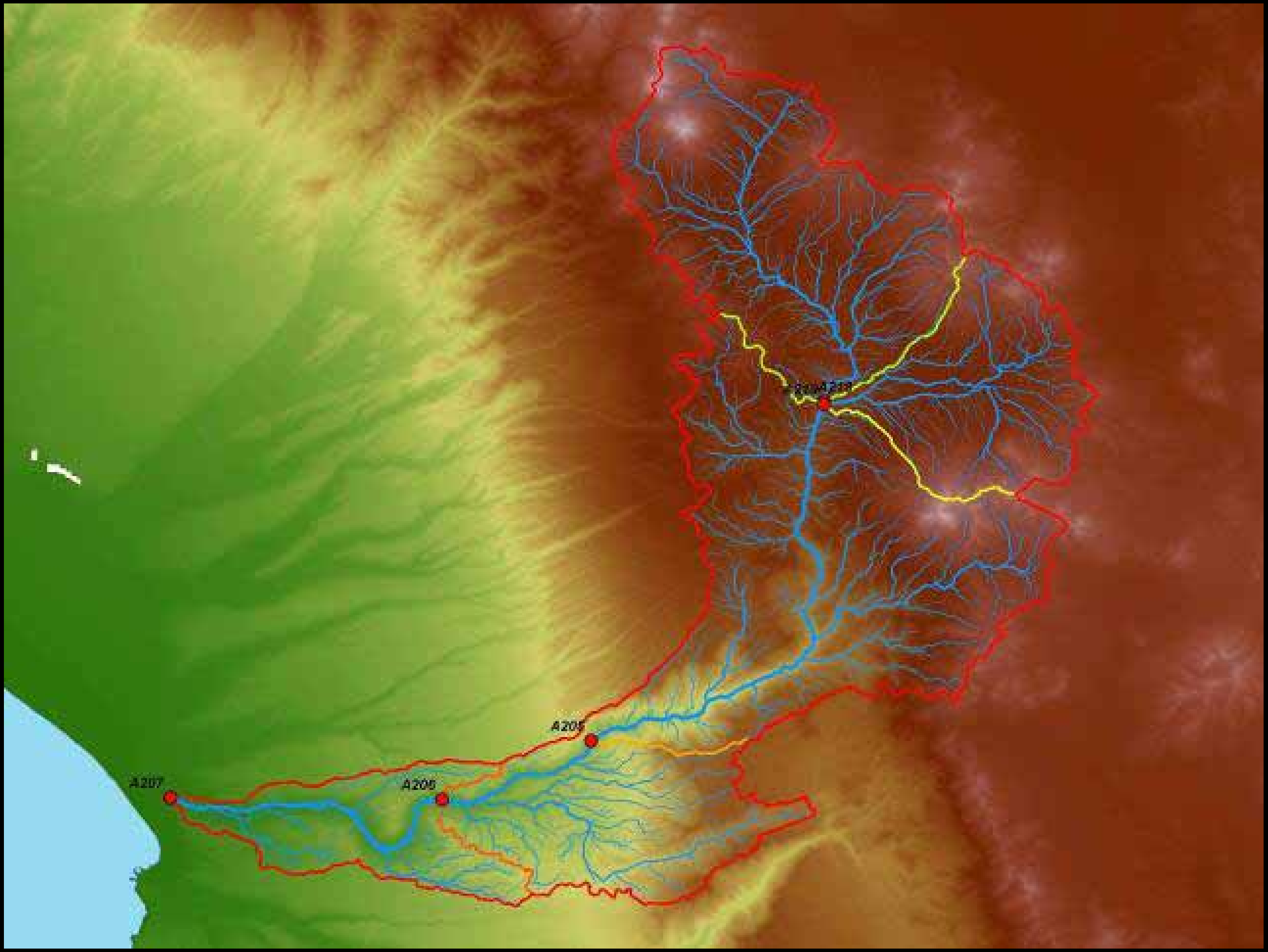

Depth (Meters)
0 - 200
200 - 400
400 - 600
600 - 800
800 - 1'000
1'000 - 1'200
1'200 - 1'400
1'400 - 1'600
1'600 - 1'800
Rio San JosÈe/Azapa
Eroded volume: 220 km^3
Drainage basin: 1700 km^2
Rio Lluta
Eroded volume: 360 km^3
Drainage basin: 3500 km^2
Qda. La
Eroded
Drainag
OXAYA ANTICLINE
Lluta Valley
Azapa Valley
compressive structures
extensional structures
N



Channel network based on SRTM 90. The watershed follows the culmination line in the central anticline structure

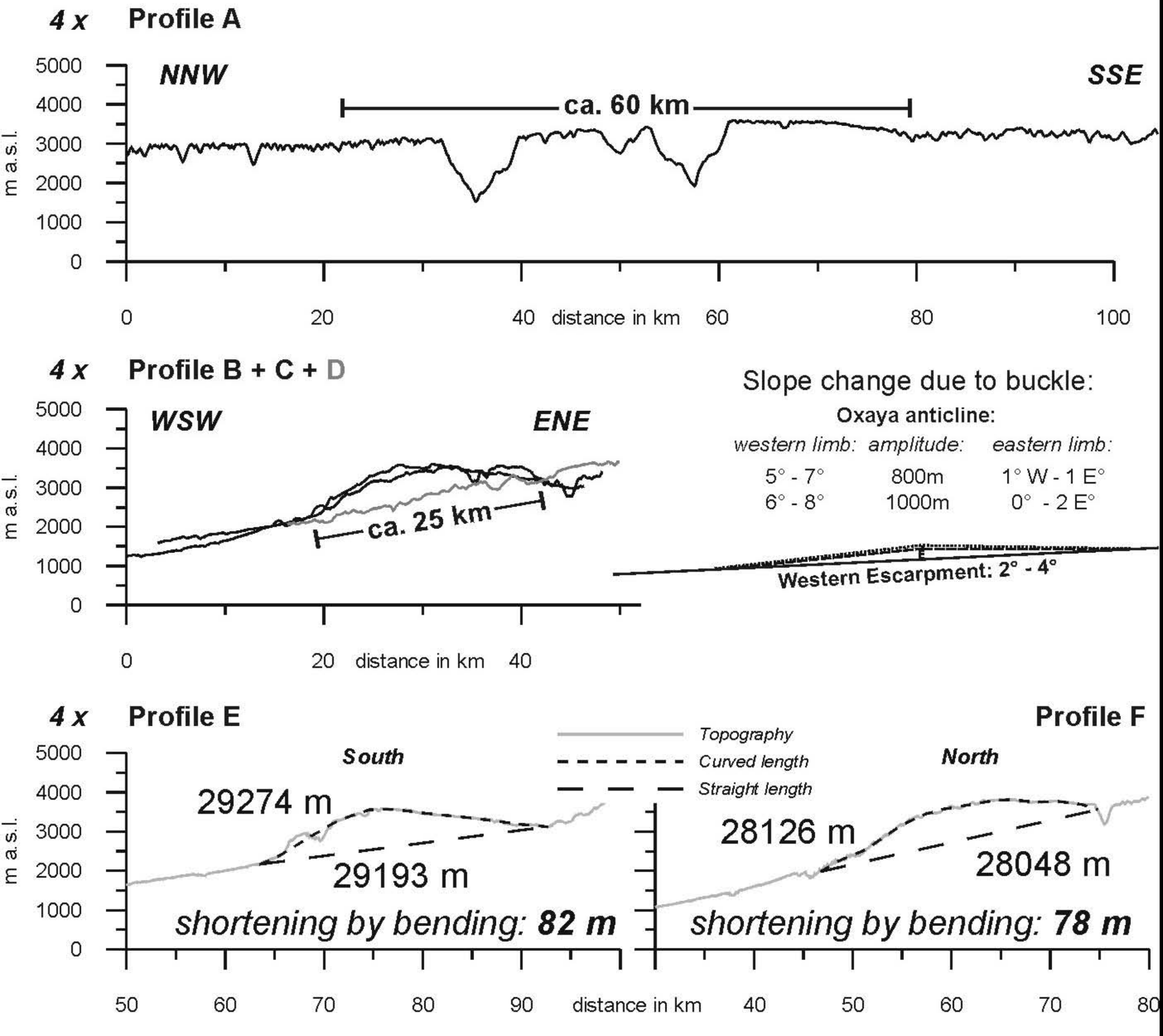


Mean slope calculated along river profiles with moving 5000m radius circles.



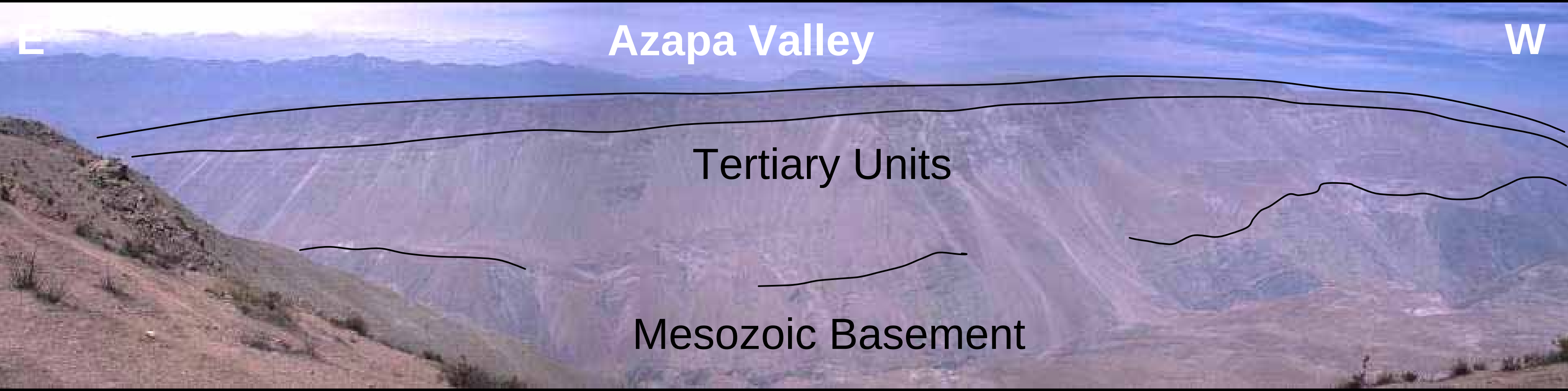
In comparison, erosion rates obtained from long-lived cosmogenic nuclides on hillsope interfluves for the Western Cordillera and those derived from preliminary data (21Ne) on catchment wide erosion rates of the Lluta-drainage system yield similar orders of magnitudes. Additionally, catchment wide erosion rates remain largely constant throughout the entire catchment

