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)

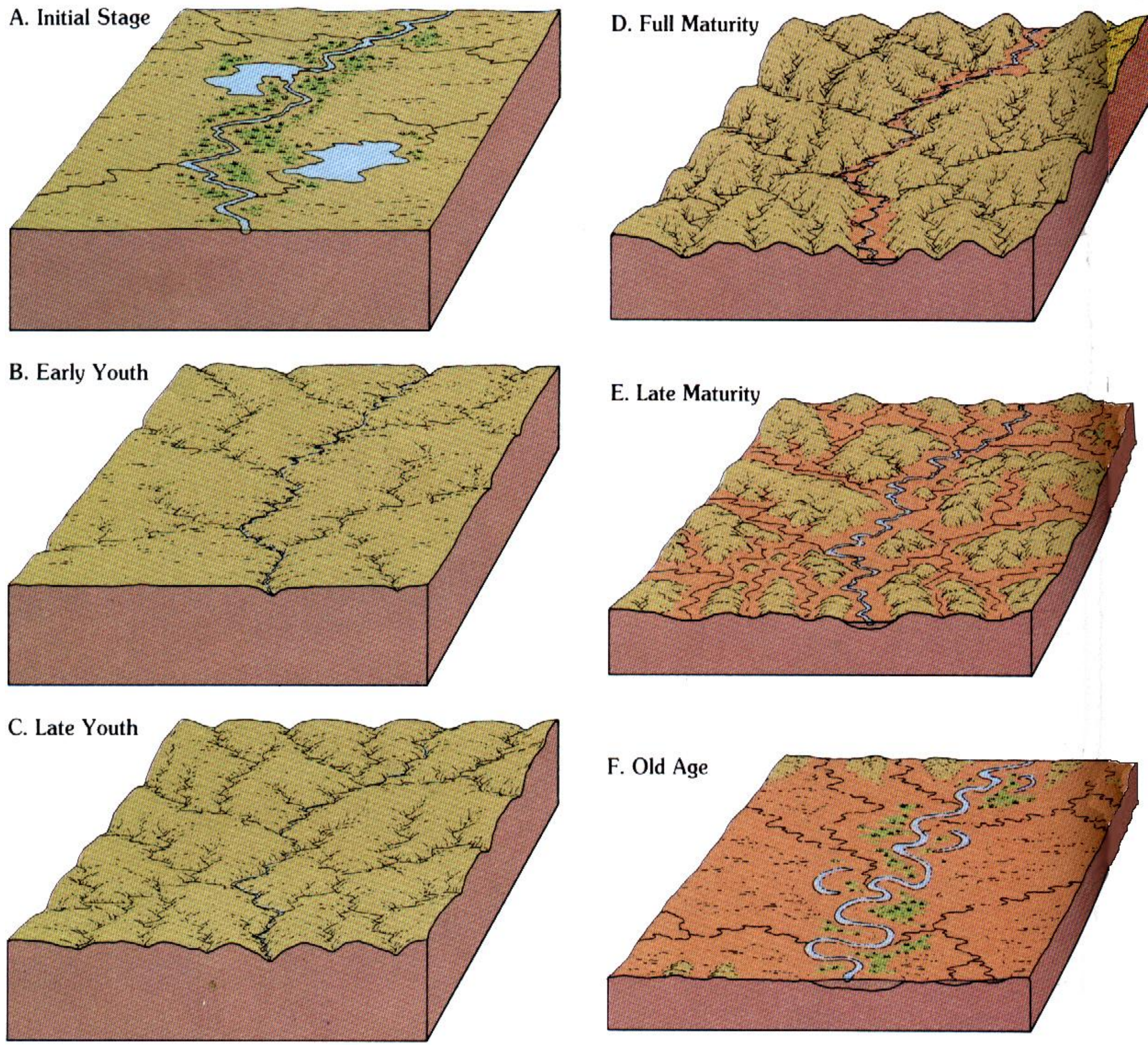
4. Thermodynamic Geomorphology

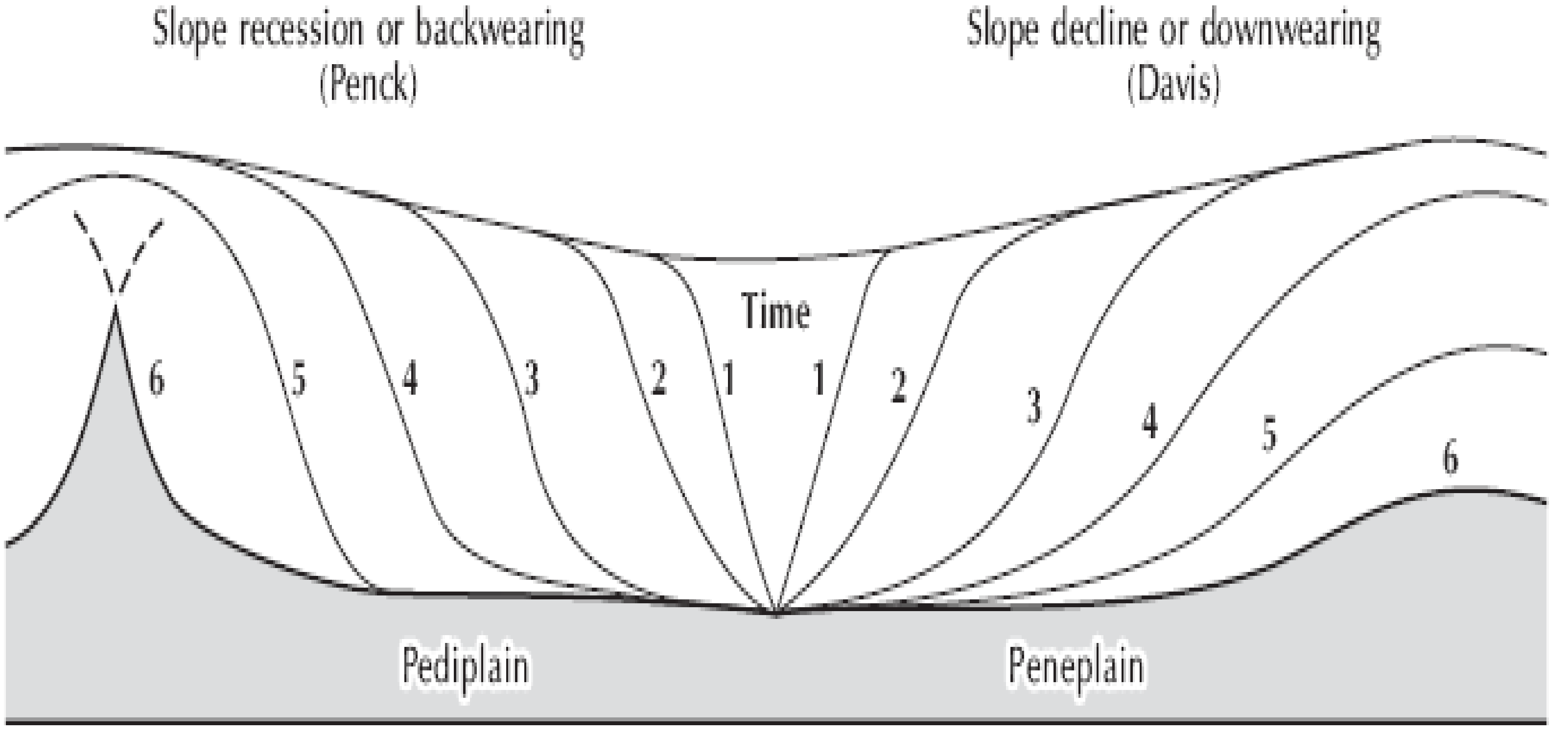
- Entropy concept (Leopold & Longbein, 1962, Scheidegger, 1970, Hugget, 2007)

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)





Landscape evolution : Davis vs Penk

Geomorphic Diversity

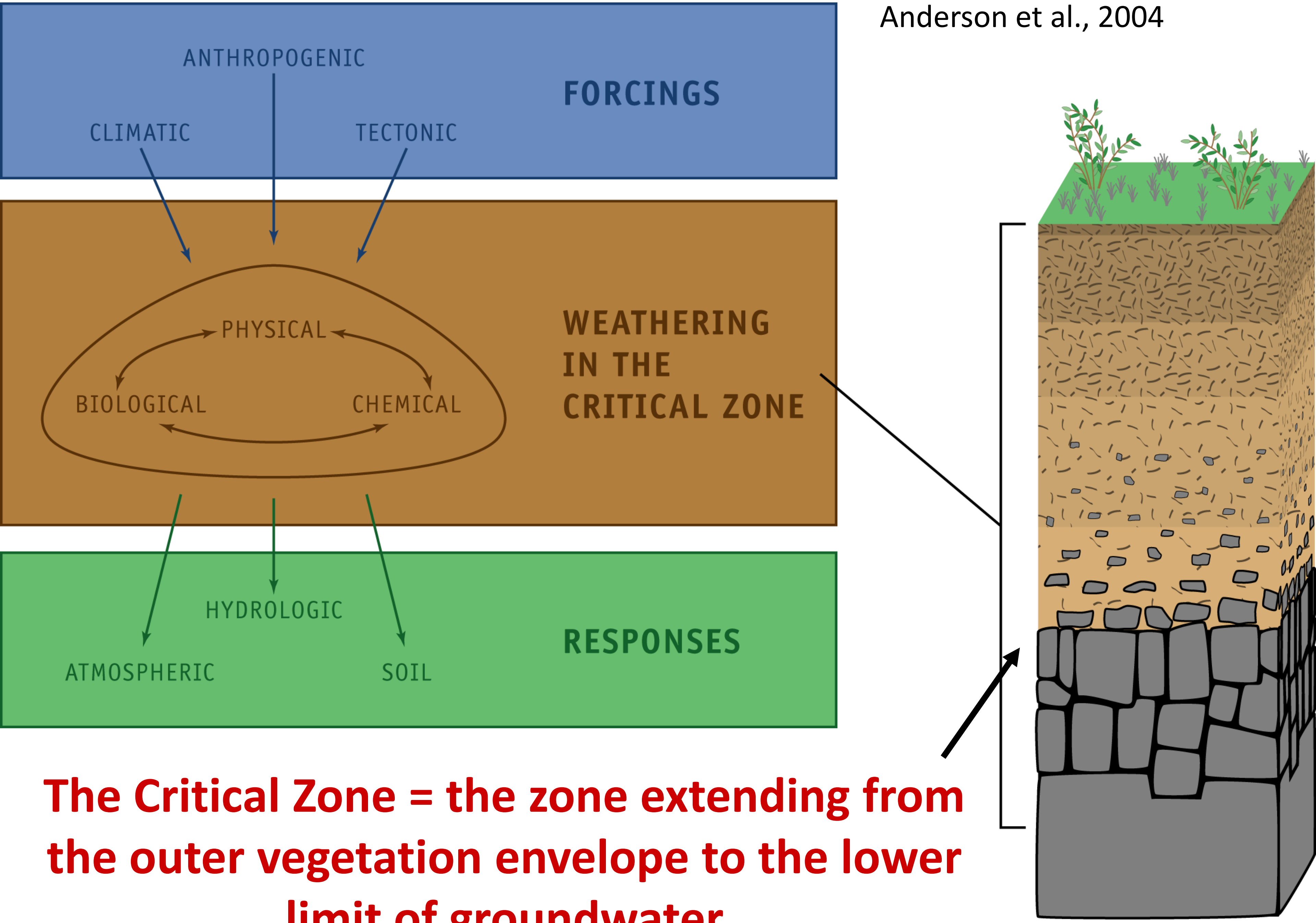
Geomorphic diversity comprises dynamic systems :

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)

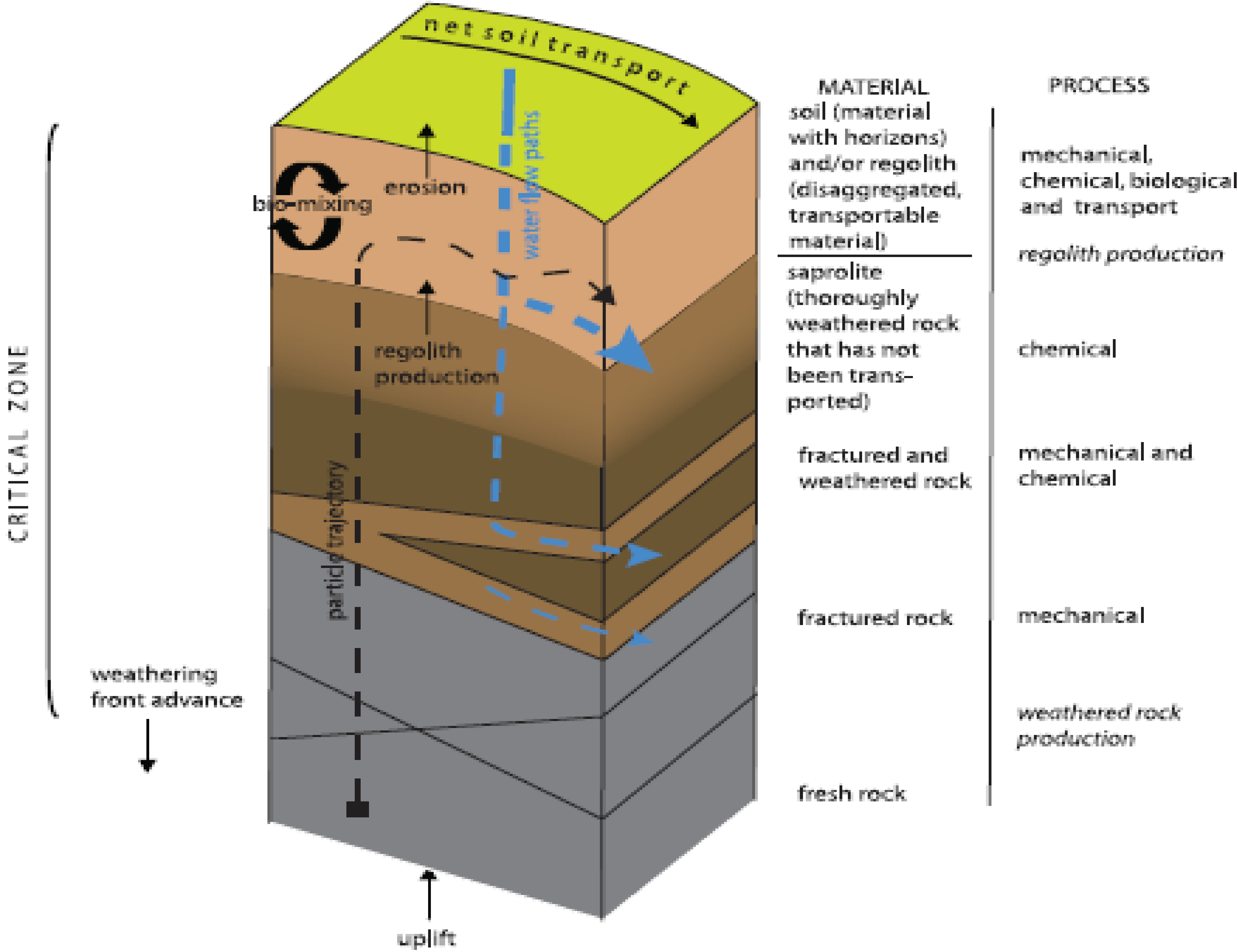
These domains constitute the Earth Surface

3D aspect of Earth Surface : CRITICAL ZONE

Anderson et al., 2004



The Critical Zone = the zone extending from the outer vegetation envelope to the lower limit of groundwater


net soil transport
water flow paths
bio-mixing
erosion
regolith production
particle trajectory
CRITICAL ZONE
weathering front advance
uplift
MATERIAL
soil (material with horizons) and/or regolith (disaggregated, transportable material)
saprolite (thoroughly weathered rock that has not been transported)
fractured and weathered rock
fractured rock
fresh rock
PROCESS
mechanical, chemical, biological and transport
regolith production
chemical
mechanical and chemical
mechanical
weathered rock production

Factors driving critical zone development

$$\mathbf{\Phi_{CZ} = f\,(P_X, L_O, t)}$$

Φ_{cz} = Specific property of critical zone (e.g. soil type and structure)

P_X = External energy (solar radiation) + mass flux (precipitation) + primary production (carbon cycle)

L_O = System state (e.g. relief, parent rock)

t = Age of system

(Jenny, 1961)

Critical zone energy balance

Energy flux balance equation :

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

E_{CZ} = Energy flux balance in critical zone
E_{ET} = Latent heat of evapotranspiration
E_{PPT} = Precipitation X specific heat of water X temperature
E_{BIO} = Net biomass production X biomass enthalpy
E_{ELV} = Potential energy of regolith X mass of regolith
E_{GEO} = Gibbs energy of mineral transformation reaction in regolith

