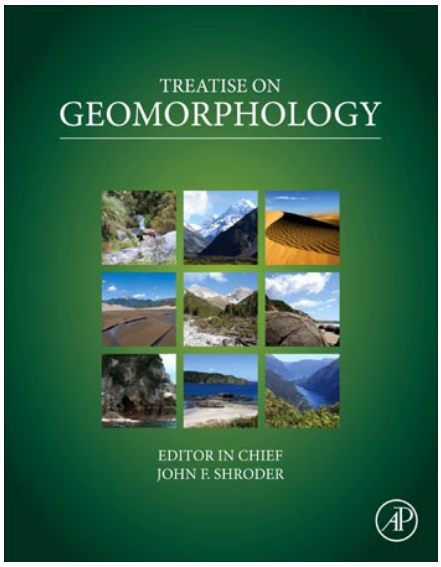

Keller E.A., and DeVecchio D.E. (2013) Tectonic Geomorphology of Active Folding and Development of Transverse Drainages. In: John F. Shroder (ed.) Treatise on Geomorphology, Volume 5, pp. 129-147. San Diego: Academic Press.

5.7 Tectonic Geomorphology of Active Folding and Development of Transverse Drainages

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5.7.1	Introduction	130
5.7.2	Lateral Propagation of Reverse Faults and Related Folds	130
5.7.3	Geomorphic Evidence of Lateral Fold Propagation	131
5.7.4	Geomorphic Methods to Analyze Laterally Propagating Folds	132
5.7.5	Santa Ynez Mountains	134
5.7.6	Complex Lateral Propagation	135
5.7.7	Development of Transverse Drainage	139
5.7.8	Directivity of Earthquake Energy and Lateral Fold Propagation: A Hypothesis of Tectonic Extrusion	142
5.7.9	Conclusions	145
References		145

Glossary

Antecedent stream A stream that developed before tectonic deformation of the terrain began, and maintained its course continuously downcutting across the growing tectonic features.

Bankfull channel width Refers to the horizontal width of a stream when water completely fills the channel at the point of incipient flooding, which has an approximate return period of 1.5 years.

Blind reverse fault A compressional fault, where fault offset does not rupture the surface. Surface deformation of the uppermost rock layers is often characterized by folding.

Directivity In regards to an earthquake, is an effect whereby seismic ground shaking is greater in the direction of rupture propagation than in other directions from the earthquake hypocenter.

Drainage density The ratio of the total length of all streams and rivers within a specific drainage basin to the area of that basin.

En echelon Refers to closely spaced parallel or subparallel structural features, such as faults and folds, that overlap or are offset in a step-like manner oblique to the overall structural grain.

Hinterland Refers to the principle region of active tectonic deformation, which has experienced significant uplift and erosion in contrast to the foreland, which lies parallel to the hinterland and is characterized by deposition and youthful deformation.

Lateral propagation Describes tectonic processes related to active faulting or folding, whereby faults or folds grow in length in response to increased displacement or amplification, respectively.

Segment boundary Refers to discrete zones of lateral fault or fold termination, which are common in en echelon (see definition, above) groups of structural features. Segment boundaries are typically regions of low elevation and therefore are often characterized by water gaps (see definition, below) in active fold belts.

Stream capture Also called stream piracy, refers to a process whereby a stream is diverted from its channel into another stream, perhaps reversing flow direction. This process is often initiated by headward erosion of one stream valley to intersect another.

Stream diversion Refers to the process where the existing channel of a stream or river is disrupted by tectonic uplift and the resultant stream path is around the tectonic topography.

Superposed stream Refers to a stream channel and its valley within resistant bedrock that developed its course through different preexisting alluvial cover. The resulting channel may cross geologic structure such as a buried ridge.

Suture zone Refers to a structurally complex region where two fault or fold segments have grown laterally together to form a single structural element.

Tear fault Refers to a steeply dipping fault that has strike-slip displacement that is typically orthogonal to the structural grain, and in compressional regions is parallel to the principle shortening direction. Tear faults accommodate differential shortening between fault segments and are often responsible for controlling the position of fault segment boundaries.

Transverse drainage Refers to a stream network in an actively deforming region, where the trunk stream is oriented perpendicular to the structural grain.

Keller, A.E., DeVecchio, D.E., 2013. Tectonic geomorphology of active folding and development of transverse drainages. In: Shroder, J. (Editor in Chief), Owen, L.A. (Ed.), Treatise on Geomorphology. Academic Press, San Diego, CA, vol. 5, Tectonic Geomorphology, pp. 129–147.

Unit stream power A one-dimensional measure of the rate of energy dissipation of a stream against the channel bottom and banks (per unit width). Units are W m^{-2}. Unit stream power is given by the equation: $\omega = \frac{\rho g Q S}{b}$ where ρ is density, g is gravity, Q is discharge, S is slope, and b is the channel width.

Water gap A notch or valley across uplifted topography through which water flows. The gap may be the result of an antecedent drainage, superposition, or may occupy the position of a fault or fold segment boundary (see definition, above).

Wind gap A notch or valley across uplifted topography through which water once flowed, but is now dry due to stream capture or stream diversion. Wind gaps are also referred to as an air gap.

Abstract

Two fundamental geomorphic questions are: (1) Do growing folds propagate laterally? and (2) how does transverse drainage develop across an active fold belt? Research during the past decade has answered the first question, and it is now known that some folds in fold-and-thrust belts definitely propagate laterally. Individual folds may propagate in one or both directions, and two folds may propagate toward each other, producing a suture zone and a longer segmented structure. Folds may also propagate laterally past one another to form an en echelon arrangement. Rates of lateral propagation and incision of streams that traverse growing folds remain poorly constrained. Adequate chronology to quantify fold growth and erosion is commonly not available and therefore remains one of the greatest limitations to understanding the evolution of surface folds. As a result, structural and geomorphic analyses are utilized, which are useful, but not adequate for quantifying fold growth processes. Development of transverse drainage across folds is a complex process related to the rate of uplift, lateral, and vertical fold growth (including change in fold width), development of water and wind gaps, lateral diversion of channels, and change in channel geometry and unit stream power. Understanding lateral propagation has important implications for earthquake hazard. If fault length is assumed to increase with fault displacement, then the folds they produce should also increase in length. Hypothetically, as folds propagate laterally due to displacement on the underlying faults, coseismic displacement along the faults themselves may have a preferred direction of propagation.

5.7.1 Introduction

Quantification of the geomorphology of active folds can provide fundamental information about the rates of tectonic processes and the spatiotemporal structural evolution of a region undergoing compressional deformation. Consequently, tectonic geomorphology of fold belts has been an area of intensive research in the past decade. Underpinning the geomorphic development of active folds is understanding the development of transverse drainages across folded regions. This chapter summarizes evidence for lateral and vertical fold growth, the response of the drainage system to fold belt development, and the implications of lateral propagation to the development of orogen-scale topography and seismic hazard.

The existence of lateral propagation of folds above concealed or blind reverse faults is an important hypothesis and is generally accepted. The majority of evidence suggests that folds do grow laterally and that propagation has a profound effect on development of drainage through a fold belt (Burbank et al., 1996, 1999; Jackson et al., 1996; Boudiaf et al., 1998; Delcaillau et al., 1998, 2007; Keller et al., 1999; Keller and Pinter, 2002; Amos and Burbank, 2007; Chen et al., 2007). What is not so clear is how the transverse drainages develop in response to folding. In some cases, simple diversion of drainage with abandonment of water gaps seems fairly straightforward. However, considerable complexity may be associated with antecedent and superimposed streams and links with lateral propagation, channel incision, stream capture, and stream diversion.

One of the most compelling transverse drainage features, indicative of lateral fold growth, is the presence of wind gaps, which develop from water gaps that have been defeated by tectonic uplift in response to lateral propagation. Several factors and processes are important for a water gap to remain open as a fold grows vertically and in width (Burbank et al., 1996): (1) rate of uplift; (2) rock resistance; (3) unit stream power (stream power per unit channel width); and (4) nature and extent of preexisting drainage. A water gap is most likely to persist in the landscape if the uplift rate is low, rock resistance is low, upstream channel slope is moderate to steep, bankfull channel width through the gap is relatively low, and upstream drainage area (a proxy for discharge) is large (Burbank et al., 1999).