F. Kober et al., 2005 AGU Abstract


4 x
Profile A
NNW
SSE
ca. 60 km
m a.s.l.
5000
4000
3000
2000
1000
0
0
20
40
distance in km
60
80
100
4 x
Profile B + C + D
WSW
ENE
ca. 25 km
Slope change due to buckle:
Oxaya anticline:
western limb:
amplitude:
eastern limb:
5° - 7°
800m
1° W - 1 E°
6° - 8°
1000m
0° - 2 E°
Western Escarpment: 2° - 4°
4 x
Profile E
Profile F
South
North
Topography
Curved length
Straight length
29274 m
29193 m
28126 m
28048 m
shortening by bending: 82 m
shortening by bending: 78 m
50
60
70
80
90
distance in km
40
50
60
70
80

Example 1: Structure

Tertiary units fold geometry

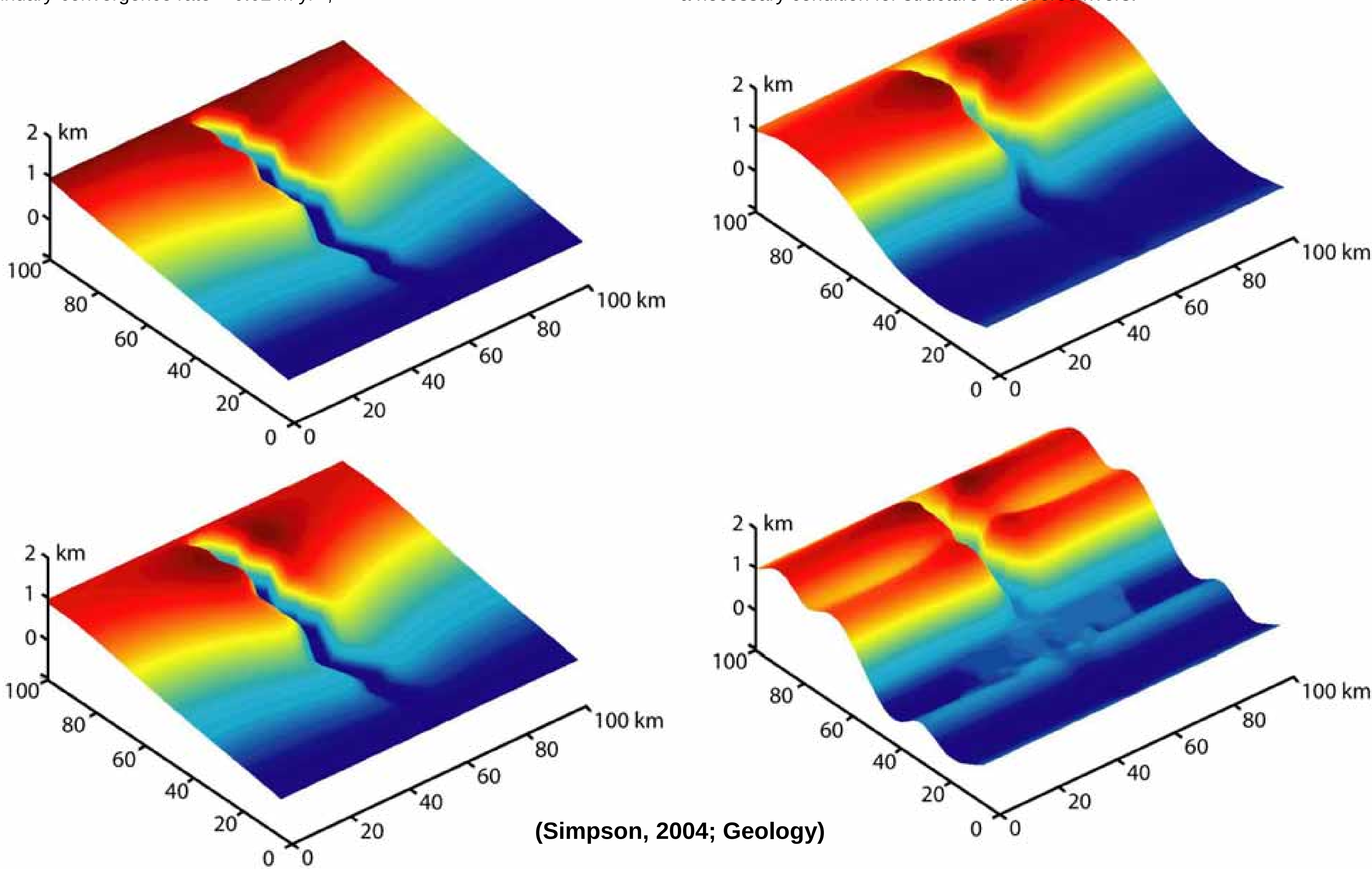


Spatial distribution of structures

The following parameters were used in the calculations presented:
plate thickness = 10 km,
Young’s modulus = 1 x 10^{11} MPa,
Poisson’s ratio = 0.3,
yield strength = 100 MPa,
density of inviscous substrate = 2700 kg·m^3,
density of eroding or depositing material = 2300 kg·m^3,
boundary-convergence rate = 0.02 m·yr^{-1},

uniform rainfall = 0 m·s-1,
water influx = 0.01 m2·s-1,
hillslope diffusivity = 6.3 x 10-7 m2·s-1,
fluvial erosion coefficient = 0.01 s·m-2,
fluvial erosion exponent = 2.

The erosion-related parameters have been chosen simply to ensure that the river is able to maintain its course across a typical growing structure, which is a necessary condition for structure-transverse rivers.

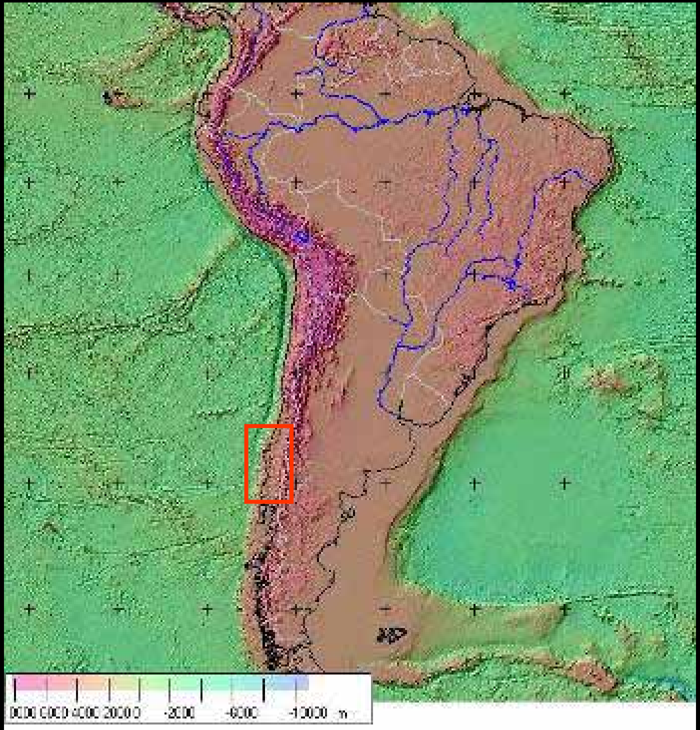


(Simpson, 2004; Geology)

Case studies 2

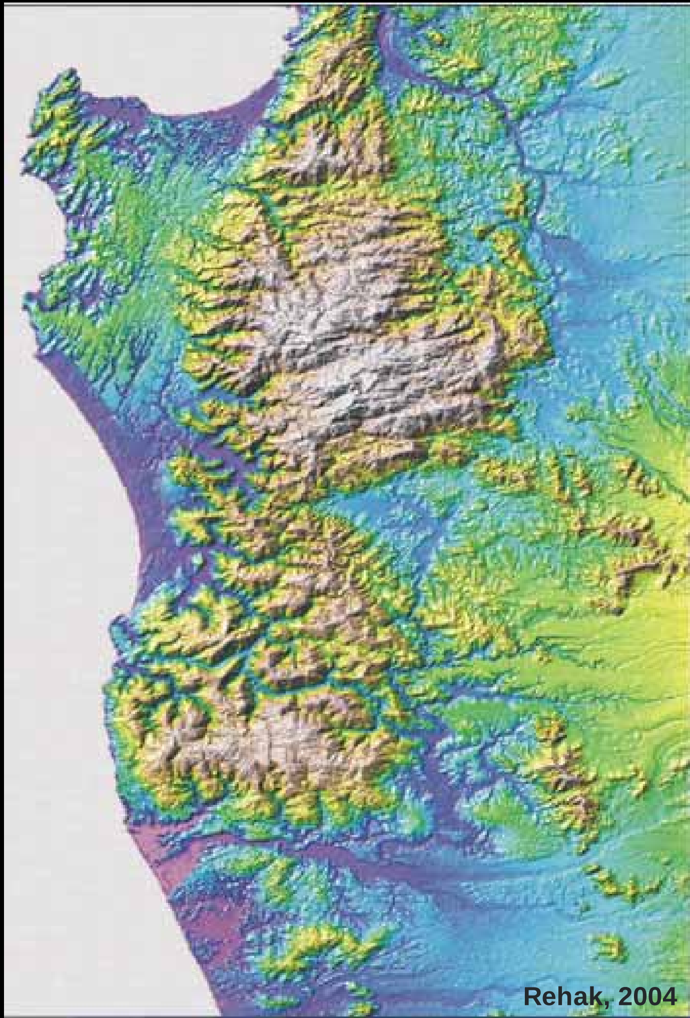
Coastal Cordillera of Southern Chile

Define segments of different tectonic and geomorphic evolution.
Quantify process rates to derive a dynamic model of Plio-Pleistocene forearc evolution.