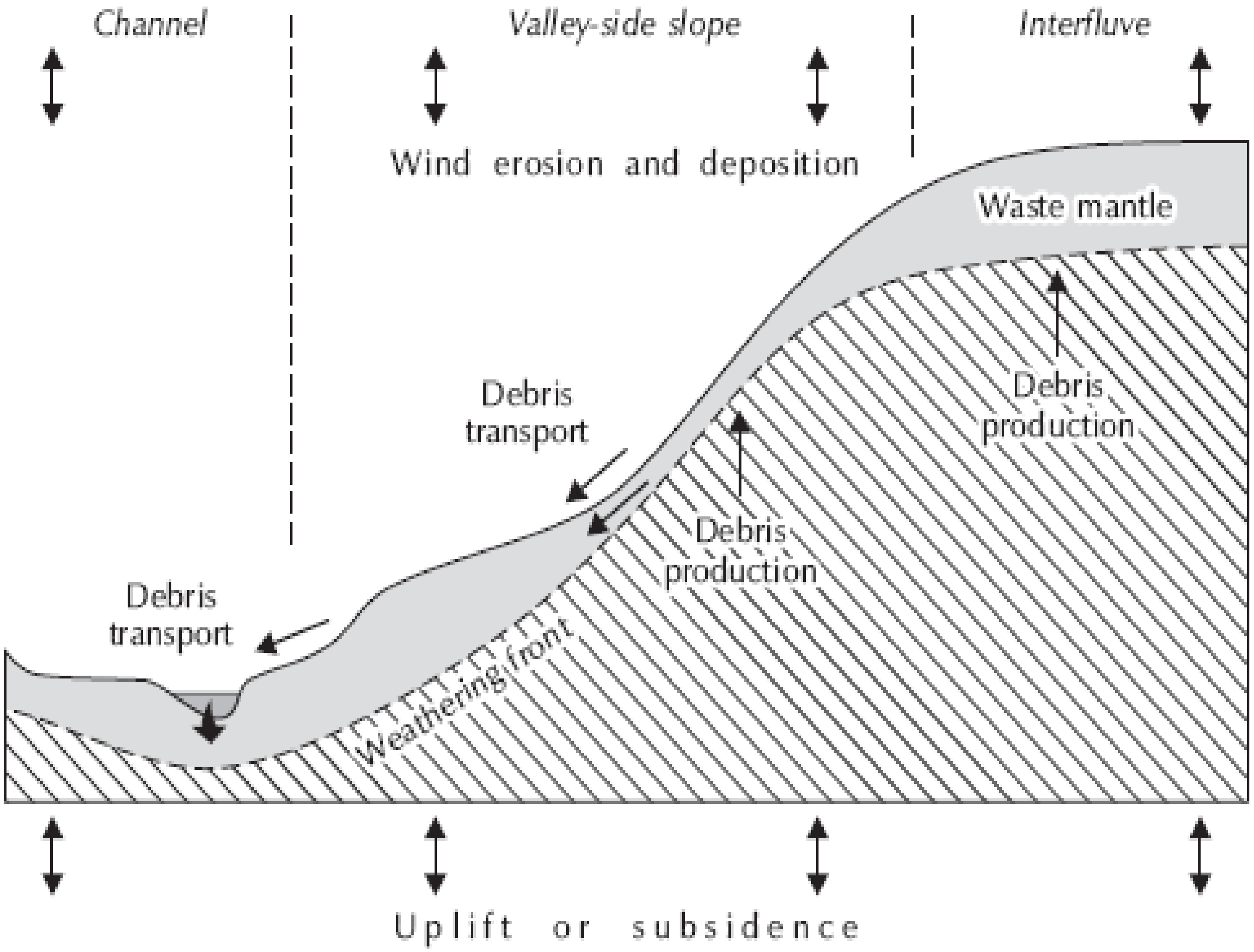
Energy flux balance (E_{CZ}) controls the composition and structure of the critical zone

Critical Zone Interfaces

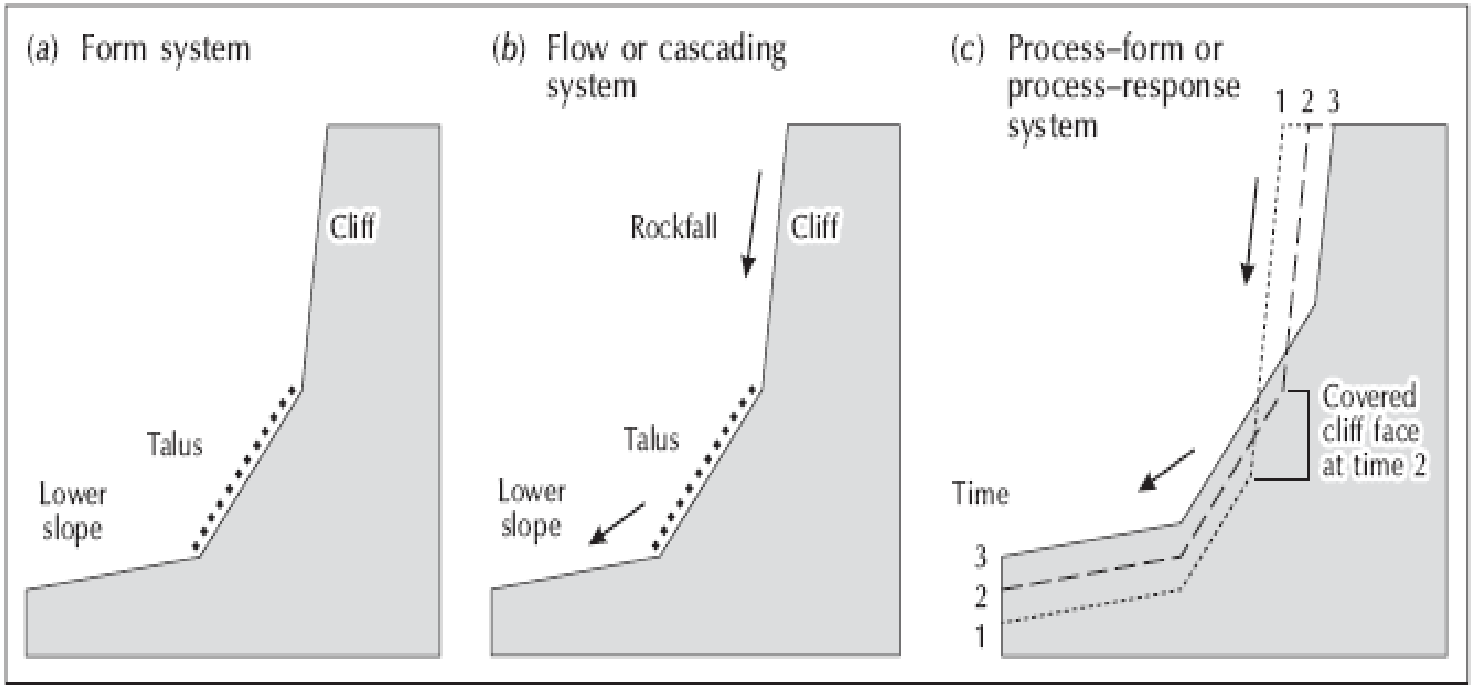
1. Landscape - atmosphere
2. Landscape - surface water
3. Soil – vegetation
4. Soil - bedrock
5. Vadose zone – groundwater
6. Microbe – soil/bedrock

- 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

$dM / dt = M_{in} - M_{out}$ = 0 (Steady-state)

= Positive (Aggradation)

= 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 (temp.) = h (height)
  H (enthalpy) = M (mass),

Entropy balance equation becomes dS = dM/h

- **Kleidon et al (2013) modified the entropy balance equation :**
  G (free energy) = A (potential + kinetic energy of water and sediment)

Entropy balance equation becomes dS = - 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

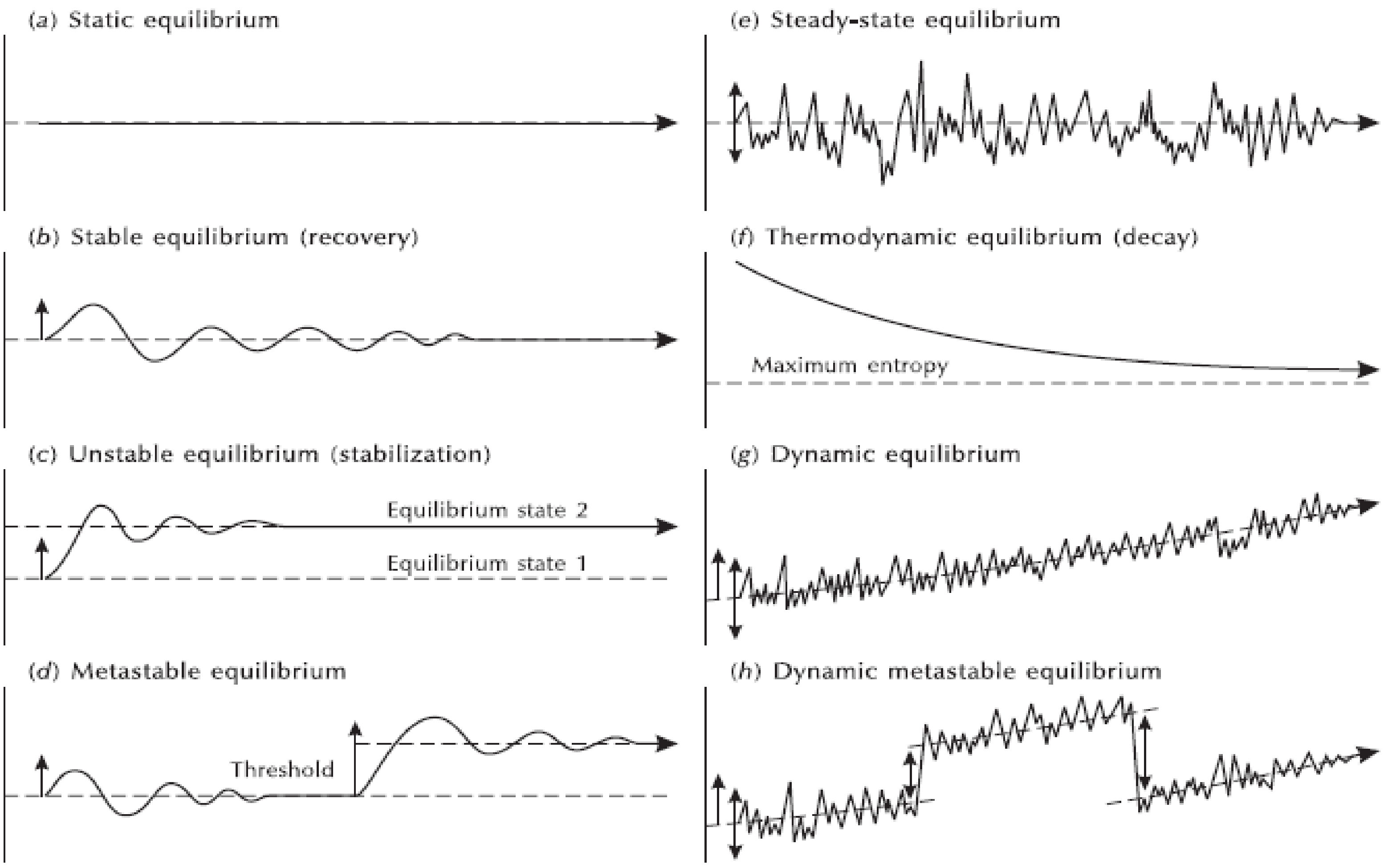
Earth-Surface System (ESS)

Two important system state conditions

1. Threshold

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

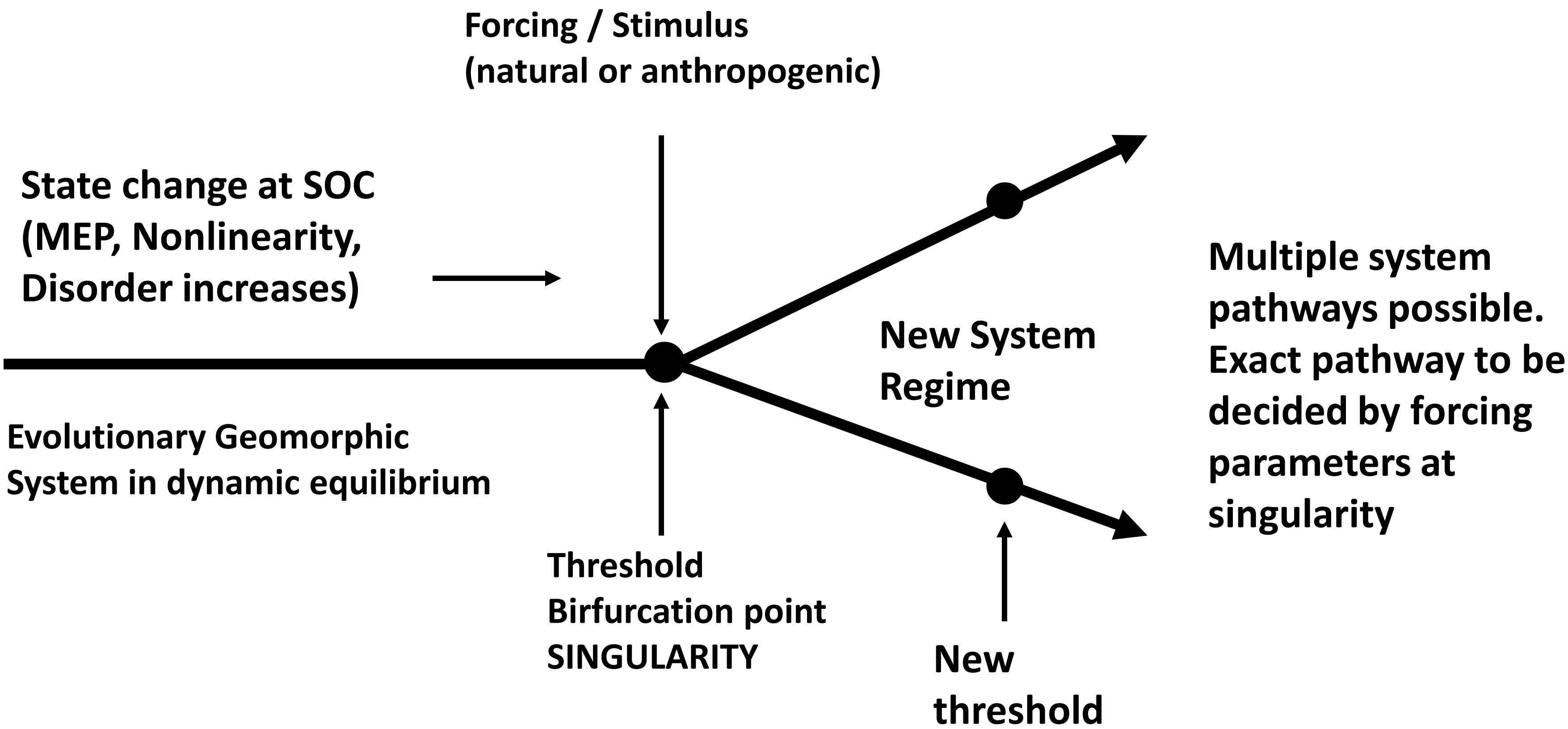
2. Equilibrium



Types of equilibrium in Earth Surface System

(Chorley & Kennedy, 2002)

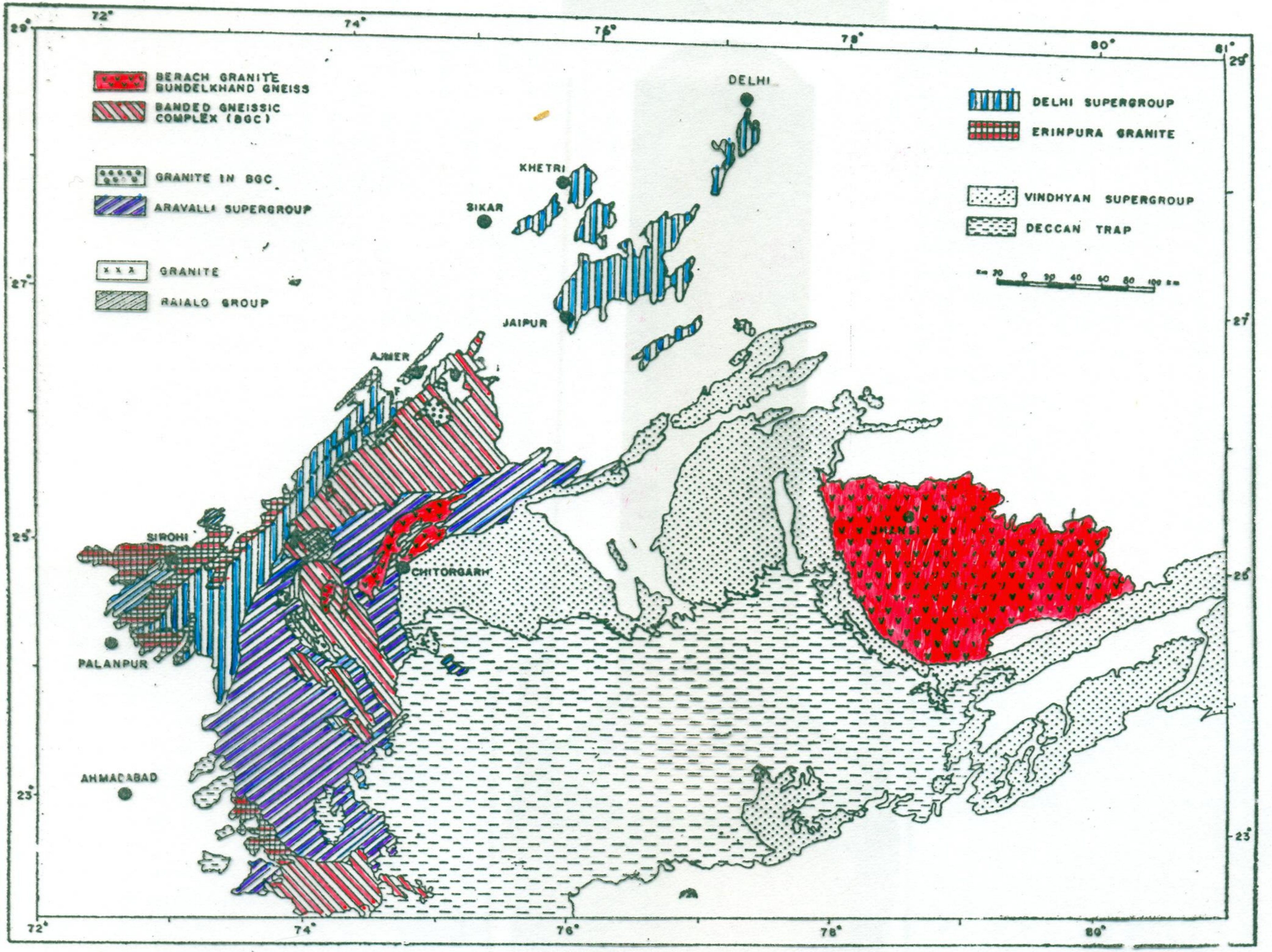
Evolutionary Earth Surface System under forcing



(Sinha-Roy, 2012)

