Comprehensive study of Tectonic Processes in Geomorphologic Perspective

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The Nober erratic are classic Geomorphologic feature from the glaciations of Northern England, one of the several hundred erratics which are spread across a low ridge at Norber, having been dumped there by a glacier which transported them from nearby Crummack Dale. This one sits nicely on a limestone plinth, and there is a theory that the erratics have protected the limestone underneath them from erosion. However there is some debate as to the natural erosion rate of the limestone compared to that which is protected. (Drury,2015)

Abstract: The subject of tectonic geomorphology is in a state of natural law. The widely availability of high-quality, high-resolution digital topographic data substantiate the development of general morphological 'tools' which can be applied to deduce recent tectonic evolution. In between, process geomorphologists recognize that current models have a significant empirical basis, and lack insight into the underlying physics of erosion processes. Most tectonic geomorphology research is related with rivers, but glaciers, debris flows and hillslope processes also play a key role in hypotheses linking climate to tectonics, via surface processes, while submarine geomorphology has simply been investigated in a tectonic reference. Analysis combining field data collection, exposure, burial and low-temperature thermochronologic dating, digital topographic analysis, laboratory experiments and numerical models are successfully incorporating physics into geomorphic process 'laws', and demonstrating key tectonic geomorphology hypotheses. The dealings required for further progress have been outlined, but many exciting challenges remain.

Keywords - Active tectonics, fluvial geomorphology, glacial geomorphology, landscape evolution, tectonic geomorphology

Introduction

Tectonic geomorphology is flourishing, attracting concentration from a growing range of geoscientists. Existing technique development permits larger quantitative insight, and interdisciplinary groups tackle increasingly challenging problems. Three principal problems drive tectonic geomorphology research:

- Seeking geomorphological metrics to deduce current or past tectonic activity;
- Using active tectonic settings as a testing-ground for geomorphological models;
- Understanding links between climate change, tectonics and evolving mountain landscapes, as mediated by erosion and sediment transport.

As such, the timescales of interest to tectonic geomorphologists range from discrete events, such as earthquakes, landslides and storms, to the evolution of orogens over millions of years.

In addition to recognition of the importance of surface processes in linking climate change with tectonic processes (eg, Molnar and England, 1990; Raymo and Ruddiman, 1992,Dongre,2012) and driving tectonic deformation (eg, Willett, 1999: Figure 1; Koons *et al.,* 2002), advances in three key areas have driven the recent surge in tectonic geomorphology research:

- The availability of high-quality digital topographic data, globally at scales appropriate for geomorphological applications (eg, NASA SRTM; Farr and Kobrick, 2000; Gesch et al., 2006) and locally at spectacularly high resolution (eg, airborne and ground-based LiDAR; McKean and Roering, 2004; Heritage and Hetherington, 2007; Dunning et al., 2009; Milan et al., 2009);
- The advance of Quaternary dating techniques (eg, Heimsath and Ehlers, 2005), allowing quantitative determination of recent exhumation (eg, (U-Th)/He; Berger and Spotila, 2008), exposure (eg, cosmo-genic radionuclides; Gosse and Phillips, 2001; Siame et al., 2006) and deposition (eg, optically stimulated luminescence; Wintle, 2008; Duller, 2008);
- The development of sophisticated numerical landscape evolution models (eg, Willgoose, 2005 Dongre,2014) and realistic laboratory analogue experiments (eg,Dongre,2013, Turowski et al., 2006).

This review is organized by process. The bias towards fluvial geomorphology reflects current research trends, though hillslope, debris flow, glacial and submarine geomorphology are also discussed. The broad topic of fluvial tectonic geomorphology is further subdivided into studies conducted at range, catchment and reach scales. The review concludes with thoughts on future research directions. For further discussion, Bishop (2007) provided comprehensive historical context for recent progress in tectonic geomorphology, focusing on the long-term perspective. Dongre (2013) summarized the state of bedrock channel research and highlighted future research directions, while Wobus et al. (2006c) detailed approaches and limitations to extracting tectonic information from quantitative analysis of fluvial landscapes. Dietrich et al. (2003) set out a definition of a geomorphic transport law, and Tucker (2009) discussed the importance of 'natural experiments', well-constrained field sites suitable for testing geomorphological models. Whipple (2009)and Dongre(2012) documented efforts to demonstrate a climatic influence on tectonics at the mountain-range scale. Contributions in this issue address dating techniques (Church, 2010), fluvial (Kleinhans, 2010) and glacial (Bingham et al., 2010) geomorphology, and Earth systems (Dadson, 2010). Now a days Dongre has conductsd scientific research which is based on the idea that everything takes place is determined by laws of nature he presented near about 50 papers in tectonics and geomorphology.(www. nldongre.com)

II Fluvial geomorphology

The vast majority of tectonic geomorphology studies focus on rivers, whether as the fundamental erosional process at the *range scale* (eg, Whipple et al., 1999; Whipple and Meade, 2004,Dongre,2012,2013,2014,2015), or looking at a *catchment scale* for clues to recent tectonic activity, in terms of longitudinal profiles and study on tectonics (Table 1), or the planform drainage network and tectonically oriented landforms (Table 2). Meanwhile, progress in understanding the physics of fluvial erosion comes principally from *reach* or *grain scale* studies (eg, Sklar and Dietrich, 2004; Whittaker *et al.,* 2007). Following a surge of interest in tectonic geomorphology in the 1990s, many recent studies have conducted a more critical examination of the models employed (either using transient conditions to differentiate between models, or reducing the dependence of models on empirical relationships), and testing model results.

Table 1. Summary of some recent tectonic geomorphology studies based on stream profile and tectonics study

Authors	Location	Technique1	Purpose of study
Boulton and Whittaker, 2009	Hatay Graben, Turkey	Location and height of knickpoints	Interpreting active tectonics and seismic hazard
Brocklehurst and Whipple,2007	Nanga Parbat; Southern Alps,New Zealand	Reference slope2	Glacial longitudinal profile response to rock uplift
Clark and Bilham, 2008	Shillong Plateau	Normalized steepness3	
Clark et al., 2005	Sierra Nevada, California	Profile reconstruction	Rock uplift history
Delcaillau et al., 1998	Western Foothills, Taiwan	Uplifted and deformed terraces	Development of active anticline
Delcaillau et al., 2006	Siwalik Hills, India	Location of knickpoints	Development of active anticlines and transfer/ thrust faults
Dorsey and Roering, 2006	San Jacinto fault zone, California	Concavity variations	Transient geomorphic response to fault initiation
Duvall et al., 2004	Santa Ynez Mountains, California	Concavity variations, normalized steepness	Geomorphic response to spatial variations in rock uplift rate and bedrock lithology
Kirby and Whipple, 2001	Siwalik Hills, Nepal	Concavity variations	Mapping spatial variations in rock uplift rate
Kirby et al., 2003	Eastern Tibetan margin	Reference slope, normalized steepness	Mapping spatial variations in rock uplift rate
Kobor and Roering, 2004	Oregon Coast Range	Reference slope	Mapping spatial variations in rock uplift rate
Mueller and Suppe, 1997	Wheeler Ridge, California, USA	Uplifted and deformed terraces	History of deformation on blind thrust
Reinhardt et al., 2007	Sierra Nevada, Spain	Location of knickpoints	Landscape response to active tectonics
Ribolini and Spagnolo, 2008	Argentera Massif, French-Italian Alps	Location of knickpoints	Spatial variations in uplift history
Safran et al., 2005	Bolivian Andes	Normalized steepness	Mapping spatial varia tions in rock uplift rate
Schoenbohm et al., 2004	Red River, Tibet	Profile reconstruction	Fault offset history
VanLaningham et al., 2006	Oregon Coast Ranges, USA	Concavity variations	Landscape response to spatial variations in lithology and tectonics
Wobus et al., 2006c	King Range, California, USA; San Gabriel Mountains, California, USA; Siwalik Hills, Nepal; Nepal Himalaya	Normalized steepness, location of knickpoints	Interpreting active tectonics
Wobus et al., 2006a	San Gabriel Mountains, California, USA; Central Range, Taiwan	Normalized steepness	Origin of fluvial hanging valleys
Dongre, N.L. (2012)	Pachmarhi, India	Numerical	Rational derivation of river
Dongre, N.L. (2012)	Pachmarhi, India	Numerical Model	Bed-load movement in the steep

			mountainous river, Denwa
Dongre, N.L. (2012)	Pachmarhi, India	Model Study	Tectonic control of Pachmarhi drainage system
Dongre, N.L. (2012)	Pachmarhi, India	Numerical Model	Tiling attributes of Denwa river
Dongre, N.L. (2012)	Pachmarhi, India	Numerical	Rift valley system of Pachmarhis
Dongre, N.L. (2012)	Pachmarhi, India	Numerical model study	Tectonically indured drainage diversion
Dongre, N.L. (2013)	Pachmarhi, India	Calculus variation	Calculus variation of basaltic river bed profiles
Dongre, N.L. (2013)	Pachmarhi, India	Variability in spatial pattern	Variability in spatial pattern of bed rock incision
Dongre, N.L. (2013)	Pachmarhi, India	Structural adjustment	the impact of structural adjustment on river networks
Dongre, N.L. (2013)	Pachmarhi, India	Fractal Mountains and integrated process	Orogenisis of fractal mountains with rivers through integrated process
Dongre, N.L. (2013)	Pachmarhi, India	Morphometric analysis	Morph metric analysis of river branching system
Dongre, N.L. (2013)	Pachmarhi, India	Equation of momentum	Equation of momentum and continuity of river network
Dongre, N.L. (2013)	Pachmarhi, India	Rationality to the behaviour	Rationality to the behaviour of river systems and disipation of drainage generated energy
Dongre, N.L. (2014)	Pachmarhi, India	Model study	Deterministic model study of river formation
Dongre, N.L. (2014)	Pachmarhi, India	Numerical Model analysis	Numerical model analysis of bedrock channel width adjustment to tectonic forcing on Pachmarhis
Dongre, N.L. (2014)	Pachmarhi, India	Scientific experiment implication	Scientific experimentâ implication on channel meanders behavior and instability
Dongre, N.L. (2014)	Pachmarhi, India	Uplift model study	The incision pattern of consequent stream into increasing uplift
Dongre, N.L. (2014)	Pachmarhi, India	Numerical -model	Numerical- model study of hanging river tributary system
Dongre, N.L. (2015)	Pachmarhi, India	Mechanics of river debouching:	Mechanics of river debouching: implication for the morpho dynamics distributary network

Table 2. Summary of some recent tectonic geomorphology studies based on plan view drainage analysis and tectonically oriented land form

Authors	Location	Technique	Purpose of study
Alvarez, 1999	Apennines, Italy	Drainage network architecture[1] and space-time substitution	Evolution of drainage associated with an emerging fold-thrust belt
Bennett eta/., 2005	Otago, South Island, New Zealand	Drainage network architecture[1] and cosmogenic dating of terraces	History of deformation on blind thrusts and river migration
Burbank eta/., 1999	Tien Shan, Kyrgyzstan	Drainage network architecture[1] and deformation of unconformity	Inferring history of distributed deformation in fold-and-thrust belt
Clark eta/., 2004	Southeastern Tibet	Drainage network architecture[1]	Uplift history
Cox eta/., 2001	Mississippi Embayment, KY, MS, and TN,USA	Drainage basin asymmetry and distribution of alluvial terraces	Tilting due to neotectonism
Delcaillau eta/., 2006	Siwalik Hills, India	Drainage network architecture[1]	Development of active anticlines and transfer/thrust faults
Ghassemi, 2005	Alborz Range, Iran	Drainage network architecture[1]	Development of active anticline
Goldsworthy and Jackson, 2000	Greece	Drainage network architecture[1]	Normal fault evolution, interaction and migration
Gupta, 1997	Siwalik Hills, India	Drainage network architecture[1]	History of deformation on blind thrusts and sediment supply
Halletand Molnar, 2001	Southeastern Tibet	Drainage basin shape distortion	History of shear strain
Jackson and Leeder, 1994	Pleasant Valley, Nevada, USA	Drainage network architecture[1]	Development of normal faults
Jackson eta/., 1996	Otago, South Island, New Zealand	Drainage network architecture[1]	History of deformation on blind thrusts
Jackson eta/., 1998	Manawatu, North Island, New Zealand	Drainage network architecture[1]	History of deformation on blind thrusts and tilting due to regional depocentre
Jones, 2004	Pyrenees, Spain	Drainage network architecture[1]	History of deformation on thrusts and sediment supply
Lock eta/., 2006	Coast Ranges, California, USA	Drainage network architecture	History of deformation due to migra tion of Mendocino triple junction
Mather, 2000	Sorbas Basin, Spain	Drainage network architecture[1]	History of river capture due to uplift
Mueller and Tailing, 1997	Wheeler Ridge, California, USA	Drainage network architecture[1]	History of deformation on blind thrusts
Ramsey eta/., 2007	Southern Taiwan	Planview rotation and drainage basin asymmetry	Active tectonics and uplift history
Ribolini and Spagnolo, 2008	Argentera Massif, French-Italian Alps	Drainage network architecture1 and spatial variations in geometry	Spatial variations in uplift history
Schlunegger and Hinderer, 2001	European Alps	Drainage network scale	Feedback between surface erosion and tectonic forcing
Stark et al., 2008	Western North Pacific	Sinuosity measurements	Linking rainfall intensity and landscape morph ology
Van der Beek et al., 2002	Siwalik Hills, India	Magnitude of horizontal deflection of rivers	Mapping variations in thrust fault dip
Vetel et al., 2004	Turkana Rift,	Drainage network	Development of normal faults

