5.2 Tectonic Geomorphology: A Perspective

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Glossary

Base level Lowest point that a drainage can flow to and is generally sea level or the level of a internally drained lake.

Continental drift The movement of Earth's continents relative to each other.

Davisian cycle of erosion A model for landscape development proposed by William Morris Davis in which landscape change from youthful to mature by processes of erosion.

Delamination Loss/detachment and sinking of part of the lowermost lithosphere.

Dendrochronology Method of dating using tree rings.

Digital elevation models (DEMs) Computer model or three-dimensional representation of a terrain's surface.

Fault scarp degradation Reduction of the original form of a scarp produced by a fault by processes of erosion, transportation, and deposition of the scarp material.

Geochronology Measurement of time intervals or dating of events on the geological timescale.

Geodesy Study of the shape and size of Earth by survey and mathematical means.

Geodetic Pertaining to the study of shape and size of landforms, landscapes, and/or Earth.

Geomorphic indices Quantitative method/descriptor for a landform and/or landscape.

Glacioisostasy Crustal subsidence or uplift related to loading or unloading of the crust due to glacier/ice sheets growth or melting.

Global positioning systems (GPS) A space-based global navigation satellite system (GNSS) that provides a location on Earth.

Ground-penetrating radar (GPR) Geophysical method that uses radar to image the subsurface.

Hot-spots Volcanic center, 100–200 km across, that persists for a few tens of millions of years.

Lahars Debris flow/mudflow comprising volcaniclastic material.

Magnetic polarity timescale A record of the succession of magnetic reversals or anomalies of Earth's magnetic field determined from the magnetic properties of\rock or sediment successions that can be used to determine the geologic age of a rock or sediment.

Magnetometer Geophysical equipment used to measure Earth's magnetic field or the magnetic characteristics of rock and sediment.

Mantle upwelling Movement of mantle material from lower depths within the mantle toward the crust.

Mountain front sinuosity Geomorphic indices that quantifies the straightness of a mountain, which is a function of the tectonically activity along the mountain front.

Optically stimulated luminescence (OSL) dating A method used to determine the age of sediment using the acquired luminescence signal induced in minerals by ionizing radiation in the ground and from cosmic ray particles.

Orogen A mountain belt.

Orogenic Pertaining to mountains.

Paleoelevation Former elevations/altitudes.

Paleoseismology Study of past earthquakes.

Passive margin The transition between oceanic and continental crust where there is little/no movement between the plates.

Radiocarbon (^{14}C) dating Method used to determine the age of material containing carbon (usually organic) by measuring the decay of the ^{14}C isotope within the material.

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Recurrence interval The characteristic time between two similar events such as an earthquake or volcanic eruption.
Stream-gradient indices Geomorphic indices that describe changes in stream gradient with respect to the position along the length of the stream.
Terrestrial cosmogenic nuclides (TCN) Nuclides produced by the interaction of cosmic ray particles with target atoms (generally in rock or sediment) at Earth's surface, including such nuclides as ^{10}Be, ^{14}C, ^{26}Al, and ^{36}Cl. TCNs are used to date surfaces or buried sediment.
Thermochronology Study of the thermal evolution of a region of a planet.
Tomography Three-dimensional imaging using sections derived from the use of any kind of penetrating wave.
Transform plate boundary A lithospheric plate margin where the relative motion of the two plates is horizontal, so that they essentially slide past each other.

Abstract

Tectonic geomorphology is a relatively young subdiscipline of geomorphology. During the past decades, tectonic geomorphology has developed into several main areas of emphasis including: landscape evolution of active plate margins; mountain building; development of active fault and fold systems; the evolution of passive margins, continental interiors and plateau uplift; volcanic geomorphology; paleoseismology and seismic hazard assessment; and interaction of tectonics, climate change, erosion, and polygenetic landscapes and hazard mitigation. These areas of focus reflect the growth of new studies in tectonics, climate and, Earth surfaces processes, and technological advances such as remote sensing, global positioning systems (GPSs), computers, geochronology, shallow geophysics and geochemistry.