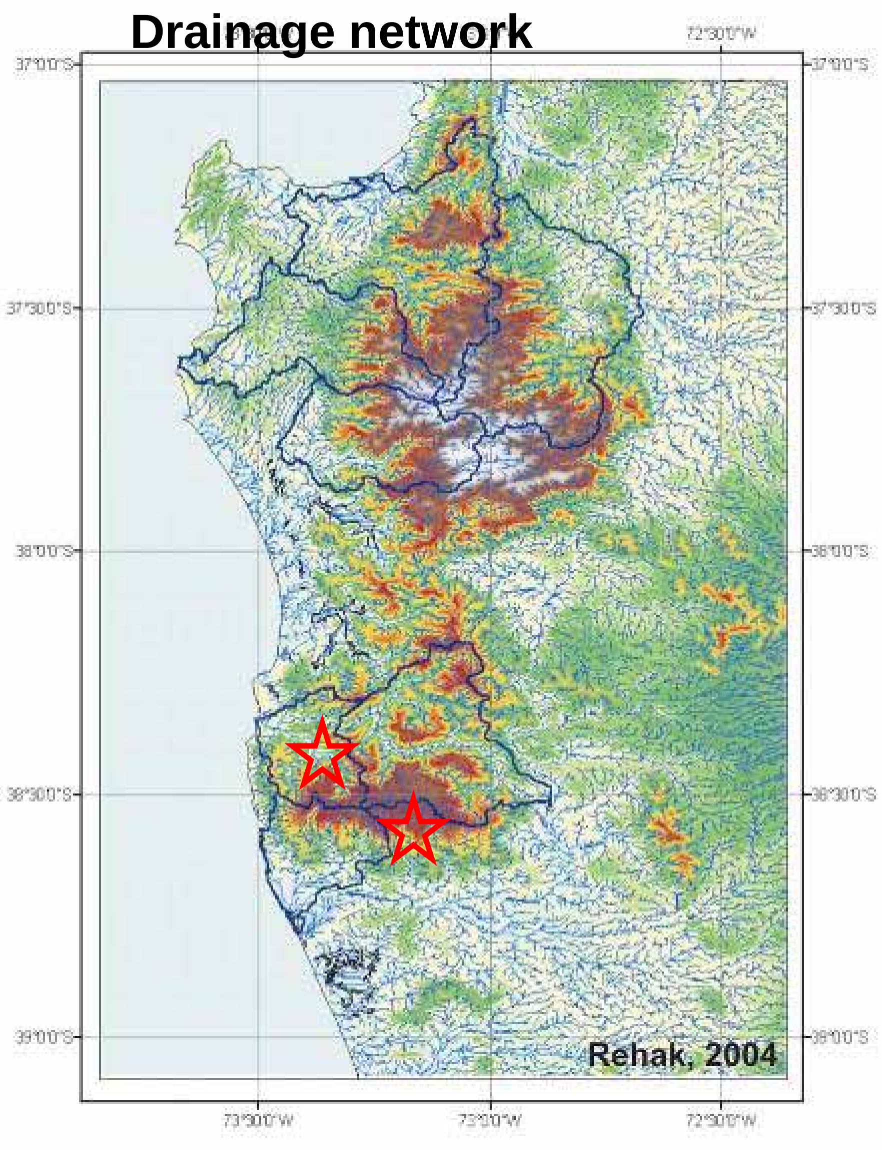
Remote sensing
- digital elevation models
- morphometry
- river profiling

- Provenance analysis
- Terrace mapping
- Surface dating (cosmogenic nuclides)


Rehak, 2004

Poster IMAF Workshop: Rehak, K.; Strecker, M.; Echtler, H.: ***DEM supported tectonic geomorphology: The South-Central Chilean active margin***

Geomorphic markers



Drainage network

Rehak, 2004

Foto: Rehak, 2005

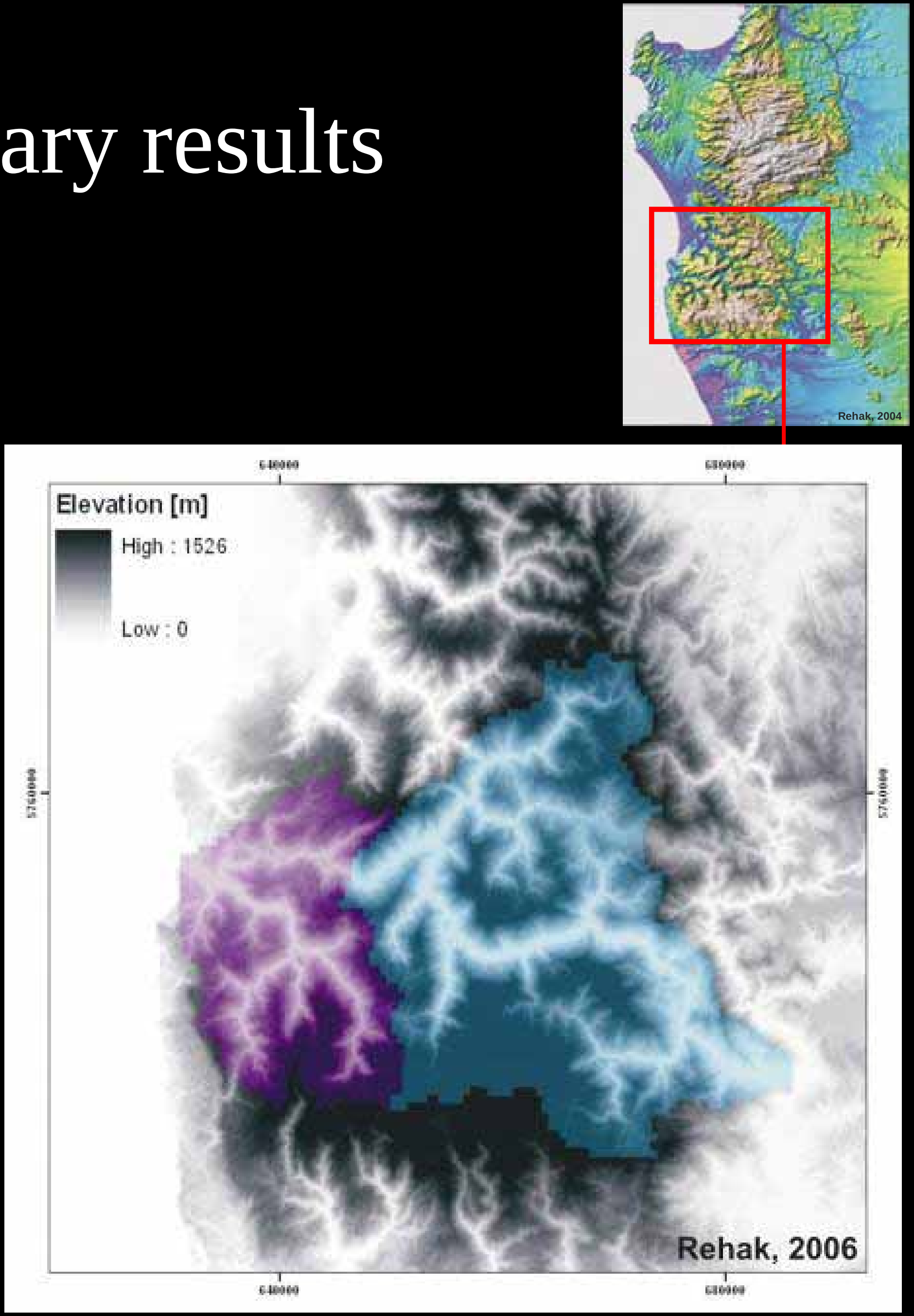
Fluvial terraces sequence

Foto: Rehak, 2005

Erosion surfaces in coastal range

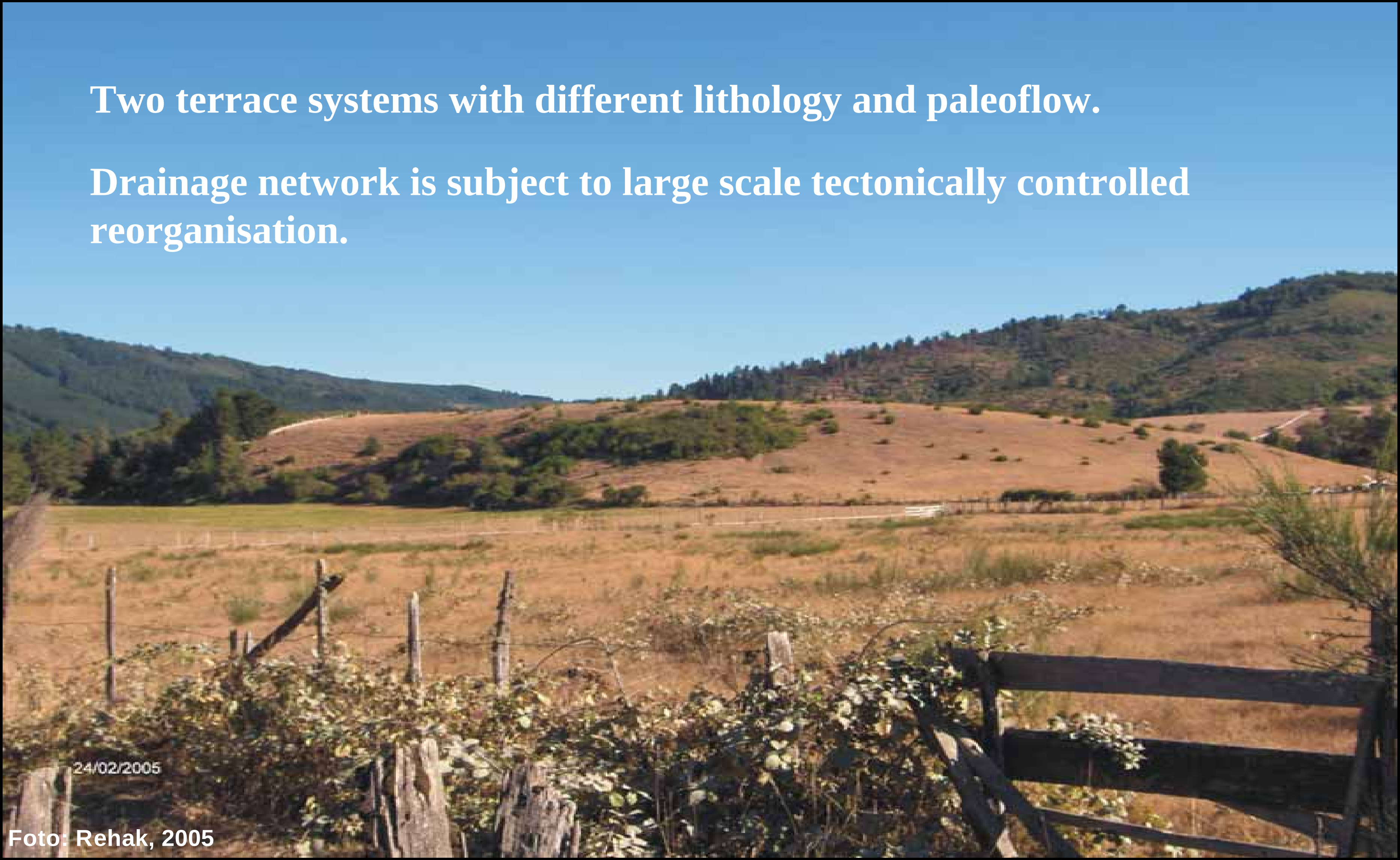
Preliminary results

- wind gap
- drainage reversal
- instability of watersheds
- decrease in catchment area



Geological studies: Coastal Cordillera of Southern Chile

Two fluvial terrace systems



Two terrace systems with different lithology and paleoflow.