A paramount question concerning lateral propagation of folding is: What is the potential significance of propagation of faults and folds to earthquake process and hazard? The authors present a hypothesis that as faults increase in length, so do the folds they produce; and the authors hypothesize that a direction of earthquake rupture is more likely to be in the direction of lateral fold propagation. In Southern California, apparently faults and folds tend to propagate to the west, south of the San Andreas fault, in the vicinity of the 'Big Bend' of the fault; and to the east north of the fault. Understanding relations between fault propagation and earthquake propagation is extremely important, as the earthquake hazard may be greatly increased or reduced relative to rupture propagation direction.

5.7.2 Lateral Propagation of Reverse Faults and Related Folds

Folding in fold-and-thrust belts (areas or regions characterized by subparallel faults and folds) is commonly closely linked

with buried reverse faulting. As total fault displacement from repeated earthquakes increases, so does total fault length. The basic argument constructed to support this statement comes from two observations (Cowie and Scholz, 1992; Jackson et al., 1996): (1) the ratio of fault slip to rupture length during an earthquake generally has a value of $\sim 10^{-5}$–10^{-4} (rupture length is generally 10 000–100 000 times fault slip as a result of an earthquake); and (2) the ratio of total displacement on a fault to fault length is $\sim 10^{-3}$–10^{-1} (fault length is generally 10–1000 times as long as total displacement). For these two relationships to be satisfied simultaneously, faults are required to increase their lengths as they increase total displacement (Cowie and Scholz, 1992; Dawers and Anders, 1995; Hetzel et al., 2004). Therefore, the rational conclusion is that fault-related folds that develop above these faults propagate laterally as they amplify.

Proving from geomorphic evidence that buried reverse faults propagate laterally is difficult. However, the folds (commonly linear anticlines) that buried reverse faults produce can provide (with adequate chronology) an estimate of both the direction and rate of lateral propagation (e.g., Keller et al., 1998; Jackson et al., 2002; DeVecchio et al., 2012). Both active faulting and folding at the surface generally occur together. As a result, fold scarps (the scarps produced by active folding) have been mapped as fault scarps. Studies of individual folds suggest that horizontal shortening produces reverse faults that cause hanging-wall deformation and development of anticlines (e.g., Yeats, 1986).

5.7.3 Geomorphic Evidence of Lateral Fold Propagation

Faults and folds can be relatively long structures (tens of kilometers) that are generally segmented. Segment boundaries may be topographically expressed (geomorphic segmentation) or be geologic structures, such as cross faults (geologic segmentation). Some faults and folds in the Zagros Mountains of Iran exceed 50 km in length (Ramsey et al., 2008). In the Zagros, for example, it can be demonstrated: (1) that fault segments have grown by lateral propagation of a single segment, or (2) that several shorter segments grew together through lateral propagation to form one longer continuous structure with a suture zone that is located in a topographic saddle along the crest of the fold. Some combination of the two processes may also occur (Ramsey et al., 2008).

Lateral propagation of folds may be demonstrated or strongly indicated by careful determination of geomorphic relations between surficial processes (uplift, folding, weathering, and erosion) and earth materials (Jackson et al., 1996). Keller et al. (1999) proposed six geomorphic criteria useful in evaluating rates and direction of lateral propagation of active folds (in the direction of lateral propagation): (1) decrease in drainage density and dissection; (2) decrease in elevation of wind gaps; (3) decrease in relief of the topographic profile along the crest of a fold; (4) development of characteristic drainage patterns (resulting from drainage diversion); (5) deformation of progressively younger deposits or landforms; and (6) decrease in rotation and inclination of fold limbs. These six criteria are consistent with lateral propagation, but do not prove propagation.

An additional useful criterion for correlating wind gaps and water gaps to the process of lateral fold propagation is the Hetzel criterion (Hetzel et al., 2004). If water gaps do, in fact, represent the position of the topographic nose of the fold and wind gaps record the previous location of the fold nose before propagation, the intersection of the 'topographic envelope' of the fold with a horizontal line from the base of wind gaps should correspond to the location of the lower and younger wind gaps and the active water gap (**Figure 1**).

Fan-shaped patterns of tributary drainage that forms on the flanks and nose of a propagating anticline have been shown as valuable indicators of lateral propagation (Ramsey et al., 2008). **Figure 2** shows an elliptical-shaped fold at 'Time 1' before lateral propagation. The tributary channels are normal to the elevation contours and form a fan shape pattern. With lateral propagation (Time 2), the channels lengthen and are reduced in slope; and if deeply incised, their curved patterns will be inherited from 'Time 1.' These channels will not be normal to the contours. Where such a pattern is present (inherited drainage), lateral propagation is the likely cause. Ramsey et al. (2008) documented folds in the Zagros Mountains that retain such information of earlier fold growth.

Rates of lateral propagation of active folding (based on a very small number of studies where chronology is established) are generally several times the rate of uplift and fault slip (Keller et al., 1998). An example of a fold that is rapidly propagating laterally is Wheeler Ridge, located at the southern end of the San Joaquin Valley (**Figure 3**). A simple geologic cross section of

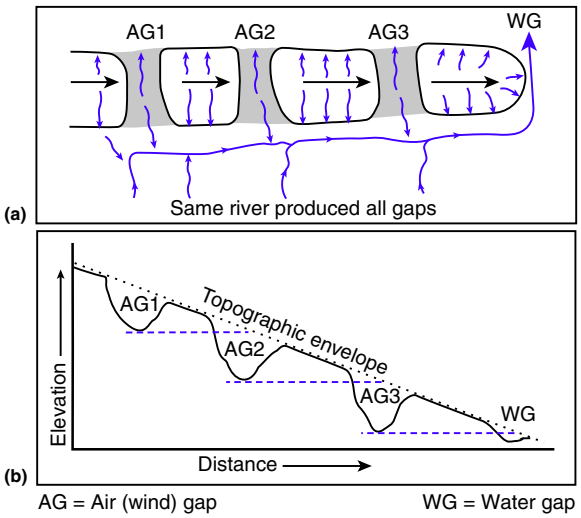


Figure 1 Idealized diagram illustrating the Hetzel criterion, which is useful in demonstrating that a series of wind gaps and a water gap are produced by the same river. (a) Propagation of the fold to the right forces the active stream channel (water gap) to migrate in the direction of propagation resulting in a series of wind (air) gaps that are young to the right (AG 1–3). (b) Horizontal lines drawn from the base of the wind gaps should intersect the topographic envelope of the fold at the position of younger wind gaps and the water gap confirming the interpretation that wind gaps form from lateral propagation of the fold.

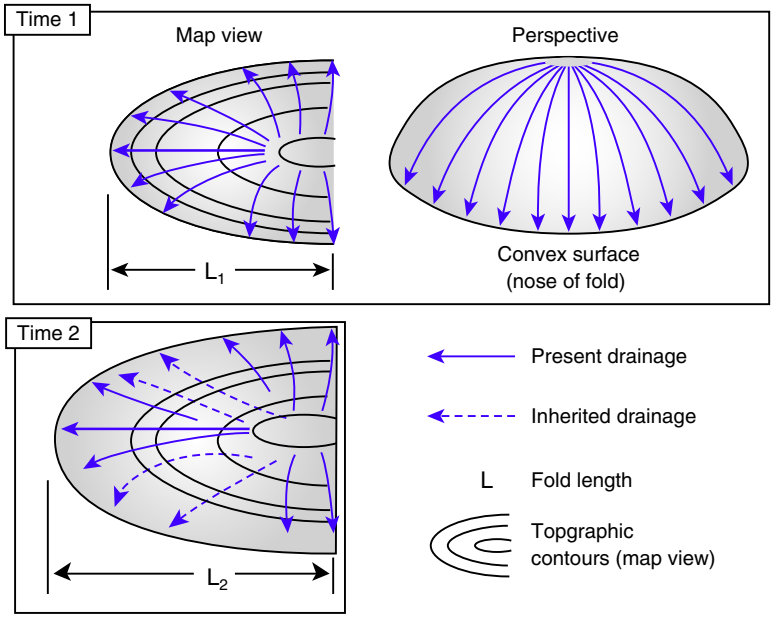


Figure 2 Idealized diagram showing fan-shaped drainages developed on the flanks and nose of a growing fold (plunge panel). Initially, drainage is perpendicular to contours (Time 1). With entrenchment of these streams, they may persist in the landscape. If propagation occurs (Time 2), the entrenched streams will not cross the contours at right angles but will be at a lesser angle and have a lesser channel slope. If this is observed in the landscape, then it is powerful evidence of lateral propagation.