5.2.1 Introduction

Tectonic geomorphology, as its name suggests, is the merging of the study of tectonics and geomorphology. But it is far more than simply an overlap between these two immense fields. Tectonic geomorphology also incorporates the study of geodesy, geophysics, geochemistry, geochronology, archaeology, and paleoclimatology among others. This chapter examines the development of the relatively young discipline of tectonic geomorphology and highlights current areas of research emphasis and possible future directions of study. In writing this perspective, the author has tried to be as objective as possible and to credit the major contributions to tectonic geomorphology. However, he should like to sincerely apologize at the outset if anyone or any major study has not been credited. Tectonic geomorphology is growing into a vast discipline and it is becoming increasingly challenging to keep track of all the exciting new developments that are emerging from so many different fields. The chapters in the treatise (Owen, 2013) that follow this perspective will expand in considerable depth and detail many of the subjects mentioned in a very cursory way in the text below.

5.2.2 Development of Tectonic Geomorphology and Advances Related to the Discipline

Tectonic geomorphology is one of the youngest branches of geomorphology. Yet the study of the relationship between Earth's internal (tectonic/endogenetic) and external (surface/exogenetic) processes in relation to the evolution of landscapes has a long history. Tectonic geomorphology, however, introduced to geomorphology a far deeper awareness of the importance of tectonics in helping to drive landscape development and influence surface processes.

Tectonics is essentially the study of structures and processes that are associated with the deformation of Earth's crust as a result of deep-seated processes. The Oxford English Dictionary defines tectonic as 'Belonging to the actual structure of the Earth's crust, or to general changes affecting it. Also with reference to other planets.'

The use of the term 'tectonic' is generally considered to be relatively new, relating to the study of plate tectonics that substantially developed during the late 1960s and 1970s. But the use of the term dates back to at least 1894, when Dawkins (1894) and Lapworth and Watts (1894) used it in relation to geologic structures in southern Britain. Tectonics has become a vital part of the Earth science lexicon with whole branches of the discipline devoted to its study, including journals with such names as 'Tectonics' and 'Tectonophysics.'

There is no formal definition of tectonic geomorphology, but it is broadly defined as the study of landforms produced or affected by tectonic processes such as faulting, tilting, folding, uplift or subsidence, and the application of geomorphology to the study of tectonic problems. Moreover, many studies in tectonic geomorphology commonly include a climate component and attempt to analyze how the evolution of landforms, tectonic processes, and climate are linked. Combining the use of the terms 'tectonic' with 'geomorphology' to distinguish the field of tectonic geomorphology really did not come into vogue until the 1980s.

Probably the first most significant publication on tectonic geomorphology was the proceedings of the fifteenth Annual Binghamton Geomorphology Symposia in 1984 for which the theme was tectonic geomorphology (Morisawa and Hack, 1985). Morisawa and Hack's (1985) proceedings volume comprised 16 contributions ranging from continental- to landform-scale studies. The first papers cited in ScienceDirect that appear with tectonic geomorphology in their titles were published in 1988 (Alexander, 1988; Wells et al., 1988). But it was not until 1998 that 'tectonic geomorphology' was used in the keywords of articles cited in ScienceDirect, which include the papers of Demoulin (1998) and Li et al. (1998). Tectonic geomorphology, for example, does not even appear as a topic in the 'Macmillan Encyclopedia of Earth Sciences' (Dasch, 1996) and the 'Encyclopedia of Geology' (Seller et al., 2005). Further, tectonic geomorphology, '*senso stricto*,' receives less than a page entry in Goudie's (2004) 'Encyclopedia of Geomorphology.' Moreover, during 2009 and 2010 only 14 papers cited 'tectonic geomorphology' in their keyword lists for papers listed in ScienceDirect. Yet, without doubt tectonic geomorphology is now one of the most rapidly growing branches of geomorphology and as such a whole volume of the Treatise of Geomorphology is devoted to this subject, which includes this perspective (Shroder, 2013; Owen, 2013).

The development of tectonic geomorphology as a discipline has a long history and has been ingrained into geomorphology for well over a century. Yet, of course, the field was not called tectonic geomorphology until the 1980s. Tectonic geomorphology was an intimate part of such concepts as the 'Davisian cycle of erosion' and various models of 'landscape evolution,' but, of course, researchers talked more of phases of uplift and subsidence, and then related geomorphology to the current paradigms of the time. Beckinsale and Chorley (1991), Burt et al. (2008), and Grapes et al. (2008) provided comprehensive and fascinating reviews of the history of the development of the study of landforms from 1890 to 1965, which highlighted some of the progress of studies of the relationship between crustal processes and geomorphology before plate tectonics was established as a theory and the key framework for geology. Kamp and Owen (2013) also described some of these developments with reference to polygenetic landscapes.