	Kenya	architecture1	
Dongre, N.L. (2012)	Pachmarhi, India	Vertical Model Study	Vertical displacement in the Pachmarhis
Dongre, N.L. (2012)	Pachmarhi, India	Numerical	Mechanical analysis of the dike pattern
Dongre, N.L. (2012)	Pachmarhi, India	Numerical	Shearing stress and faulting
Dongre, N.L. (2012)	Pachmarhi, India	Numerical and model Study	Dynamics of orogenic wedges at Pachmarhis
Dongre, N.L. (2012)	Pachmarhi, India	Numerical Model	The magnitude of strain in the Pachmarhi
Dongre, N.L. (2012)	Pachmarhi, India	Numerical Model	Development of structures within tectonic wedges
Dongre, N.L. (2012)	Pachmarhi, India	Numerical Model	Climate and tectonics of Pachmarhi mountains
Dongre, N.L. (2012)	Pachmarhi, India	Folding System analysis	Mechanism of folding in the Pachmarhis
Dongre, N.L. (2012)	Pachmarhi, India	Analysis of weather	Tectonic control on weathering
Dongre, N.L. (2012)	Pachmarhi, India	Analysis	Deccan traps, mantle activity and extentional tectonics in Pachmarhi
Dongre, N.L. (2012)	Pachmarhi, India	Fault analysis	Dome mountains associated withfaults
Dongre, N.L. (2012)	Pachmarhi, India	Model study	Temporal changes in the Pachmarhis
Dongre, N.L. (2012)	Pachmarhi, India	Numerical and laboratory experiments	Wrench-fault of the Pachmarhis
Dongre, N.L. (2012)	Pachmarhi, India	Thermal equilibrium	Perturbation of thermal equilibrium in the satpura basin
Dongre, N.L. (2013)	Pachmarhi, India	An experimental study	An experimental study of the effect of monochromatic wave on cliff recession
Dongre, N.L. (2013)	Pachmarhi, India	Quantitative analysis	Quantitative analysis of tectonically uplifted topography
Dongre, N.L. (2014)	Pachmarhi, India	Geometry	Geometry and mechanics of normal faults
Dongre, N.L. (2015)	Pachmarhi, India	Experimental study of geomorphic response	Experimental study of geomorphic response to tectonic uplift
Dongre, N.L. (2015)	Pachmarhi, India	Scientific experiments	Scientific experiments for temporal and spatial relationships between hillslope and knick point retreat
Dongre, N.L. (2015)	Sonawani, India	Kinematics and dynamics nodl study	Kinematics and dynamics of the sonawani (Balaghat) tectonic nappes
Dongre, N.L. (2015)	Pachmarhi, India	Dykes analysis in laborotory	Rheology of crystal-bearing magmas and implication for dykes ascent dynamics
Dongre, N.L. (2015)	Pachmarhi, India	Numerical analysis	tectonically dominated drainage establishment
Dongre, N.L. (2015)	Pachmarhi, India	Laboratory experiments	Investigating granulars for laboratory experiments in context of tectonics and Surface process
Dongre, N.L. (2015)	Baihar, India	Numerical Model Study	Evolution of anorogenic baihar (india) plateau: the effect of mantle composition on density in extending lithosphere
Dongre, N.L. (2015)	Sonawani, India	Kinematics and dynamics nodl study	Kinematics and dynamics of the sonawani (Balaghat) tectonic nappes
Dongre, N.L. (2015)	Pachmarhi, India	Dykes analysis in laborotory	Rheology of crystal-bearing magmas and implication for dykes ascent dynamics
Dongre, N.L. (2015)	Pachmarhi, India	Numerical analysis	tectonically dominated drainage

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Dongre, N.L. (2015)	Sonawani, India	Kinematics and dynamics nodl study	Kinematics and dynamics of the sonawani (Balaghat) tectonic nappes
Dongre, N.L. (2015)	Pachmarhi, India	Dykes analysis in laborotory	Rheology of crystal-bearing magmas and implication for dykes ascent dynamics

A number of variations on the stream-power/shear-stress model for bedrock channel erosion (Howard et al., 1994, Dongre, 2012,2013) have been proposed, considering erosion as either detachment- or transport-limited, and with different treatments of the role of sediment in erosion(eg, Whipple, 2004; Sklar and Dietrich,2006). There is little difference between the topography generated by each model at steady-state, ie, erosion matches uplift (Willett et al., 2001). However, in the transient response to perturbation - be it relative sea-level change (eg, Bishop et al., 2005), deglaciation (eg, Meigs et al., 2006), or tectonic (eg, Whittaker *et al.,* 2007) - and the route taken towards steady-state, the predictions of the different models, and hence the understanding of the underlying processes, may be discriminated (eg, Niemann *et* al., 2001; Whipple and Tucker, 2002). This realization has stimulated much research in tectonically active settings, particularly on the role of knickpoints in bedrock channel profile evolution (eg, Crosby and Whipple, 2006; Whittaker et al., 2008).

While the stream-power/shear-stress formulation for fluvial erosion links morphological parameters that can be determined from digital topographic data to more elusive quantities, such as rock uplift rate, a number of the power-law relationships used in the formulation have an empirical basis (eg, Whipple and Tucker, 1999, Dongre, 2014). The most common formulations assume steady, uniform flow and single, representative discharges, while neglecting erosion thresholds and sediment flux (eg, Whipple and Tucker, 2002). Furthermore, the width-discharge relationship is drawn from alluvial rivers, and may not be applicable to bedrock streams. A clear example of this is the narrowing of rivers carving gorges in response to uplift (eg, Finnegan et al., 2005; Whittaker et al., 2007; Turowski et al., 2009). Stock et al. (2005) built a compelling case, based on erosion pin measurements of incision in debris-flow and bedrock channels, that 'the stream power law is too simple and provides insufficient insight about the mechanisms that control valley incision'. Hence a concerted effort has arisen, through carefully designed laboratory experiments (eg, Sklar and Dietrich, 2001, Dongre, 2015) and field measurement (eg, Whittaker et al., 2007), to develop physically based surface process models.

Numerical coupled tectonic-landscape evolution models have made a number of exciting predictions about the interactions between surface processes and tectonics, for example the potential for erosion to control range-scale lithospheric dynamics (Figure 1; Willett, 1999; Koons etal., 2002) or set the scale of mountain ranges (eg, Whipple and Meade, 2004; 2006; Tomkin and Roe, 2007; Whipple, 2009). These predictions are now being tested in field settings, typically through an interdisciplinary combination offield measurement, Quaternary dating, numerical modelling and topographic analysis (eg, Bergeret al., 2008).

1 Range-scale fluvial geomorphology

Numerical, analytical and analogue models, and field-based studies, have all demonstrated that the interaction between tectonics and surface processes is fundamental to orogen development. Hilley and Strecker (2004), Whipple and Meade (2004; 2006), and Roe et al. (2006) Dongre,(2012,2013,2013,2014,2015) coupled stream-power based fluvial erosion models (eg, Howard et al., 1994) with the critical wedge model of small convergent orogens (eg, Dahlen and Suppe, 1988) to demonstrate the link between surface processes, the scale of the wedge, and deformation within the wedge. Whipple and Meade (2004) showed that rock uplift rate is generally

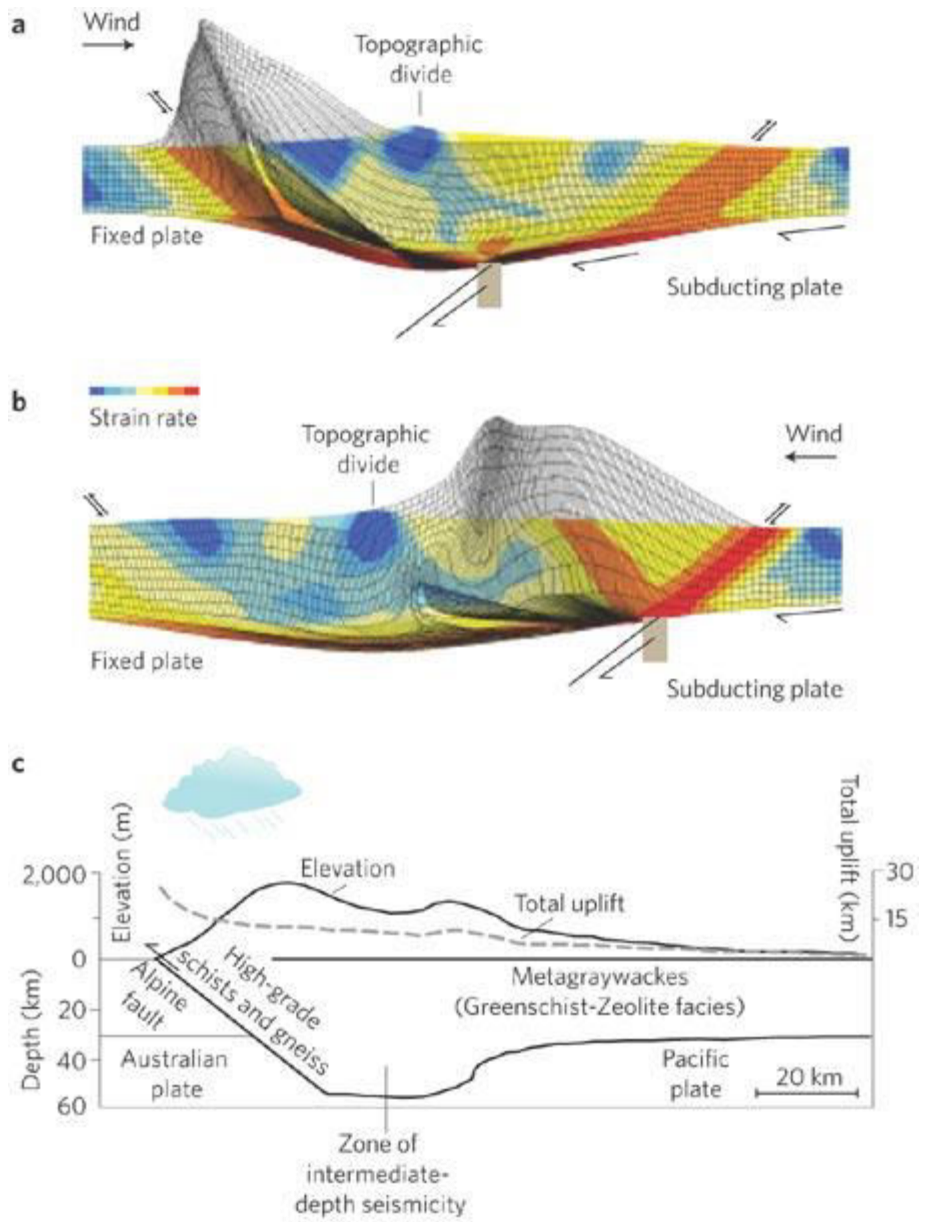

Figure 1. Results of numerical models aimed at understanding the exhumational and structural response of mountain belts to unidirectional moisture flux. Tectonic convergence velocity and subduction direction match conditions for the Southern Alps of New Zealand. (a) Moisture-laden winds arrive from the west (left). Uplift and exhumation, indicated by the extension of the Lagrangian tracking mesh above the topographic surface (top of the shaded domain), is focused over an active thrust fault (indicated by high strain rate). (b) Moisture-laden winds arrive from the east (right). Both uplift and exhumation are focused east of the drainage divide. The western thrust fault is nearly inactive. (c) The observed topography and pattern of total uplift and exhumation (difference between topography (scale to the left) and total uplift (scale to the right)) in the Southern Alps closely match the numerical experiment shown in (a). ***Source:*** **(a, b) Willett (1999), © 1999 American Geophysical Union; (c) Koons (1990), © 1990 Geological Society of America**

controlled by erosional efficiency rather than by the accretionary flux of material, that rock trajectories are dictated by the spatial distribution of erosional efficiency, and that a doubling in precipitation causes a ~40% increase in the rate of rock uplift. Roe et al. (2006) predicted that rockuplift rate scales with precipitation rate to the one-quarter power. Willett et al. (2006) used critical-wedge analysis to account for the cessation in outward expansion of the European Alps at the end of the Miocene, relating the focusing of exhumation and rock uplift towards the interior of theorogen to a climate-driven increase in erosion, reflected in the contemporaneous increase in sediment yield from the southern European Alps.