Wheeler Ridge is shown in **Figure 4**. The abundance of oil wells that pass through the buried Wheeler Ridge reverse fault help to establish the fault depth and geometry (Medwedeff, 1992).

At Wheeler Ridge, ages of folded alluvial fan surfaces across the fold were used to determine the rate of lateral propagation at ~ 3 cm yr^{-1} (**Figure 3**). Rates of uplift were estimated to be approximately 3 mm yr^{-1}, indicating that the rate of lateral propagation is 10 times the rate of uplift and, therefore, is a rapid tectonic process (Keller et al., 1998). Lateral propagation at Wheeler Ridge appears to be linked to a series of propagation events associated with tear faults (faults at a high angle to the strike of the ridge) (Medwedeff, 1992; Mueller and Talling, 1997). Evaluation of subsurface data at Wheeler Ridge suggests that the position of major wind and water gaps coincide with tear faults that have a topographic expression (apparent fault scarp with vertical relief) facing the direction of lateral propagation. The change in relief (down to the direction of propagation) helps to establish stream position at the base of the scarps of the tear faults.

The criteria discussed above are useful in recognizing lateral propagation of folds but are not sufficient to prove lateral propagation. This results because the criteria, given specific scenarios, may be consistent with both fold propagation and fold axis rotation models with different rates of surface uplift along the fold during fold growth (**Figure 5**). Criteria 4 and 5 are strong evidence of lateral propagation; and if at least two wind or water gaps from the same stream, then this is strong evidence of lateral propagation. Assuming that the stream can only be in one place at a time, a model of fold rotation (**Figure 5(b)**) is unlikely to produce two or more gaps at progressively lower elevations in the direction of fold growth. In other words, there could only be one gap and one diversion of drainage. Once a stream is defeated by uplift in the rotation model, it would be deflected to the nose of the fold (which, in that model, is fixed), and another gap would not form. Even if multiple wind gaps could be produced by rotation, the Hetzel criterion would not be satisfied (see **Figure 1**). In general, lateral propagation of active anticlines and anticlinal ridges can be visualized as illustrated on an idealized diagram (**Figure 6**). A buried reverse fault and fold propagate laterally to the left in **Figure 6**. Drainage from the steeper forelimb has been diverted around the nose of the fold. During lateral fold growth, a wind and a water gap were produced. Locations of gaps correspond to locations of cross faults that segment the fold. Drainage density is greater in the higher, older part of the fold where limb rotation is greater. The profile through the wind gap is convex, representing folding of the abandoned valley as lateral propagation continued. The idealized diagram is consistent with what was learned at Wheeler Ridge (**Figure 3**) and Mission Ridge (discussed below), and is a visual representation of the geomorphic criteria that help identify lateral fold propagation (Keller et al., 1999).

5.7.4 Geomorphic Methods to Analyze Laterally Propagating Folds

Geomorphic methods employed to analyze lateral propagation of folds are keyed to the six geomorphic indicators of lateral propagation of Keller et al. (1999), and include:

1. Construction of a detailed drainage map of the folded forelimb and backlimb, as well as the plunge panel (nose ramp). This is illustrated in **Figure 3** for Wheeler Ridge and

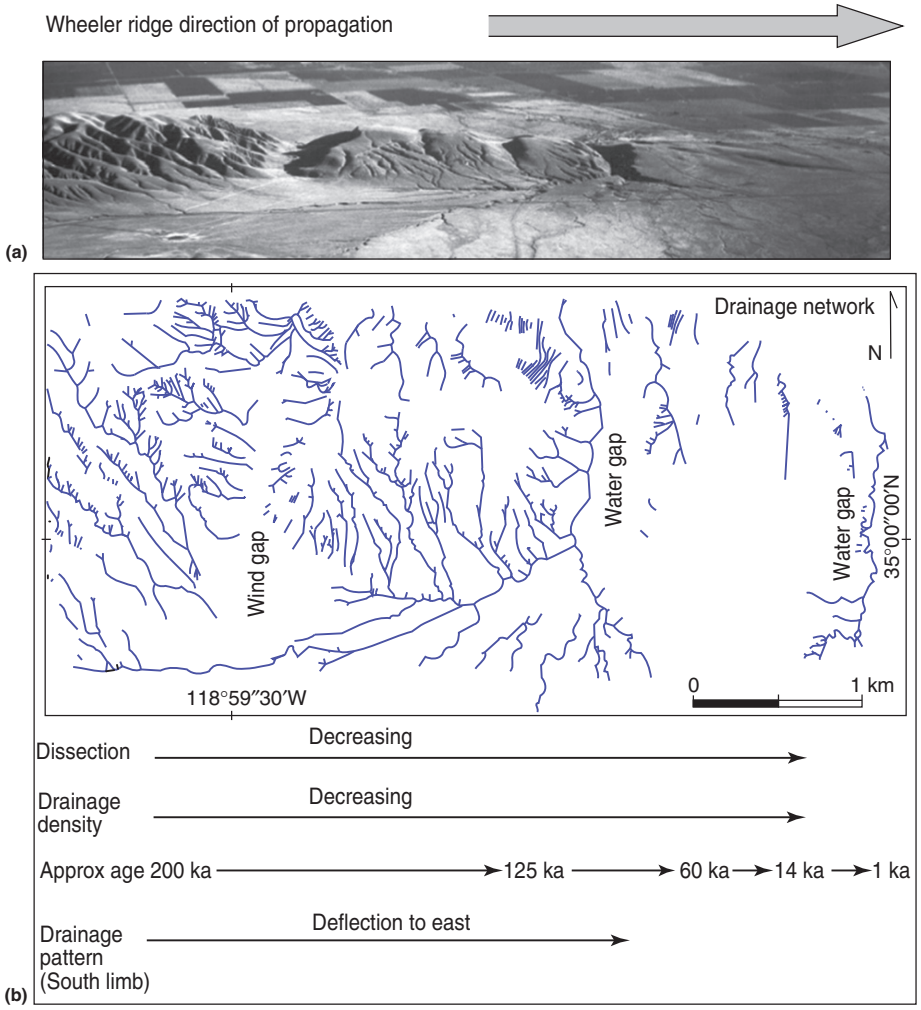


Figure 3 Evidence for eastward propagation of the Wheeler Ridge anticline. (a) View toward the north of Aerial Wheeler Ridge (courtesy of John S. Shelton). Note the eastward decrease in relief along the axis of the fold. (b) Other geomorphic indicators of lateral propagation of Wheeler Ridge to the east (right). Modified from Keller, E.A., Gurrola, L., Tierney, T.E., 1999. Geomorphic criteria to determine direction of lateral propagation of reverse faulting and folding. Geology 27(6), 515–518.

Figure 7 for the Mission Ridge anticline in Santa Barbara. This analysis may be completed by using aerial photographs, detailed topographic maps, and digital elevation models (DEMs).