The first step toward the development of tectonic geomorphology was the continental drift hypothesis of Wegener (1915). With the development of the magnetic polarity timescale, which was an essential part of the Vine–Matthews–Morley hypothesis connecting patterns of magnetic reversals on the ocean floors with sea-floor spreading, Wegener's view was confirmed and ultimately the theory of plate tectonics was established (Vine and Matthews, 1963). Marvin (1973), Hallam (1973), Glen (1982), Schwarzbach (1986), and Stewart (1990) presented good reviews of these developments of the science of plate tectonics. Plate tectonics clearly set the background for tectonic geomorphology.

With plate tectonics established, geomorphologists had a modern framework to examine landscapes and their development on all scales, but most significantly on global and continental scales. Of particular note during the early years of the development of plate tectonics was the pioneering work done by Hack (1973) who developed a stream-gradient index, which crudely correlates to stream power and reflects the extent of surface uplift, and Bull (1977) who analyzed landscape development along active mountain fronts. Bull and McFadden (1977), Keller (1986), and Bull (1991) continued the development of geomorphic indices to quantify and compare how tectonic activity, notably including mountain front sinuosity and ratio of valley-floor width to valley height. The study of fault scarp degradation was an area of great focus during this period (Wallace, 1977; Bucknam and Anderson, 1979; McCalpin, 1982). Much attention was also given to understand the origin of marine terraces and how they could be used to reconstruct former sea level stands (e.g., Chappell, 1974), rates of tectonic uplift (Bull and Cooper, 1986; Muhs et al., 1990), and rates of glacioisostatic uplift (Mörner, 1990).

Probably two of the most significant events in helping to formulate tectonic geomorphology as a discipline were the Geological Society of America Penrose Conference held in 1983 at Winnemucca, Nevada and the fifteenth Annual Binghamton Geomorphology Symposium, both on tectonic geomorphology.

The Penrose Conference set the stage for what would be the focus of much work for the next decade or so. The 56 scientists from six countries who attended discussed the following topics: (1) tectonic processes, forms, and rates; (2) geomorphic processes, rates, and landforms; (3) interactions of tectonic movements and fluvial systems; (4) marine terraces and landforms of tectonically active coastlines; (5) effects of Quaternary climate change on fluvial systems in areas of differing rates of vertical and horizontal tectonic deformation; (6) chronosequences of soils and dating of displaced landforms; (7) faults, slip rates, and recurrence intervals; and (8) modeling of the effects of base-level fall on elements of fluvial landscapes (Bull and Wallace, 1985).

At the Penrose Conference, many new exciting developments were presented and discussed, including: (1) the recognition of landforms that are particularly sensitive in recording vertical or horizontal deformation; (2) devising new dating techniques (and extension of old techniques) in assessing the ages of stream terraces, glacial deposits, and marine terraces; and (3) development of process–response models to explore the relative importance of tectonism in the operation of geomorphic systems and to estimate times of discrete tectonic events.

The Annual Binghamton Geomorphology Symposium that followed a year later helped crystallize the current thinking and the conference proceedings, Morisawa and Hack (1985), became a reference source for many of the young geomorphologists who began to take an interest in tectonics.

As tectonic geomorphology was beginning to take on meaning, there was also growing interest in neotectonics and active tectonics. Neotectonics, a subdiscipline of tectonics, is essentially synonymous with active tectonics, and as such, is the study of contemporary motions and deformations of Earth's crust including those of the very recent geologic past. The term neotectonics is attributed to Obruchev (1948). Methods used in the study of neotectonics can include remote sensing, structural geology, seismology, regional geophysics, engineering geology, and geomorphology (Hancock and Williams, 1986).

Much of what was being done under the auspice of neotectonics included studies in tectonic geomorphology (Doornkamp, 1986). However, neotectonics and active tectonics are generally considered a broader range of study than what many geomorphologists were studying in the latter decades of the twentieth century. Nevertheless, the overlap between neotectonics and tectonic geomorphology is considerable.

Interest in neotectonics grew in the 1980s with the establishment in 1981 of the Commission on Neotectonics of the International Union for Quaternary Research (INQUA), which was presided over by Nils-Axel Morner. The commission ran numerous workshops and conference symposia.