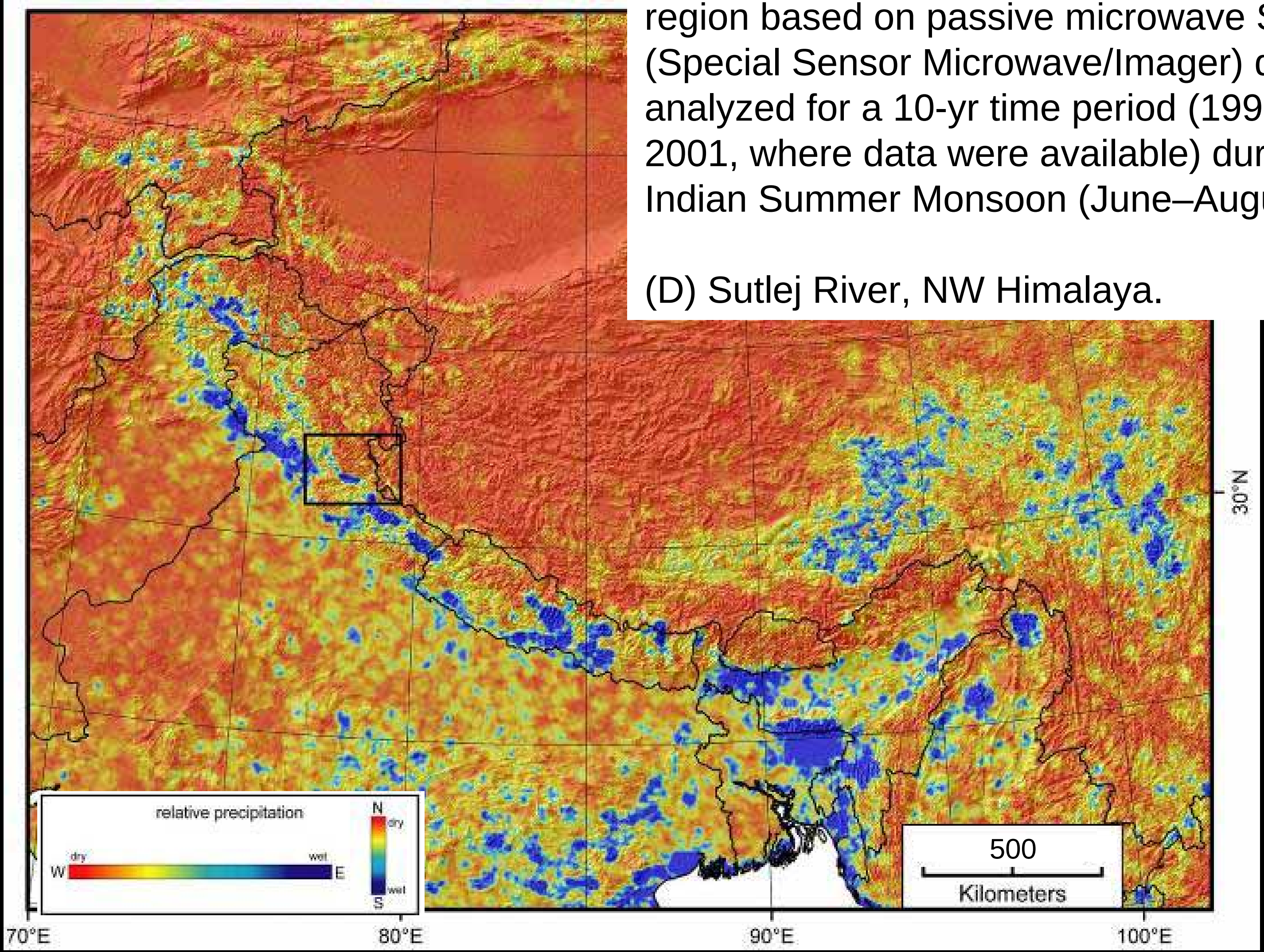
Drainage network is subject to large scale tectonically controlled reorganisation.

24/02/2005

Foto: Rehak, 2005

Case studies 3

Passive microwave (SSM/I) derived precipitation

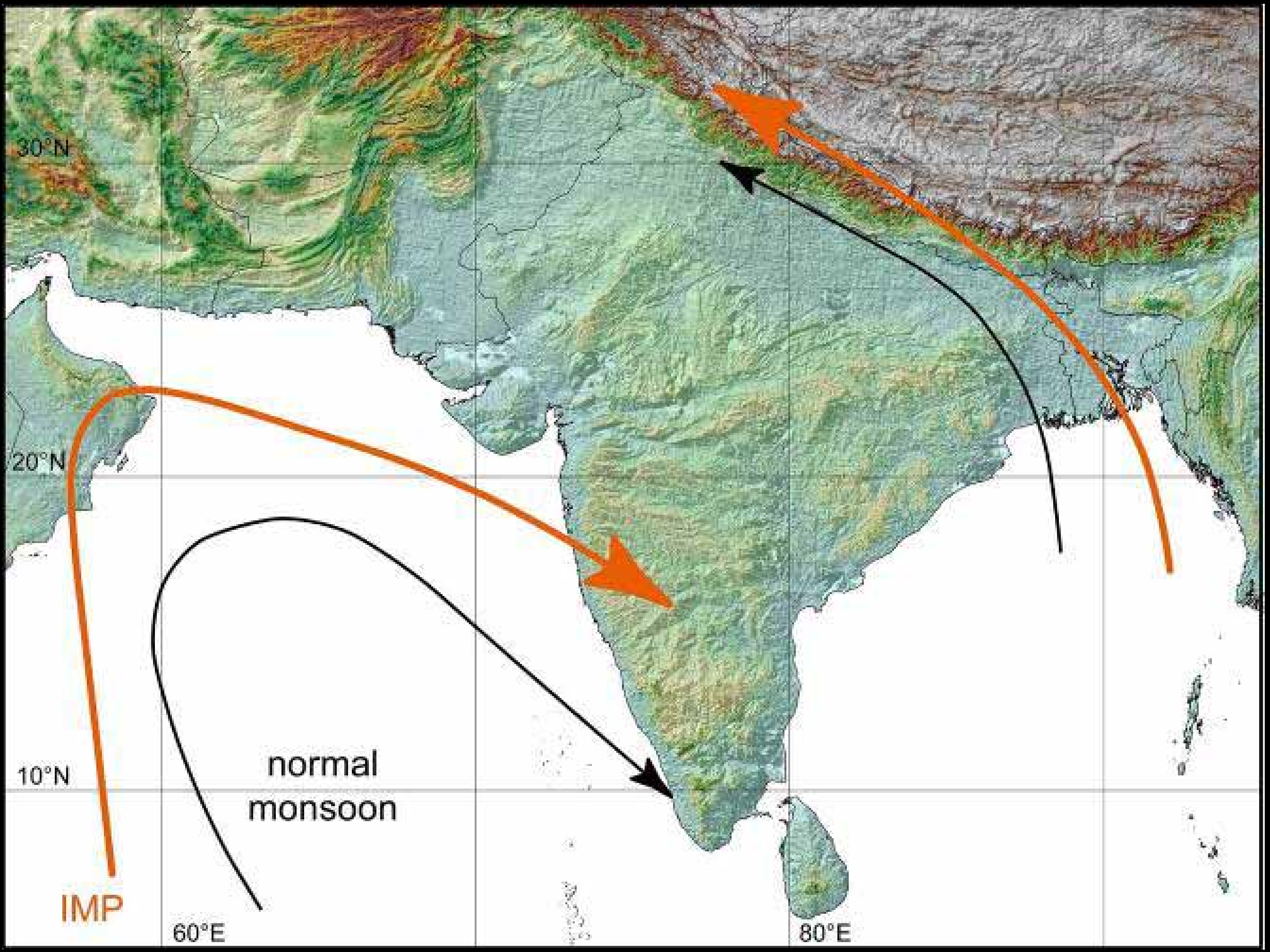


Mean annual precipitation for the Himalayan region based on passive microwave SSM/I (Special Sensor Microwave/Imager) data, analyzed for a 10-yr time period (1992–2001, where data were available) during the Indian Summer Monsoon (June–August).

(D) Sutlej River, NW Himalaya.

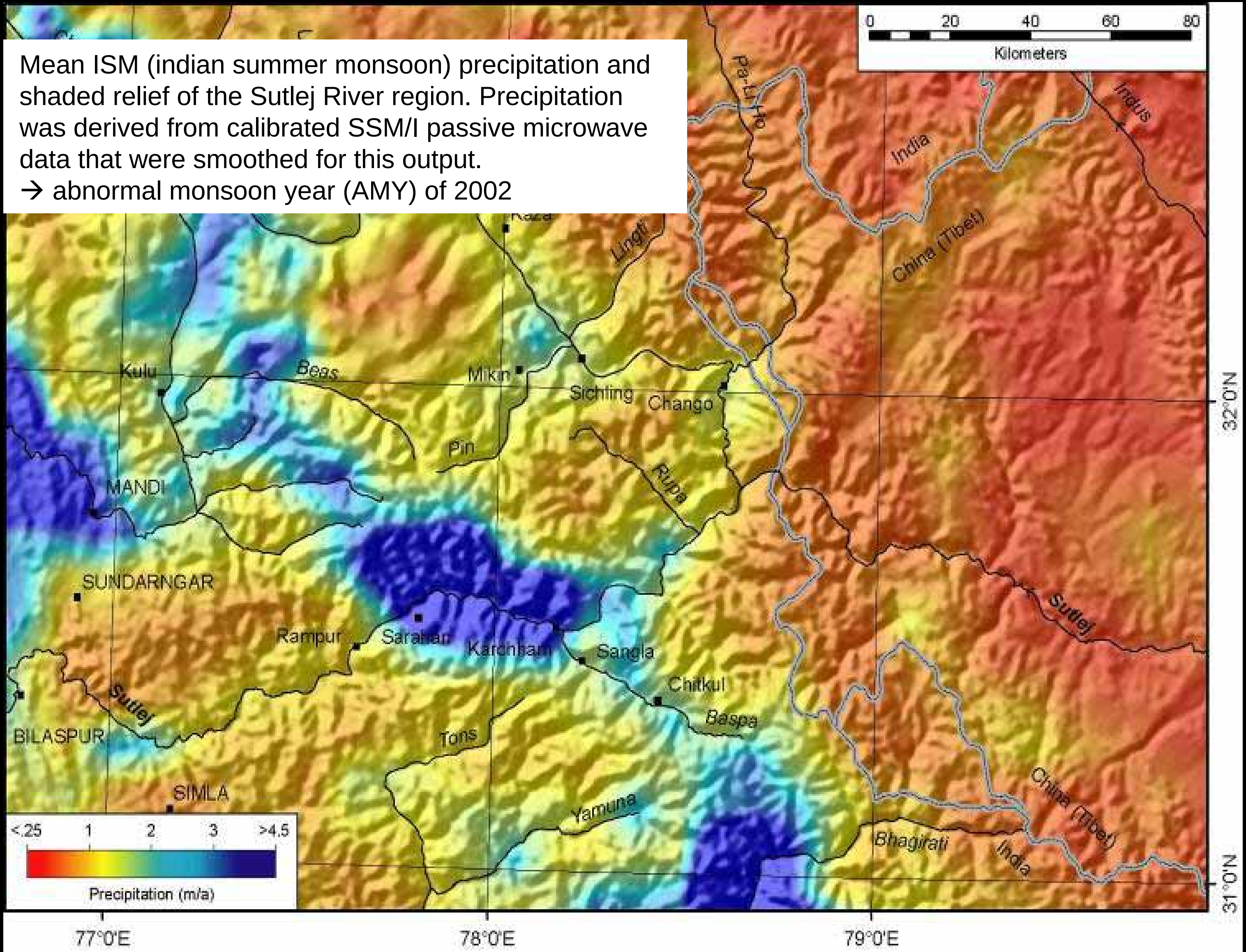
Bookhagen, Thiede & Strecker, *EPSL*, 2005

Present-day Precipitation Patterns: ‘Normal’ vs. Intensified Monsoons IMP



Bookhagen, Thiede & Strecker, *Geology*, 2005

Precipitation in the Sutlej region, AMY 2002



Mean ISM (indian summer monsoon) precipitation and shaded relief of the Sutlej River region. Precipitation was derived from calibrated SSM/I passive microwave data that were smoothed for this output.