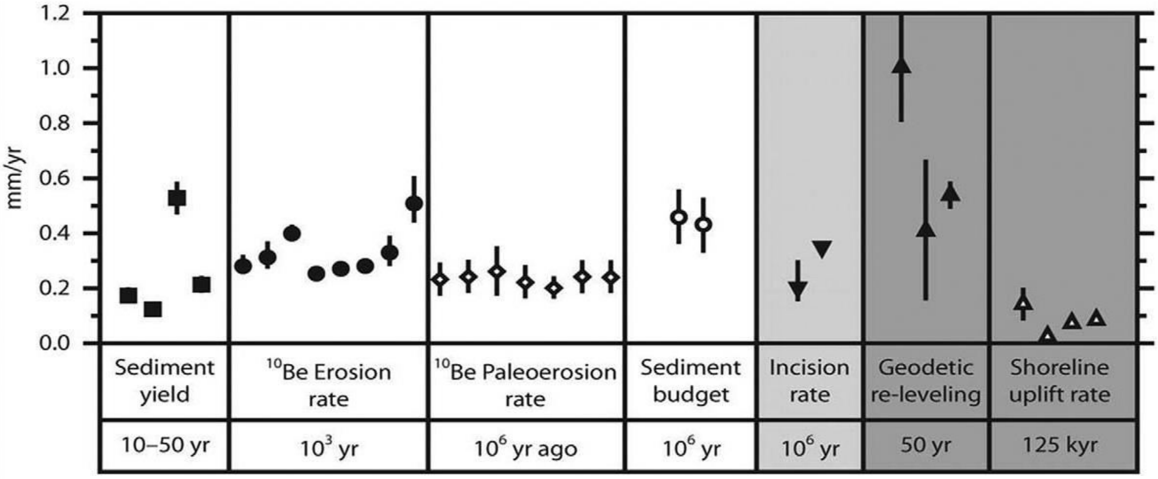

Figure 2. Rates of denudation (white area), fluvial incision (medium-grey area), and uplift (dark-grey area) in the northern and central Apennines, Italy, inferred from seven different techniques over decadal to million-year timescales. ***Source:*** **Cyr and Granger (2008), © 2008 Geological Society of America**

As an example of a field-based study of the timescales of orogen development, Cyr and Granger (2008) combined ^{10}Be basinwide erosion and palaeoerosion rates with river incision rates, marine terrace and geodetic uplift rates, and short- and long-term sediment yield estimates, to demonstrate consistency in rates of exhumation in the northern and central Apennines, Italy, across the last ~1 Ma (Figure 2). Prior to this, exhumation rates were significantly higher, as shown by apatite fission track data. Cyr and Granger (2008) postulated that the Apennines, which emerged in the Pliocene, reached dynamic equilibrium between uplift and erosion within ~3 Ma, after which exhumation rates decreased.

Laboratory studies are overcoming the challenge of constructing analogue experiments with appropriate scaling relationships to permit comparison with natural landscapes. An experimental set-up allows full control over conditions and detailed observations throughout the evolution of an orogen, compared with the snapshot of the natural landscape. Following Bonnet and Crave (2003) and Babault *et al.* (2005), Turowski *et al.* (2006) modelled orogen development with uniformly uplifted silica paste, eroded by artificial rainfall, and analysed using a stereogrammetric camera system. Channel width decreased as uplift rate increased, while flow depth increased, and flow velocity scaled linearly with uplift rate.

Applying geomorphological techniques at the largest scale, Clark *et al.* (2004) interpreted the drainage capture and reversal events across the southeastern Tibetan Plateau margin as a reflection of long wavelength (>1000 km) uplift by lower-crustal flow. In contrast, Hallet and Molnar (2001) treated the long, thin planform geometries of the Salween, Mekong and Yangtze Rivers as markers of pervasive shear strain.

In recent years, tectonic geomorphology has been predominantly concerned with the vertical aspect of exhumation and/or surface uplift. In many orogens, however, the horizontal component of tectonic displacement exceeds the vertical, with largely unexplored consequences for orogen evolution. Craw *et al.* (2003) documented the recent captures of the Landsborough and Clarke Rivers, formerly on the eastern side of the Southern Alps, New Zealand, by the westerly flowing Haast River (Figure 3).

This was attributed to the eastward stepping of southeast-vergent reverse faults, antithetic to the northwest-vergent shortening component on the Alpine Fault. Effectively, material travels east to west across the drainage divide. Further north, Herman and Braun (2006) explicitly incorporated a horizontal shortening component in their numerical model of the development of the Mt Cook region of the Southern Alps. A combination of tectonic advection and fluvial erosion (driven by a pronounced asymmetry in precipitation) govern the position and height of the Main Divide. Miller and Slingerland (2006) noted that drainage basins and valleys are aligned across the main divide of the Siwalik Hills, Nepal (Figure 4), and demonstrated the advection of topography across the divide with a landscape evolution model above a fault-bend fold.

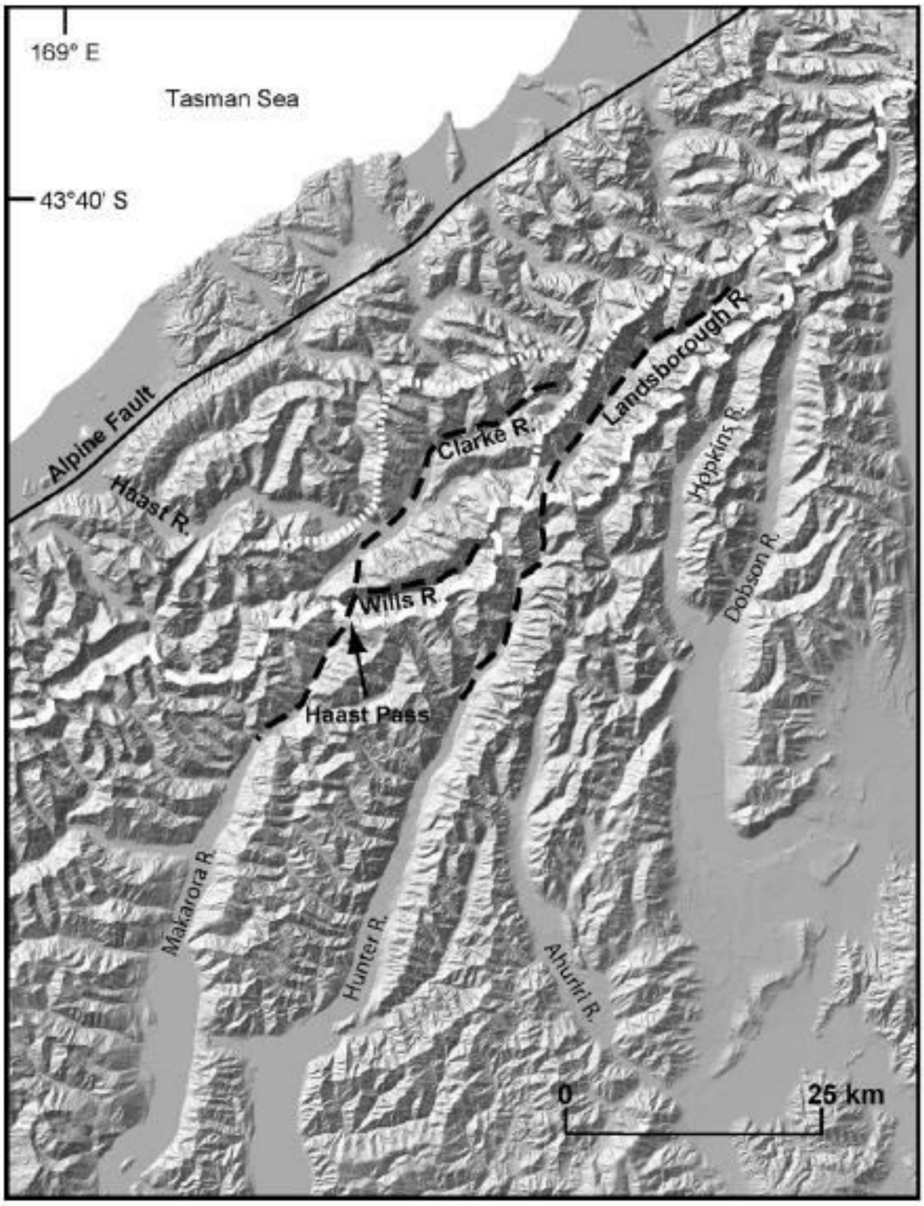

Figure 3. Structural and geomorphic model showing positions of the Main Divide of the Southern Alps, New Zealand, during three stages of geomorphic evolution, overlain on a shaded relief image of the modern topography. River geometry is indicated with black, dashed lines for precapture times when Clarke, Wills and Lands borough Rivers were east of the Main Divide. Early drainage divide indicated by white dotted line, intermediate drainage divide by white dash-dot line, and modern drainage divide by white dashed line. ***Source:*** **Adapted from Craw *et al.* (2003)**

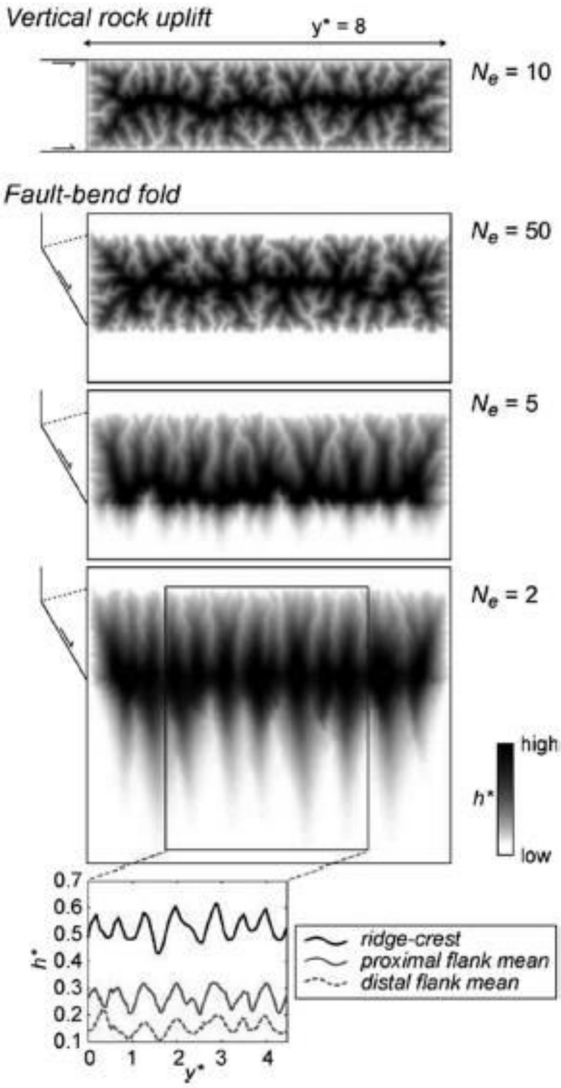

Figure 4. Effect of horizontal tectonics on landscape evolution. Series of maps of topography formed by a numerical model with vertical uplift, and over a fault-bend fold, for different fluvial erosion numbers *N*e (describing the relative efficacy of fluvial erosion versus bedrock velocity). Rotated cross-sections are shown on the left; strike-wise topographic profiles are shown at the bottom. h* and y* are non-dimensional elevation and horizontal distance, respectively. Source: Miller and Slingerland (2006), © 2006 Geological Society of America

2 Catchment-scale fluvial geomorphology and geologic structures

Various modelling and field approaches have been used to demonstrate that erosion can control the development of geologic structures. Finnegan *et al.* (2008) ,and Dongre (2014) provided field verification of the 'tectonic aneurysm' hypothesis, that erosion by major rivers can influence deformation in active orogens (eg, Zeitler *et al.,* 2001; Koons *et al.,* 2002). A tight spatial correspondence, on the Yarlung Tsangpo-Brahmaputra River where it traverses the Namche Barwa-Gyala Peri massif, Tibet, between calculated river power (incorporating channel width measurements), inferred excess fluvial-transport capacity (based on the presence/absence of valley-bottom sediment storage), high relief, rapid ^{10}Be-derived catchment erosion rates, and young cooling ages, is most readily explained by a long-term balance of rock uplift and erosion-driven exhumation. Without compensatory uplift of the Namche Barwa-Gyala Peri massif, the steep reach would have eroded headward rapidly into Tibet.