2. Analyzing drainage patterns to calculate drainage density, which is a measure of degree of dissection. Drainage density (D_d) is defined as the ratio of total length of channels divided by the drainage basin area. Drainage density on the south flank of Wheeler Ridge (backlimb) decreases systematically from about 15–18 km^{-1} for surfaces older than 100 ka, to $\sim$0.4 km^{-1} for surfaces of 17–60 ka, and is nearly zero for Holocene surfaces (see **Figure 3**). For Mission Ridge (see **Figure 7**), drainage density decreases from about 8.0 to 3.3 km^{-1}, and limb rotation decreases significantly in the direction of lateral propagation. For Wheeler Ridge and the western propagation of Mission Ridge, the Hetzel criterion holds for position of gaps. For the eastern end of Mission Ridge (**Figure 8**, the ridge is more complex, and a simple model of eastern lateral propagation does not explain the position of gaps. Here, the morphology is dominated by Sycamore Creek. The water gap that Sycamore Creek flows through probably has been stable during fold growth. East of Sycamore Creek, the fold may have propagated east at least as far as Montecito Creek, but this is not supported by the geomorphology (**Figure 8**).
3. Construction of topographic profiles along the crest; profiles normal to the fold and DEMs may assist in identifying geomorphic parameters of folds. Elevations of wind gaps along the crest of an anticline may be measured directly, and these elevations are generally lower in the direction of propagation (see **Figures 1**, **6**, and **8**) (Jackson et al., 1996; Burbank et al., 1999; Keller et al., 1999). The topographic profile along the crest of the fold may reveal the direction of fold plunge, as is shown for Wheeler Ridge (**Figure 3**) and western Mission Creek (**Figure 8**).

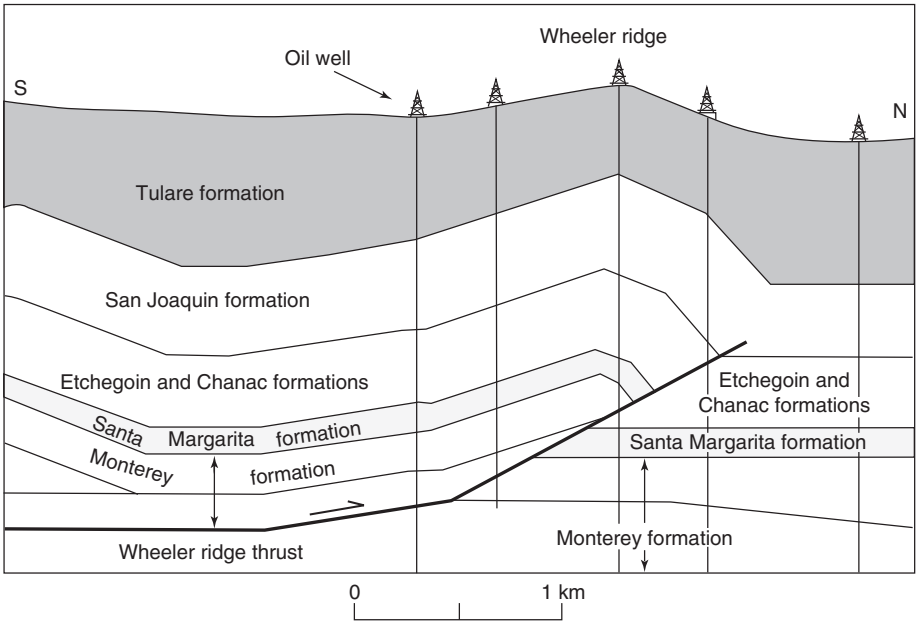


Figure 4 Geologic cross-section across Wheeler Ridge in the midportion of the ridge shown in **Figure 3**. The numerous oil wells that penetrate the subsurface provide geologic control to understand the fault propagation fold that produced Wheeler Ridge.

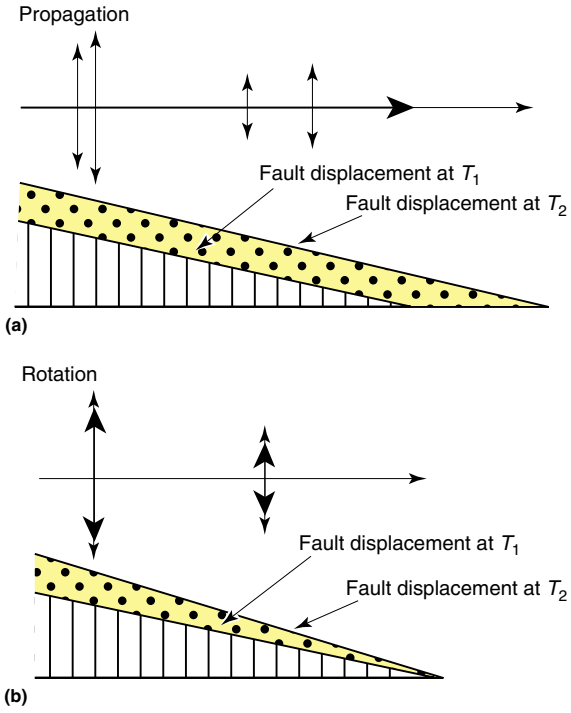


Figure 5 Two models (upper-plan view; lower-profile along fold crest) of fold growth. (a) Lateral fold propagation, where fault length increases with fault displacement. (b) Fold rotation, where the fault tip is fixed and limb rotation occurs in response to uplift, producing a displacement gradient along the fault. Reproduced from Keller, E.A., Gurrola, L., Tierney, T.E., 1999. Geomorphic criteria to determine direction of lateral propagation of reverse faulting and folding. Geology 27(6), 515–518

4. Establishing the chronology of Late Pleistocene and Holocene alluvium being folded is arguably the most difficult and neglected aspect of studying active folding. However, with no dates there can be no rates. Lacking dates, the understanding of geomorphic processes will remain inadequate to address active tectonics. Methods of dating alluvial deposits folded over young anticlines have improved dramatically in recent years (Keller and Pinter, 2002). As new dating methods are discovered and developed, our understanding of active tectonic processes will significantly improve.

5.7.5 Santa Ynez Mountains

The Santa Ynez Mountains (an anticlinorium above the piedmont of Santa Barbara, CA, and part of the Santa Barbara fold belt) is an example of a large, complex, linear structure that is segmented (Tierney, 2002). **Figure 9** illustrates the important geomorphic and structural features of the range. Notice the three, gently curved, geomorphic segments, two of which are divided by the geology into subsegments. The range crest is ~100 km long, and individual segments range from about 20 to 50 km. The segments decrease in elevation to the west, and the westernmost segment (segment 1 on **Figure 9**) appears to be propagating laterally to the west.

The present topography of the Santa Ynez Range developed during the past 500 000 years (perhaps as young as 200 000 years) in response to displacement on one or more north-dipping, buried reverse faults (Namson and Davis, 1988, 1992). Individual fault-and-fold segments apparently grew simultaneously, but the segments are generally young to the west (Tierney, 2002). The boundary between segments 1 and 2 is a major oblique left-lateral strike-slip cross fault known as