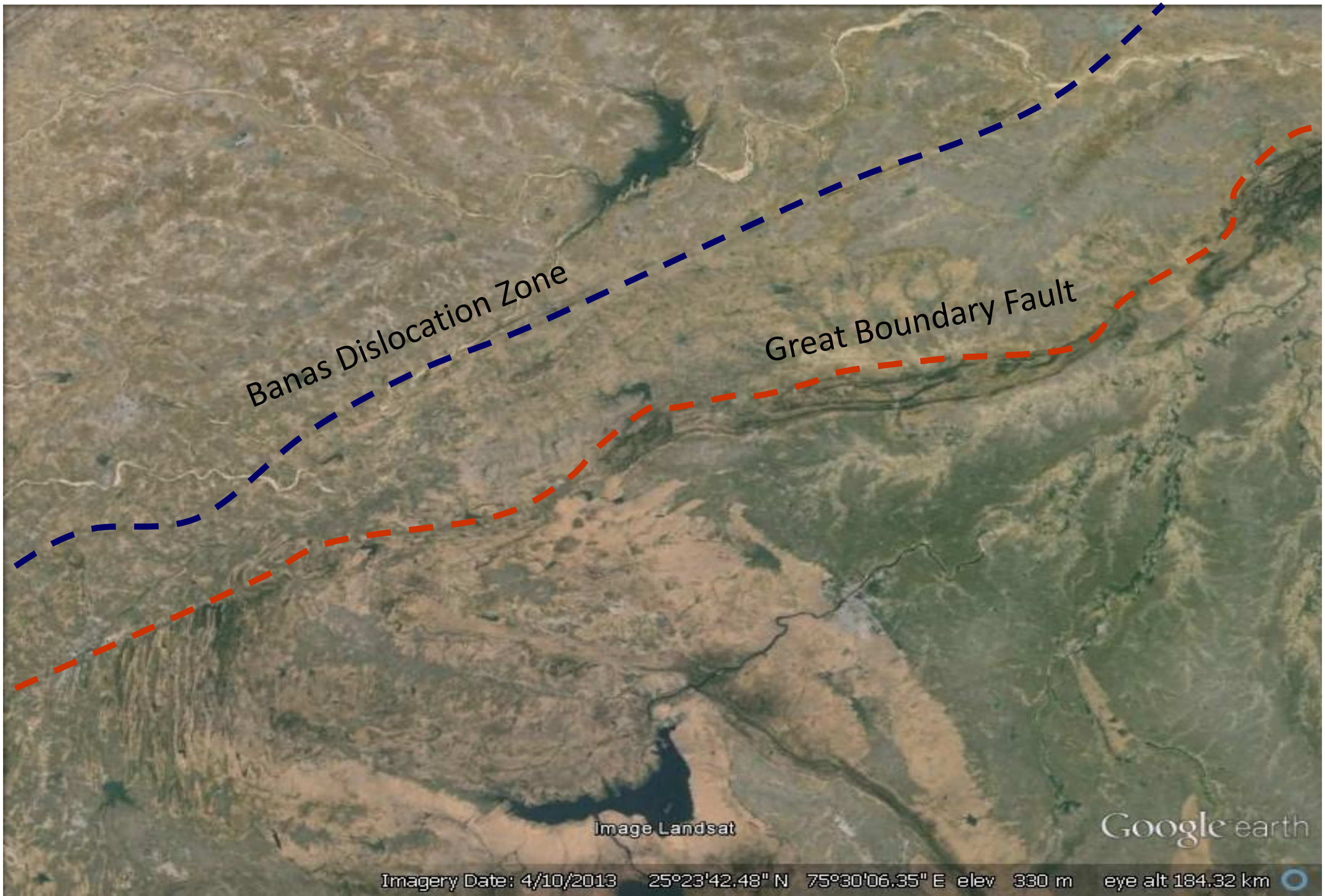
Tectonic forcing

- 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

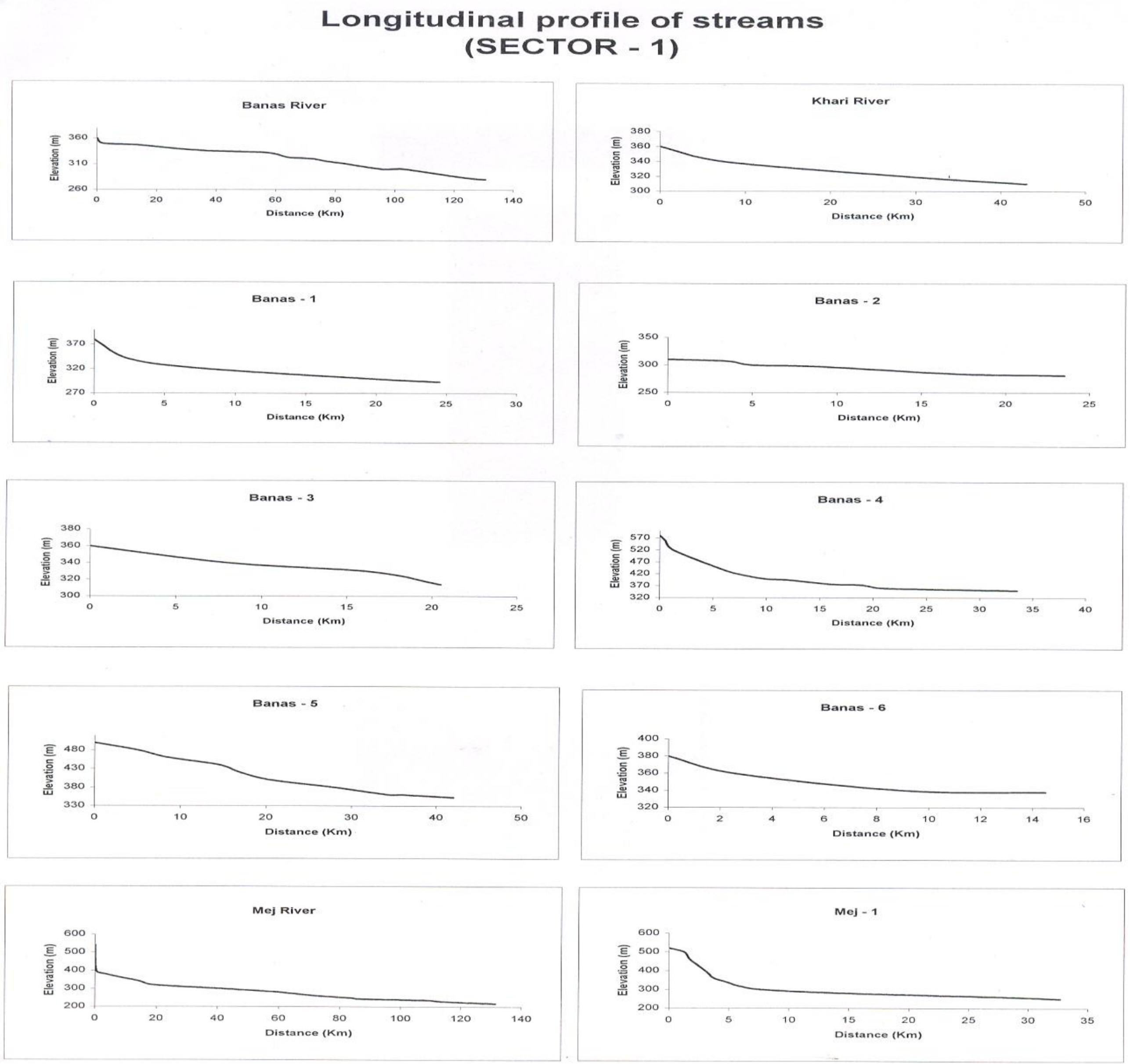


BERACH GRANITE
BUNDELKHAND GNEISS
BANDED GNEISSIC COMPLEX (BGC)
GRANITE IN BGC
ARAVALLI SUPERGROUP
GRANITE
RAIALO GROUP
DELHI SUPERGROUP
ERINPURA GRANITE
VINDHYAN SUPERGROUP
DECCAN TRAP
DELHI
KHETRI
SIKAR
JAIPUR
AJMER
SIROHI
CHITORGARH
JHANSI
PALANPUR
AHMADABAD
72°
74°
76°
78°
80°
81°
29°
27°
25°
23°

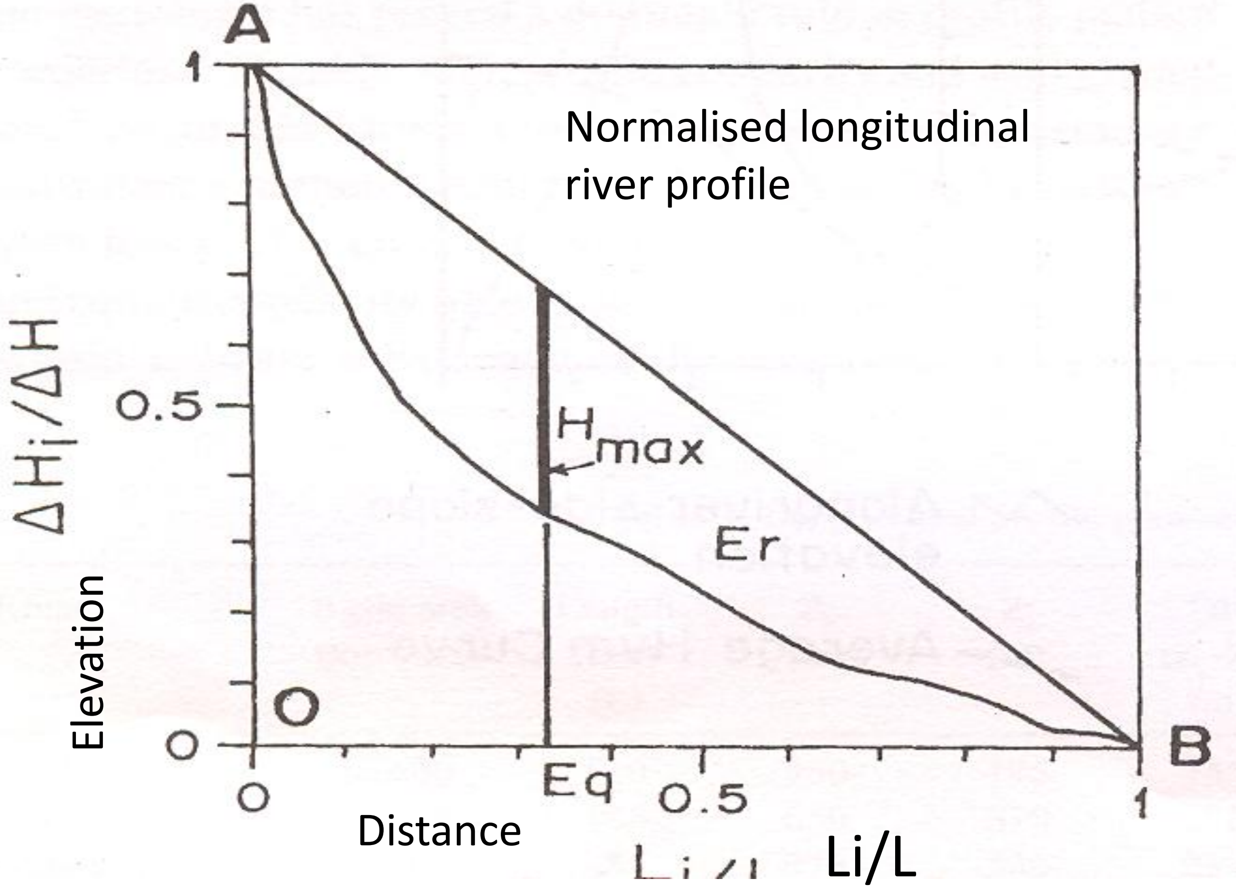
GBF and BDZ Traces



1. Longitudinal River Profiles



Sinha Roy, 2006



Er = Profile integral
Hmax = Maximum profile curve concavity

Normalised longitudinal river profile and its relation with river gradient

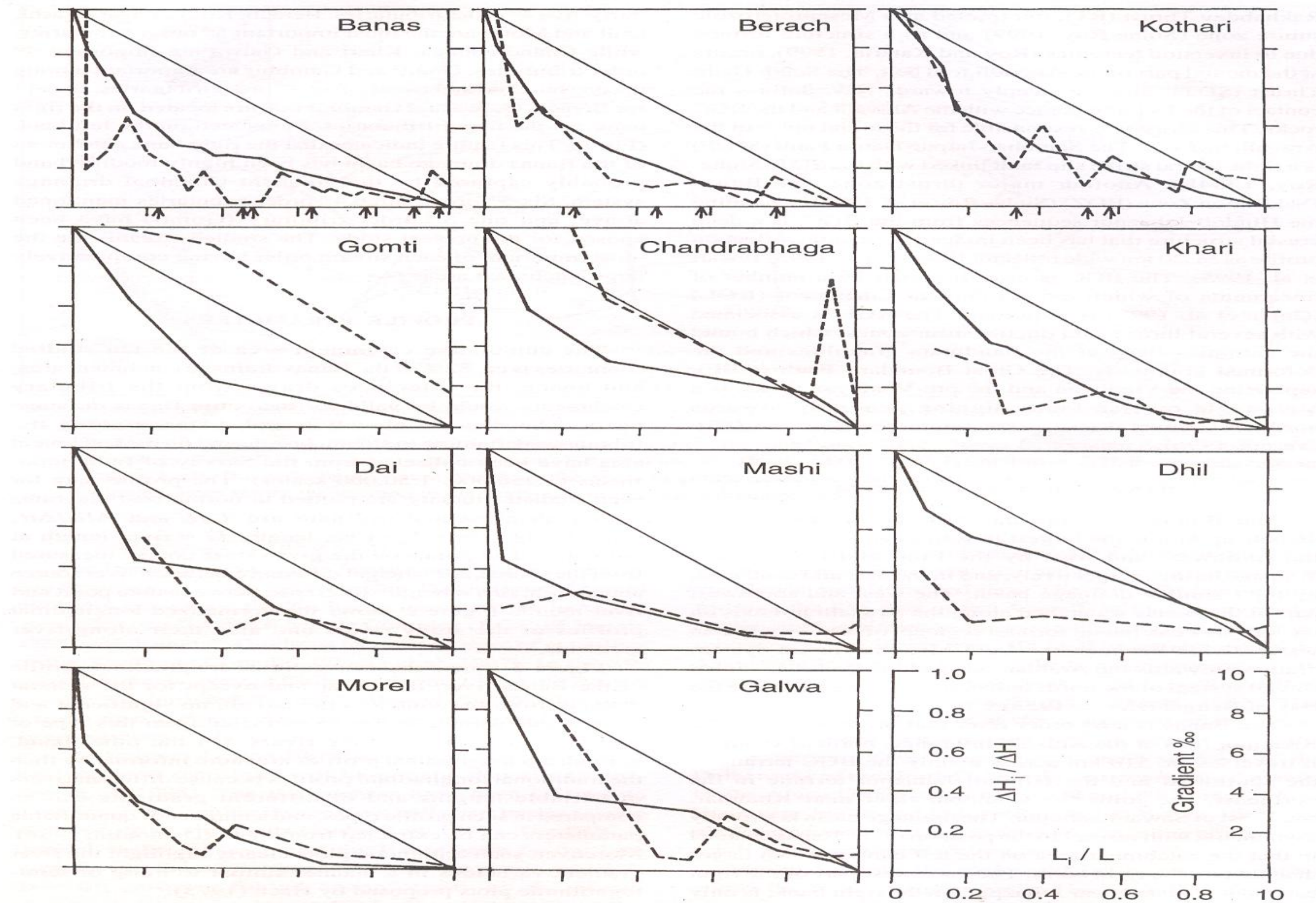
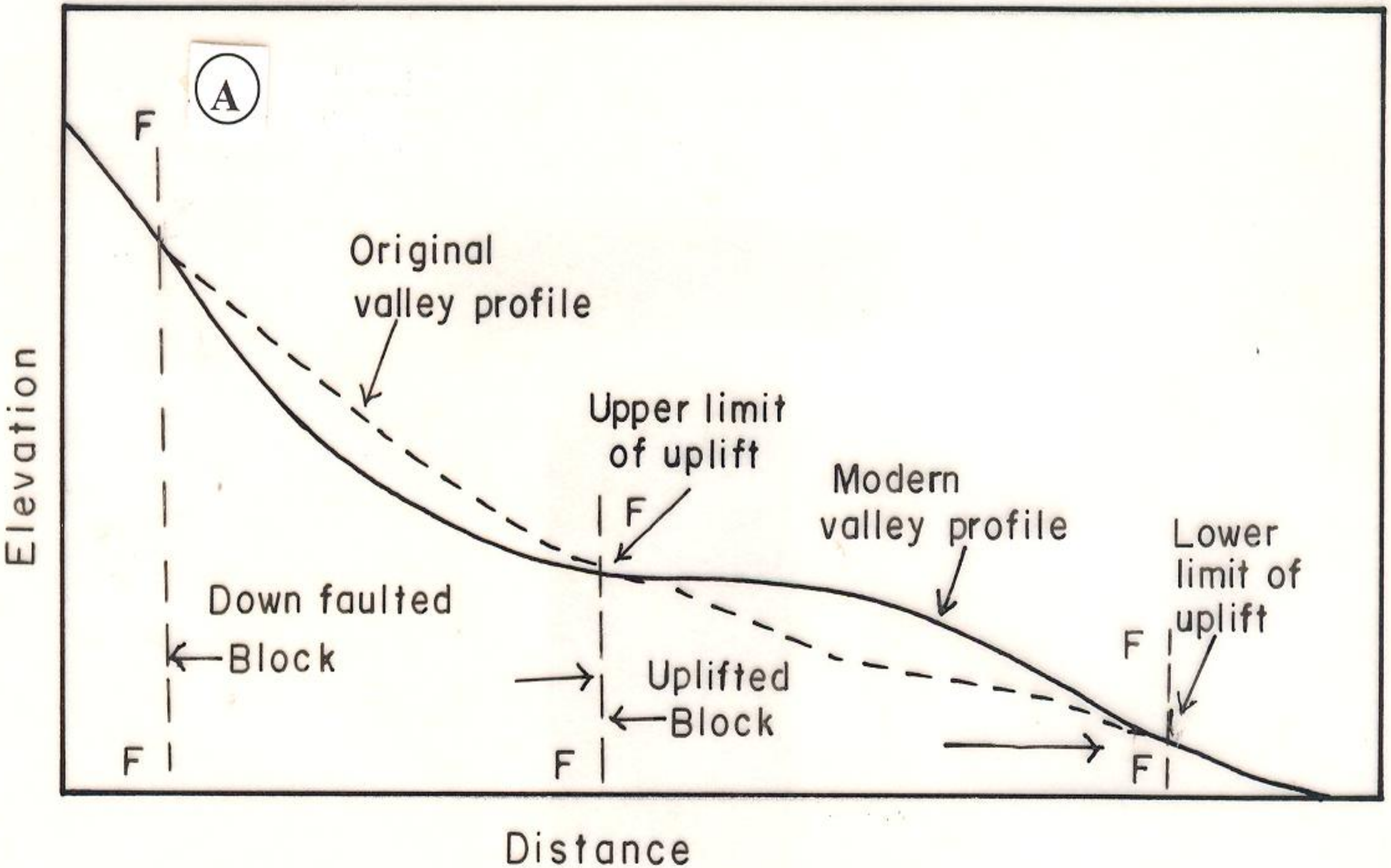


Fig.2. Normalised longitudinal profiles (solid thick lines) and along-river gradients (broken lines) of the studied rivers. Arrows indicate confluence of major tributaries.

