Quantitative geomorphology in earth surface processes and tectonic analyses

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Talk layout

1. Basic concepts of geomorphology
2. Critical Zone
3. Earth Surface System Science
4. Tectonic Geomorphology (Examples)
Earth Surface Architecture : Geomorphology

Changing Paradigms

1. Evolutionary Geomorphology
   - Davisian Erosion Cycles / peneplain (Davis, 1840) (Footprints of Darwinian Evolution)
   - Time is a process
   - Questioned by Penk (1845) (Slope retreat / pediplain)

2. Process Geomorphology
   - Landforms achieve equilibrium between resisting forces and driving forces (Gilbert, 1918)
   - Triad : Process - Form – Time

3. Quantitative Dynamic Geomorphology
   - Drainage basin morphology (stream order, density etc.) (Horton, 1945, Strahler, 1952)
   - Newtonian mechanistic approach (stream power, fluvial erosion, diffusion/transport laws (Schumm, 1956, Melton, 1958)
   - Dynamic equilibrium approach (Tectonic geomorphology : Landform/Tectonics/Climate coupling)

4. Thermodynamic Geomorphology

5. Predictive Geomorphology
   - Earthcast ( extreme events – flood, landslide)
   - Mathematical morphology (Fractal, Spatio-temporal Geoscience Information System analysis)
   - Deterministic & Numerical models
   - Artificial Neuron Network (ANN)
Landscape evolution model of Davis (1840)

A. Initial Stage
B. Early Youth
C. Late Youth
D. Full Maturity
E. Late Maturity
F. Old Age
Landscape evolution: Davis vs Penk
Geomorphic Diversity

Geomorphic diversity comprises dynamic systems:

1. **Morphologic System (Form)** (e.g. Landform, hill-slope geometry, drainage system, soil system etc.)
2. **Cascading System (Flow)** (e.g. erosion, mass-flow, chemical flux etc.)
3. **Process-Response System** (e.g. process-product dynamics produce process-form domains)

These domains constitute the Earth Surface

3D aspect of Earth Surface: **CRITICAL ZONE**
The Critical Zone = the zone extending from the outer vegetation envelope to the lower limit of groundwater

Anderson et al., 2004
Factors driving critical zone development

\[ \Phi_{cz} = f (P_X, L_0, t) \]

\[ \Phi_{cz} = \text{Specific property of critical zone (e.g. soil type and structure)} \]

\[ P_X = \text{External energy (solar radiation) + mass flux (precipitation) + primary production (carbon cycle)} \]

\[ L_0 = \text{System state (e.g. relief, parent rock)} \]

\[ t = \text{Age of system} \]

(Jenny, 1961)
Critical zone energy balance

Energy flux balance equation:

\[ E_{CZ} = E_{ET} + E_{PPT} + E_{BIO} + E_{ELV} + E_{GEO} \text{ (W m}^{-2}\text{)} \]  
(Rasmussen et al, (2011))

- \( E_{CZ} \): Energy flux balance in critical zone
- \( E_{ET} \): Latent heat of evapotranspiration
- \( E_{PPT} \): Precipitation \times \text{specific heat of water} \times \text{temperature}
- \( E_{BIO} \): Net biomass production \times \text{biomass enthalpy}
- \( E_{ELV} \): Potential energy of regolith \times \text{mass of regolith}
- \( E_{GEO} \): Gibbs energy of mineral transformation reaction in regolith

Energy flux balance (\( E_{CZ} \)) controls the composition and structure of the critical zone.
Critical Zone Interfaces

1. Landscape - atmosphere
2. Landscape - surface water
3. Soil – vegetation
4. Soil - bedrock
5. Vadose zone – groundwater
6. Microbe – soil/bedrock

- The interface dynamics controls Critical Zone geometry and composition
- Critical Zone is a timed memory of the past and present biosphere-geosphere dynamics.
- Interface dynamics and fluxes of critical zone control earth-surface architecture and produce Earth-Surface System
Earth Surface System
Hill-slope as a geomorphic system
Hill-slope dynamic system
Earth Surface : System Approach

System characters

1. **Nonlinearity**
   - System output (or response) is not proportional to input (or forcing)
   - Possess self-organised criticality (SOC) producing geopatterns caused by system’s internal dynamics without external forcing
   - Attain dynamic equilibrium until SOC is reached
   - SOC defines system disturbance that separates two sub-systems
2. Fractal geometry