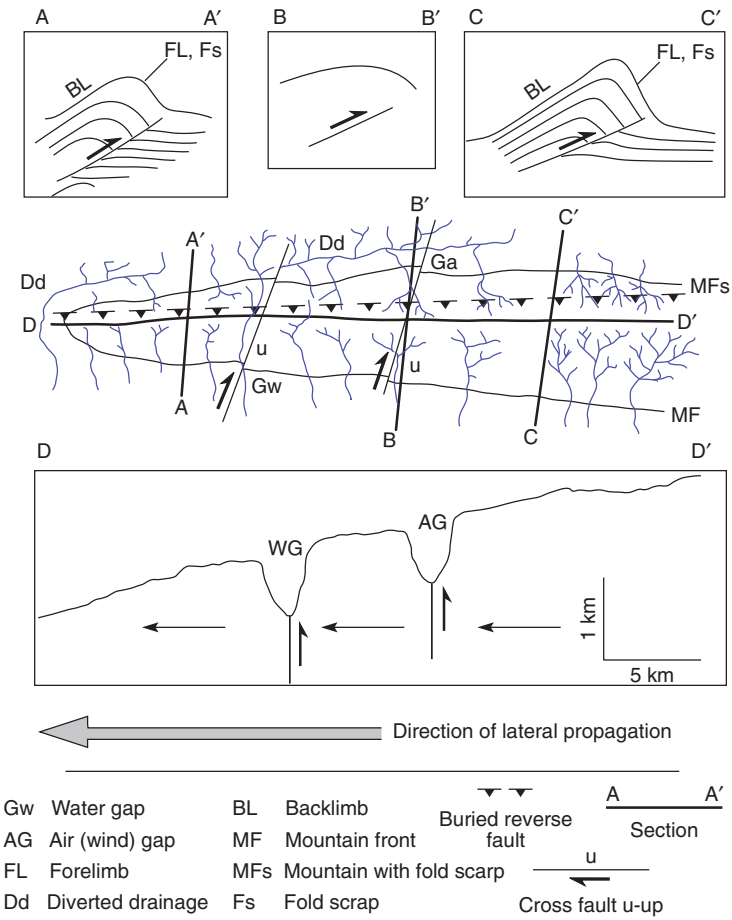


Figure 6 Idealized diagram of a fold that is propagating laterally. Major geomorphic features are shown by the three cross-sections: A–A′ is near the terminus or nose of the fold (plunge panel) to the left; B–B′ is through a wind gap, which has been deformed by folding since it was abandoned; C–C′ is located at an older part of the fold, where a greater amount of shortening has occurred. Notice that the degree of dissection and drainage density decreases in the direction of lateral propagation, as does the elevation of the topographic profile along the crest of the fold (D–D′). Positions of wind and water gaps coincide with cross faults that have both lateral and vertical components of slip. The steepest limb of the fold is the forelimb and forms a relatively straight-prominent fold scarp. Modified from Keller, E.A., Pinter, N., 2002. Active Tectonics. Prentice Hall, Upper Saddle River, NJ, 362 pp.

the South Branch of the Santa Ynez fault. The Santa Ynez fault is a major east-to-west trending, left-lateral oblique (south side up) fault that generally follows the Santa Ynez River Valley just north of the range. The boundary between segments 2 and 3 is a series of cross folds (San Marcus folds in **Figure 9**). Apparently, the lateral growth of segment 3 to the west impacted segment 2, causing cross folds to form (with perhaps faults at depth). The Ramero Saddle is the boundary between the two parts of segment 3. This may represent a suture zone, as noticed in one of the Zagros Mountain folds (Ramsey et al., 2008). Thus, it appears that the Santa Ynez Range was formed by amalgamation of several segments that grew together to form a continuous structure that propagated to the west (Tierney, 2002).

5.7.6 Complex Lateral Propagation

Lateral propagation of faults and folds with drainage diversions can be complex. A good example of this is the El Asnam anticline in Algeria (Boudiaf et al., 1998). A series of maps illustrates some of the processes related to the anticline, which is propagating to the southwest (**Figure 10**).

The El Asnam anticline is underlain by the El Asnam reverse fault, which has been a very active structure, producing earthquakes such as the 1980 (M_w7.3) event that caused extensive deformation (mostly uplift with lesser subsidence) in the region. Geologic and geomorphic analysis using DEMs suggest that an interesting series of drainage diversions occurred as the anticline has propagated laterally.

Figure 10(a) shows the position of the El Asnam anticline in the recent geologic past when two water gaps cut across the anticline. The much larger Ech Cheliff River forms a prominent water gap that is present till today. This river has not been diverted, as it retained sufficient stream power to erode its banks and bed as the anticline was uplifted. The second more southerly water gap is that of the Fodda River. The more recent situation is shown in **Figure 10(b)**. As the fold continued to propagate to the southwest, the Fodda River was diverted, leaving behind a wind gap and a younger water gap. It is

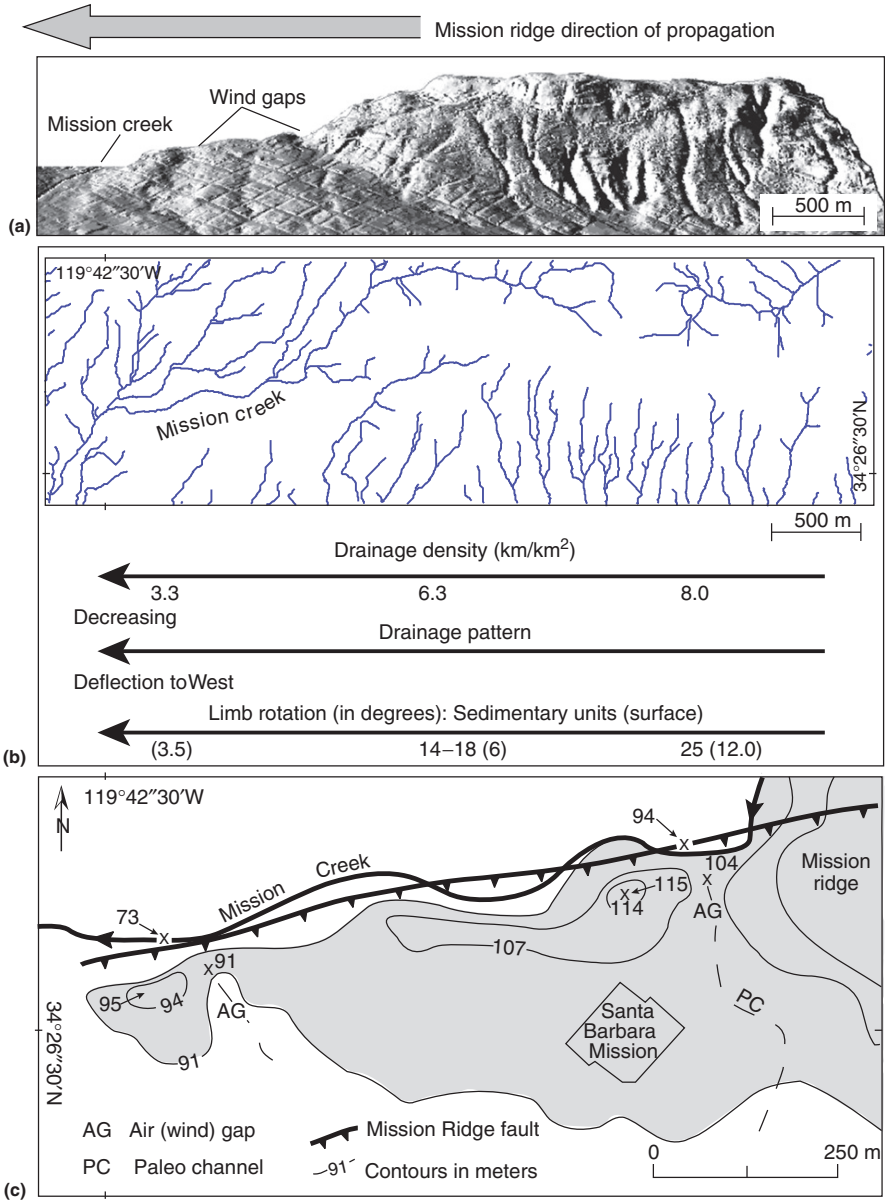


Figure 7 Evidence of lateral propagation of Mission Ridge to the west. (a) 1 m resolution hillshade of Mission Ridge north of the city of Santa Barbara, CA, showing the position of several wind (air) gaps that developed from westward deflection of Mission Creek. (b) Three geomorphic criteria suggest lateral propagation to the west. (c) Topographic contours along Mission Ridge showing the position and decreasing elevation of wind gaps toward the west. The sum total of data suggests that Mission Creek is propagating laterally to the west. Modified from Keller, E.A., Gurrola, L., Tierney, T.E., 1999. Geomorphic criteria to determine direction of lateral propagation of reverse faulting and folding. Geology 27(6), 515–518.

highly likely that this diversion resulted from the Fodda River, as the Hetzel criterion (see **Figure 1**) is satisfied. We might expect that with further lateral propagation, additional wind and water gaps would form to the southwest. However, this was not the case (**Figure 10(c)**). In 1980, a magnitude 7.3 earthquake uplifted the anticline approximately 5 m and caused approximately 1 m of subsidence in the adjacent Cheliff Basin. As a result, a topographic gradient to the north developed. The earthquake also ponded drainage along the fault, and, presumably, a tributary flowing to the northwest captured the Fodda River. Thus, the recent history of the El Asnam anticline is one characterized by lateral propagation with drainage diversion in the direction of propagation and then reversal of that drainage in response to a large earthquake that changed the slope of the topography initiating stream capture. Thus, we see that drainage diversion and stream capture are important processes in the topographic and geomorphic history of the area.