In 1983, the American Geophysical Union ran a symposium entitled 'Active Tectonics' which was directed by Robert E Wallace. It brought together geomorphologists, structural geologists, Quaternary geochronologists, and geophysicists (including geodesists) mainly with a focus on establishing earthquake geology as a discipline. The meeting resulted in the publication of the book, 'Active Tectonics,' under the auspice of the Geophysics Study Committee, Geophysics Research Forum, Commission on Physical Sciences, Mathematics, and Resources, and the National Research Council, which included studies of tectonic geomorphology. The book was edited by Wallace (1986a) and its first chapter, also written by Wallace (1986b), providing an overview and recommendations, was particularly important as it showed the significance of active tectonics to society. Wallace is not credited in the publication, which was probably a reflection of Wallace's sincere modesty (Yeats, 2002). The conference and publication were instrumental in bringing the use of the term 'active tectonics' into vogue (somewhat replacing the use of term 'neotectonics').

Yet notable conferences continued to be held under the title of neotectonics, and neotectonics still persists as a distinct discipline. Important conferences on neotectonics include a Tectonics Study Group (TSG) meeting of the Geological Society of London (GSL) and the International Conference on Neotectonics hosted jointly by the Neotectonics Commission of INQUA, the Quaternary Research Association and the TSG at Burlington House in London during December 1984 and January 1992, respectively (Hancock and Williams, 1986; Stewart, 1993; Stewart et al., 1993; Owen et al., 1993). Vita-Finzi's (1986) book, 'Recent Earth Movements' provided a great introduction to the modern study of neotectonics, alluding much to the geomorphology aspects of the study of active tectonics.

Keller and Pinter's (1996) book, 'Active Tectonics' provided a wealth of information on tectonic geomorphology, including a chapter called 'Landforms, Tectonic Geomorphology, and Quaternary Chronology,' and other chapters on geomorphic indices, rivers, coastlines, and mountain building, all pertinent to tectonic geomorphology. The second edition, published in 2002 (Keller and Pinter, 2002), retains the same structure, but provides more updated examples. Yeats et al. (1997) devoted a whole chapter to tectonic geomorphology in their seminal book, 'The Geology of Earthquakes.'

By the turn of the twenty-first century, tectonic geomorphology had truly become a discipline in its own right. The publication of Burbank and Anderson's (2001) textbook, 'Tectonic Geomorphology,' solidified the discipline and has been a main reference source for tectonic geomorphology over the last decade and is used by many universities as a textbook for teaching tectonic geomorphology courses. The second edition of Burbank and Anderson (2012) updates much of this seminal volume.

From the 1970s through the 1990s, much research focused on the role of climate in geomorphology, and the discipline of climatic geomorphology became well established (Derbyshire, 1973, 1976; Büdel, 1982; Bull, 1991). As detailed paleoclimate records evolved through ice core studies in the 1990s (e.g., Dansgaard et al., 1993), it became evident just how rapidly climate could change and that the magnitude of that change was large. Increasing recognition was given to how landscapes likely adjust after times of climatic transition (Ballantyne, 2002). As such, the role of climate became integrated into tectonic geomorphic studies.

As new technologies developed throughout the 1990s and 2000s, tectonic geomorphology acquired additional boosts. These included advances in remote sensing, geochronology, geophysical exploration methods, numerical modeling, and enhanced computing, particularly developments in microcomputing.

Remote sensing now involves numerous methods, including simple photography from balloons and airplanes to spaceborne techniques ranging from multispectral imaging to space-geodetic methods. As the National Research Council (2008) highlighted in their report on the first 50 years of scientific achievements in Earth Observation from Space, the transformative nature of modern remote sensing is demonstrated by the fact that a mere 50 years ago, a traveler might not know his/her position on Earth to better than 500 m, even after expending considerable effort in tedious reduction of geodetic observations, yet, today, a person can determine their position to within a meter's precision in real time, anywhere on the planet, using an inexpensive Global Positioning System (GPS) receiver.

Since GPS technology measures a highly accurate three-dimensional position on Earth's surface at a precise time relative to the known positions of several satellites, it is possible to determine rates of tectonic motion and develop highly precise maps. Moreover, the International Earth Reference System is accurate to better than 1 cm in all components, including the time-dependent position of the geocenter, to provide us with a robust reference frame (National Research Council, 2008). Even more impressive is that we now have the ability to determine relative positioning to a millimeter anywhere on the surface of the planet, or in orbit. Developments in light detection and ranging (Lidar), which use a laser beam mounted on an aircraft, satellite, truck, ship, or hand-held device to measure accurate distances to a target point on land or underwater, has allowed us to use this method for precise surveying in numerous tectonic geomorphic studies (National Research Council, 2010). In addition, the development of interferometric synthetic aperture radar (InSAR) which uses radar mounted on an airplane or satellite to measure the strength and round-trip travel time of a microwave signal to gather elevation data, has allowed us to determine and map deformation experienced during an earthquake over large areas (10^2–10^3 km^2) with centimeter accuracy (Massonnet et al., 1993; Zebker et al., 2000).