- Many landscapes show fractal pattern, power-law scaling and evolve self-similarly (Evolutionary Geomorphology (cf. Phillips, 2006)

- If landscape morphology follows Chaos theory simple perturbation (Butterfly effect) can cause complex geopatterns and drastic response (catastrophe) in non-linear manner

- This makes prediction/forecasting (Earthcast) of extreme events (e.g. flood, landslide etc) difficult. Mathematical morphologic analysis may help earthcasting.
Thermodynamics of Earth-Surface System

1. Mass Balance
   \[
   \frac{dM}{dt} = M_{in} - M_{out} = 0 \text{ (Steady-state)}
   \]
   \[
   = \text{Positive (Aggradation)}
   \]
   \[
   = \text{Negative (Degradation)}
   \]
   
   where  \( M = \) Mass of system
   
   \( M_{in} = \) Mass input
   
   \( M_{out} = \) Mass output

   Law of mass conservation controls basin storage & mass flux which controls threshold parameters of the system

2. Entropy Balance
   \[
   dG = dH - TdS
   \]
   where  \( dG = \) Free energy change
   
   \( dH = \) Enthalpy change
   
   \( dS = \) Entropy change
   
   \( T = \) Temperature
Entropy balance in Earth-surface System (ESS)

- In geomorphology, Scheidegger (1970) suggested:
  \[ T \text{ (temp.)} = h \text{ (height)} \]
  \[ H \text{ (enthalpy)} = M \text{ (mass)}, \]
  Entropy balance equation becomes \[ dS = \frac{dM}{h} \]

- Kleidon et al. (2013) modified the entropy balance equation:
  \[ G \text{ (free energy)} = A \text{ (potential + kinetic energy of water and sediment)} \]
  Entropy balance equation becomes \[ dS = - \frac{dA}{T(h)} \]

Inferences:
All natural processes are Max. Entropy Production (MEP) process
So: 1. Free energy of Earth-Surface System (ESS) decreases with time
   2. MEP happens if mass of ESS increases and/or height is reduced
   3. MEP happens if free energy of ESS decreases
   4. MEP causes chaos/disorder of ESS to increase, ESS becomes increasingly nonlinear and unpredictable
Two important system state conditions

1. Threshold
   - Intrinsic (variability absorbed by the system (e.g. stream gully formation))
   - Extrinsic (external forcing creating permanent change in the system) (e.g. climate change, tectonics)

2. Equilibrium
Types of equilibrium in Earth Surface System

(Chorley & Kennedy, 2002)
Evolutionary Geomorphic System in dynamic equilibrium

State change at SOC (MEP, Nonlinearity, Disorder increases)

Evolutionary Geomorphic System in dynamic equilibrium

Forcing / Stimulus (natural or anthropogenic)

Threshold Birfurcation point SINGULARITY

New System Regime

Multiple system pathways possible. Exact pathway to be decided by forcing parameters at singularity

New threshold

(Sinha-Roy, 2012)
Tectonic forcing

- Tectonic forcing makes geomorphic systems to cross thresholds and change equilibrium dynamics
- Therefore, geomorphic systems record and preserve signatures of tectonic features, their degree and scale of activity
- Response of drainage systems and landforms to tectonic forcing is relatively quick and definitive
- Quantitative geomorphology for neotectonic and active deformation studies deals mainly with fluvial systems and their products in terms of Tectonic Geomorphic Indices.
- I discuss 10 geomorphic attributes linked with tectonic forcing in landform system
GBF and BDZ Traces
1. Longitudinal River Profiles

Longitudinal profile of streams
(SECTOR - 1)

Banas River

Khari River

Banas - 1

Banas - 2

Banas - 3

Banas - 4

Banas - 5

Banas - 6

Mej River

Mej - 1

Sinha Roy, 2006
Normalised longitudinal river profile

\[ \Delta H_i / \Delta H \]

Distance

Elevation

\[ H_{\text{max}} \]

\[ E_r \]

\[ E_r = \text{Profile integral} \]

\[ H_{\text{max}} = \text{Maximum profile curve concavity} \]
Normalised longitudinal river profile and its relation with river gradient

Fig. 2. Normalised longitudinal profiles (solid thick lines) and along-river gradients (broken lines) of the studied rivers. Arrows indicate confluence of major tributaries.