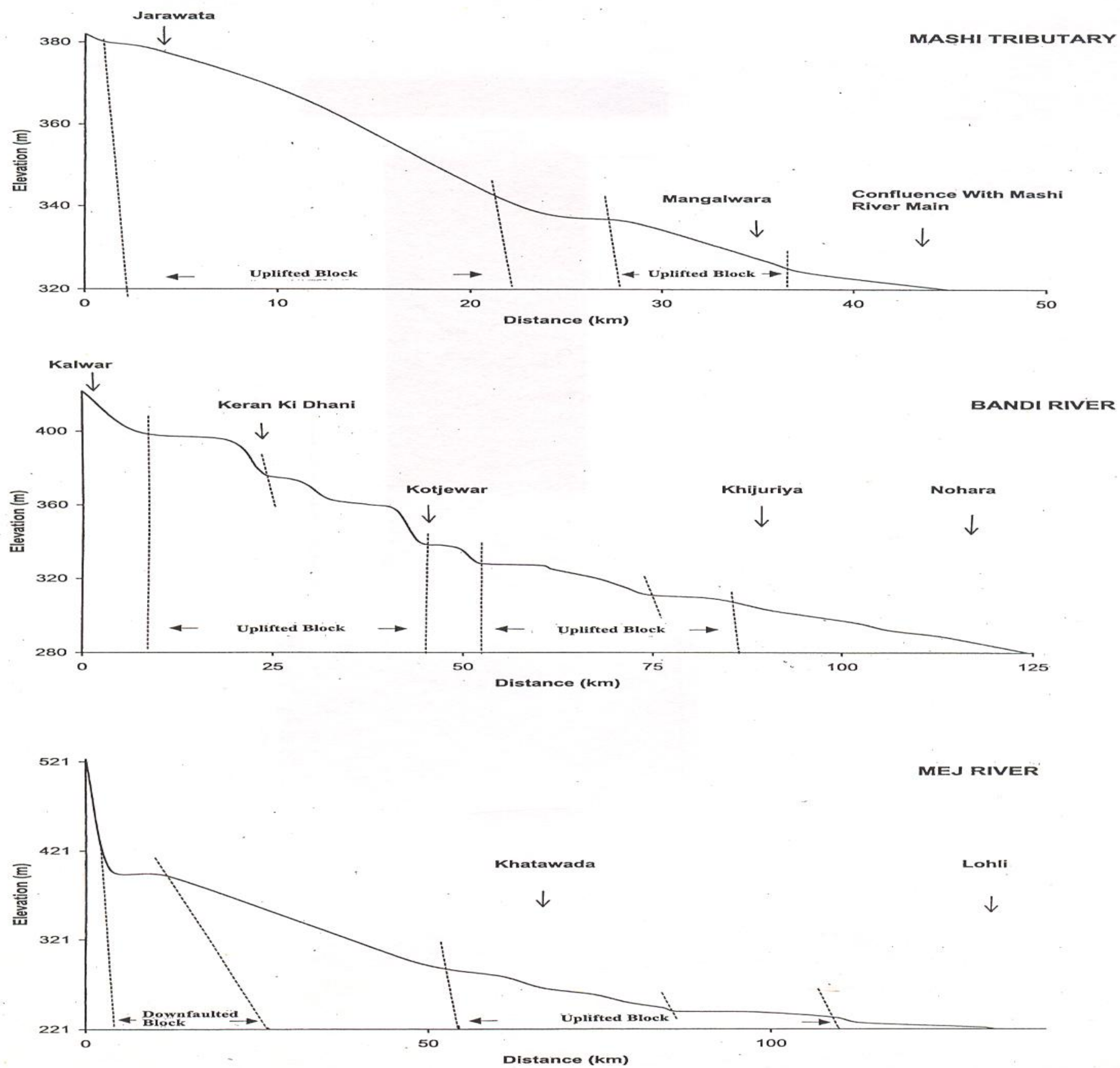
Sinha-Roy,2001

Hypothetical longitudinal river profile showing methodology of recognising neotectonic fault-block movement



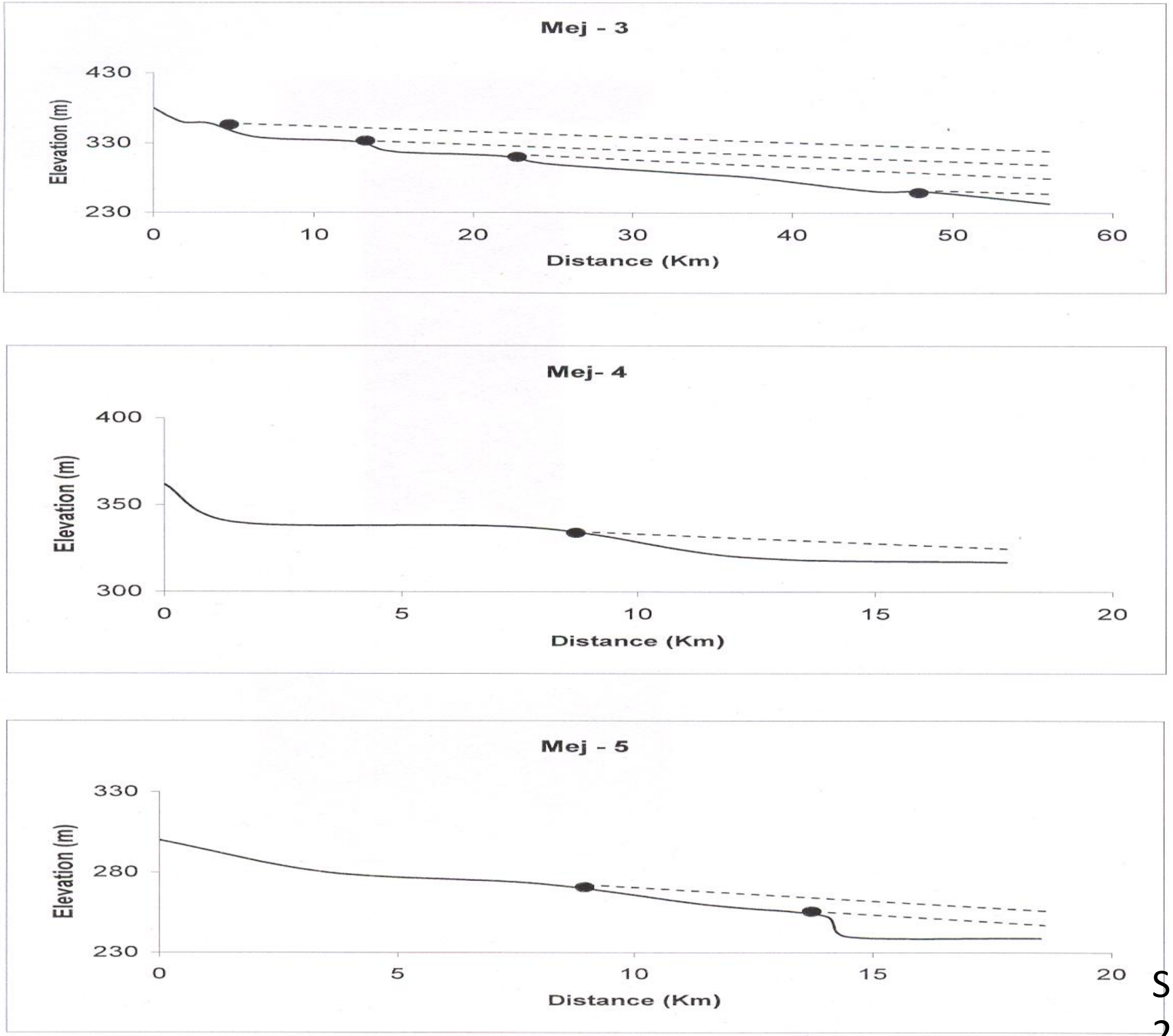
FAULT GEOMETRY AND BLOCK MOVEMENT PATTERN DEDUCED FROM LONGITUDINAL RIVER PROFILE

Figure 16



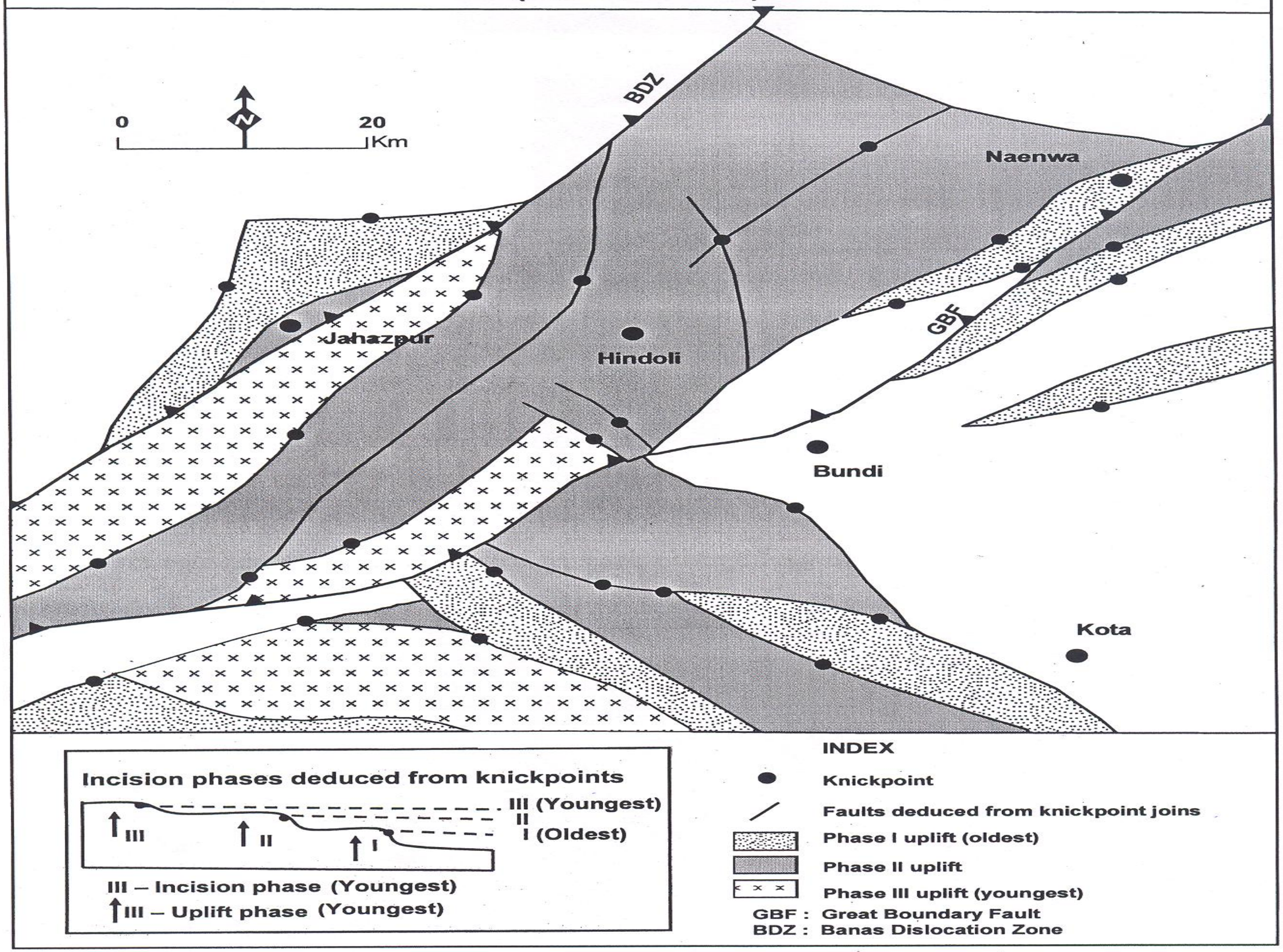
Sinha-Roy, 2006

Longitudinal river profiles showing position of knckpoints and stages of incision

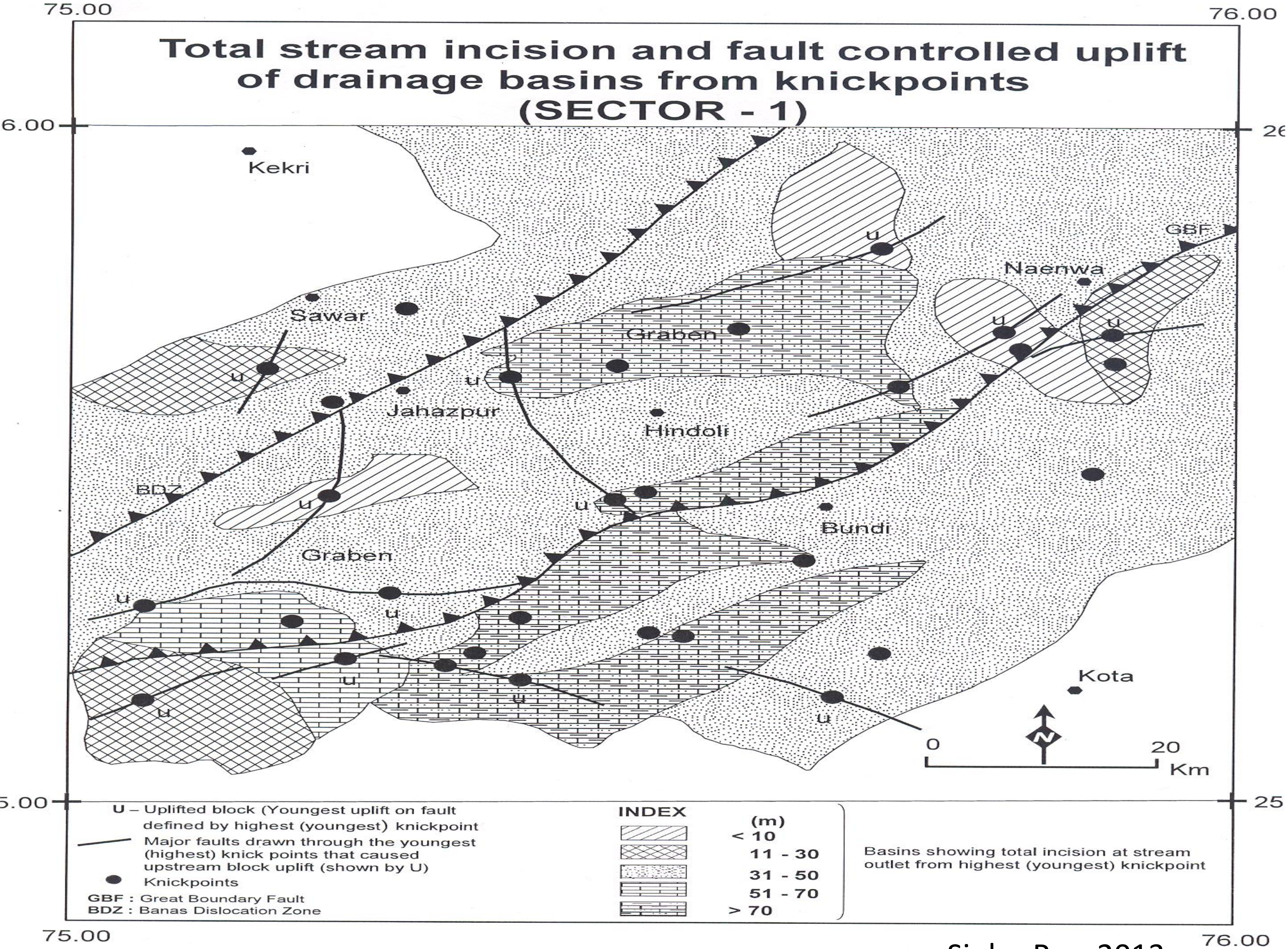


Sinha-Roy, 2013

Neotectonic blocks uplifted at different phases deduced from stream incision phases downstream of knickpoints and corresponding upstream uplift (SECTOR - 1)