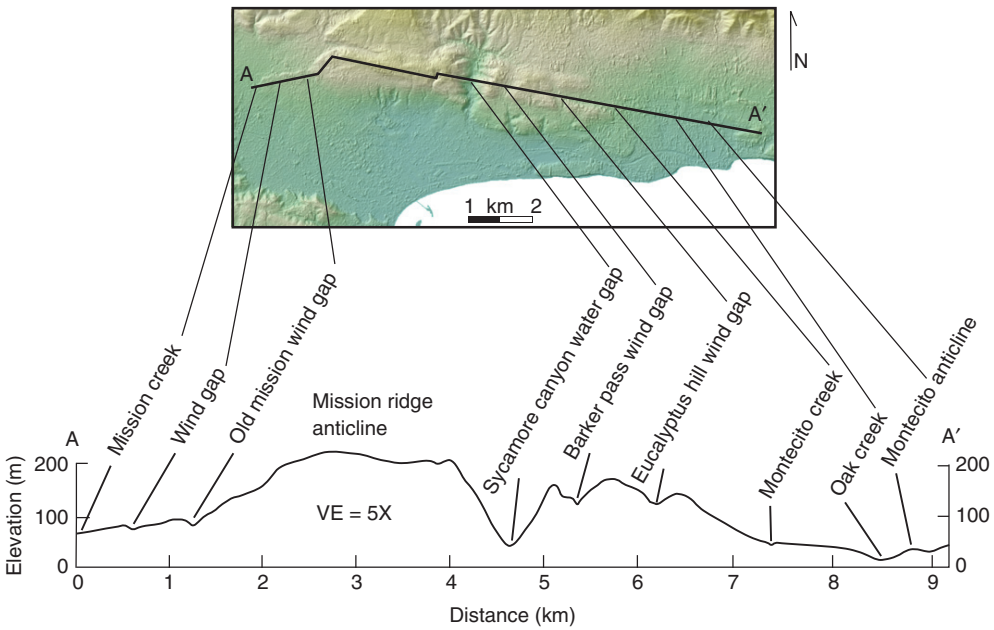


Figure 8 Longitudinal profile of Mission Ridge anticline showing the tectonic geomorphology. Shown are topographic expressions of water and wind gaps, as well as a decrease in elevation to the west that suggest lateral propagation. The eastern part of the fold exhibits a more complex history. Modified from Keller, E., Gurrola, L., 2000. Earthquake hazard of the Santa Barbara fold belt. Final Report to the US Geological Survey, NEHRP Award 527726, 78 pp. http://www.scec.org/research/98research/98gurrolakeller.pdf

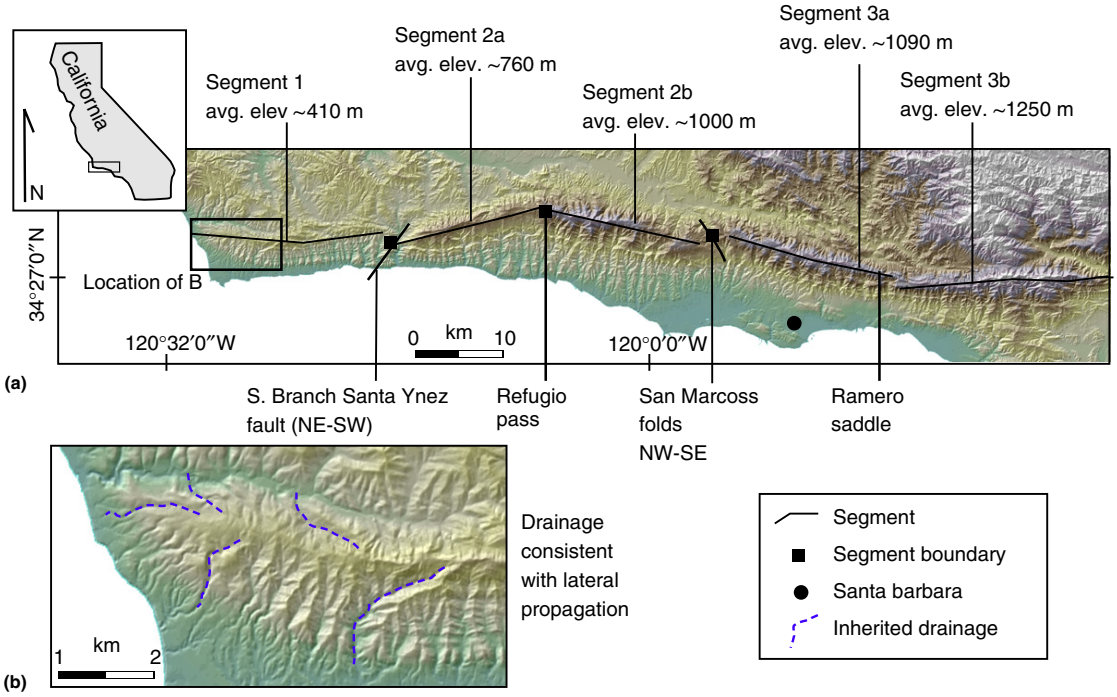
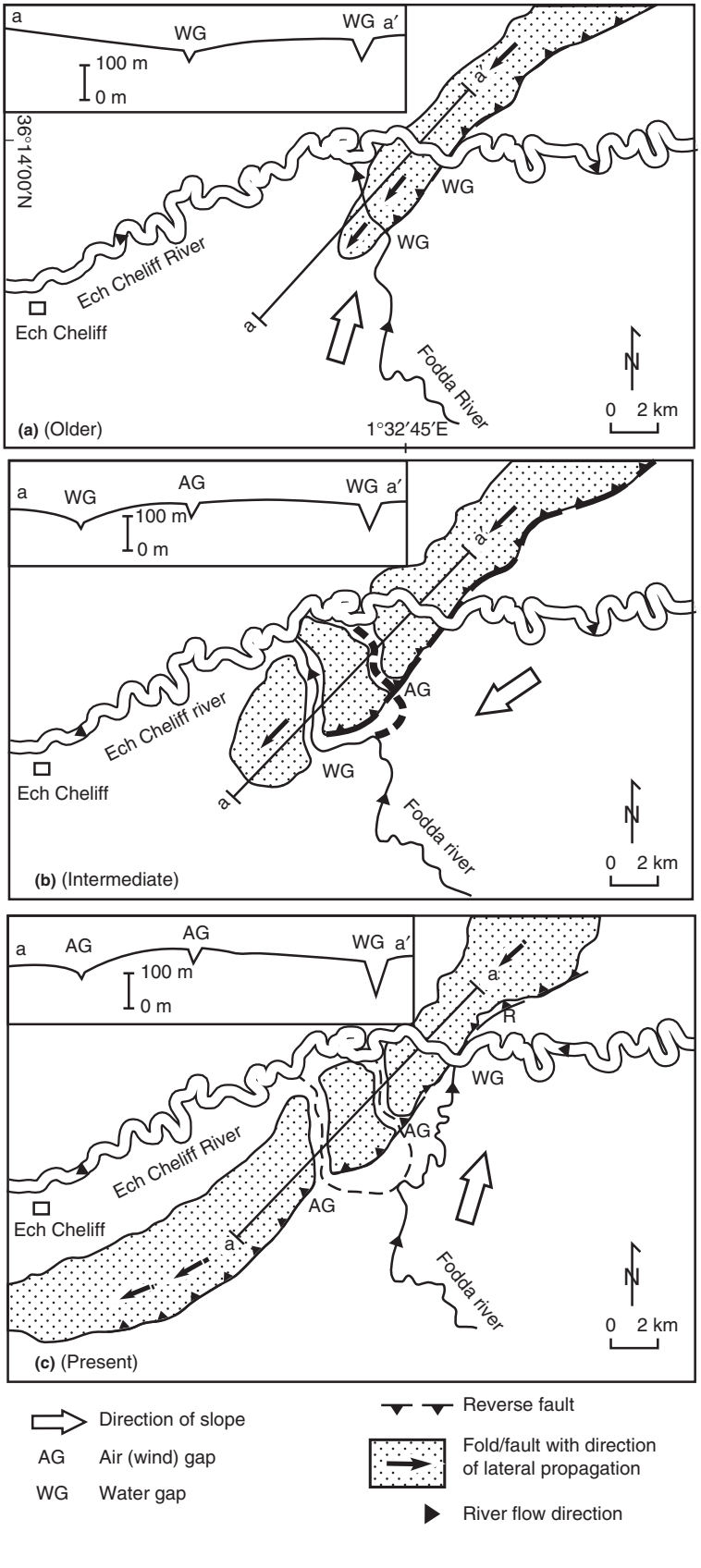