Sinha-Roy, 2001
Hypothetical longitudinal river profile showing methodology of recognising neotectonic fault-block movement.
FAULT GEOMETRY AND BLOCK MOVEMENT PATTERN DEDUCED FROM LONGITUDINAL RIVER PROFILE

Figure 16

Sinha-Roy, 2006
Longitudinal river profiles showing position of knckpoints and stages of incision
Neotectonic blocks uplifted at different phases deduced from stream incision phases downstream of knickpoints and corresponding upstream uplift (SECTOR - 1)

INDEX

- Knickpoint
- Faults deduced from knickpoint joins
- Phase I uplift (oldest)
- Phase II uplift
- Phase III uplift (youngest)

GBF: Great Boundary Fault
BDZ: Banas Dislocation Zone

Incision phases deduced from knickpoints

III - Incision phase (Youngest)

II - Incision phase (Youngest)

I - Incision phase (Youngest)

III - Uplift phase (Youngest)
Total stream incision and fault controlled uplift of drainage basins from knickpoints (SECTOR - 1)

INDEX (m)
- U - Uplifted block (Youngest uplift on fault defined by highest (youngest) knickpoint
- Major faults drawn through the youngest (highest) knick points that caused upstream block uplift (shown by U)
- Knickpoints
- GBF : Great Boundary Fault
- BDZ : Banas Dislocation Zone

Basins showing total incision at stream outlet from highest (youngest) knickpoint
- < 10
- 11 - 30
- 31 - 50
- 51 - 70
- > 70

Sinha-Roy, 2013
2. Hypsometry

Ea = Hypsometric integral
Eh = Maximum concavity of the curve
I = Curve slope inflection point
Examples of normalised hypsometric curves

Sinha-Roy, 2002
Hypsometry and relative terrain uplift

\[ U = Z + Qs \]

- **U** = Terrane uplift
- **Z** = Elevation
- **Qs** = Mass efflux (both advective & diffusive)

Replace **Z** by \( h_m \) (mean elevation i.e. Elevation covering 50% area normalized against max. height)

Replace **Qs** by \( (1 - E_a) \) (where \( E_a \) = Hypsometric Integral)

Uplift equation becomes:

\[ U = h_m + (1 - E_a) \]

Hypsometry of relative terrane uplift

- Low relative uplift, high denudation
- Steady state landform
- High relative uplift, low denudation
Blocks of relative terrane uplift deduced from drainage basin hypsometry (Sector- 1)

Relative Uplift (U) Index

- ≤ 0.90
- 0.91 – 0.96
- 0.97 – 1.02
- 1.03 – 1.08
- ≥ 1.08

Normal Fault

Sinha-Roy, 2013
3. Topographic Profiles and Planation Surfaces

Topographic Profiles and Planation Surfaces (SECTOR - 1)

Profile A - B

Profile C - D

Profile E - F

INDEX

- Topographic Profile
- Planation surface
- (GBF) Great Boundary Fault
- (BDZ) Banas Dislocation Zone
- Other Faults

Sinha-Roy, 2013
4. Stream Sinuosity Index

\[ S = \frac{SL}{L} \]

Where
- \( S \) = Stream Sinuosity Index
- \( L \) = Straight line distance of stream
- \( SL \) = Actual distance along the stream

\( S > 1.0 \) High tectonic activity
(Slope-steepening due to fault)
Fault demarcated from stream sinuosity and stream gradient changes
(SECTOR - 1)

INDEX

- Dotted lines: Faults demarcated on stream sinuosity change
- Solid lines: Faults demarcated on stream gradient change
- Dashed lines: Faults deduced from planation surface attitude
- Block tilt direction derived from stream sinuosity
- Block tilt direction derived from planation surface attitude
- Knick points

N: Normal fault
R: Reverse fault
GBF: Great Boundary Fault
BDZ: Banas Dislocation Zone

Sinha-Roy, 2013
5. Drainage Basin Asymmetry

\[ AF = 100 \left( \frac{Ar}{At} \right) \]

where
AF = Drainage basin asymmetry
At = Total basin area
Ar = Basin area on right bank

Lower the value of AF higher is the tectonic tilting

Channel migration and abandoned channels of Mangli river on GBF Footwall
6. Drainage Basin Relief Ratio

\[
RR = \frac{(Ed - Ev)}{L}
\]