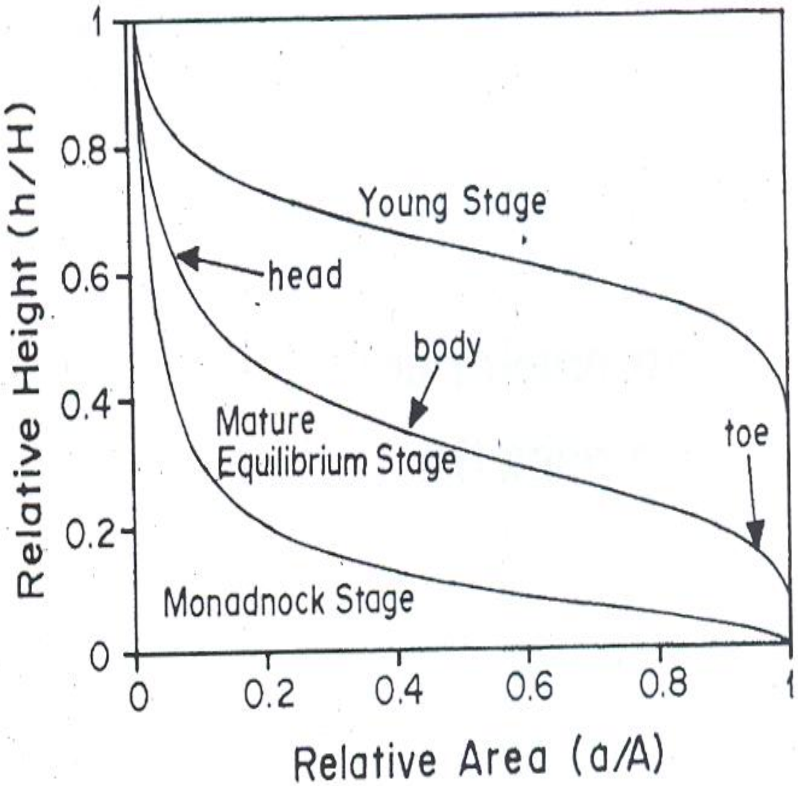


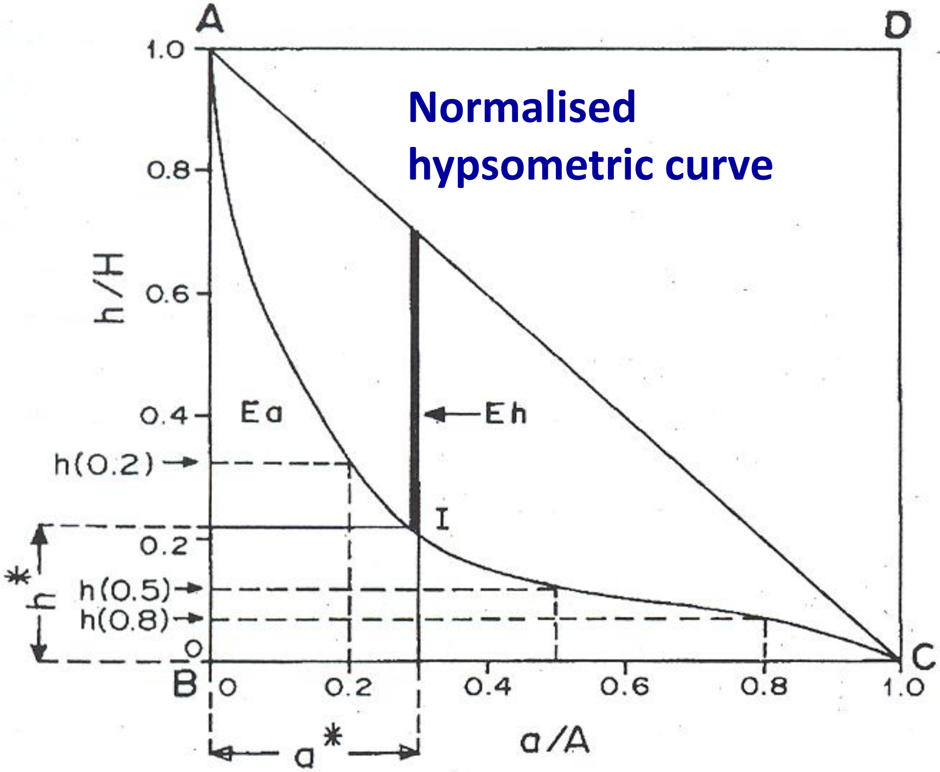
Sinha-Roy,2013



Sinha-Roy, 2013

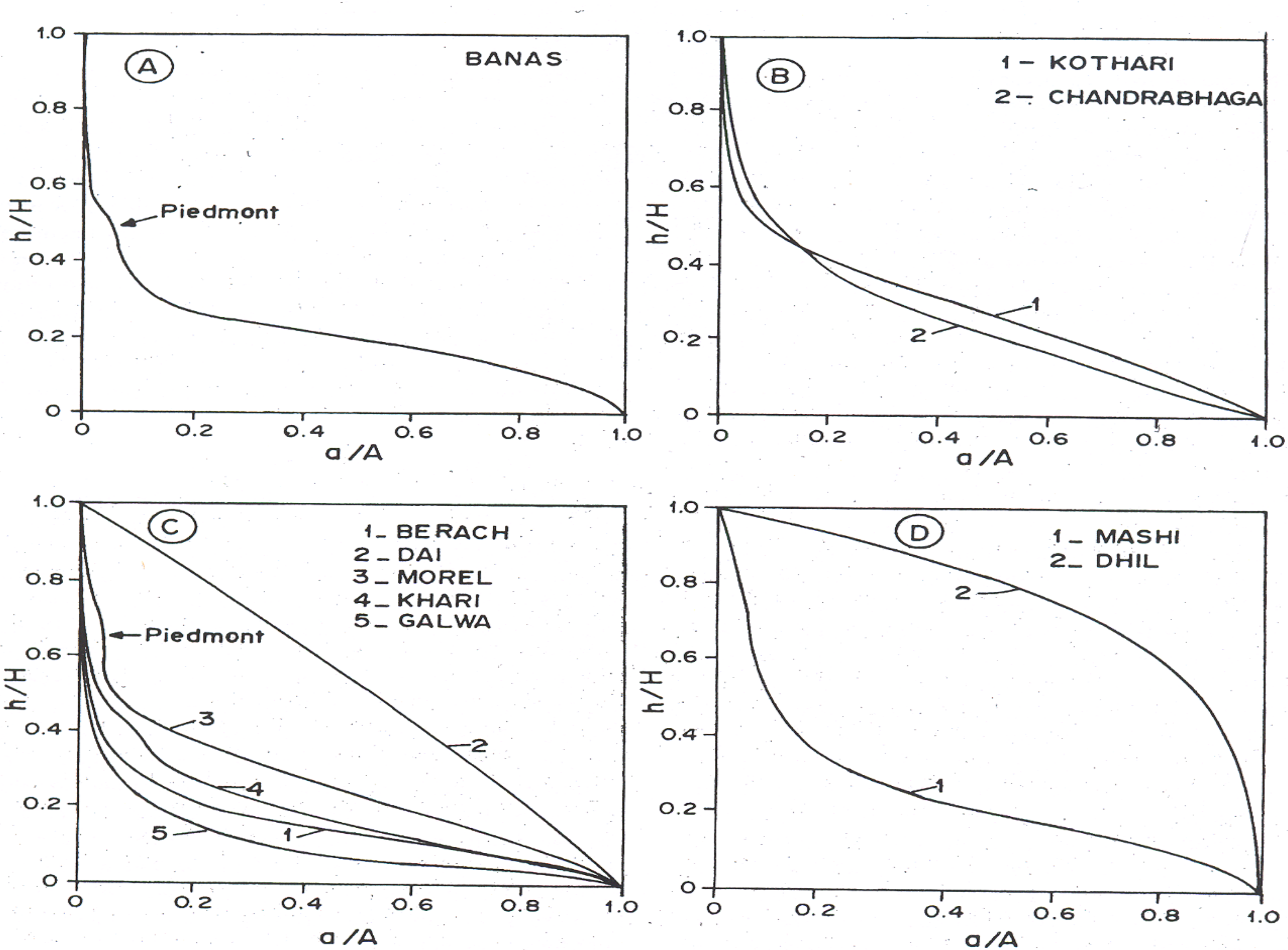
2. Hypsometry





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

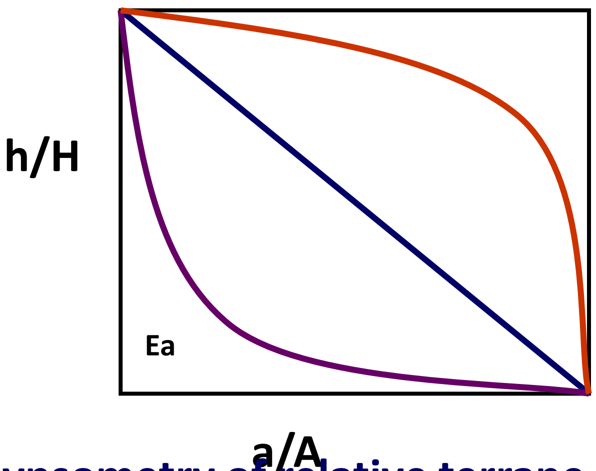
U = Z + Qs where U = Terrane uplift
Z = Elevation
Qs = Mass efflux (both advective & diffusive)

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

Replace Qs by (1-Ea) (where Ea = Hypsometric Integral)

Uplift equation becomes :

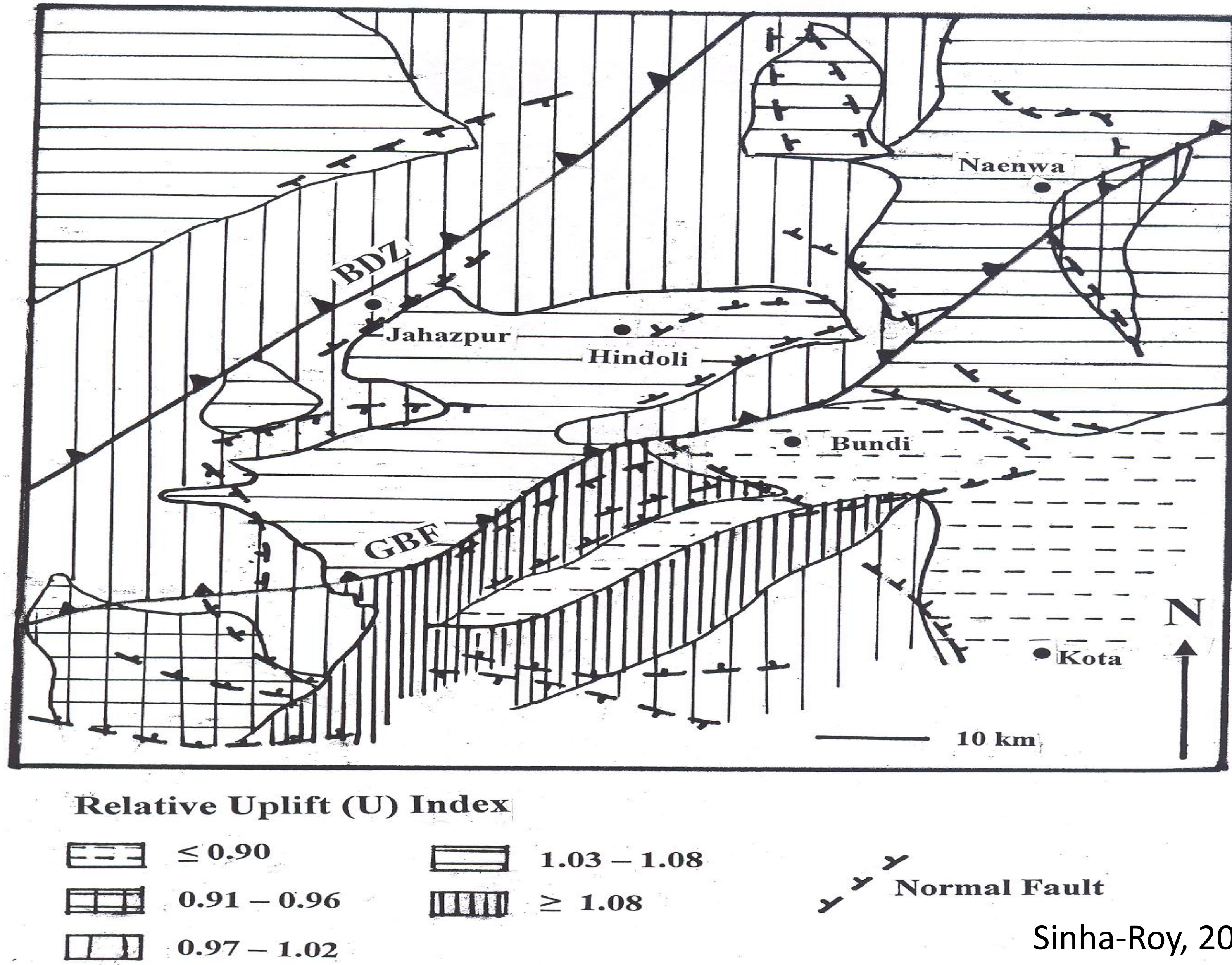
U = hm + (1-Ea)



Hypsometry of relative terrane uplift

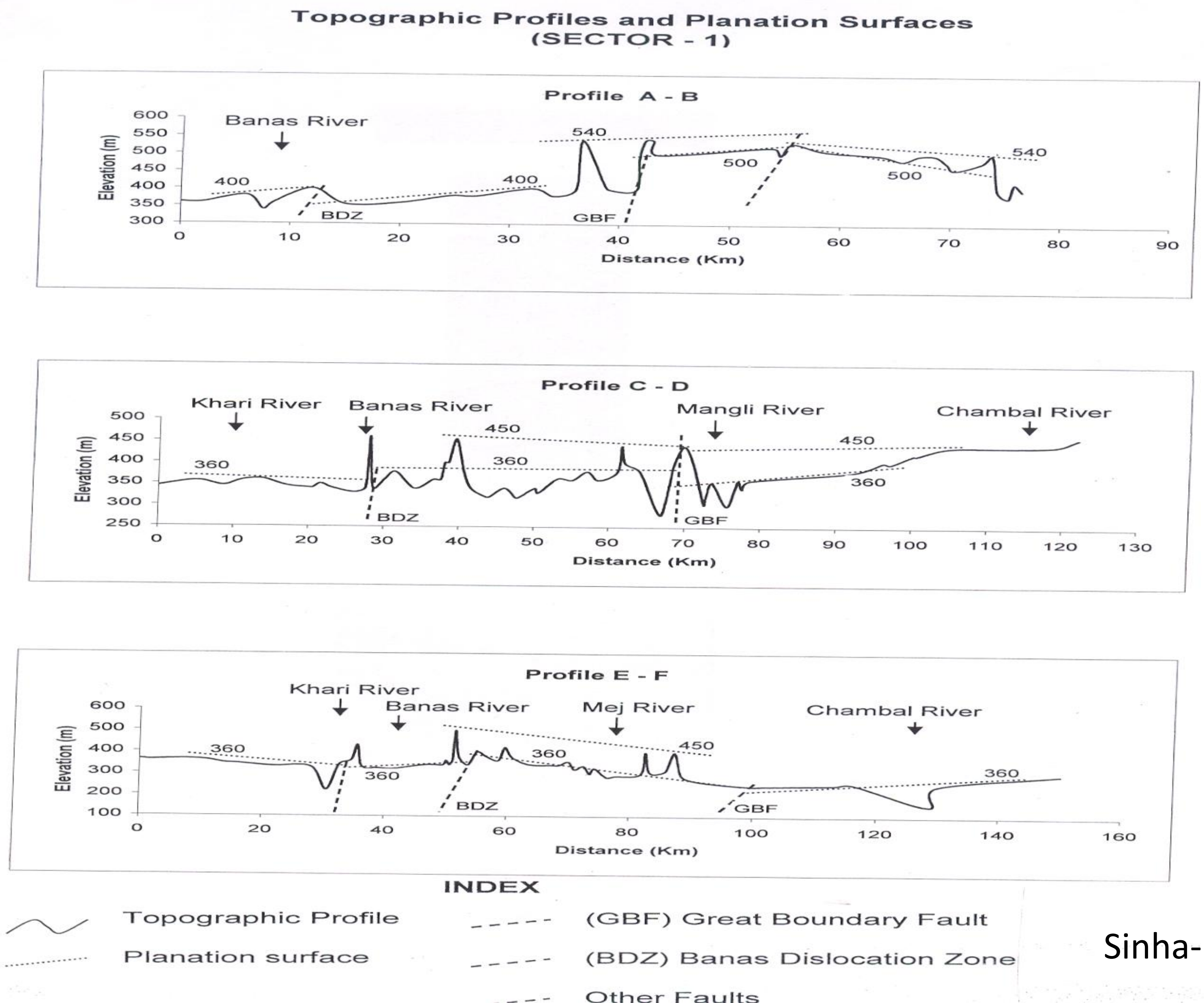
- Low relative uplift, high denudation
- Steady state landform
- High relative uplift, low denudation

Blocks of relative terrane uplift deduced from drainage basin hypsometry (Sector- 1)



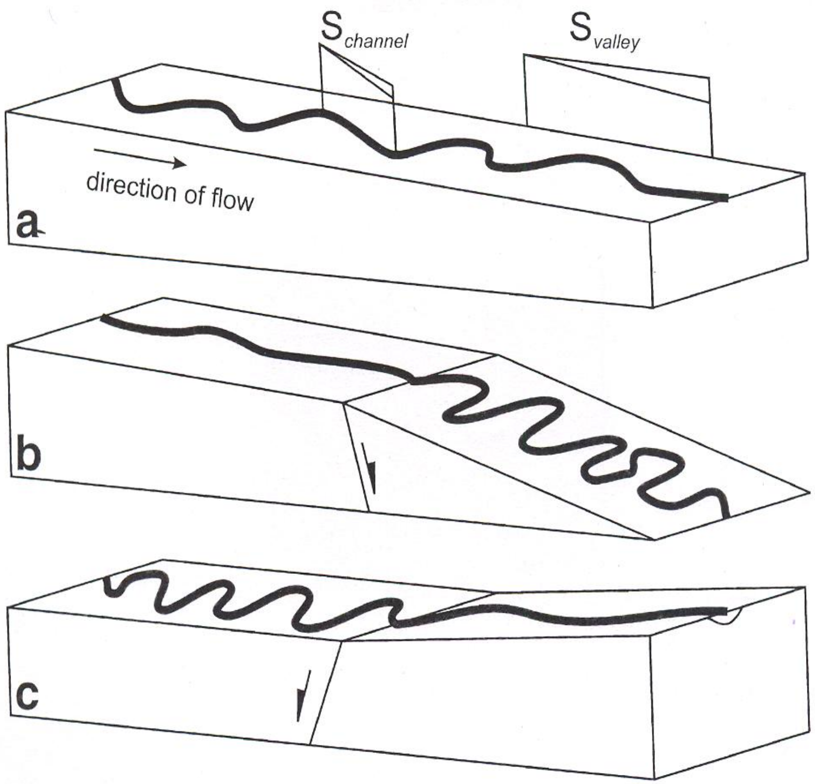
Sinha-Roy, 2013

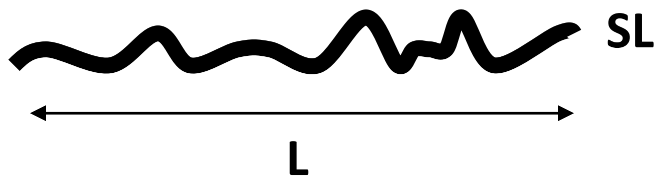
3. Topogarphic Profiles and Planation Surfaces