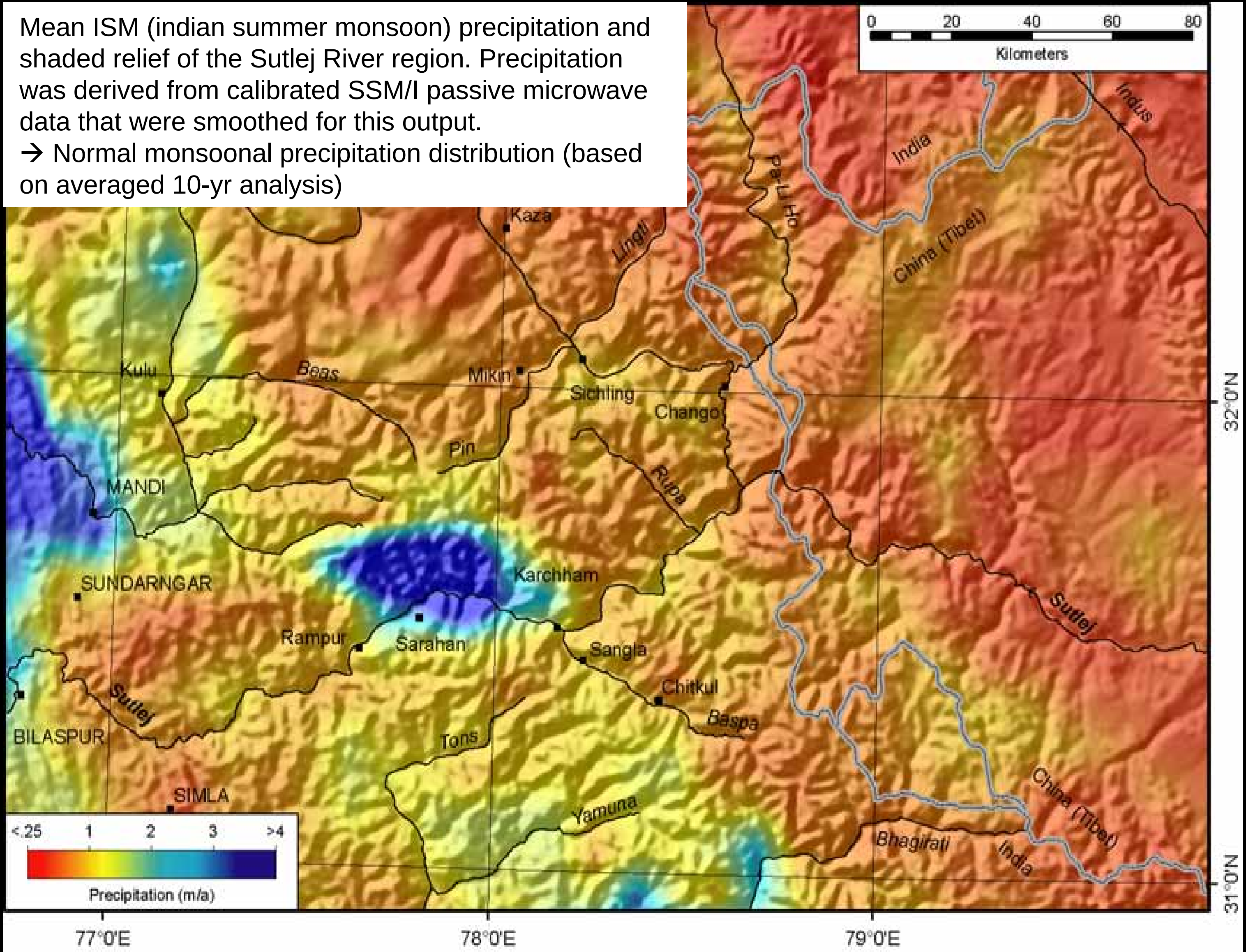
→ abnormal monsoon year (AMY) of 2002

Bookhagen, Thiede & Strecker, *EPSL*, 2005

Precipitation in the Sutlej region (last 10 years)

Mean ISM (indian summer monsoon) precipitation and shaded relief of the Sutlej River region. Precipitation was derived from calibrated SSM/I passive microwave data that were smoothed for this output.

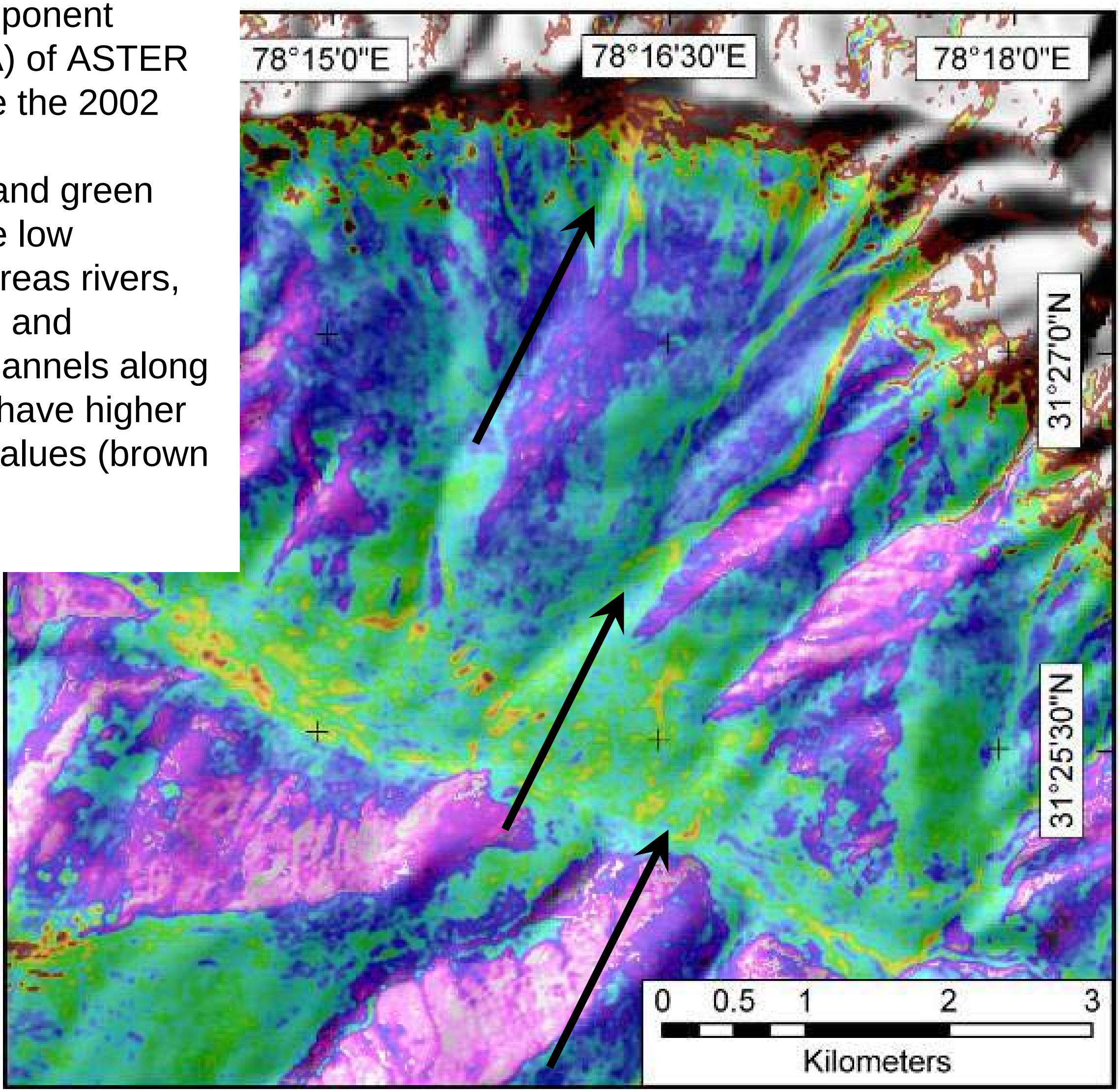
→ Normal monsoonal precipitation distribution (based on averaged 10-yr analysis)

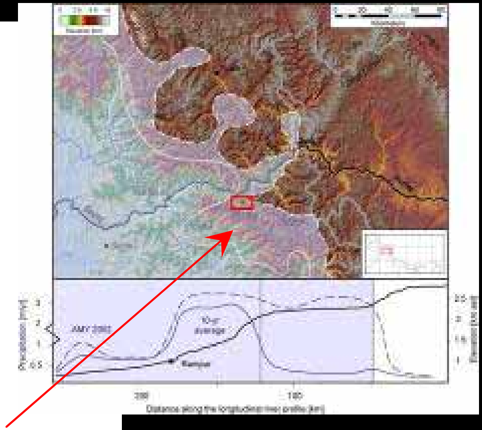


Bookhagen, Thiede & Strecker, *EPSL*, 2005

Baspa Valley – April 2002 – **Before** Indian Summer Monsoon

Principal Component analysis (PCA) of ASTER Images before the 2002 AMY event.
Purple, blue, and green colors indicate low variance, whereas rivers, newly formed, and reactivated channels along the hillslopes have higher reflectances values (brown colors).