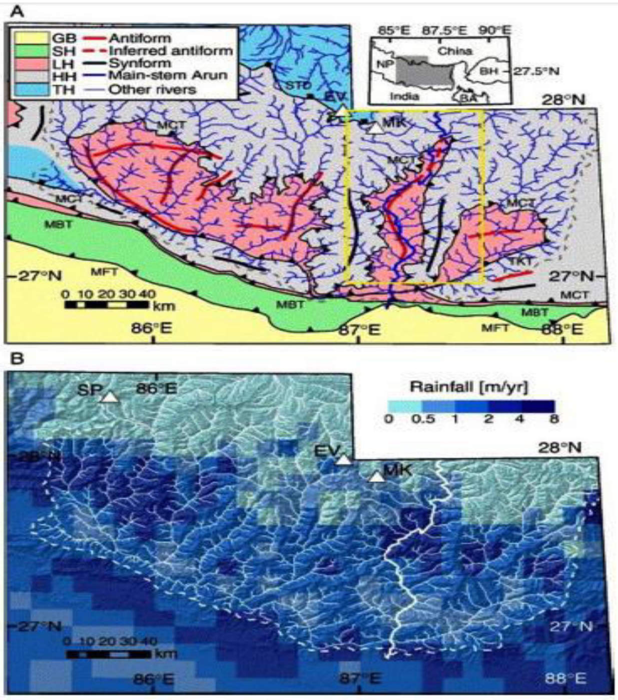

Figure 5. Montgomery and Stolar (2006) suggested that erosion by the Arun River (highlighted), near Mount Everest in the Nepal Himalaya, caused focused rock uplift resulting in the antiformal structure and deep exhumation of the Ama Drime Massif. Detailed structural data and (U-Th)/He apatite ages obtained byJessup *etal.* (2008) support this interpretation. (A) Geologic map of eastern Nepal, and (B) precipitation map draped on shaded DEM of the area. Triangles show locations of major peaks (EV = Everest; MK = Makalu; SP = Shisha Pangma). Inset shows location of study area (NP = Nepal; BH = Bhutan; BA = Bangladesh). Stratigraphic abbreviations: GB = Ganges Basin, SH = Sub-Himalaya; LH = Lesser Himalaya; HH = High Himalaya; TH = Tibetan Himalaya. Structural abbreviations are: MFT = Main Frontal Thrust; MBT = Main Boundary Thrust; MCT = Main Central Thrust; STD = South Tibetan Detachment; TKT = Tamar Kola Thrust. The Arun River marks a zone of high precipitation, and is one of several rivers to coincide with antiformal traces.*Source:* Montgomery and Stolar (2006), © 2006 Elsevier B.V.

Simpson (2004) reported a numerical model of fluvial incision unloading the crust and enhancing local deformation, provided the crust is already under regional compression. This effect is exhibited by the Arun River, near Mount Everest in the Nepal Himalaya, which flows along the exhumed core of an antiform (Figure 5; Montgomery and Stolar, 2006; Jessup et al., 2008).

New dating techniques highlight contrasting styles of deformation in different tectonic settings. Wobus et al.'s (2005) basinwide cosmo-genic ^{10}Be data indicated a fourfold increase in erosion rates over a distance of less than 2 km along the Burhi Gandaki river, coincident with a distinct physiographic transition in the central Nepalese Himalaya, and consistent with longer-timescale ^{40}Ar/^{39}Ar exhumation data. They proposed an active thrust fault at the physiographic transition, also the location of greatest monsoon rainfall. Thus rainfall-driven erosion drives the tectonics. Schildgen et al. (2007), however, found no breaks in (U-Th)/ He zircon ages along the Cotahuasi-Ocona Canyon on the western margin of the Andean Plateau. Here, the margin warped upward into its present monoclinal form, without major surface-breaking faults.

The combination of numerical modelling of sedimentary processes and field-based stratigraphic studies has also proven valuable in deducing tectonic histories. Gawthorpe et al. (2003) mapped faults, folds and syn-rift stratigraphy to demonstrate the history of fault growth and linkage in the Hammam Faraun fault block, Suez rift, Egypt. Bernal et al. (2004) used a coupled tectonic and stratigraphic model to investigate the along-strike stratigraphic expression of fault-related folds; modelled strata reflected the mode of fault propagation. Wilson et al. (2009) employed ground-based LiDAR analysis of the stratigraphy to provide an unprecedented view of the evolution of a half-graben scale normal fault array in the Suez rift, Egypt, elucidating a history of fault-segment linkage and associated folding.

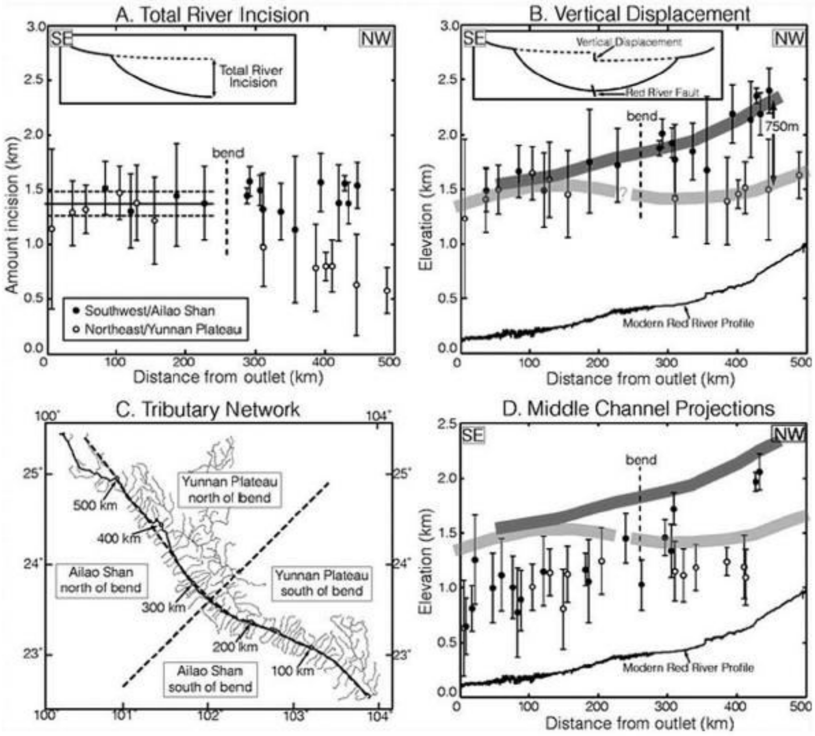

Figure 6. Fault displacement history inferred from projecting river longitudinal profiles from two generations of relict landscapes in Yunnan Province, China. Projected channel segment data plotted against distance from the outlet of the Red River basin near the Chinese-Vietnamese border. (A) River incision, calculated by projecting upper segments of tributaries and subtracting modern river elevations (see inset). (B) Projected upper-segment elevations. Interpreted vertical displacement across the Red River fault (see inset) shown by thick lines, with a maximum vertical displacement of ~750 m. Longitudinal profile of Red River also shown. (C) Approximate distances upstream from outlet and location of bend shown in relation to the Red River tributary network. (D) Projected middle-segment elevations. Upper segment displacement lines and Red River longitudinal profile shown. Incision is approximately two times greater from the middle to lower segments than from the upper to middle segments. *Source:* Schoenbohm *et al.* (2004), © 2004 Geological Society of America

The shear-stress/stream-power bedrock channel erosion model (eg, Howard et al., 1994) can be cast in terms of the power-law slope-drainage area relationship at steady state (see summaries by Whipple and Tucker, 2002, and Wobus *et al.,* 2006c). Kirby and Whipple (2001) mapped spatial variations in tectonic uplift rate in the Siwalik Hills, Nepal, on the basis of changes in profile concavity. Comparing zones of demonstrably different rock uplift rate in the King Range, California, Snyder *et al.* (2003a) found that the greatest change associated with faster uplift was an increase in discharge due to enhanced orographic precipitation.

However, they cautioned that a non-zero threshold stress for incision (counter to the most commonly applied model) gave the most straightforward interpretation of their results. Schoenbohm *et al.* (2004) projected longitudinal profiles from two generations of relict landscapes to determine the incision, surface uplift and vertical displacement history across the northern Red River fault in Yunnan Province, China (Figure 6). DiBiase *et* al. (2008) demonstrated the first field-verified functional relationship between erosion rate and normalized channel steepness index (Wobus *et al.,* 2006c). They compared basin-wide cosmogenic radionuclide erosion rates in stream sands from 50 drainage basins in the San Gabriel Mountains, California, with normalized channel steepness indices, and found erosion rate scaled with the square of channel steepness. Further examples of insights into active tectonics from longitudinal profile analysis are given in Table 1.

However, aspects of the bedrock channel erosion model have been questioned, in particular the assumptions that:

- width is a power-law function of drainage area, increasing monotonically downstream (eg, Finnegan *et al.,* 2005);

- sediment load can be incorporated into a single-valued erosivity term (eg, Sklar and Dietrich, 1998);
- precipitation is uniform and steady (eg, Tucker and Bras, 2000);
- the threshold stress to initiate bedrock erosion or sediment transport can be neglected (Snyder *et al.,* 2003b).

The keys to improving this model lie at the reach scale.

3 Reach-scale fluvial geomorphology

Sklar and Dietrich (2004) illustrated a physically based approach to geomorphological processes in their analysis of erosion by bedload abrasion. They postulated that:

1. wear is proportional to the flux of impact kinetic energy normal to the bed;
2. bedload saltation trajectories can be represented as power functions of non-dimensional excess shear stress;
3. rock resistance to bedload abrasion scales with the square of rock tensile strength;
4. bed cover depends linearly on the ratio of sediment supply to sediment transport capacity.

This saltation-abrasion model was constrained using experimental data. According to the model, steady-state channel gradient is most sensitive to changes in sediment grain size (Sklar and Dietrich, 2006). Since this in turn is driven primarily by sediment delivery from hillslopes, this emphasizes the significance of hillslope-channel coupling, and suggests the effects of variations in rock uplift rate and rock strength on river profiles are indirect. Profile concavity is most sensitive to spatial gradients in runoff and the rate of downstream sediment fining (Sklar and Dietrich, 2008). Turowski *et al.* (2007) derived an exponential formulation for the cover effect in bedrock channels, to replace the linear sediment load-cover relationship employed by Sklar and Dietrich (2004). Bed cover was found to increase with increasing uplift rate, but the channel width-to-depth ratio is a function of both tectonic and climatic forcing. Resulting variations in the slope-area relationship as a function of uplift rate are likely to be too subtle to be measurable in practice, though.