Figure 9 Geomorphology of the Santa Ynez Range in the Western Transverse Ranges. (a) The Santa Ynez Range, showing three gently curved geomorphic segments, two of which may be subdivided into subsegments. Topographic elevation of the crest of the Santa Ynez Range decreases systematically along the segments to the west, and boundaries between segments are structural. It is hypothesized that the segments are older in the eastern part of the range and youngest to the west, and the entire range developed as segments interacted with each other through time. (b) Entrenched fan-shaped drainage network on the westernmost segment of the Santa Ynez Range is suggestive of lateral propagation to the west.



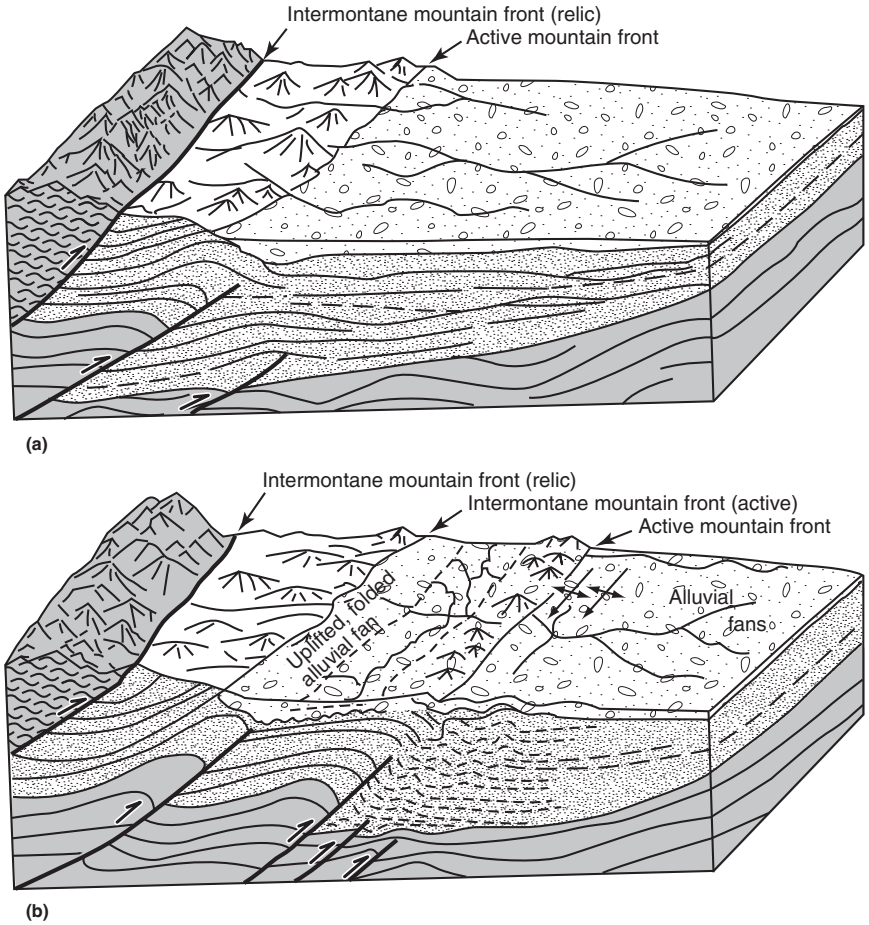


Figure 11 Idealized diagram showing the development of buried reverse faults and overlying anticlines that, through time, propagate from the hinterland toward a basin that has not been deformed. (a) An intermontane mountain front is present. (b) Buried reverse faults have propagated into the basin, folding the overlying alluvial fan gravels forming a series of anticlines parallel to the range front. Notice that upper parts of fans have been faulted and folded and incorporated into the mountain block with the development of a new active mountain front (Courtesy of Burbank)

5.7.7 Development of Transverse Drainage

Until recently, our knowledge of fold-and-thrust belt evolution centered on the belief that fold growth migrated away from the hinterland into an adjacent basin in a systematic way. It was thought that only one thrust fault was active at a time; and with continued shortening, deformation was transferred (migrated) to a new structure farther into the basin. We now understand that multiple faults and folds may be active simultaneously and that deformation does not often migrate systematically into a basin (**Figure 11**; Burbank et al., 1999). With the further understanding that folds commonly propagate laterally, new ideas concerning development of drainage across and around growing folds have been discussed. The evidence supporting new ideas about transverse drainage across fold belts is largely geomorphic.

The origin of transverse drainage (drainage across structures from linear ridges to mountain ranges) is a longstanding geomorphic problem (Bloom, 1998). Transverse drainage may be antecedent, that is, it is present prior to uplift of a growing structure and has sufficient stream power (proportional to the product of discharge and channel slope, where drainage basin area or channel length is a surrogate for discharge). For example, the Ech Cheliff River (**Figures 10(a)–10(c)**) has been

Figure 10 Development of drainage across the El Asam anticline in Algeria. (a) The anticline is propagating laterally to the southwest, and two water gaps were present. The larger gap is along the Ech Cheliff River, and a smaller gap has formed where the Fodda River crosses near the nose of the fold. (b) With further lateral propagation, the Fodda River has been deflected to the southwest, leaving behind an air (wind) gap. (c) The present topography has the Fodda River flowing north into the Ech Cheliff River. This diversion was in response to the M3 earthquake that occurred in 1980. Uplift of about 5 m in the southwest with about 1 m of subsidence farther north produced a topographic gradient to the north. Stream capture was most likely responsible for the diversion of the Fodda River to a point farther north on the Ech Cheliff River.

in the same location across the active El Asnam anticline during fold growth; and thus, the river is antecedent to the uplift of the anticline.

Alternatively, some streams are transverse to structure because of the presence of cover material that has a drainage pattern that is let down over buried structures. As the cover material is removed by erosion, the resulting transverse drainage is said to be superposed. Superposition is difficult to demonstrate unless some of the cover material remains.

Antecedent stream segments are obvious for drainage across young fold belts where some of the folds migrate with time into a largely undeformed basin. With the migration of thrust faults and folds into a depositional basin, growing faults and folds transform areas that were formerly depositional to growing folds with their associated erosional processes (Burbank et al., 1999).

Drainage development associated with fold belts can be complex. This results because folds may grow laterally as well as vertically as a response to displacement of buried faults within anticlines. Also, new folds may be added to a fold belt as the series of folds and faults propagate into undeformed areas (commonly in adjacent basins, see **Figure 11**). Streams draining from a mountain range (hinterland) deposit alluvial fans that, as younger folds develop basinward, are in turn folded. Thus, a series of parallel folds form, and previous cover materials (alluvial fan deposits) are folded. This process is illustrated in **Figure 12** for San Emigdio Canyon and associated alluvial fans on the north flank of the San Emigdio Mountains of Southern California. The oldest mountain front, now an intermountain (relict) front, was the apex for alluvial fan deposition about 100 ka. Today, the fan gravels are folded by the Wheeler Ridge and Los Lobos faults to the south.