Sinha-Roy, 2013

4. Stream Sinuosity Index

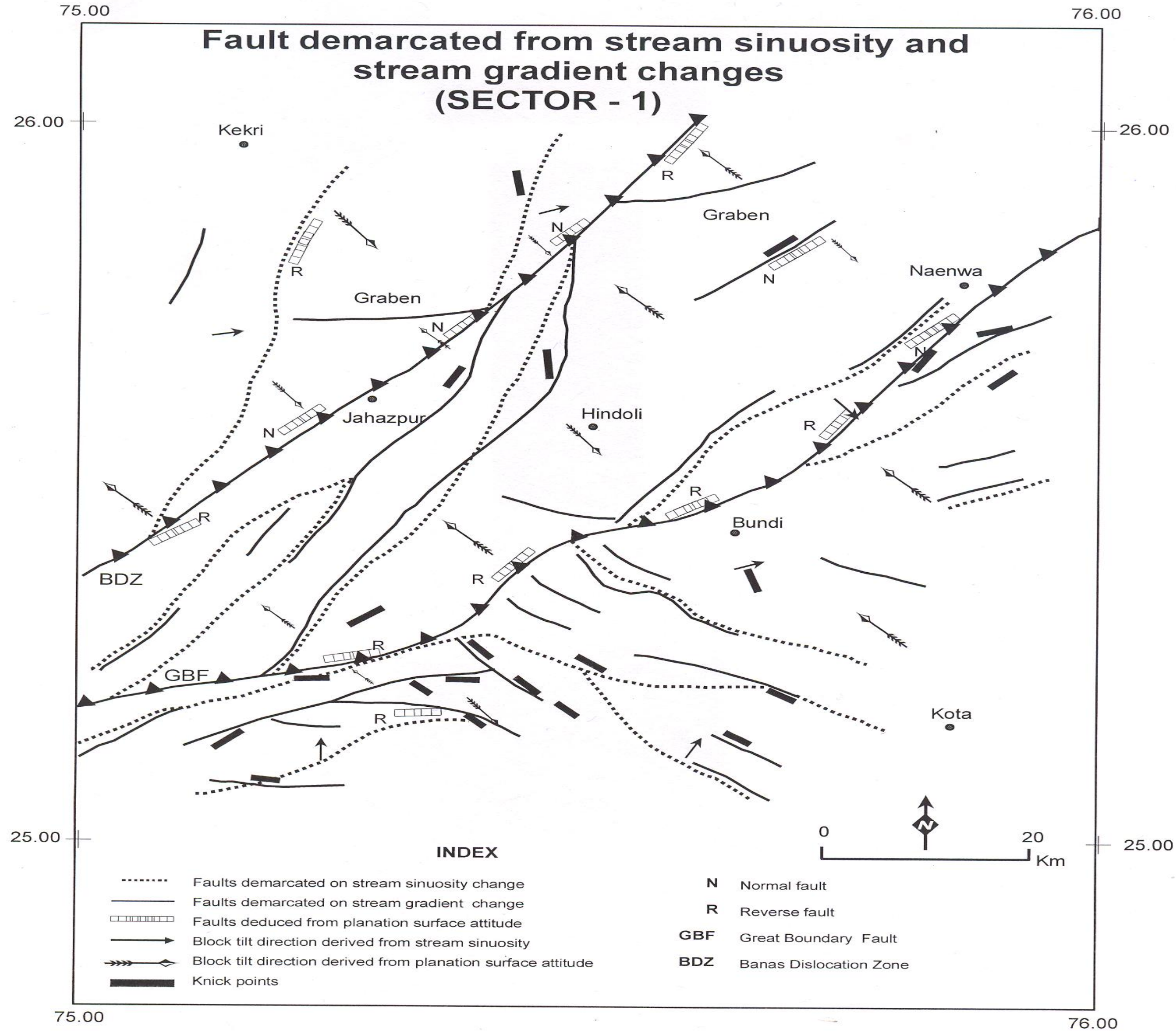




S = SL / L

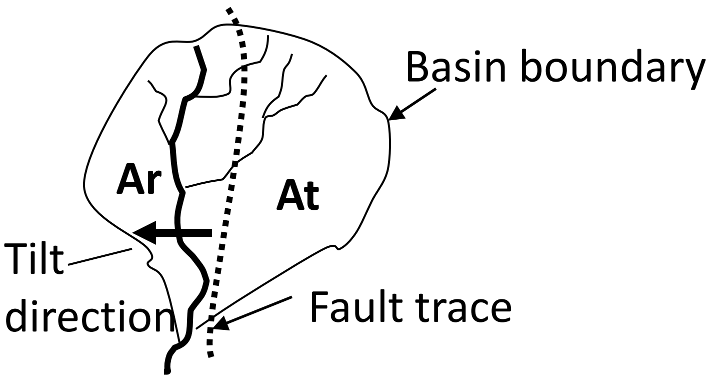
Where
S = Stream Sinuosity Index
L = Straight line distance of stream
SL = Actual distance along the stream

S > 1.0 High tectonic activity (Slope-steepening due to fault)

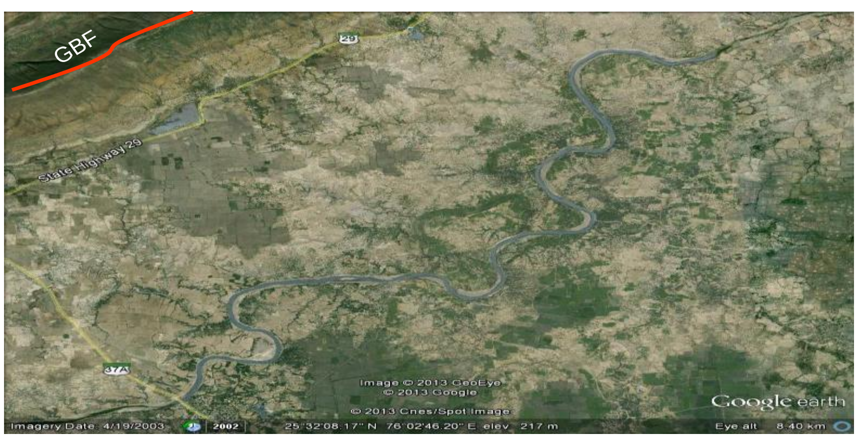


Sinha-Roy, 2013

5. Drainage Basin Asymmetry



Channel migration and abandoned channels of Mangli river on GBF Footwall



AF = 100(Ar/At)

where

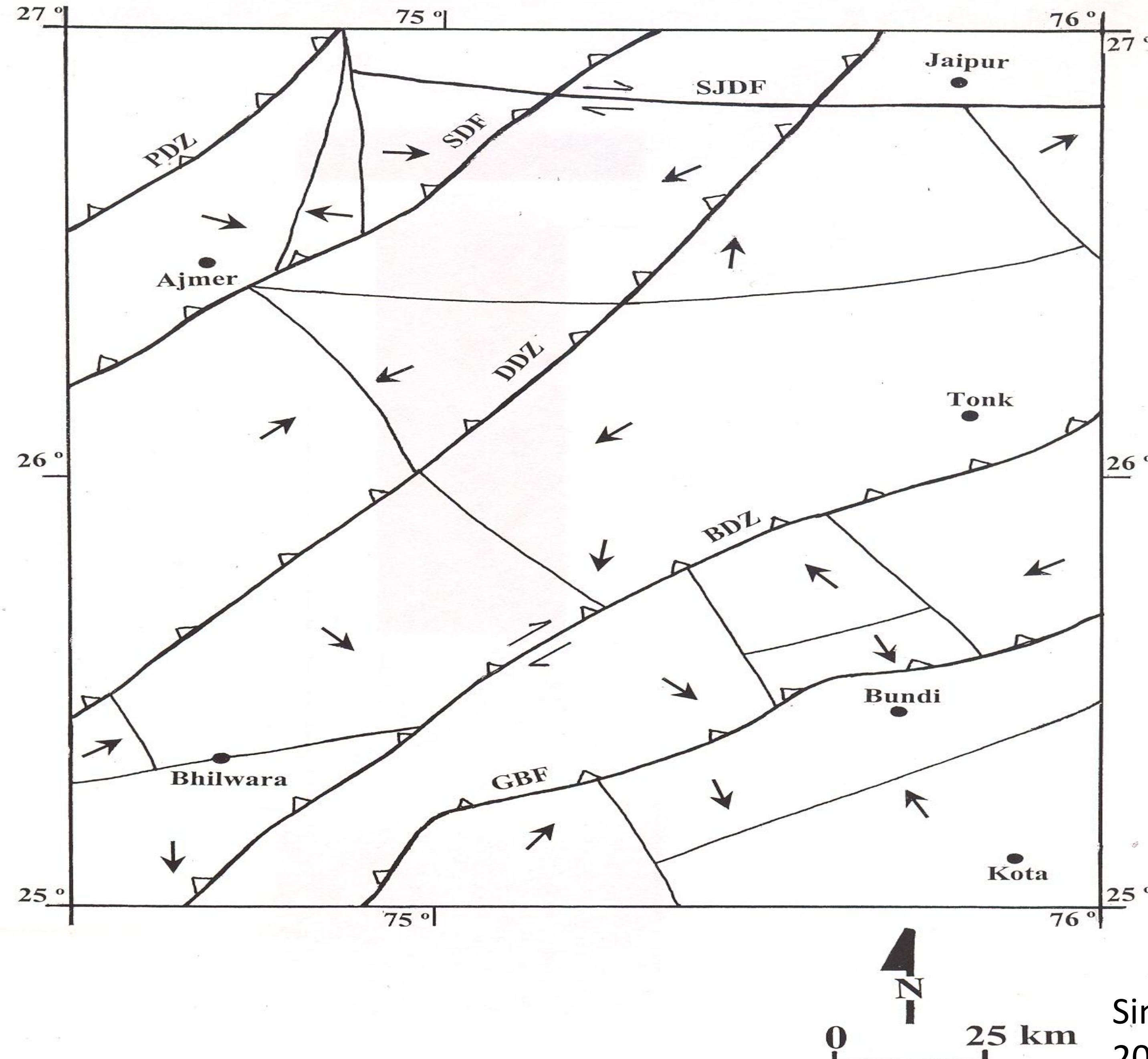
AF = Drainage basin asymmetry

At = Total basin area

Ar = Basin area on right bank

Lower the value of AF higher is the tectonic tilting

Fault – bound tilted tectonic blocks



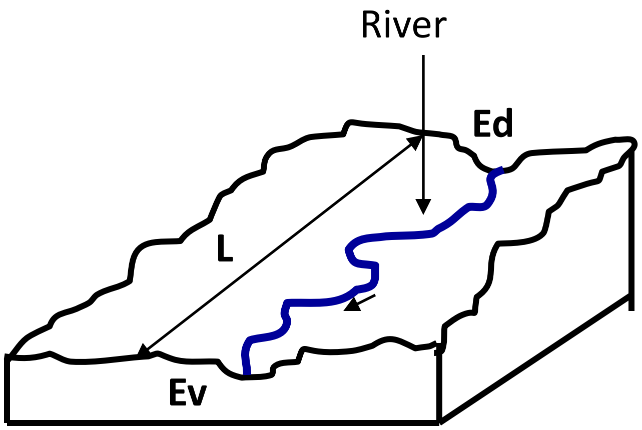
Sinha-Roy, 2006

6. Drainage Basin Relief Ratio

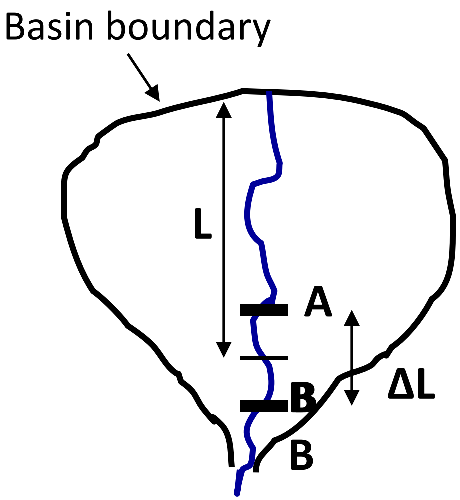
RR = (Ed – Ev) / L

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



$$SL = (\Delta H/\Delta L)L$$

where

SL = Stream length gradient ratio

ΔH = Change of elevation of reach (A-B)

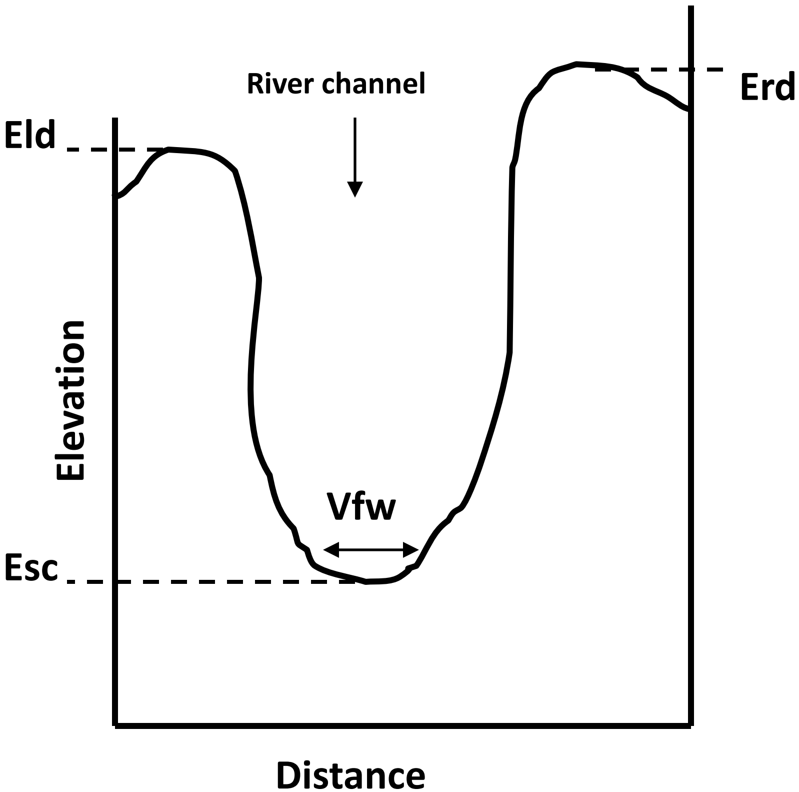
ΔL= Length of reach

L = Total length of the channel from ΔL mid-point of the reach where the index is calculated to the highest point of the channel

SL = < 50 : very low tectonic activity

= > 200 : very high tectonic activity

9. Valley Floor Width to Height Ratio



$$Vf = 2Vfw / [(Eld - Esc) + (Erd - Esc)]$$

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.