Detailed field observations in tectonically active regions have prompted notable progress in understanding bedrock river incision. Hartshorn *et al.* (2002) elegantly documented spectacular bedrock incision by the LiWu River within the Taroko Gorge, Taiwan, attributable to Super-typhoon Bilis, highlighting both the need to consider storms as discrete stochastic events, and the importance of abrasion by suspended sediment. However, the dramatic variation in incision within a single river cross-section also underlines the complexity of bedrock incision. Cowie *et al.* (2008) compared field-based bed shear stress calculations for the Rio Torto and Torrente L'Apa in the Italian Apennines with the Voagris andXerias Rivers, Gulf of Evia, Greece, and found no straightforward relationship between peak shear stress and relative uplift/ erosion rates. Instead, they explained their data with a model incorporating a parabolic influence of bedload on incision rate. This constitutes a field demonstration of the 'tools-versus-cover' effect (Sklar and Dietrich, 1998): some sediment enhances erosion through impact abrasion or assisting fracturing prior to quarrying, whereas too much sediment armours the bed, protecting it from erosion. Further examination of the LiWu River by Turowski *et al.* (2008) showed that erosion is set by the balance between the sediment load and transport capacity, rather than the distribution of shear stress - ie, the tools-versus-cover effect dominates the partitioning of lateral and vertical erosion. In situ measurements of bedload and impulse counts by Turowski and

Rickenmann (2009) in the Pitzbach, Austria, emphasized the importance of the tools-versus-cover effect, and the inadequacy of a single representative discharge in modelling fluvial erosion. Such field studies are essential in developing and testing models, even though many such efforts principally highlight the challenges involved in developing physically based models of fluvial erosion. Knickpoints have proven particularly fertile ground in tectonic geomorphology research, both for identifying active faults (see Table 1) and for investigating erosion processes. Bishop *et al.* (2005) exploited glacio-isostatic uplift on the east coast of Scotland, and determined that knickpoint recession rate is a function of catchment area. Crosby and Whipple (2006), studying knickpoints within the Waipaoa catchment, North Island, New Zealand, had equal success with a similar model of retreat rate as a function of drainage area, and a model whereby knick-points initiate near a threshold drainage area, below which channels cannot incise with the same efficacy as further downstream. Reinhardt *et al.* (2007) found that knickpoints have retreated much faster than the adjacent hillslopes have adjusted in response to the active tectonics of the Sierra Nevada, southern Spain. A low-relief upland topography (cf. Clark *et al,* 2006) is being replaced at both short (fluvial erosion) and medium (hillslope erosion) timescales. Boulton and Whittaker (2009) related river profile convexities to the transient response to active faulting in the Hatay Graben, Turkey, and further used systematic variations in the height of the convexities to quantify increased slip rates following fault linkage. They advocated geomorphic analysis as a tool for predicting earthquake hazard. Alongside changes in gradient (Table 1), river channels are expected to narrow in response to uplift, although the straightforward bedrock channel erosion model does not incorporate this effect. Finnegan *et al.* (2005) used a simple analysis of a channel with a rectangular cross-section to derive an expression for the steady-state width of river channels as a function of discharge, slope, roughness and width-to-depth ratio (Figure 7). Whittaker *et al.* (2007) demonstrated that traditional hydraulic scaling cannot account for the measured width of the Rio Torto where it crosses the Fiamignano Fault in the Italian Apennines (Figure 8). This well-constrained normal fault accelerated at *c.*1 Ma, so the river is in the midst of a transient response to accelerated footwall uplift. An empirical modification of the Finnegan *et al.* (2005) model provided the best fit to the data. Snyder and Kammer (2008) documented the response to the 1941 diversion of Furnace Creek Wash (439 km^2) into Gower Gulch (5.8 km^2), in Death Valley National Park, California. Two steep knickzones showed narrowing, knickpoint retreat and bedrock incision (detachment-limited), whereas the low-gradient main reach widened due to the extra post-diversion sediment load (transport-limited). Alluvial streams also adjust their width and gradient in response to differential uplift, as shown by Amos and Burbank (2007) in the Ostler fault zone on the South Island of New Zealand. Channel narrowing alone is sufficient to allow channels to remain antecedent following modest uplift, whereas larger folds that demand greater incision require both narrowing and channel steepening. Stark (2006) and Wobus *et al.* (2006b) pursued a theoretical approach to physically realistic models of evolving bedrock channel cross sections. Stark (2006) divided the cross-sectional geometry into four segments, two on the channel floor, which can have a cross-channel slope, and tilt further during channel evolution, and one on each channel wall, at a fixed angle to the vertical.

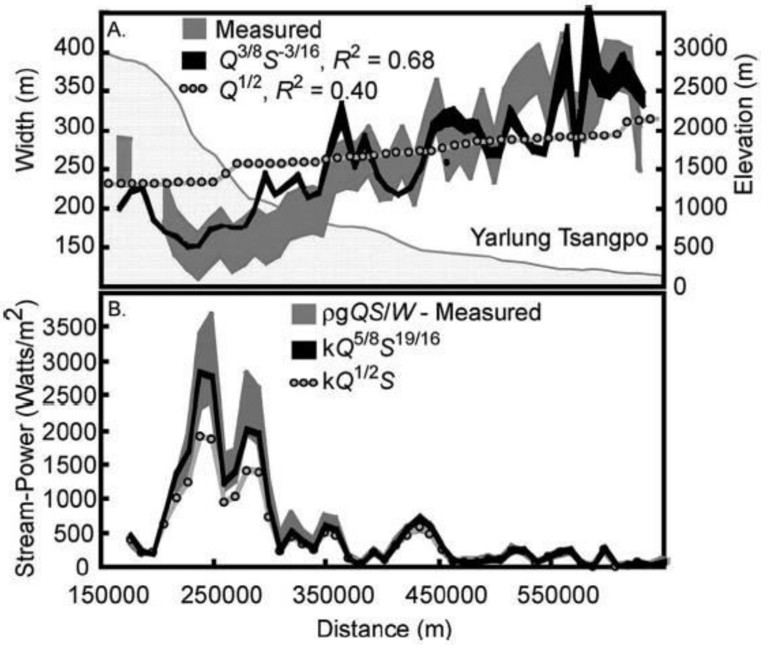

Figure 7. The relationship between channel width and discharge for the Yarlung Tsangpo, southeast Tibet. (A) River longitudinal profile and comparison of measured channel width, channel width derived from a $Q^{1/2}$ relationship, and channel width derived from a relationship involving both discharge and slope. (B) Comparison of unit stream power $\rho gQS/W)$ for Yarlung Tsangpo using measured channel width, width derived from a $Q^{1/2}$ relationship, and width derived from a relationship involving both discharge and slope. Uncertainties due to errors in width measurements and digital elevation model-derived slopes are represented by line thickness for both A and B. ***Source:*** **Finnegan *et al.* (2005), © 2005 Geological Society of America**

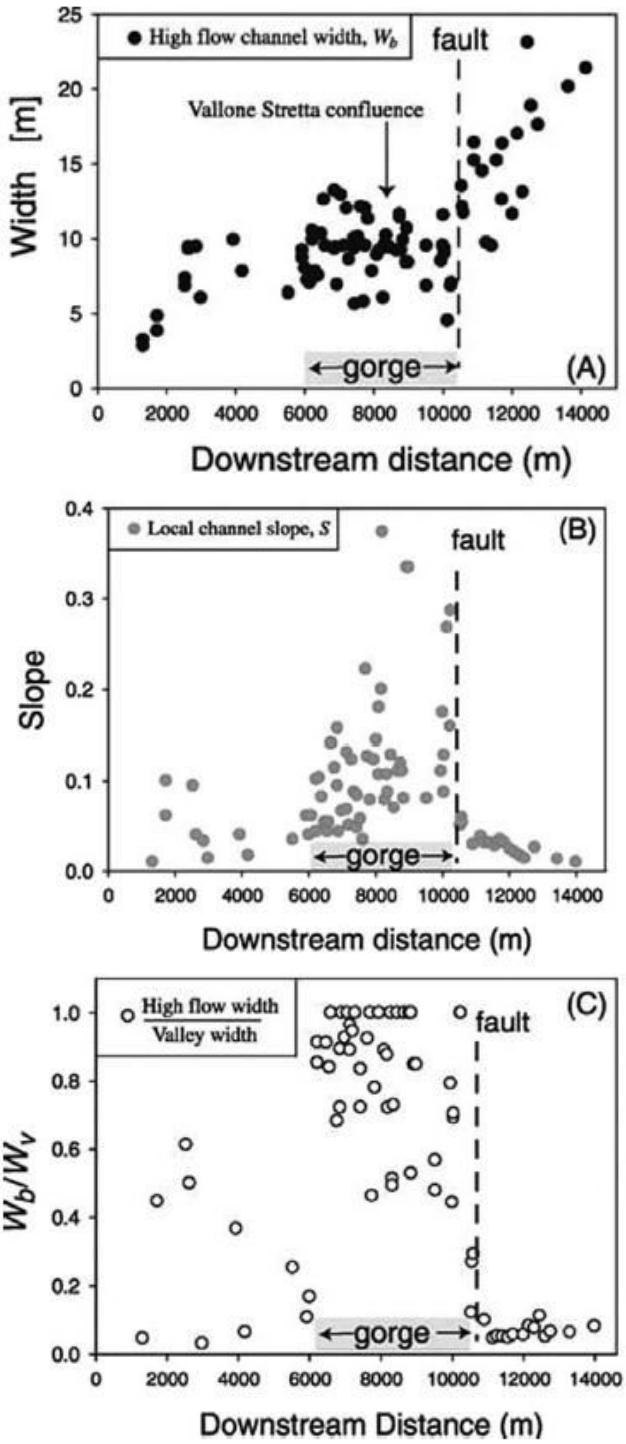

Figure 8. Transient channel response to uplift on the Fiamignano Fault, Italian Apennines. (A) High flow channel width. (B) Local channel slope. (C) Ratio of high flow channel width to valley width against downstream distance in the Rio Torto. Source: Whittaker et al. (2007), © 2007 Geological Society of America

Wobus *et al.* (2006b) explicitly modelled the erosion rate at each point along the wetted-perimeter of the channel, and thus allowed the cross-section to evolve from any initial geometry. Turowski *etal.* (2009) developed both a numerical model of the cross-sectional evolution of a detachment-limited channel, and an analytical model assuming minimization of potential energy expenditure. However, except in one case, neither could describe observed width-discharge scaling, again highlighting a shortcoming of shear stress/stream-power models. The case for landscape evolution models that allow evolving channel geometries is clear.

4. Hillslopes and debris flows

On soil-mantled hillslopes, sediment flux tends to be a linear function of gradient (ie, sediment flux can be described as a diffusive process). Once erosion rates are sufficiently high that soil production rates cannot keep pace, hillslopes are stripped of soil, detachment-limited processes such as landsliding dominate, and denudation rates increase rapidly, while gradients remain roughly constant (ie, the 'threshold hillslope' concept; eg, Burbank etal., 1996). In other words, erosion rate ceases to be linearly related to topographic relief. Such behaviour can be accounted for by a non-linear transport model (eg, Roering etal., 2007). Binnie *etal.* (2007) combined digital topographic analyses with low-temperature ther-mochronometry in the San Bernadino Mountains, California, to demonstrate a highly non-linear denudation rate-hillslope gradient relationship. Threshold hillslopes are treated as effectively coupled to the adjacent bedrock streams (eg, Ramsey *et al,* 2007; Whipple *et al,* 1999), such that bedrock channel erosion and drainage density are the primary controls on landscape morphology. Under such circumstances, hillslope morphology is not a potential source of tectonic information, although, as previously discussed, Sklar and Dietrich (2006) emphasized the coupling between hillslopes and channels as a means for tectonics to influence bedrock channel erosion.

While the threshold hillslope is the prevailing paradigm intectonically active, fluvially sculpted mountain ranges, important exceptions occur. The presence of gorges (eg, Tsangpo Gorge, Montgomery etal., 2004; Taroko Gorge, Schaller *et al.,* 2005) is an obvious case. Such gorges reflect rapid fluvial incision (Schaller *et al.,* 2005), but also require strong bedrock to maintain steep valley walls. Furthermore, the potentially key role of debris flows in linking hillslope and fluvial processes has only recently been appreciated (eg, Stock *et al.,* 2005; Stock and Dietrich, 2006), and the role of debris flows in a tectonic geomorphology context is barely explored (Densmore *et al.,* 2007). Stock and Dietrich (2003; 2006) made a strong case that, in many steepland valleys, debris flows dominate at slopes of less than ~0.03-0.10, which can represent much of the relief (25-100%), and generate a topographic signature that is fundamentally different from that predicted by bedrock river incision models.