These positioning data can be used to produce a digital surface model (DSM) which can then be processed to yield digital elevation models (DEMs), digital terrain models, contours, and three-dimensional feature data (National Research Council, 2008, 2010). The topographic models that are developed can be used to in conjunction with computer modeling for analysis of landscape evolution.

The National Research Council (2010) highlighted new developments in geochronology in their report on new horizons for research on Earth's surface that have helped advance the study of Earth surface processes and landforms. In particular, new geochronologic methods have accelerated the study of tectonic processes on geomorphic timescales (10^0–10^5 years). It should be noted that it was only in 1949 that Willard Frank Libby and his colleagues at the University of Chicago developed radiocarbon dating (Arnold and Libby, 1949), probably the most widely used numerical dating technique in tectonic geomorphology. So it really has only been during the last 40–50 years that radiocarbon dating has been providing ages on landforms and sediments in geomorphology. The method essentially revolutionized much of what we can do in tectonic geomorphology and other branches of geomorphology.

The development of terrestrial cosmogenic nuclide (TCN) surface exposure dating methods since about the late 1980s has helped accelerate interest in tectonic geomorphology because now many landforms that could not be previously dated with radiocarbon methods, due to the lack of organic material, can today be relatively easily dated. Moreover, the TCN method can allow landforms from a few decades to several million years old to be dated, far beyond the radiocarbon range of about 30–50 ka. Common TCNs used in tectonic geomorphic studies include ^{10}Be, ^{26}Al, ^{36}Cl, and ^{10}Ne (Frankel et al., 2007). Advances in luminescence dating, specifically optically stimulated luminescence (OSL) dating, have paralleled those of TCN dating. In particular, OSL methods have now been very successfully applied to dating sediments in fault trenches for paleoseismic studies and other tectonic studies (Tsukamoto et al., 2009). Recently, OSL methods have also been applied as a thermochronological tool (Herman et al., 2010).

Another major area of growth has been the use of low-temperature thermochronometer techniques to provide information on hundred thousand- to million-year rates of erosion and topographic evolution. Common systems used include U-Th-Sm/He and fission track methods in apatite and zircon, and $^{40}Ar/^{39}Ar$ age-spectrum dating of a variety of silicate minerals (Lee et al., 2009; Adams et al., 2009). In addition, sidereal methods such as lichenometry, dendrochronology, and varve chronology have contributed significantly to defining ages on landforms for tectonic geomorphic studies (Bull, 2007).

Advances in geophysical prospecting technologies have also contributed greatly. These include advanced seismic methods that use two- and three-dimensional imaging with acoustic waves to resolve fossilized surface features to resolutions of 1 m or better at shallow depths and up to several meters to kilometers below the surface (National Research Council, 2010). Other advances include electromagnetic resistivity surveys, tomography, and magnetometers that measure electrical or magnetic fields, to yield data on groundwater flow and subsurface geometry and structures. Ground-penetrating radar can now yield two- and three-dimensional subsurface images at imaging depths between 1 and 50 m. These instruments can be hand-held or mounted on vehicles.

Computing has advanced so much now that sophisticated programs can be run on desktop computers. Of particular note in examining the relationships among tectonics, climate, and surface processes is the modeling work pioneered Beaumont et al. (1999, 2001, 2004).

5.2.3 Recent Research Foci (Subdisciplines)

Since its recent establishment as a distinct branch of geomorphology, tectonic geomorphology has developed several main areas of emphasis. These reflect the growth of tectonics, climate studies, and Earth surfaces processes over the past few decades, particularly in the light of the new technological advances discussed in the previous section. Each one of these areas of emphasis is outlined briefly below and is reflected in the chapters in this treatise (Owen, 2013) that follow this perspective. A common theme in each of these areas of study is the interrelationship among tectonics, climate, and Earth surface processes. Probably the most exciting and rewarding aspect of tectonic geomorphology is the realization of the complex links and feedbacks between exogenic and endogenic processes in the evolution of landscapes and the need for multidisciplinary, collaborative research. Fully understanding these links and feedbacks is essential for environmental management and sustainable development.