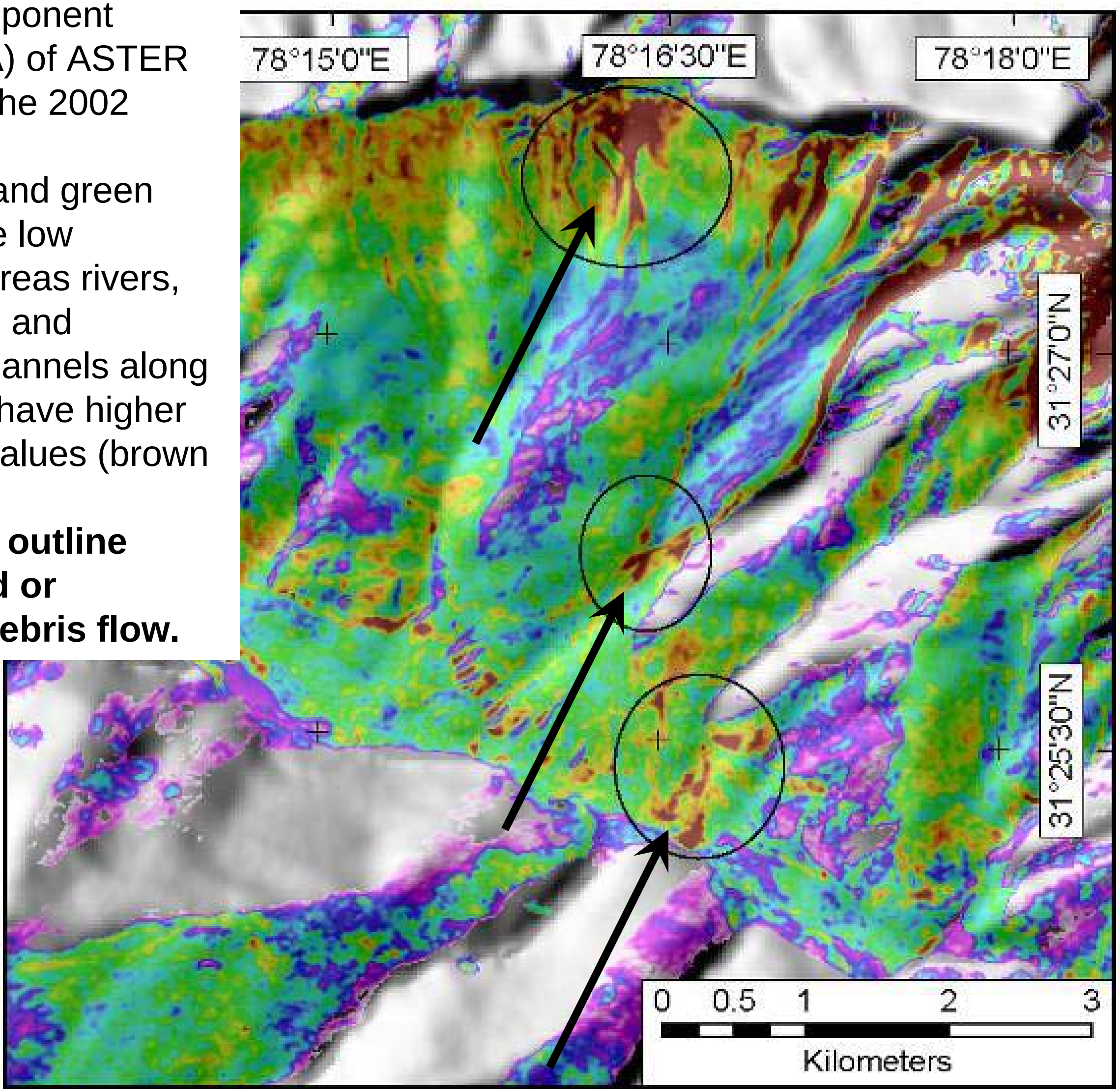




Bookhagen, Thiede & Strecker, *EPSL*, 2005

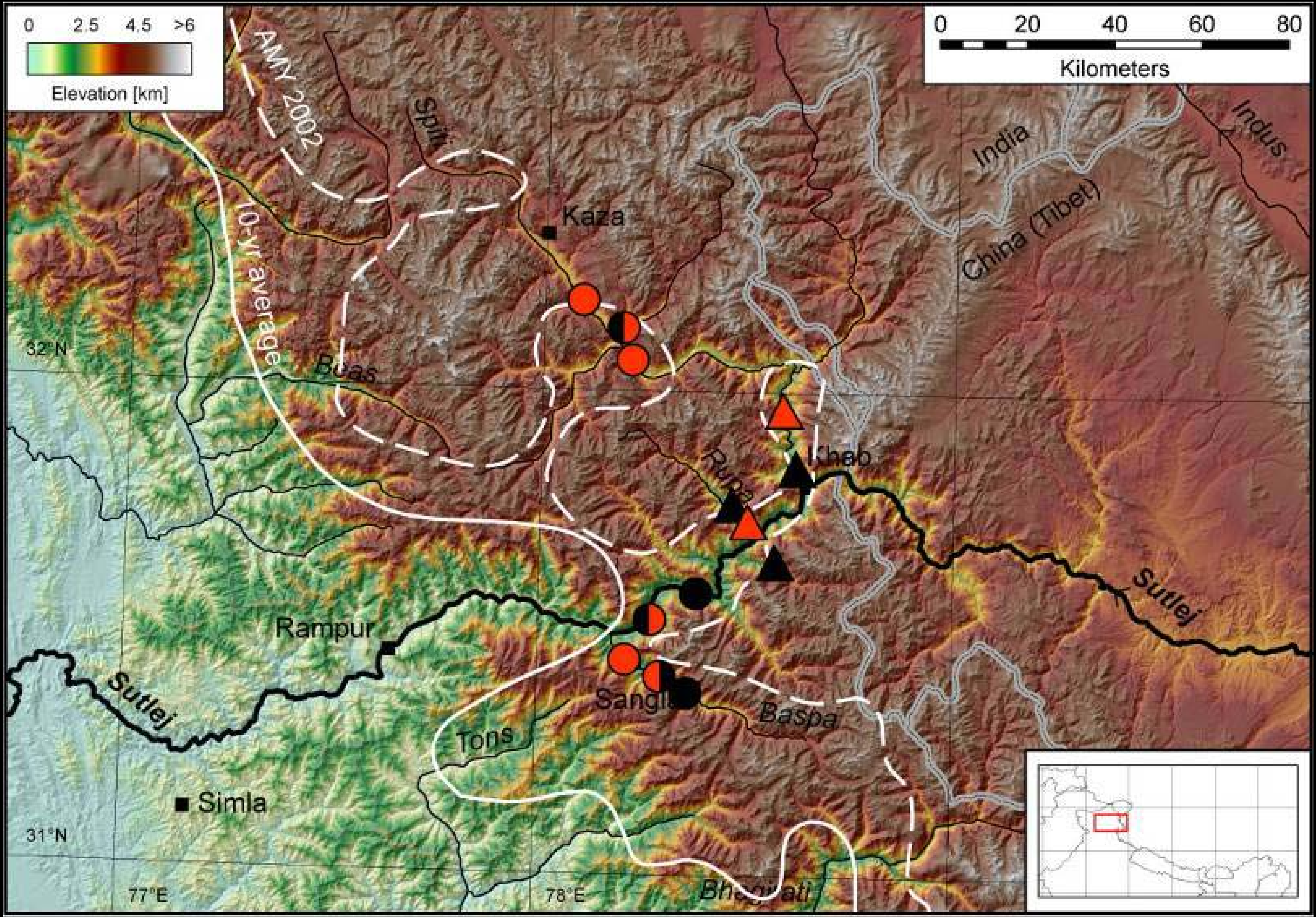
Baspa Valley December 2002 – **After** Indian Summer Monsoon

Principal Component analysis (PCA) of ASTER Images after the 2002 AMYevent.
Purple, blue, and green colors indicate low variance, whereas rivers, newly formed, and reactivated channels along the hillslopes have higher reflectances values (brown colors).
Black circles outline newly formed or reactivated debris flow.



Bookhagen, Thiede & Strecker, *EPSL*, 2005

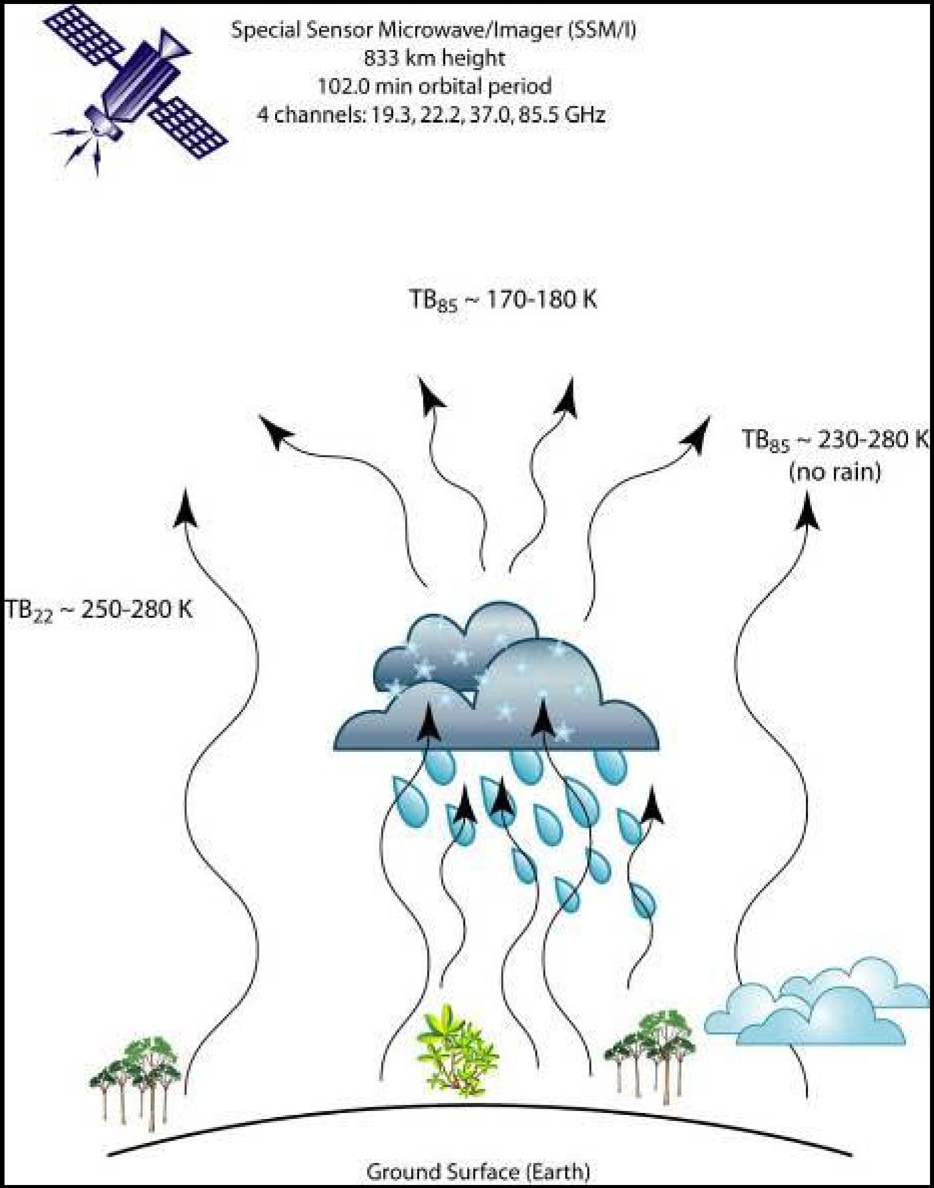
Late Pleistocene & Holocene Landslides in the Sutlej Valley