Landslides represent a major hazard, particularly in association with seismic activity (eg, Keefer and Larsen, 2007), but are also a significant influence on channels. Ouimet et al. (2007) detailed how large landslides along the Dadu and Yalong rivers, on the eastern margin of the Tibetan Plateau (Sichuan, China) represent a primary control on channel morphology and river profiles. These landslides overwhelm channels with $>10^5$ m^3 of coarse material, forming landslide dams, and causing prolonged aggradation upstream, a key component of the transient response to rapid uplift. Landslides are also a primary cause of epigenetic gorges, sites of extremely rapid bedrock channel incision (Ouimet et al., 2008; Pratt-Sitaula et al., 2007).

5. Tectonic factors affecting the drainage system: Morphological evidence in the Pachmarhi Land scape

While the rivers of the Pachmarhi landscape are largely consequent, following courses through relatively downthrown basins and fault angles, there are usually rivers that have cut gorges across upheaved blocks, Though such courses may have been first taken on covering strata and are then, strictly speaking, superposed where they are cut down into underlying rocks, gorges across mountain blocks are in the main of antecedent origin. Simple antecedence is probably the correct explanation of the Pachmarhis rivers that have maintained courses in gorges through block mountains of the Pachmarhi.

However, these gorges, notably the Tawa, Denwa, Sonbhadra, Dudhi, Bainganga and Nagduari through ranges of tectonic origin in various parts of Pachmarhi seem to have originated in two stages. In an early stage of deformation of the terrain, they were consequent on the range and basin pattern as it was then developed, but as deformation proceeded or was renewed after a pause, this pattern changed and some ranges that were earlier non-existent or discontinuous rose and became continuous across rivers, which maintained antecedent courses through them. The well- known gorge of the Denwa, Sonbhadra, Bainganga and Nagduari, originated in this way when the main axial range, formerly discontinuous, rose and became continuous across the course of the river. Through this gorge, the drainage of a large area east of the axial range is carried westward to the Narbada.

The drainage of the Pachmarhi is consequent on the laccolitic displacement. The uplifting of a laccolite, like the upbuilding of a basalt intrusion is an event of so rapid progress that the corrosion of the Mahadeva Gondwana offers peculiar facilities for the study of the origin of drainage forms, and its marvellous sculpture has excited the interest of every observer. This study will prove entirely fruitful, and for the sake showing the bearing of its peculiar features upon the general subject, I shall take the liberty to restate certain principles of erosion which have been derived or enforced by New Berry (1862), Powell (1873),

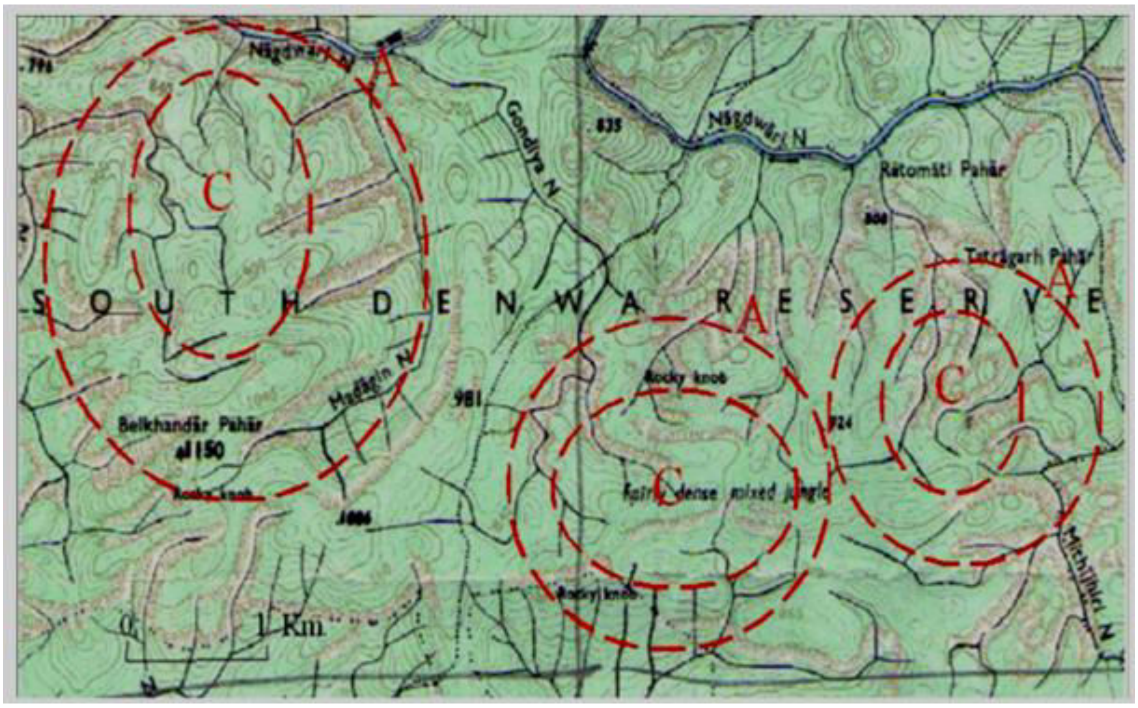

Figure 9. Tectonically dominated drainage system of the Belkhandar Brijlal-deo and Chintaman Mountain arch in Pachmarhi. Tectonics plays a very important role in the geomorphic evolution of drainage and well reflected in fluvial processes. This figure are reflective of an interaction of tectonics, surface geological processes ,rock resistance and influences of rock structures resulting in landscape evolution.

The drainage of the Pachmarhi (topo sheet-55/J-7) is consequent on the laccolitic displacement. The uplifting of a laccolite, like the upbuilding of a basalt intrusion is an event of so rapid progress that the corrosion of a stream bed cannot keep pace with it. It is not known that the site of the mountains was dry land at the time of their elevation; but if it was, then whatever streams crossed it were obstructed and turned from their courses. If it was not, there were no pre-existent waterways, and the new ones, formed by the first rain which fell upon the uplifted strata, radiated from the crests in all directions. The result in this case is the same, and can be determined from the present drainage system, wheather the Pachmarhi formation were lifted from the bed of the lake or arose after its subsidence of the Pachmarhi is consequent on the whole, it is not consequent in all its details, and the character of its partial inconsequence is worthy of examination.

Let us begin with the simplest case. The drainage system of the Denwa is more purely consequent than any other with drainage system in the area. In Figure 9,10 and 11, the point C marks the crest of the upland the Belkandhar, Dhupgarh, Mahadeva, Chauragarh and Pachmarhi Hills Domes. The inner circle represents the line of maximum dip of the arching strata and the outer circle the limit of the disturbance. It will be seen that all the waterways radiate from the crest point) and follow closely directions in which the strata incline. At A, the arch touches and the effect of the compound inclination is to modify the directions of waterways the region of tectonically important.Turning now to arch B, it is found that its ridges are not equally respected by the drainage lines.

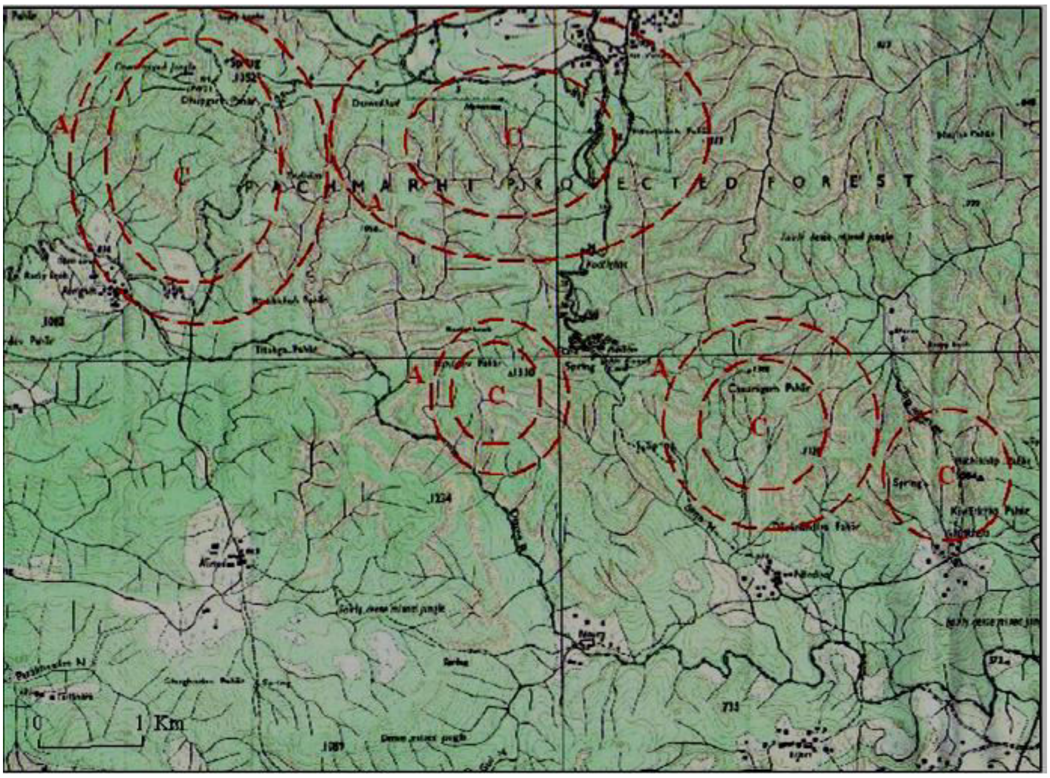

Figure 10. Tectonically oriented drainage in Dhupgarh , Mahadeva and Chauragarh Arch of Pachmarhi . This figure reflects the tectonic forces result in a slow and steady deformation in the form of folding, uplift, warping and tilting of rock unites. Among geomorphological evidence of active tectonic,drainage system and their characteristics like drainage anomaly,confluence angle of drainage and river direction play an important role in identifying active tectonics and their spatial variations.

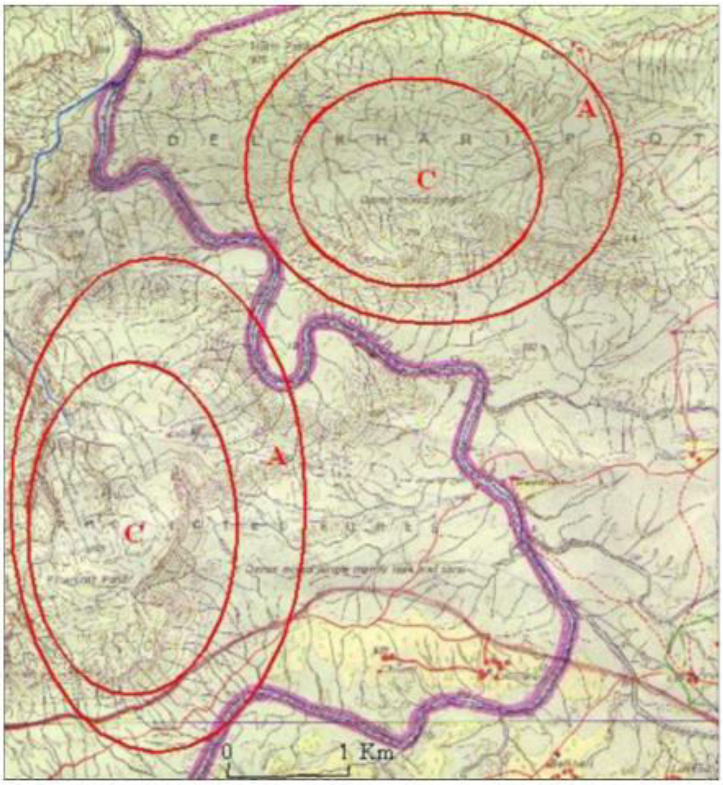

Figure 11 . Tectonically dominated drainage prevailing in Patalkot Arch related to Pachmarhi The structural and lithological controls on the river system are reflected by distinct drainage patterns,abrupt changes in flow direction, offset channels, straight lines, meander cutoffs multy-terrace river valley.