5.2.3.1 Landscape and Tectonic Evolution of Active Plate Margins

With the development of plate tectonics a need has arisen to quantify rates of vertical and horizontal crustal displacement to help understand how plate margins evolve over time. In particular, recently there has been growing interest in comparing rates over geologic (10^0 to 10^7 years), geomorphic (10^0 to 10^5 years), and geodetic (10^{-1} to 10^2 years) timescales. Knowledge of the rates of displacement is essential in helping to formulate tectonic and landscape models.

The Himalayan–Tibetan collisional orogen and the Gulf of California-San Andreas transform plate boundary are probably the most studied in terms of tectonic geomorphology. Owen (2010) described the development of the study of landscape evolution for the Himalayan–Tibetan orogen, specifically in terms of the advancement of tectonic–climate–landscape concepts and models. Some of concepts and models are reviewed and expanded on in more detail in Hodges and Adams (2013), Koons et al. (2013) and Spotila (2013); and Schoebohm (2013) provide an overview of our understanding of the geomorphology of continental–continental collision. Bull (2007, 2009) and Frankel and Owen (2013) provided overviews and summaries of the tectonic geomorphology of the Gulf of California–San Andreas transform plate boundary.

It is probably an understatement to say that tectonic geomorphic studies have been undertaken on nearly every active plate margin. These studies are now providing important insights into how landscapes develop in varied tectonic and climatic settings and are building frameworks for applied studies such as seismic hazard mitigation.

5.2.3.2 Mountain Building

Tectonic geomorphology has been used extensively in the study of mountain building. As Koons et al. (2013)

emphasize, some of the most spectacular topography on the planet arises from the product of localized interactions among tectonics, climate, and erosion. Schoenbohm (2013) highlights that one of the key topics is whether or not steady state can be achieved, and how it can be recognized. Moreover, Schoenbohm (2013) highlights that one of the main topics is determining the importance of the relative controls of tectonics and climate on the width and asymmetry of mountain belts.

Tectonic geomorphology is beginning to be used to identify the lateral transport of crust, either brittlely along strike-slip faults, or ductility through lower crustal flow. In particular, Schoenbohm (2013) shows how drainage reorganization is a particularly powerful tool for inferring uplift patterns. Hodges and Adams (2013) show how the Tibetan Plateau serves as a model for understanding the possible influence of middle and lower crustal flow on the geomorphic and tectonic evolution of continental plateaus. They present arguments in favor of a weak middle (and, in some areas, lower) crust beneath the plateau, and explore the development and features of popular models of the Himalayan–Tibetan orogenic system that incorporate lateral flow of this weak crust under the influence of gravity. Hodges and Adams (2013) argue that many of the long- and short-wavelength features of Tibetan and Himalayan landscapes are reasonably explained as a consequence of crustal flow.

Schoenbohm (2013) points out that study of tectonic geomorphology can also be important in helping to explain the persistence of topography over long-dead orogens.

5.2.3.3 Development of Fault and Fold Systems

The development of fault and fold systems has attracted much attention, not only for understanding landscape development, but also for seismic hazard mitigation. In particular, there is growing recognition that large earthquakes can occur within fold belts, commonly on blind thrusts, such as in the case of the North Ridge earthquake in Southern California in 1994 (Davis and Namson, 1994). This recognition has stimulated much research on the development of fold and thrust belts for earthquake hazard assessment. Keller and DeVecchio (2013) highlight that the questions being addressed at present in the field of tectonic geomorphology of fold and thrust belt systems mainly relate to the lateral propagation of folds and the development of traverse drainages across fold belts. Recent studies are concerned with examining the development of transverse drainage across folds to relate them to uplift and fold growth. Much effort, therefore, has been focused on developing adequate chronology to quantify fold growth and erosion by determining rates of lateral propagation and incision by streams that cross-cut growing folds.

Recent studies on fault systems have addressed a range of scales. These vary from continental-scale transform and strike-slip faults, to mountain/basin-scale bounding faults, to individual fault scarps (Frankel and Owen, 2013; Nash, 2013). Much attention has been focused on the Pacific–North American plate boundary incorporating the San Andreas fault and the Eastern California Shear Zone, and the Pacific–Australian plate boundary, the Caribbean–North American plate boundary, and intracontinental strike-slip systems with the Himalayan–Tibetan orogen to help develop tectonic and landscape evolution models, but also for seismic hazard mitigation in the most densely populated areas (Frankel and Owen, 2013; Kondo and Owen, 2013).