Bookhagen, Thiede & Strecker, *Geology*, 2005

Special Sensor Microwave/Imager (SSM/I)

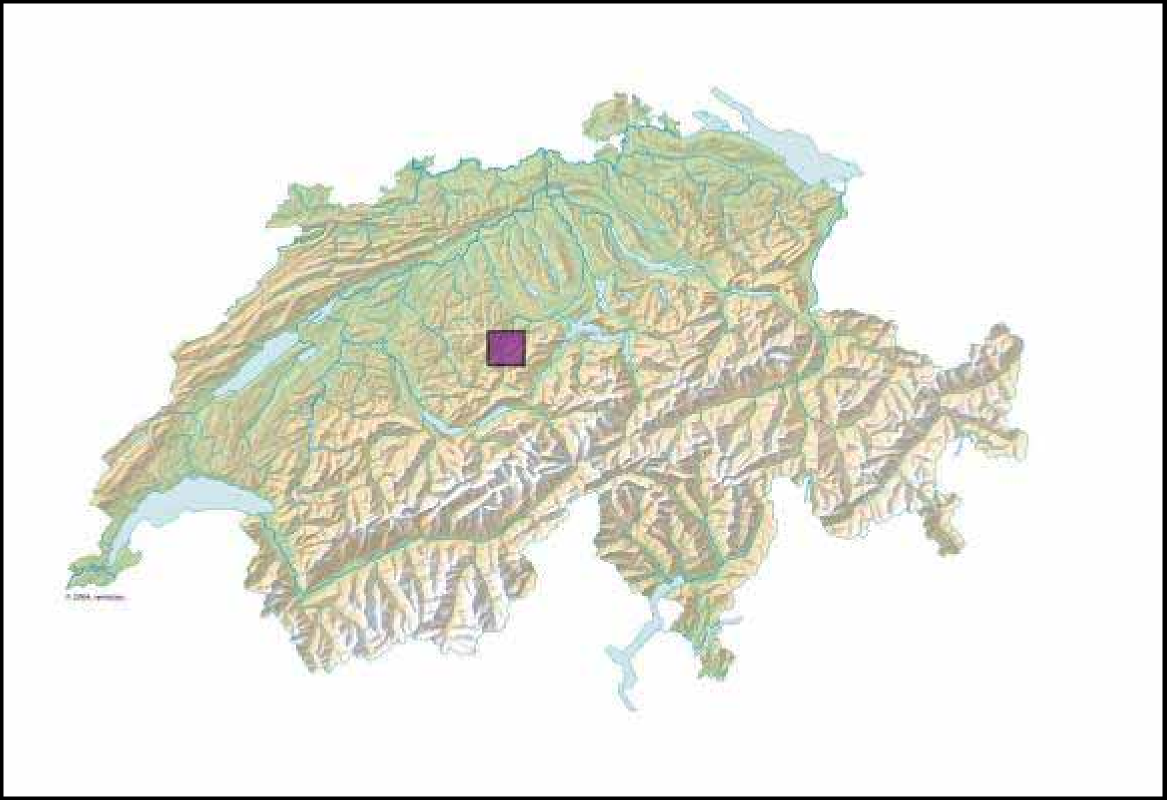
- Scattering of passive microwaves on ice crystals
- Footprint of 12.5 km
- Coverage 2x a day



Case studies 4

Landslides in the Swiss Alps

Location of the landslide area: on the northern border of the Swiss Alps, between Bern and Luzern. The landslide affects Flysch sediments, known to be affected by landslides all along the northern alpine front.



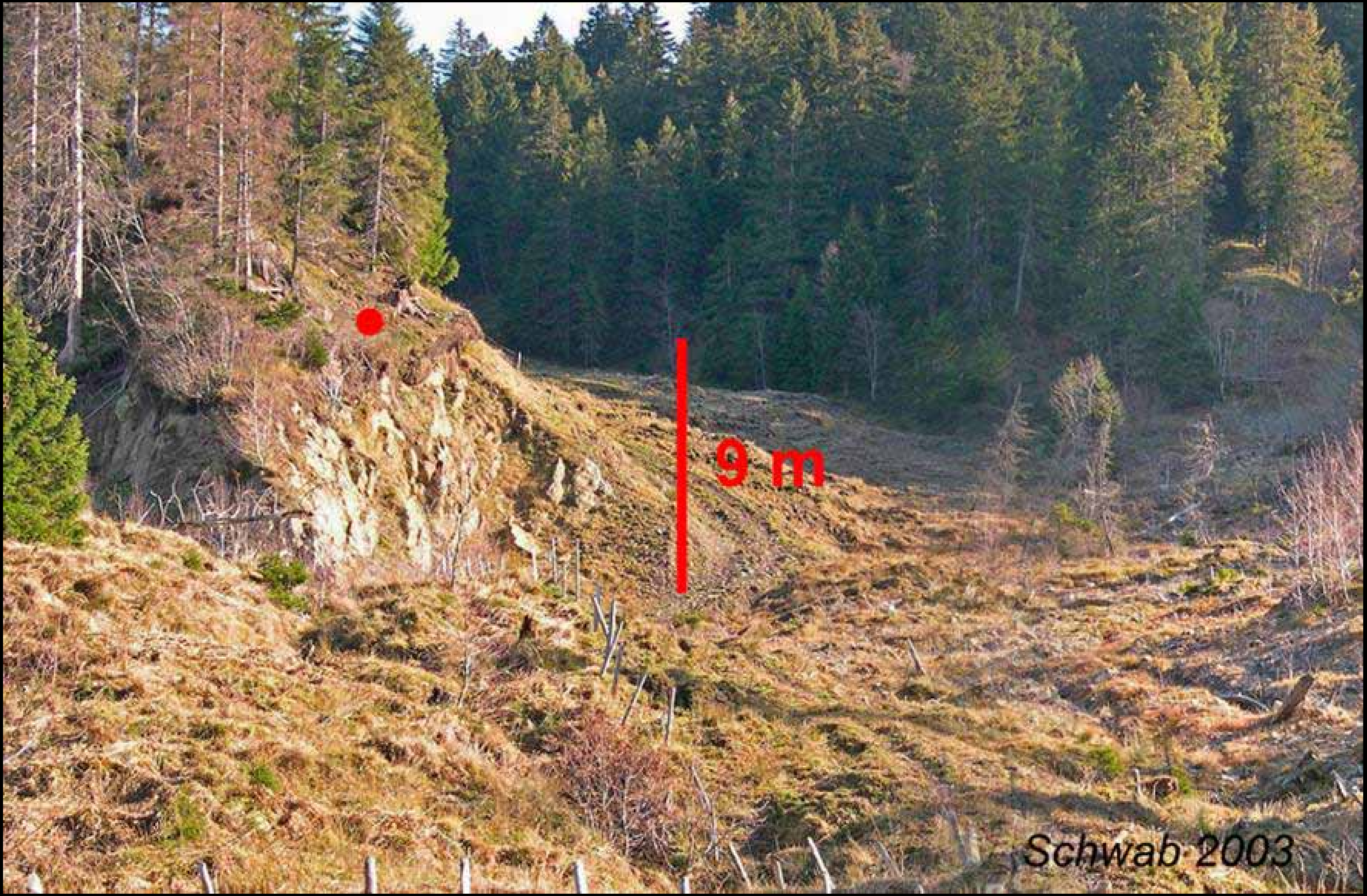
M. Schwab, PhD Thesis University of Berne, 2006

Before the 1994 landslide surge

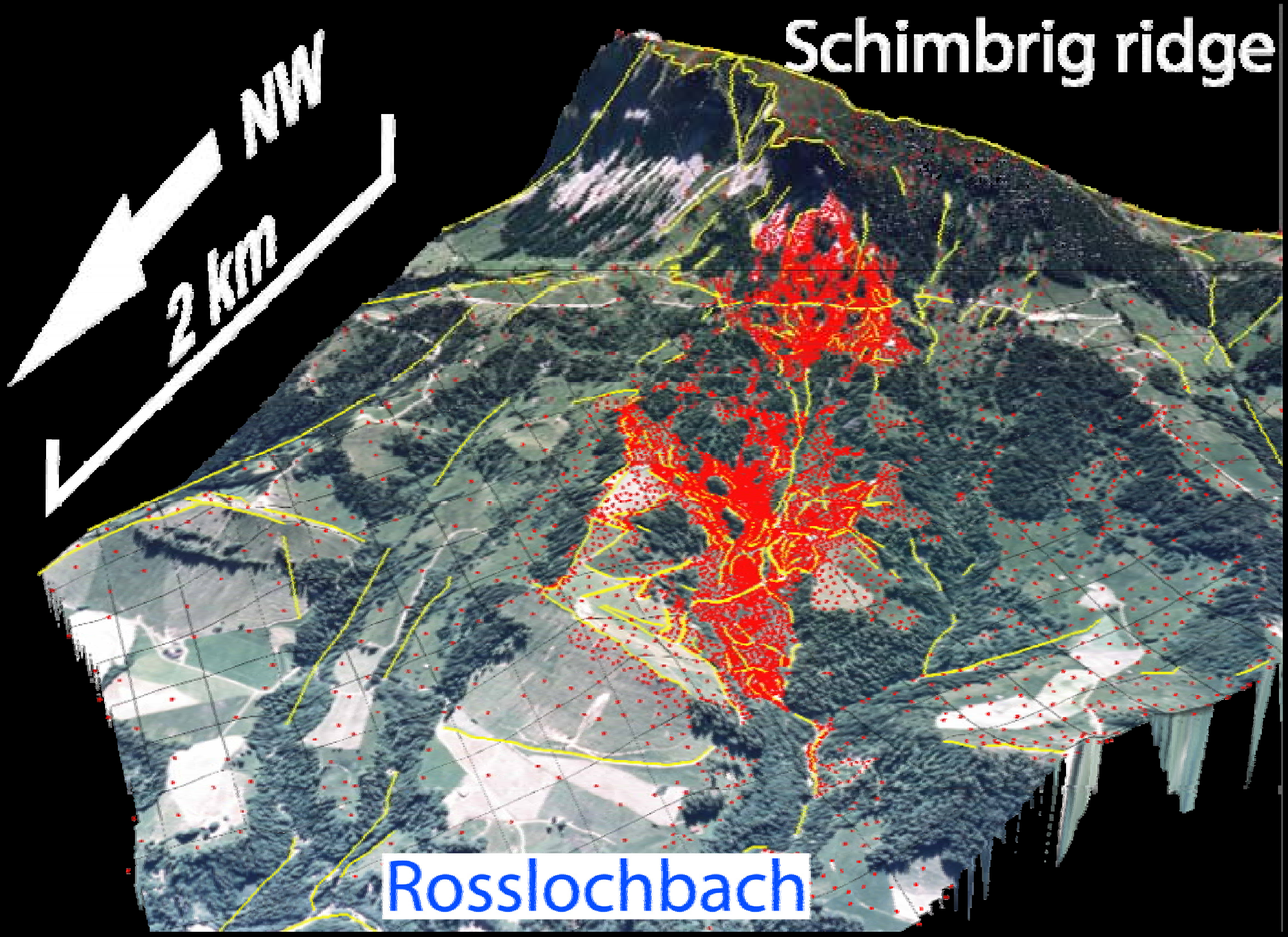
M. Schwab, PhD Thesis University of Berne, 2006