Where
- \(RR\) = Relief ratio
- \(Ed\) = Elevation of the highest point
- \(Ev\) = Elevation of the lowest point
- \(L\) = River length

Higher the RR value higher is the incision at river mouth due to tectonically controlled basin uplift
8. Stream Length Gradient Ratio

\[ SL = \frac{\Delta H}{\Delta L} \]

where

\( SL = \) Stream length gradient ratio
\( \Delta H = \) Change of elevation of reach (A-B)
\( \Delta L = \) Length of reach
\( L = \) Total length of the channel from \( \Delta L \) mid-point of the reach where the index is calculated to the highest point of the channel

\[ SL = \begin{cases} < 50 : & \text{very low tectonic activity} \\ > 200 : & \text{very high tectonic activity} \end{cases} \]
9. Valley Floor Width to Height Ratio

\[ Vf = \frac{2Vfw}{(Eld - Esc) + (Erd - Esc)} \]

Where
- Vf = Valley floor width to height ratio
- Vfw = Width of the valley floor
- Eld = Elevation of left-hand valley divide looking downstream
- Erd = Elevation of right-hand valley divide looking downstream
- Esc = Elevation of stream channel (valley floor)

Vf = < 1.0 : Very high tectonic activity (V-shaped valley)
   = 1.0 – 1.5 : Moderate tectonic activity
   = > 1.5 : Low tectonic activity (U-shaped valley)
Deciphering reactivation of old faults using Smf, SL and Vf indices

Tectonic Activity Rank (TAR) of indices

(Smf : >3.0 = very low, <1.4 = very high.
SL : <50 = very low, >200 = very high,
Vf : >1.5 = very low, <1.0 = very high

Relative Tectonic Activity (RTA)

(RTA = Sum of TAR / Total no. of geomorphic indices used)
5 RTA classes: very low (<1.5), low (1.5-2.0), moderate (2.0-2.5), high (2.5-3.0), very high (>3.0)
Segments (numbered) of Great Boundary Fault and Banas Dislocation Zone used for Smf, SL, Vf estimation for comparison of Relative Tectonic Activity
Variation of Relative Tectonic Activity along Banas Dislocation Zone

Distance from SW end of BDZ toward NE

(Km)

Segment-1
Segment-2
Segment-3
Segment-4
Segment-5
Segment-6

Relative Tectonic Activity Class

Sinha-Roy, 2013
Variation of Relative Tectonic Activity along Great Boundary Fault
Comparison between Relative Tectonic Activity along Great Boundary Fault and Banas Dislocation Zone based on Smf, SL and Vf data

Sinha-Roy, 2013
Relative neotectonic activity in segmented Great Boundary Fault and Banas Dislocation Zone deduced from Smf, SL, Vf in relation to major faults inferred from other geomorphic indices and space imagery study.
10. Fault Scarp

Fault Scarp Geometry

Extensional component of fault

\[ e = \frac{d}{\tan \theta} \] (Wikins & Schultz, 2001)

Where
- \( e \) = Extension (m)
- \( d \) = Fault scarp surface offset
- \( \theta \) = Scarp mid-slope angle

Morphogenic dating of fault scarp
\[ \tan \theta = \frac{a}{\sqrt{\pi \tau}} + b \] (Avouac, 1993)

Where
- \( \theta \) = Midslope angle
- \( a \) = Half scarp surface offset
- \( b \) = \( \tan \) of upslope angle
- \( \tau = kt \) (where \( k \) = coefficient of mass diffusion, \( t \) = oldest age of scarp formation (faulting)

(k in tropical climate = 5 sq. m per yr)
Segmented nature of fault reactivation deduced from morphogenic age of fault-scarps

Morphogenic age (ka) of fault scarp (fault reactivation oldest age)

- Blue: < 2
- Orange: 2 - 30
- Purple: 30-100
- Light purple: 100-300
- Green: 300-600
- Red: > 600

Sinha-Roy, 2013
Shear system related to transpressional
Great Baudnary Fault and Banas Dislocation Zone

INDEX

PDZ (Principal Displacement Zone, GBF, BDZ Transpression Zones)
R(Reidal Synthetic Shear)
R'(Reidal Antithetic Shear)
P Synthetic Shear
Y Synthetic Shear

GBF : Great Baudnary Fault
BDZ : Banas Dislocation Zone

Sinha-Roy, 2013
Geotectonic conclusion from quantitative geomorphology
Thank you