5.2.3.4 Evolution of Passive Margins, Continental Interiors, and Plateau Uplift

Explaining continental-scale landforms such as great escarpments and plateaus along passive margins has attracted much attention in recent years. Blenkinsop and Moore (2013) explain how passive margins and their associated landscapes and landforms are created when extension related to rifting forms oceanic crust. Blenkinsop and Moore (2013) point out that the diversity of passive margins reflects variations amongst thermal, isostatic, flexural, buckling, and dynamic (mantle) sources of stress that affect margins. Flexural isostasy plays a significant role in defining the shape of passive margins as a consequence of erosion. Blenkinsop and Moore (2013) present three current models for escarpment evolution which are: (1) backwearing from an initial abrupt increase in topography; (2) downwearing to an inland drainage divide; and (3) downwarping. Recent research is beginning to focus on constraining these models using thermochronology, numerical modeling, and geomorphic observations. Blenkinsop and Moores (2013) point out that the elevation of the continental interior might be due partially to mantle upwelling (dynamic topography), however, drainage divides within the continent, at least in southern Africa, are more likely the result of plate boundary stresses.

Studies of the evolution of continental interiors have focused on the very long-term geomorphic evolution of shield areas. However, with the development of climatic geomorphology and the recognition of the complex behavior of continental ice sheets, there has been much recent focus on the Late Quaternary glacial and periglacial development of continental interiors.

One of the great challenges in tectonic geomorphology has been to define rates of plateau uplift, specifically quantifying paleoelevation. Babault and Van Den Driessche (2013) provide a detailed review of the many aspects of the tectonic geomorphology of plateau uplift. New techniques have included the use of oxygen, hydrogen, and carbon isotopes within paleosols and the size of vesicles in volcanic rocks (Garzione et al., 2000; Sahagian et al., 2002; Quade et al., 2007; Sahagian and Proussevitch, 2007; Ghosh et al. , 2006). Various mechanisms for plateau uplift have been proposed, including denudational unloading, uplift associated with hotspots, and delamination (Blenkinsop and Moore, 2013). A further area of research related to plateau development concerns the feedback between plateau uplift and global climate change (Raymo and Ruddiman, 1992; Ruddiman, 1997; Clift et al., 2010).

5.2.3.5 Volcanic Geomorphology

The tectonic geomorphology of volcanoes has focused much on hazard mitigation (Huff and Owen, 2013). This commonly includes the study of volcanic landslides/lahars, many of which have had catastrophic consequences. The Nevada del Ruiz eruption in Columbia in 1985 resulted in the death of >23 000 people when Armero was buried by a lahar (Barberi et al., 1990).

A clear area of interest in tectonic geomorphic studies of volcanoes is the evolution of volcanic islands, which varies from the formation of new, ephemeral islands such as Kavachi and Surtsey, to large islands over hotspots such as Hawaii and Iceland, and large archipelagoes along subduction zones, such as Japan and the Philippines (Villeneuve and Bachelery, 2013; Huff and Owen, 2013).

Active volcanoes are continuously and rapidly evolving and this makes them one of the most exciting topics of tectonic geomorphology. Real-time monitoring by such research groups and organizations as the US Cascade Volcano Observatory has yielded important new insights into how volcanoes grow and erupt. Clearly, these studies are important for volcanic hazard mitigation and monitoring will continue in the coming years, especially in areas near large populations. These studies are adding greatly to our understanding of tectonic geomorphology.

5.2.3.6 Paleoseismology and Seismic Hazard Assessment

The seminal work of Wallace (1975) and Sieh (1978) that included studies of Late Quaternary history of faults has led to a mini-revolution in earthquake geology. Studies first concentrated on trying to define earthquake recurrence intervals for important faults such as the San Andreas, Himalayan Frontal Thrust, and then determining potential seismic hazards (Sieh and Jahns, 1984; Kumar et al., 2010). Most of this work involved fault trenching and dating sediment layers using radiocarbon methods. As paleoseisomology developed, earthquake geologists began to recognize that earthquakes may cluster in time and so other dating methods such as OSL were more readily applied (Rockwell et al., 2000). As TCN methods became more utilized, much work focused on defining partitioning of deformation across plate boundaries such as the San Andrea–Gulf of California transform plate boundary and along individual faults for seismic hazard assessment (Blisniuk et al., 2010; Frankel et al., 2011). Paleoseimological methods and studies are described in much detail in Kondo and Owen (2013).