The crest of the Greater arch (Figure 12 and 13) is the center of a radiating system, but the crest of the lesser arch is not; and waterways arising on the Greater traverse the lesser from side to side. More than this a waterway after following the margin of the lesser arch turns toward it and penetrates the flank of the arch for some distance. In a word, the drainage of the Greater arch is consequent on the structure, while the drainage of the lesser arch is inconsequent. There are at least two ways in which this state of affairs may have arisen.

First, the Greater arch may have been lifted so long before the lesser that its waterways were carved too deeply to be diverted by the gentle flexure of the latter.

Figure 12. Tectonic activities clearly diverting the drainage of the Pachmarhi - Belkhandar and Chintaman Arch. Overall, result reveal a strong correlation between channel adjustment to regional forcing. Although drainage could represent a transient wave of incision, such a mechanism cannot easily explain highly-concave profile in the region.

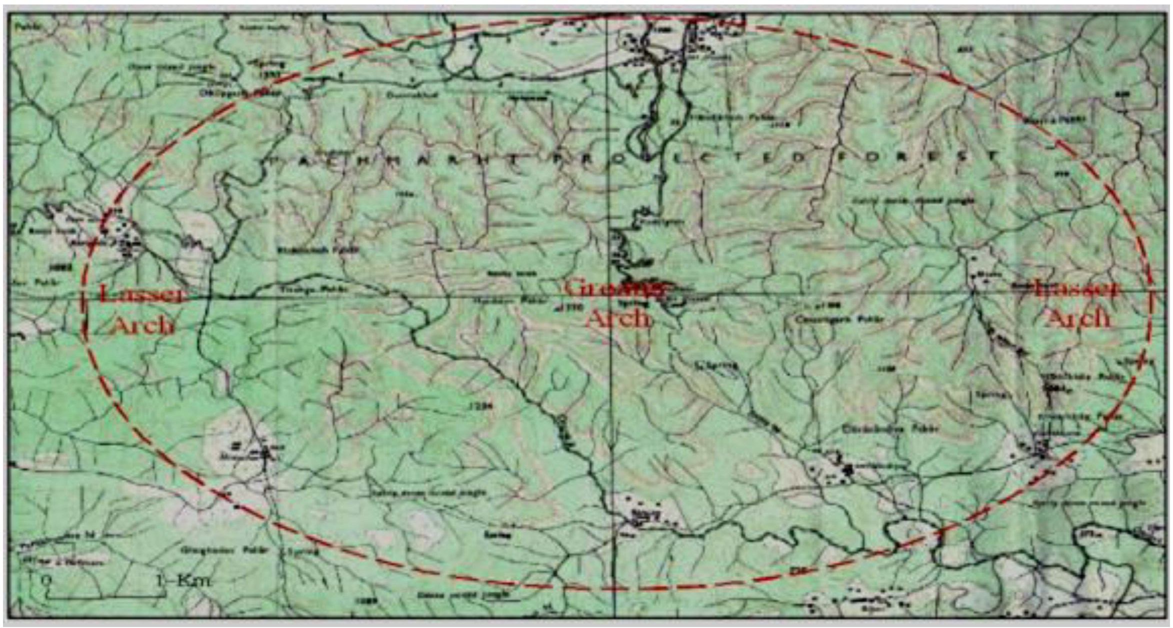

Figure 13. Drainage system of the Dhupgarh and Chauragarh Arch depended on Tectonic activities. The drainage patterns is not the indication of the maturity of the basin but an indication of the presence of faults, shear zones and offset of the ridges. Presence of "V" shaped valleys and straight mountain fronts support such an interpretation that reflect deep valleys, in which streams are actively incising their valleys, which is an indicator of active uplift of the area. These features are also associated with the high level of tectonic activity present in that area.

The drainage of the lesser would in that case be classed as antecedent. If the Lesser arch were first formed and carved, the lifting of the Greater arch might throw a stream across its summit; but it could not initiate the waterways which skirt the slopes of the lesser especially if those slopes were already furrowed by streams which descended them. If the establishment of the drainage system depended on the order of lift, the Greater arch is surely the older.

Second the drainage of the lesser arch may have been imposed upon it by plantation at a very late stage of the degradation. Whatever was the origin of the arches, and whatever was the depth of cover which they sustained, the Greater is certain to have been a centre of drainage from the time of its formation. When it was first lifted it became a drainage center because it was an eminence; and afterward it remained an eminence because it was a drainage center.

When in the progress of the denudation its dykes were exposed their hardness checked the wear of the summit and its eminence became more pronounced. It was perhaps at about this time that the last of the cretaceous rocks were removed from the summits and slopes of the two arches and the Denwa rift basalt was laid bare, and as soon as this occurred the condition for lateral corrasion were complete. With trachyte in the peaks and basalt upon the slopes planation would naturally result and a drainage system would be arranged around the dykes as a centre without regard to the curves of the strata. The subsequent removal of the shale would impart its drainage to the underlying sandstone.

Either hypothesis is competent to explain the facts, but the data do not warrant the adoption of one to the exclusion of the other. The waterway of the lesser arch may be either antecedent or superimposed by plantation. The Greater arch may have been the first to rise or the last.

The drainage of the area is consequent to the main uplift and to the majority of the minor, but to the greater arch it is inconsequent. In this case there is no question that the arch has been truncated by planation. The Satpura rising five to ten times as high as the Mahadeva become the center of drainage for the cluster and the trachyte-laden streams which it sent forth were able to pare away completely the lower arch while it was still unprotected by the hardness of its nucleus. The foot plain of Pachmarhi, which extends unbroken to the outcrop of the conglomerate, is continued on several lines across, although in the intervals the central area is deeply excavated. The planation stage is just started and an epoch of fixed waterways is inaugurated.

The drainage of Jatashankar is consequent in regard to the main uplift, but inconsequent to some of the minor. A stream which rises on the south flank not merely runs across one of the upper series of laccolites, a companion to the Denwa but has cut into it and divided it nearly to the base. It is probable that the position of the waterway was fixed by planation, but no remnant of the plain was seen too little is known of the erosion cycle of the central area of Pachmarhi to assert its relation to the drainage. About its base there are three localities which have lost all or nearly all their cover, and each of these is a local centre of drainage. The streams which head in the mountain crest are very ancient document of the land surface. Other rivers have been laid bare at a few points only, and these are each crossed by one or two streams from higher levels. The remainder are not exposed at all, and their arches are crossed by numerous parallel streams. The Northern arch is freshly truncated by planation, and there is physiographical proof that they have at some time been truncated. The loccolites which stand highest with reference to the general surface are exempted from cross drainage, and the arches which lie low are completely overrun.

If go back in imagination to a time when the erosion of the mountain was so little advanced that the stream- beds were five hundred meter higher than they are now (Crookshank ,H**.1936),** it may suppose that very little trachyte was laid bare. As the surface was degraded and a few laccolites were exposed, it would probably happen that some of the then- existing streams would be so placed as to run across the trachyte. But being unarmed as yet by the debris of similar material they would corrade it very slowly; and the adjoining streams having only shale to encounter, would so far outstrip them as eventually to divert them by the process of "abstraction" In this way the first bared laccolites might be freed from cross drainage and permitted to acquire such radiating systems of waterways as found them to possess. At a later stage when trachyte was exposed at many points and all streams were loaded with its waste, the power to corrade was increased, and the lower-lying laccolites could not turn aside the streams which over ran them.

The work of planation is so frequently seen about the flanks of the Chauragarh that there seems no violence in referring the entire cross drainage of lateral arches to its actions; and if that is done, the history of the erosion of the mountains takes the following form:

When the laccolites were intruded, the mounds which they uplifted either rose from the bed of a lake or else turned back all streams which crossed their sites; and in either case they established upon their flanks a new and "consequent" set of waterways. The highest mounds become centers of drainage, and sent their streams either across or between the lower. All the streams of the disturbed region rose within it and flowed outward. The degradation of the mounds probably began before the uplift was complete, but of this there is no evidence. As it proceeded the convex forms of the mounds were quickly obliterated and concave profiles were substituted. The rocks which were first excavated were not uniform in texture, but they were all sedimentary and were soft as compared to the trachyte. The Tertiary and probably the Upper Cretaceous were removed from the summits before any of the igneous rocks were brought to light, and during their removal the tendency of divides to permanence kept the drainage centers or maxima of surface at substantially the same points. When at length the trachyte was reached its hardness introduced a new factor. The eminences which contained it were established more firmly as maxima, and their rate of degradation was checked. With the checking of summit degradation and the addition of trachyte to the transported material, planation began upon the flanks, and by its action the whole drainage has been formed. One by one the lower laccolites are unearthed, and each one adds to the complexity and to the permanence of the drainage. If the displacements were completed before the erosion began, the mountains were then of greater magnitude than at any later date. Before the igneous nuclei were laid bare and while sedimentary rocks only were subject to erosion, the rate of degradation was more rapid than it has been since the hardness and toughness of the trachyte have opposed it. If the surrounding plain has been worn away at a uniform rate, the height of the mountains (above the plains) must have first diminished to a minimum and afterward increased. The minimum occurred at the beginning of the erosion of the trachyte, and at that time the mountains may even have been reduced to the rank of hills. They owe their present magnitude, not to the uplifting of the land in Middle Tertiary time, but to the contrast between the incoherence of the sandstones and shales of the Mesozoic series and the extreme durability of the laccolites which their destruction has laid bare. And if the waste of the plain shall continue at a like uniform rate in the future, it is safe to prophesy that the mountains will for a while continue to increase in relative altitude. The phase which will give the maximum resistance to degradation has been reached in none of the mountain, except perhaps Dhupgarh, Mahadeva, Chauragarh and Belkandhar in Satpura. It is unassailed, and the present prominence of their forms has been accomplished simple by the valour of their skirmish lines of dykes and spurs.

The question now is to explain the presence of the major drainage lines they are discordant with not only the scarp, but the entire structural grain of the Satpura Basin. In fact, the Denwa, Sonbhadra, Dudhi, and Nagduari, etc, originate in the lowland landscape (gorges) south of the Pachmarhi scarp, and flow directly into the Pachmarhi Plateau, across the axis of the Satpura Dome and flow emerge north to debouch into the Narmada rift valley. These major rivers could hardly be superimposed from higher planation levels, for there is nothing to suggest that the Deccan Trap plateau to the south of the study areas was very higher than the Satpura Dome. Moreover, it does not seem possible for a minor stream on the northern flanks of the dome to be drawn across the domal axis by head ward erosion and capture streams on the Lowland Landscape. The only plausible hypothesis, and one that fits the field evidence is that the major streams antedate the domal uplift and were able to maintain their courses across the uplift to the local baselevel in the Narmada river rift valley.

From the moment the streams were initiated, they have laterally planated and vertically eroded the valley then occupied as a funtcion of the rate of uplift, changes in local base level, or presence of contrasting lithologies of differing resistances to erosion (Verma 1972)**.** The recurrent and often spamodic nature of uplift and still stand in the Pachmarhi area has been preserved in the stepped land-forms. (Venkatakrishnan, 1975, the recurrent nature of tectonism in Central India, especially along the Narmada Son lineament (Choubey, 1971) has recently been documented in geophysical studies as well (Qureshi and Warshi, 1980)**.**

5. Glacial geomorphology

In comparison with fluvial settings, the interactions between glaciers and tectonics have received little attention. Glaciers tend to dominate landscape evolution (eg, Brozovic *et al.*, 1997), and can even change the location of tectonic deformation (Berger *et al.*, 2008). The efficiency of glacial erosion, and the fact that the development of glaciers in most major mountain ranges is a conspicuous consequence of late Cenozoic climate cooling, means that glaciers have an essential role to play in tectonic-climate interactions (eg, Whipple *et al* /., 1999).

Brozovic *et al*.'s (1997) regional-scale analysis of the topography of the Nanga Parbat region of the Pakistan Himalaya demonstrated that, despite some of the most rapid rock uplift rates in the world, glacial erosion dominates landscape evolution. The 'glacial buzzsaw hypothesis posits that glacial erosion can keep pace with tectonic uplift rates, and, since glacial erosion is generally most efficient close to the equilibrium line altitude (ELA), there will be a strong correlation between hypsometry (frequency distribution of elevations) and the ELA. Egholm *et al* s (2009) global topographic analysis demonstrated a correlation between maximum mountain height and snowline altitude for many high mountain ranges, across orogenic ages and tectonic styles.