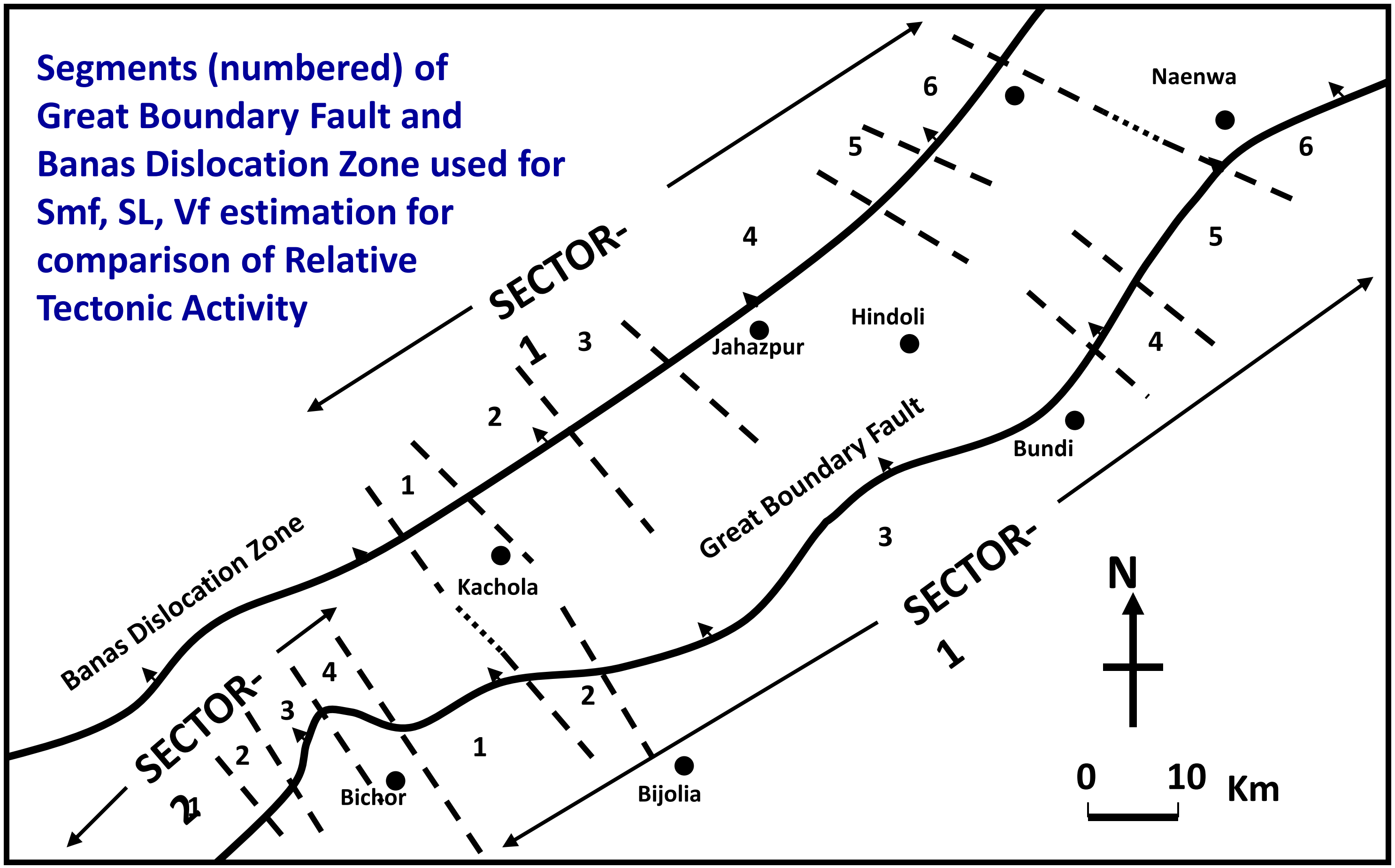
SL : <50 = very low, >200 = very high,

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)



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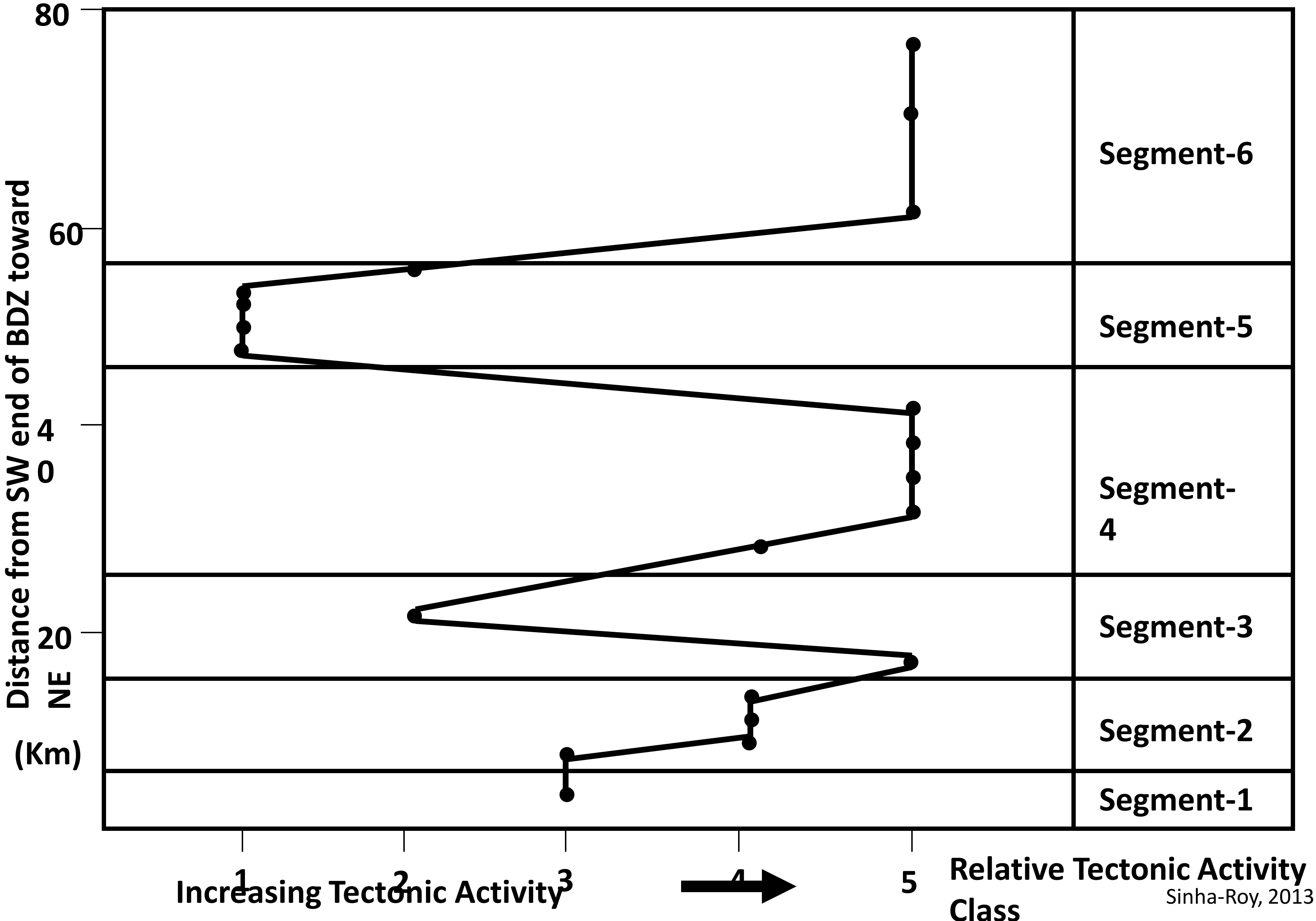
Variation of Relative Tectonic Activity along Banas Dislocation Zone



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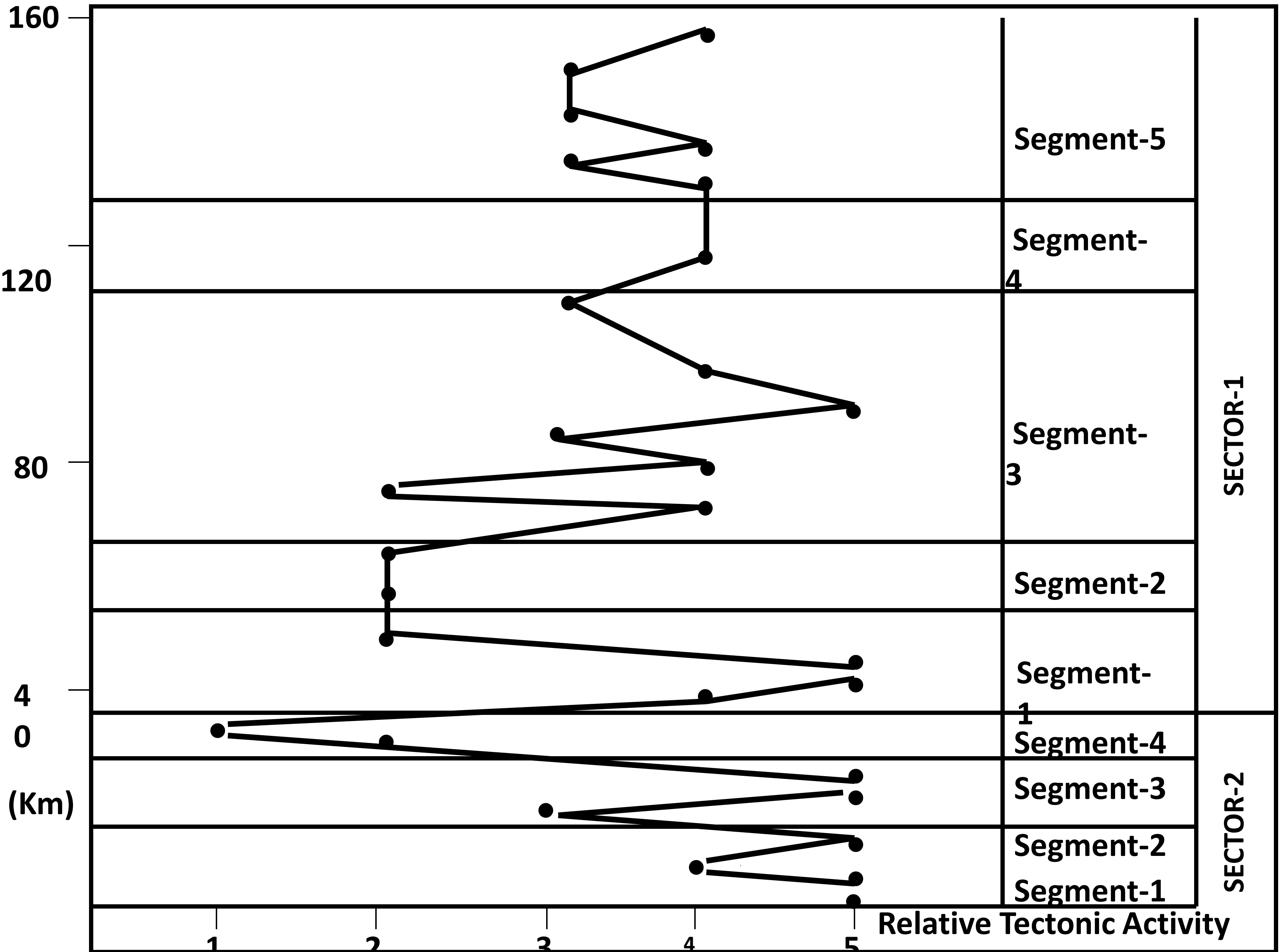
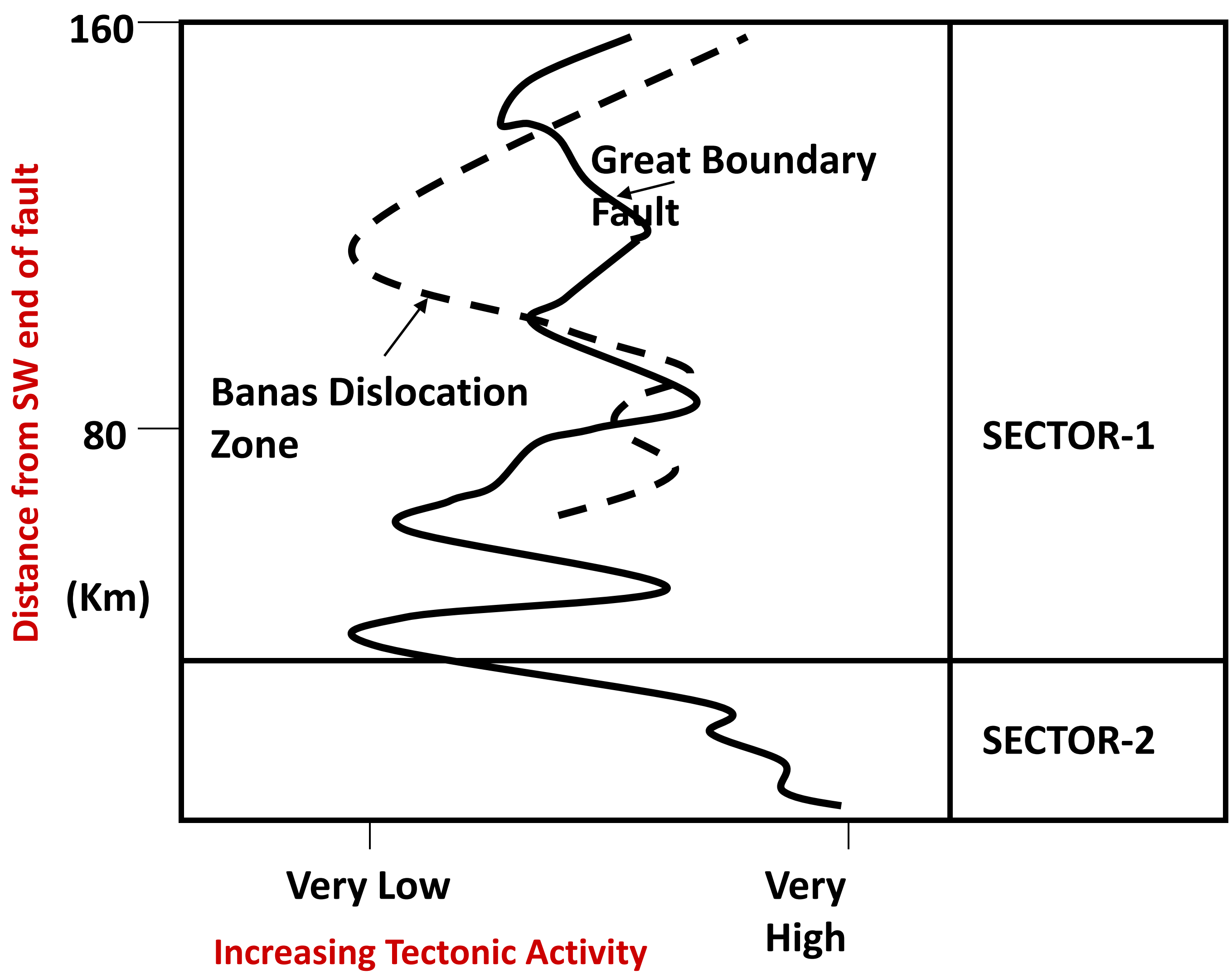
Variation of Relative Tectonic Activity along Great Boundary Fault



Comparison between Relative Tectonic Activity along Great Boundary Fault and Banas Dislocation Zone based on Smf, SL and Vf data



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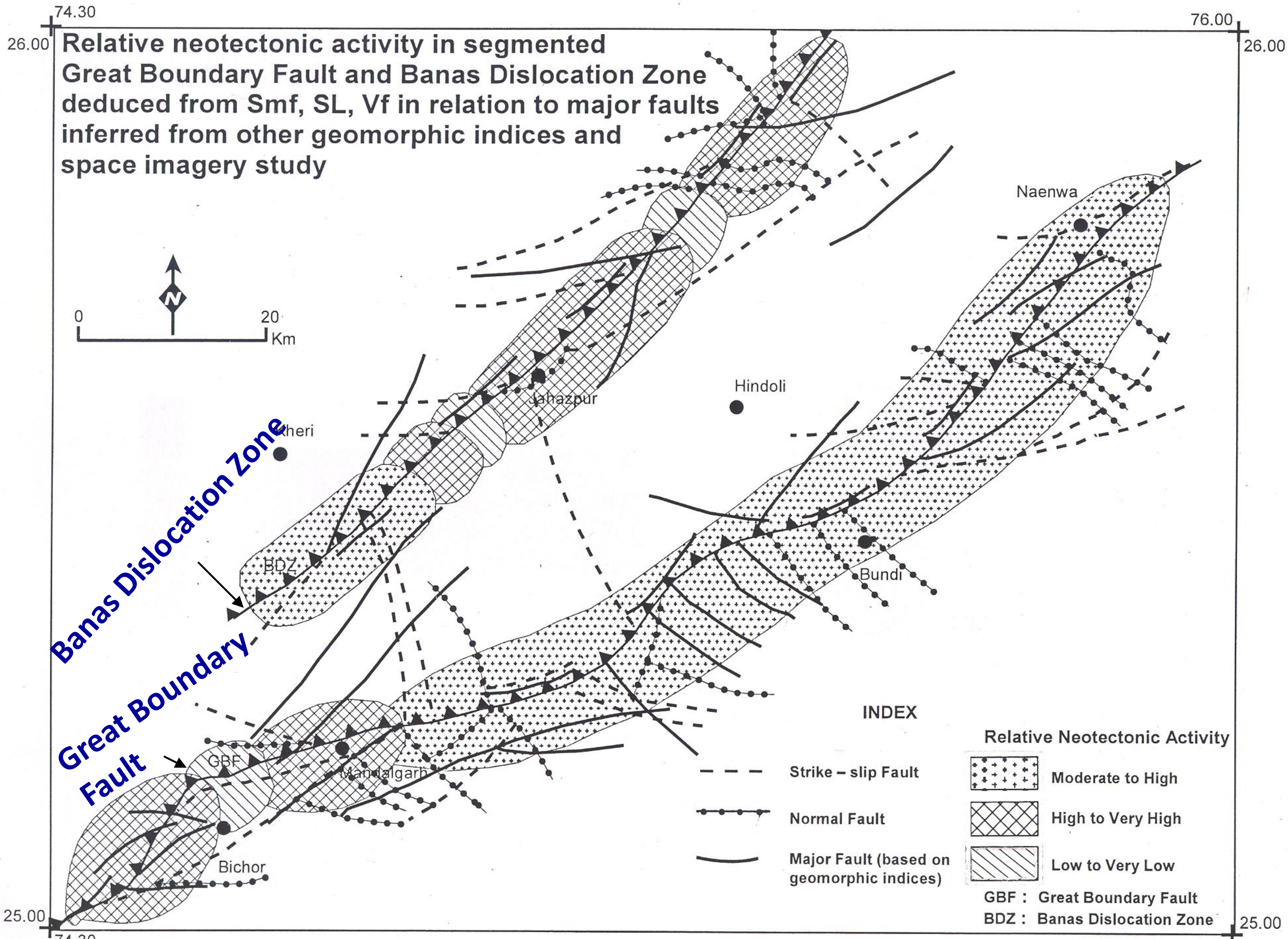
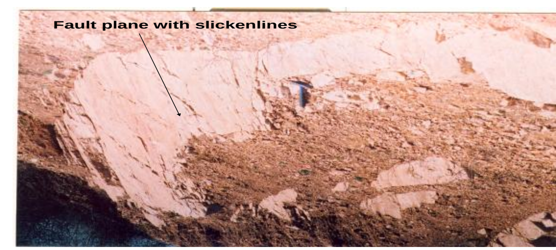
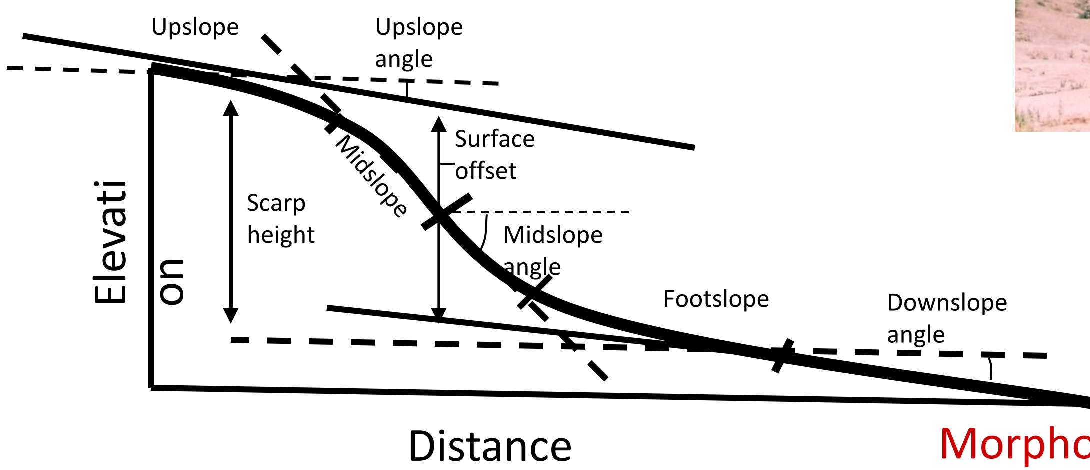
Neotectonic segmentation of older faults