Another major focus of interest has been earthquake-triggered landslides. Keefer (2013) highlights the many different types of seismically generated landslides and emphasizes that they occur in virtually every geologic environment. Keefer (2013) stresses that even small earthquakes ($M = 4$) can trigger landslides, and of course, the number and geographic distribution of landslides increases substantially for earthquakes of larger magnitude. Earthquake-triggered landslides can be extremely devastating as highlighted by the Kashmir earthquake in 2005 (Owen et al., 2008). During the largest earthquakes, tens of thousands of landslides can occur throughout regions ranging from tens to hundreds of thousands of square kilometers, moving millions of cubic meters of debris, (Keefer 2013). Much emphasis has been placed on explaining the distribution of earthquake-triggered landslides for hazard mitigation (Kamp et al., 2008, 2010).

5.2.3.7 Tectonics, Climate Change and Erosion, and Polygenetic Landscapes

Probably the overarching theme that has enhanced the study of tectonic geomorphology over the past few decades has been the realization that landscapes are continuously evolving and are the result of complex interactions between endogenetic and exogenetic processes. Intimate links exist between tectonics, climate and erosion, and there has been a growing realization that landscapes are polygenetic in origin. The history and an overview of the study of these links are provided by Kamp and Owen (2013).

Of particular note is the development of the glacial buzz-saw model in which glacial erosion generates local relief in the cores of mountain ranges, driving rock uplift because of erosional unloading of the crust. Spotila (2013) describes how this mechanism has the potential for significant positive feedbacks since rock uplift raises peaks, which in turn results in larger glaciers. The tectonic aneurysm model argues that localized uplift caused by enhanced glacial and fluvial erosion can weaken the lithosphere through increased crustal heat flux and thereby enhancing bedrock uplift (Koons et al., 2013). Koons et al. (2013) point out that mountain uplift can lead to orographic effects that cause inhomogeneous distribution of precipitation that then becomes further concentrated by rivers and glaciers into spatially restricted zones with a high potential of erosion. However, as Spotila (2013) highlights, there is significant debate over the relative importance of mountain glaciers, fluvial erosion, and mass movement in shaping mountain landscapes. Koons et al. (2013) show that petrologic, geomorphic, and geodynamic investigations of areas of anomalous high uplift and topography suggest a nonlinear interaction but reinforcing actions between tectonics and surface processes, which are likely universal, but are most clearly manifested in those regions where high process rates produce a high signal-to-noise ratio. These models and hypotheses linking tectonics, processes of surface erosion, climate and their interactions have generated much research in recent times and are among the most exciting branches of tectonic geomorphology.

5.2.4 Future Advances

Tectonic geomorphology is clearly an exciting and expanding branch of geomorphology, which has seen many significant advances in the past few decades. Predicting its future development is difficult, but the areas of concentration highlighted in the past section will clearly continue to expand, and attract much interest and research.

As the discipline develops, we are likely to see increasing interest in examining the complex variability between regions and on different timescales (ranging from 10^0 to 10^6 years). Increasing attention is also likely to be paid to quantifying the timing, rates, and magnitude of landscape evolution, particularly since we have so many new tools now at their disposal, including satellite remote sensing and global positioning systems, plus new developing analytical methods, specifically those for numerical dating.

As with many branches of science, we are increasingly asked to provide justification in terms of broader impacts.

As Hough and Bilham (2005) eloquently highlight in their book 'After the Earth Quakes: Elastic Rebound on an Urban Planet' human population is increasing dramatically in tectonically active regions, and most of the world's megacities are located in areas of high seismic risk. Never has there been a more important and urgent time in Earth's history to understand and study tectonic geomorphology to aid in hazard mitigation. Exciting times are ahead for tectonic geomorphology and the discipline is likely to continue to expand and develop in the coming years.

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Biographical Sketch

Prof. Lewis Owen received his PhD in Geomorphology from the University of Leicester, U.K., in 1988. Before joining the University of Cincinnati in 2004, he held positions at the Hong Kong Baptist University, Royal Holloway – University of London, and the University of California – Riverside. Prof. Owen's research focuses on the Quaternary geology and geomorphology of tectonically active mountain belts and their forelands, particularly in the Himalayan-Tibetan orogen and the Cordilleras of North and South America. He has also undertaken research in other tectonically active regions, including the Red Sea margin in Yemen and the Atlas and Anti-Atlas Mountains of Morocco. In 2011, Prof. Owen was awarded the Busk Medal from the Royal Geographic Society for his field research in Quaternary history and geomorphology in tectonically active areas.