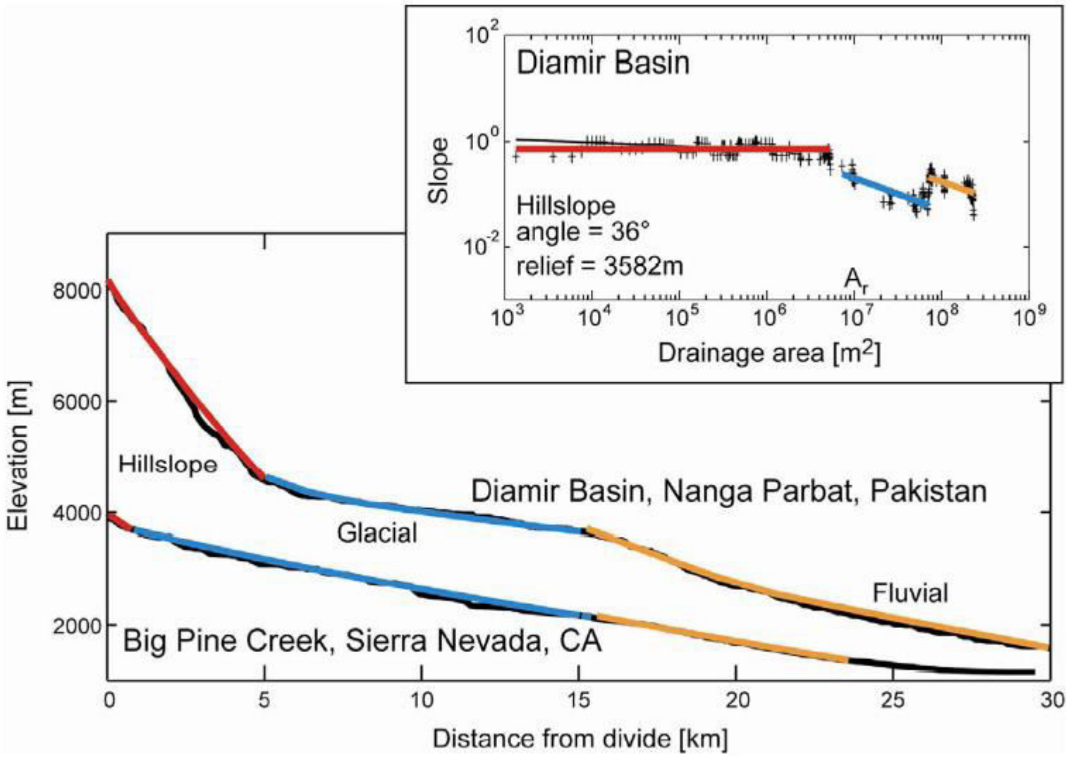

Figure 14. Longitudinal profiles of the Diamir Basin, Nanga Parbat, Pakistan Himalaya (after Brocklehurst and Whipple, 2007), and Big Pine Creek, Sierra Nevada, California (after Brocklehurst and Whipple, 2006). Inset: slope-area data for the Diamir Basin. Notice that the glaciated reaches have very similar gradients, but the cirque headwall relief is radically different.

Their accompanying numerical model showed how the combination of glacial erosion and isostatic uplift due to erosional unloading drives elevations towards an altitudinal window just below the snowline. In other words, differences in the height of mountain ranges mainly reflect variations in local climate, and little evidence of spatial variations in tectonic activity would be anticipated in glacial landscapes.

Brocklehurst and Whipple (2007) carried out drainage basin-scale topographic analysis, revi-siting the Nanga Parbat region, and also studying the Southern Alps, New Zealand. They discovered that the relationship between tectonics and glacial erosion is a function of drainage basin size. Larger glaciers maintain shallow downvalley gradients even in the face of rapid tectonic uplift, and, because of their areal extent, account for the regional glacial buzzsaw effect described by Brozovic *et al*. (1997). However, smaller glaciers evidently do not erode as efficiently, and their down valley gradients are steeper in areas of more rapid rock uplift. Brocklehurst and Whip-ple (2007) also noted a correlation between the height of cirque headwalls and rock uplift rate; while glacial erosion may be efficient, periglacial hillslope processes are not as rapid, and spectacular hillslopes can develop. In the case of Nanga Parbat, it is the hillslope exceeding 3500 m tall that permits the peak to rise beyond 8000 m (Figure 14). This observation is in line with the 'Teflon peaks' described by Anderson (2005).

Foster et al. (2010) also found drainage area dependence in glacial landscape evolution in the Teton Range, Wyoming, accentuated by orographic precipitation, which is only delivered efficiently to the largest, shallowest valleys on the eastern side of the range. Grand Teton owes its height to rapid rock uplift, wide drainage spacing, high rock strength, and efficient glacial erosion in neighbouring valleys. Hence the geo-morphology of glacial landscapes may provide some clues to active tectonics.

Tomkin (2007) described a numerical model explicitly coupling convergence and rock uplift with glacial and fluvial erosion. With a high equilibrium line altitude (ELA), glacial erosion is confined towards the peaks, which are also the focus of rock uplift. A lower ELA and more extensive glaciation are associated with faster rock uplift on the margins of the range. Tomkin (2007) also demonstrated that a literal glacial buzzsaw model yields different results from the explicit surface processes model, and determined that late Cenozoic cooling might have doubled rock uplift rates in some orogens.

Meanwhile, Tomkin and Roe (2007) developed an analytical critical wedge model (eg, Whipple and Meade, 2004) incorporating glacial erosion, and showed that the sensitivity of the glaciated orogen width to either accretion or precipitation rate is higher than in equivalent fluvially eroding wedges.

Berger et al. (2008) provided the first compelling field evidence of a tectonic response to enhanced glacial erosion. The development of larger glaciers in the St Elias Range, Alaska, due to the Middle Pleistocene Transition (~ 1 Ma) is associated with: more rapid exhumation (indicated by (U-Th)/He dating) close to the intersection of the topography with the ELA; the cessation of activity on thrust faults further from the range in the Gulf of Alaska (seen on seismic reflection profiles); the switching of tectonic activity to faults closer to the core of the range; and increased sediment flux to the Gulf of Alaska. Thus glacial erosion has driven a reorganization of the tectonics of the St Elias Range, narrowing the active wedge in line with model predictions.

6. Submarine geomorphology

While good-quality bathymetric data are now available, in situ observations of the processes responsible for submarine landscape evolution are elusive. Nevertheless, progress has been made in elucidating submarine tectonics with an approach based on terrestrial geomorphological techniques (eg, Mitchell, 2006). Huyghe et al. (2004) examined bathymetric and seismic data, and found a substantial increase in both incision and gradient of submarine channels crossing the active frontal folds of the southern Barbados prism. They suggested that variations in channel gradient correspond to variations in substrate uplift rate, while cautioning that variations in sediment flux and transient erosional conditions represent additional complications. Heinio and Davies (2007) attributed knickpoints in 3D seismic data for the western Niger Delta to gradient changes caused by the uplift of a fold-and-thrust belt. Upstream of a growing fold, reduced channel gradients cause turbidity currents to decelerate, depositing the coarsest sediment, while on the downstream limb local steepening causes increased flow velocity and turbulence, enhanced erosion, and knickpoint formation. However, Straub and Mohrig (2009), interpreting 3D seismic data from offshore Brunei Darussalam, described how, unlike their terrestrial counterparts, submarine canyons are notnecessarily erosional features; they may be formed under conditions of net deposition, as faster sedimentation on ridges increases submarine canyon relief.

With the 3D perspective of seismic reflection data offering insights into both the geological structure and depositional record that are impossible in terrestrial settings, there are many opportunities to approach submarine tectonics from a geomorphological perspective.

7. Discussion

The last decade has seen a revolution in the geomorphological techniques and approaches applied to understand tectonics at a range of spatial and temporal scales. In some instances the results have been remarkably elegant; in other cases the lack of consensus has highlighted the complexity of the problem, and raised more questions than have been answered. Empirical models have been successful in tectonic geomorphology applications (eg, Kirby and Whipple, 2001). There is a temptation to be content with existing geomorphological models, and to continue to use these, for example, to map active tectonic deformation from digital topographic data. The greater challenge is to develop physically realistic models of geomorphological processes, and scale these for tectonic geomorphology applications. The analyses conducted by Sklar and Dietrich (2006) and Whipple and Tucker (2002), for example, elegantly highlight the different responses to perturbation arising from different parameterizations. While the drive towards more physically based models has seen progress in many directions, a synthesis, bridging scales from local conditions, through reach and catchment to range scale (eg, Sklar and Dietrich, 2006), is some way off.

Since it is the transient response of surface processes that is one of the major foci in tectonic geomorphology (ie, looking for evidence of active tectonics), this will be a key area of development. Considerable effort has been directed towards the dynamic adjustment of channel width, both from a numerical modelling perspective (eg, Stark, 2006; Wobus *et al* 2006b; Turowski *et al.*, 2009), and through careful field-work in well-chosen, well-constrained field sites (eg, Finnegan *et al* 2005; Whittaker *et al.*, 2007). Similarly, knickpoints (eg, Crosby and Whipple, 2006; Reinhardt *et al.*, 2007) and the role of sediment load in river incision (eg, Sklarand Dietrich, 2004; Cowie *et al* 2008; Turowski *et al* 2008) have received considerable attention. Field studies are not easy, though. Gabet *et al* (2008), for example, with their study of the Marsyandi River, Nepal, demonstrated the considerable care, effort and complexities involved in obtaining discharge and sediment flux data in high-relief, active settings.

This review has highlighted several successful examples of interdisciplinary studies which have combined some or all of digital topographic and seismic reflection analyses, fieldwork, numerical and analogue modelling, and cosmogenic isotope/OSL/thermochronometric dating (eg, Berger *et al* 2008; Cyr and Granger, 2008).Large, interdisciplinary studies have yielded spectacular results, but are also expensive. Such collaborations are often necessary to gain a quantitative understanding of the interaction of surface processes with range-scale tectonics and climate change. However, experimental design is important: there is still a place for detailed, small-scale, well-constrained studies. Improved synergy between geomorphologists and sedimentologists represents a clear focus for furthering the understanding of landscape evolution in active tectonic settings (eg, Gawthorpe *et al* /.,2003; Berger *et al* 2008).

Given the excitement generated by hypotheses linking climate change, tectonics and surface processes, it is tempting to focus research where tectonics is most active and topography most dramatic - eg, the Himalayas. However, these are not necessarily the best places to conduct hypothesis-testing research, due to the complexities of the system - eg, glaciation in the headwaters of most Himalayan rivers, dramatic gradients in precipitation, difficulty of monitoring and mapping due to the challenging terrain. There is still much to recommend field sites where as many complexities as possible are removed, allowing a more straightforward experimental test - eg, the small catchments developed on the rising footwalls of normal faults (Densmore et al., 2004; 2005; 2007), neighbouring catchments with different headwater lithologies (Johnson et al., 2009), or along-strike variations in the degree of glacial modification (eg, Brocklehurst and Whipple, 2002; 2006).

8. Conclusions

Many recent studies have exhibited the key role of surface processes in the development of active orogens. Present formulations of bedrock channel erosion permit prediction of spatial differences in tectonic uplift from topographic data, although local calibration is necessary, and there are well-understood shortcomings with the model. Knickpoints may also be interpreted on a tectonic basis, although other sources of base-level change, particularly sea-level and lithologic variations, are also important. Plan-view geometries and stratigraphic architecture can be particularly informative in interpreting fault growth and linkage. Down valley gradients of smaller glaciers and cirque headwall heights may provide clues towards active tectonics of glacial landscapes, although this remains largely untested. Similarly, hillslope, debris flow and submarine geomorphology remain little explored in a tectonic geomorphology context.

The current status of tectonic geomorphology is not as close to providing the suite of tools for remote assessment of active tectonics as some geoscientists would like, but at the same time, a wealth of opportunities exist for stimulating research and important progress.

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