10. Fault Scarp



Fault Scarp Geometry



Extensional component of fault

$e = d/\tan\theta$ (Wikins & Schultz, 2001)

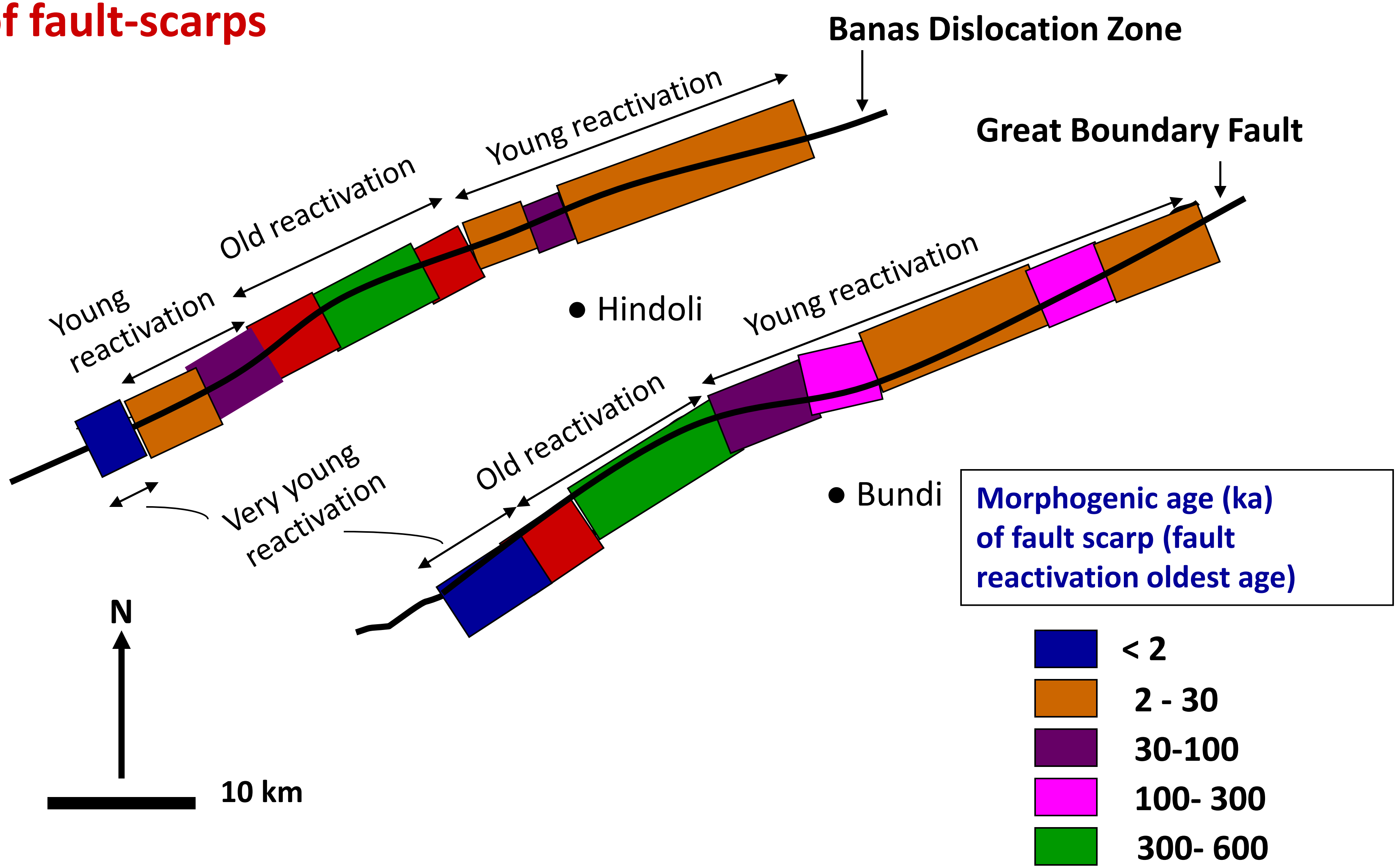
Where
e = Extension (m)
d = Fault scarp surface offset
θ = Scarp mid-slope angle

Morphogenic dating of fault scarp

$\tan\theta = a/\sqrt{\pi\tau} + b$ (Avouac, 1993)

Where
θ = Midslope angle
a = Half scarp surface offset
b = tan of upslope angle
τ = 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



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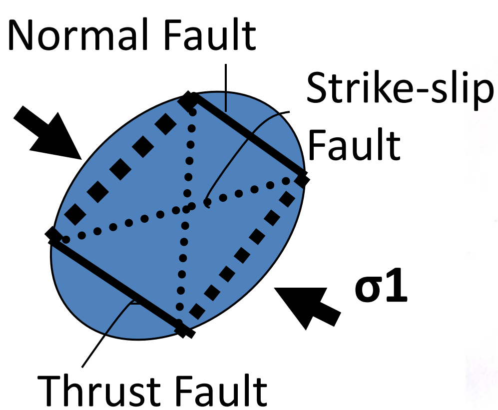
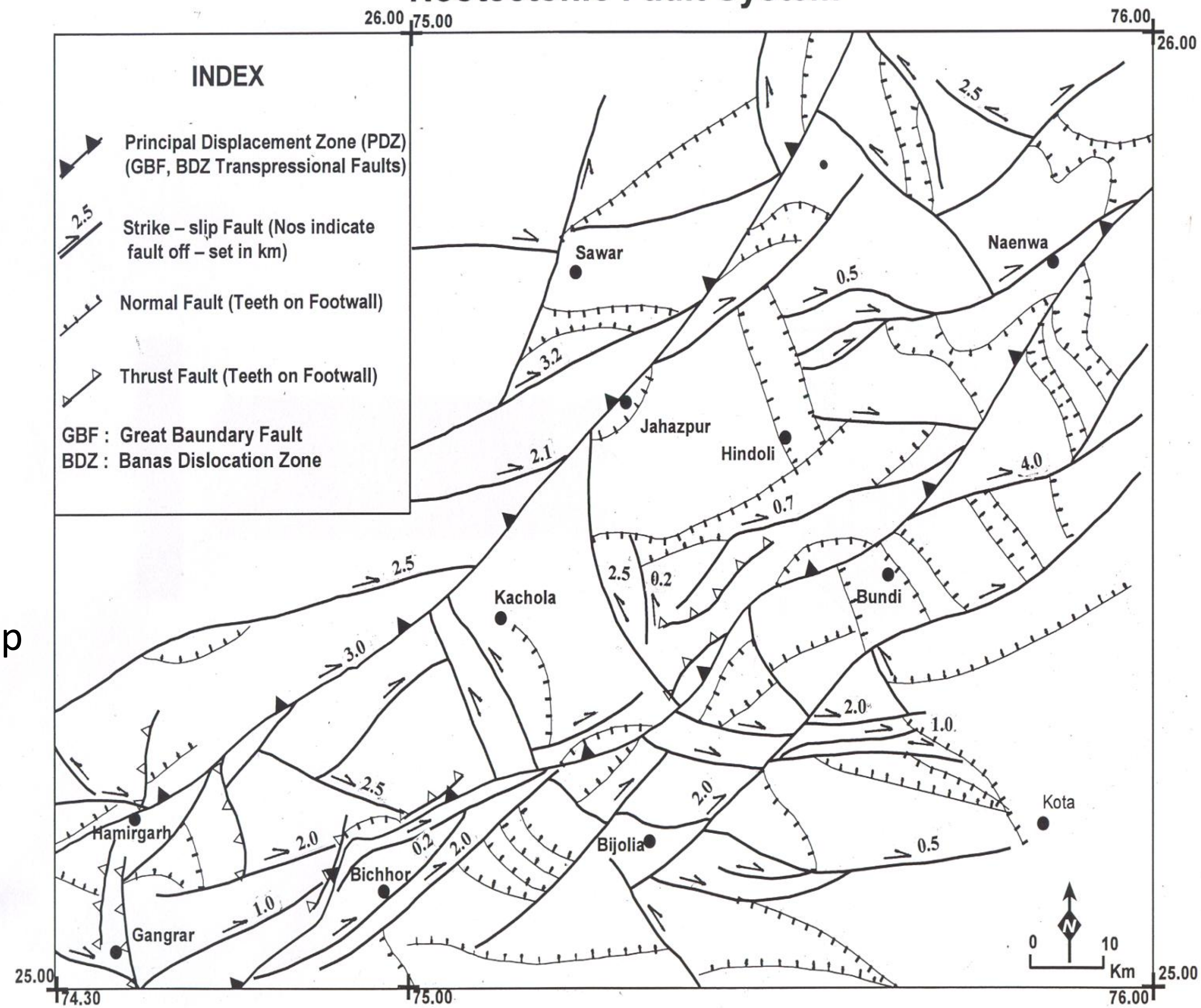


Neotectonic Fault System



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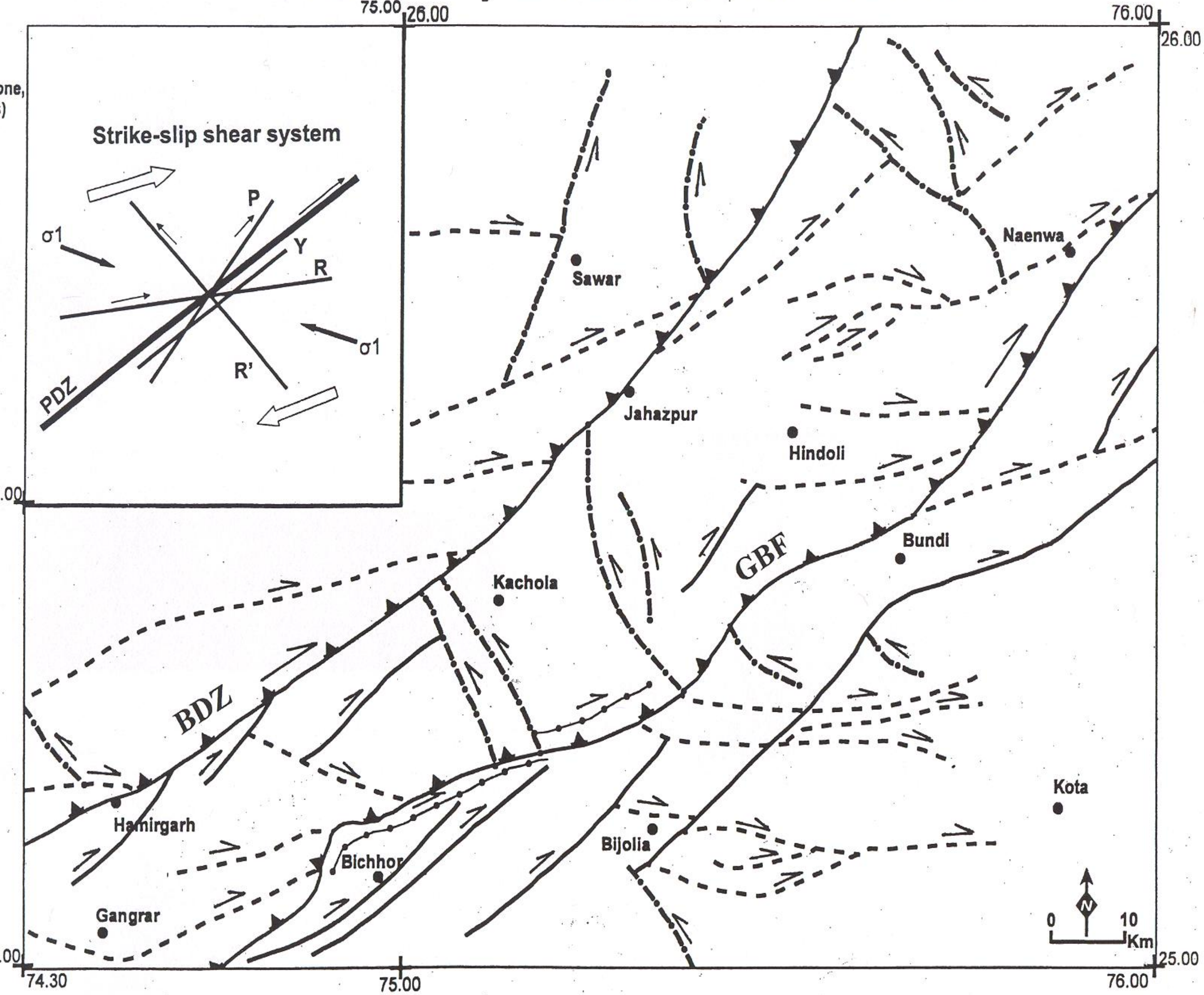
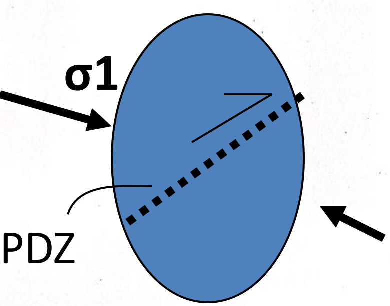
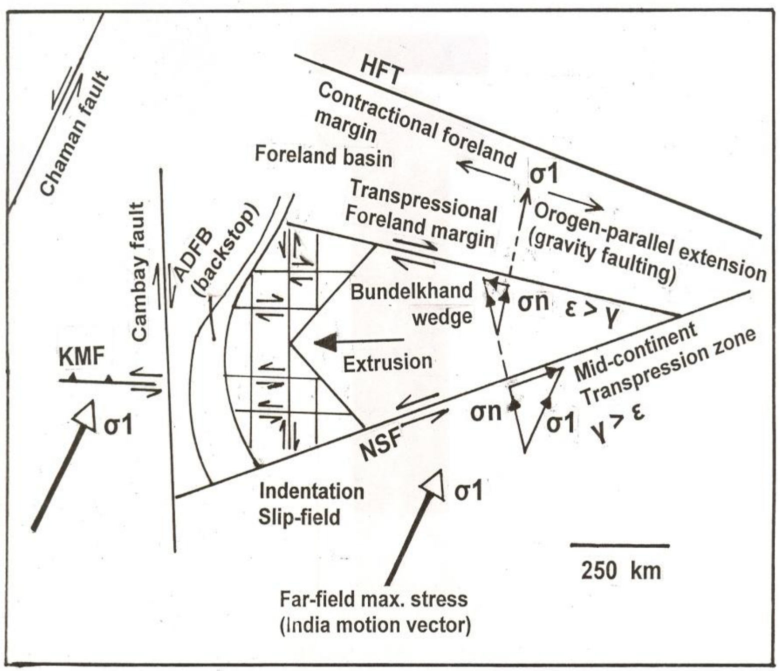
Shear system related to transpressional Great Baundary Fault and Banas Dislocation Zone

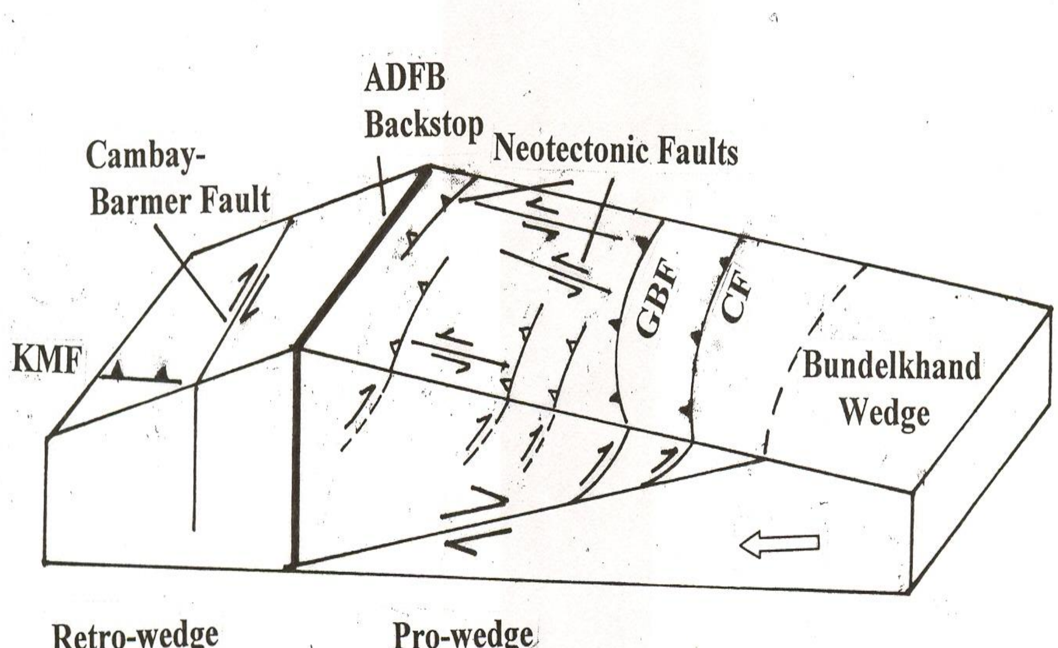




Sinha-Roy, 2013

Geotectonic conclusion from quantitative geomorphology





Thank you