10 years after…

The red dot is at the same location on slide 1



M. Schwab, PhD Thesis University of Berne, 2006



Arcscene view of the area with points (red dots) and breaklines (yellow) which were digitized for the production of 1 DEM.

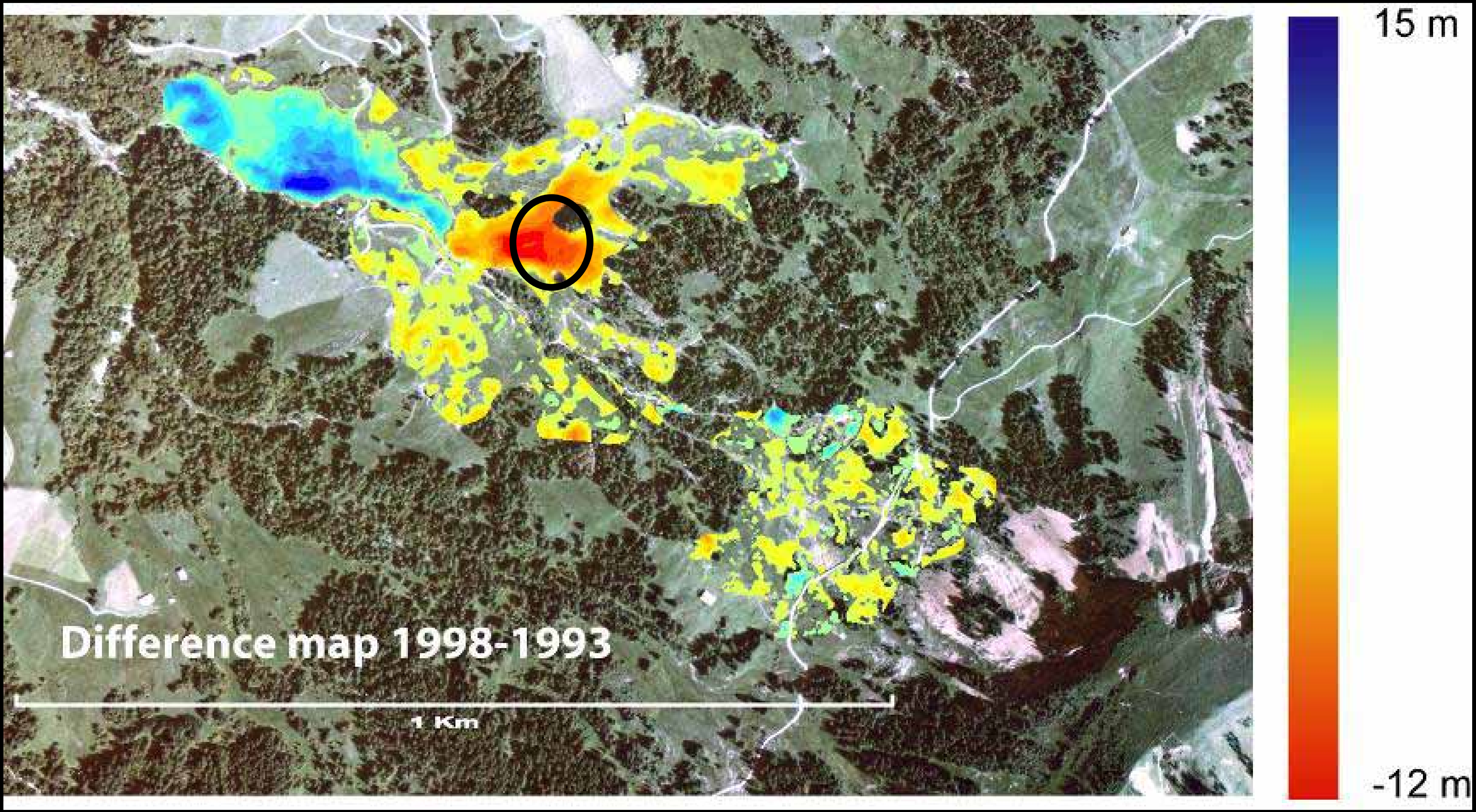
Note that forested area where exclude (bad photogrammetric precision and difficult to interpret as terrain movement, or volume of export)

The accuracy of the points in elevation is +/- 0,5m

M. Schwab, PhD Thesis University of Berne, 2006

Difference map between the 1998-DEM and 1993-DEM. Erosion is displayed in red, accumulation in blue.

The pictures of slide 1 and 2 are taken in the circle.



M. Schwab, PhD Thesis University of Berne, 2006

Outlook

The presented examples, although representing only a short and limited selection of projects using remote sensing data in geology, have as a common approach the goal to ***quantify geological processes***.

- Why is this so important?

→It is crucial for the analysis of natural hazards like:

Earthquakes / Tsunamis

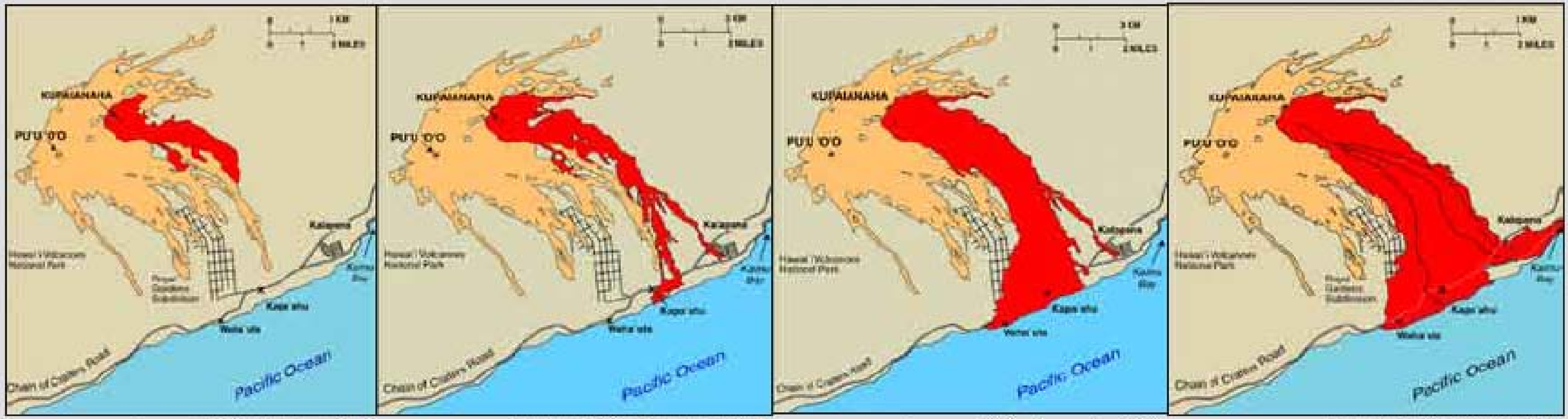
The city of Banda Aceh, Indonesia, suffered catastrophic damage as a result of the tsunami that struck on 26 December 2004. These QuickBird Natural Colour images on 23 June 2000 and on 28 December 2004 (below) clearly show the city before the devastation and the extent of the damage after the tsunami.

Source: Digital Globe: http://www. digitalglobe.com/images/tsunami/Banda_Aceh_ Tsunami_Damage.pdf

UNEP (2005), "One Planet Many People: Atlas of Our Changing Environment."

- Volcanoes

Maps of lava-flow field from the Pu`u `O`o and Kupaianaha vents of Kilauea Volcano, Hawaii, January 1983 - January 1991



January 1983 - October 1986

January 1983 - December 1986

January 1983 - December 1989

January 1983 - January 1991

23 April 1990

6 June 1990

13 June 1990

UNEP (2005), “One Planet Many People: Atlas of Our Changing Environment.”

Landslides

In early summer of 2004, a landslide in the Zaskar Mountains, a range of the Himalayas, created a natural dam blocking the Pareechu River in its course from the Tibet Autonomous Region of China to the Himachal Pradesh State of northern India. The dam is 35 km (22 miles) from India’s border with China. The water is slowly building behind the dam, creating an artificial lake in the remote mountain region. By 13 August, the lake had spread over 188 hectares and had reached a depth of 35 m (115 feet), with water levels rising daily.

UNEP (2005), “One Planet Many People: Atlas of Our Changing Environment.”

- climate variability related hazards

Tropical storm Jeanne struck the Island of Hispaniola on 18 September 2004; a wall of water and mud buried much of Gonaïves, Haiti as shown in this Ikonos imagery captured four days later, on 22 September 2004. Roads visible on 17 September 2000 image have disappeared, as have a number of buildings and adjacent farmlands submerged by water and mud. Note the damaged ship and changes in the water colour in the 22 September 2004 image.

Credit: Ikonos imagery provided on spaceimaging.com, courtesy of NASA's Earth Observatory

UNEP (2005), "One Planet Many People: Atlas of Our Changing Environment."

Conclusion

Classical geological approaches at a variety of scales and levels of resolution can be enhanced substantially with remote sensing techniques.

Combined remote sensing and ground-truthing is particularly important as geologic, seismicity and hydrologic data are crucial for the understanding of geological processes and determination of process-rates.

Monitoring ongoing processes and evaluating the remotely sensed data in terms of recurrence of events will eventually enhance our ability to assess and mitigate natural hazards.

But never forget ground-truthing!