A drainage that is defeated by uplift of a structure and flows parallel to a fold axis will likely be further diverted in the direction of propagation (Burbank et al., 1996, 1999; Jackson et al., 1996). As diversions develop, streams are captured; and the drainage basin area increases until sufficient stream power is available to temporarily maintain a channel at the nose of the fold where uplift has not yet occurred. As lateral propagation of the fold continues, this area becomes a water gap and eventually may become a wind gap if the channel is defeated by uplift and/or stream capture. If defeat occurs, the channel may be diverted again in the direction of lateral propagation and, in the course of a fold development, may make several passes around the fold as the drainage develops. For some folds, several wind gaps may be produced in this manner.

Evaluation of drainage patterns for specific folds may suggest that some folds are propagating in two directions, that adjacent folds are propagating toward each other, or that younger folds are propagating parallel toward or against older folds in a fold belt (Jackson et al., 1996; Ramsey et al., 2008). **Figure 13** shows the process of how drainage may be diverted as two segments of a fold propagate laterally to form a seemingly single structure. The profile along the ridge crest has a topographic saddle where the suture zone developed. Ramsey et al. (2008) reported folds in the Zagros Mountains (fold belt) where two segments have grown together by lateral propagation. The process of lateral fold growth may also squeeze two rivers together to flow through a single gap. This process will increase total and unit stream power, which favors persistence of the gap even with further fold growth (Burbank et al., 1999; Ramsey et al., 2008). Fold growth may also involve the development of a series of folds that are en echelon because the buried fault producing the folding is segmented and en echelon. With fold growth of such a system, individual folds may propagate laterally past one another (Burbank et al., 1999).

Because rates of uplift are commonly larger than rates of incision and because many more small streams are present than large rivers that traverse growing folds, water gaps are often defeated to become wind gaps. As an antecedent stream flows across a growing fold, sufficient unit stream power is necessary for a water gap to persist. With uplift of a fold, the upstream limb of the fold (generally the backlimb) will experience a reduction in slope, which lowers stream power, favoring defeat of the water gap. Across the crest of the fold, on the downstream fold limb (generally the forelimb) channel gradient increases, which increases the stream power. In response to the uplift, the channel in the water gap incises and narrows, sometimes producing a wineglass shape (wider at the top with stem-like incision of a narrow channel lower in the channel cross section). Narrowing increases the unit stream power, favoring incision (Amos and Burbank, 2007). Duvall et al. (2004) showed that with constant rock resistance that a sevenfold increase in uplift rate resulted in a factor of twofold increase in channel slope and a threefold decrease in channel width. The narrower, steeper channels would have a unit stream power increase of about 5 times.

With all the possibilities, it is not surprising that the processes that transform a water gap into a wind gap can be complex. Two of several hypotheses, proposed by Keller et al. (1999), for defeat of a water gap are: (1) uplift of the fold, as a result of a single or series of large earthquakes, may block the channel in the water gap, forcing a diversion in the direction of lower topography, which is likely to be in the direction the fold propagation; and (2) a tributary channel to the stream crossing the nose of the fold on the hinterland side of the fold that erodes headward parallel to the axis of the fold (the opposite direction the fold is propagating) may form. Headward growth or extension of that drainage may capture the drainage feeding a water gap. In many cases, a wind gap may form by a combination of both tectonic and fluvial processes (uplift diversion and capture of drainage).

Consideration of these processes allows for a hypothetical explanation for the development of drainage across an actively developing fold belt (see Burbank et al., 1999, for additional explanations). The process is illustrated in **Figure 14**. A stream establishes a channel across the path of the propagating fold before it arrives, and that stream reach is antecedent to the uplift. As fold growth continues, a water gap may form, as discussed above. With this hypothetical model, drainage is established across a developing fold belt by a series of captures, diversions, and antecedent positioning. That is, the process involves development of relatively short antecedent reaches across the path of propagating folds, followed by defeat and stream deflection along relatively longer reaches parallel to the fold axis (Keller et al., 1999).

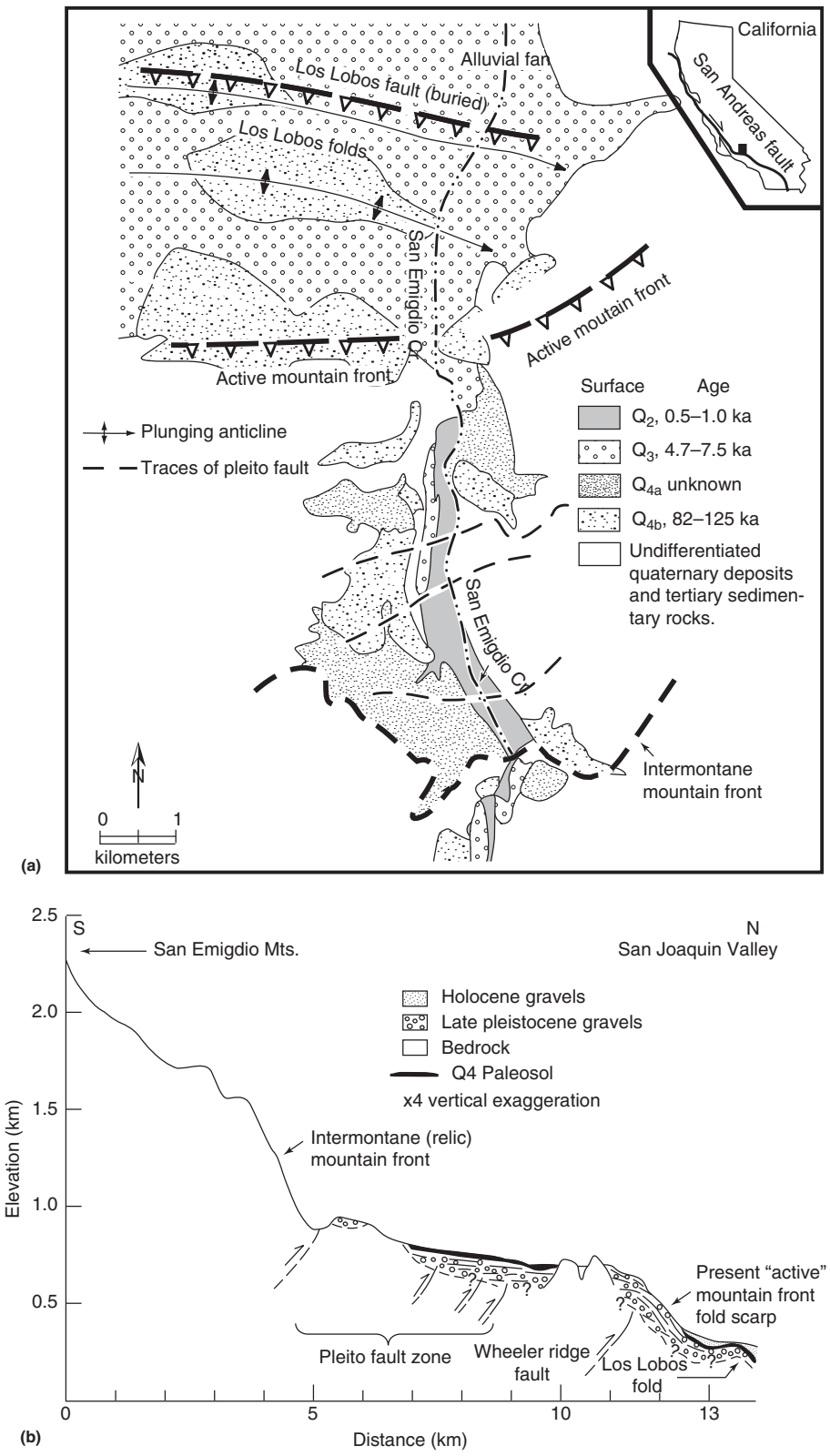


Figure 12 (a) A map showing the Holocene and late Pleistocene deposits (Q_2–Q_4) in San Emigdio Canyon in the southern end of the San Joaquin Valley, CA. Black box in inset shows the location of San Emigdio Canyon with respect to the San Andreas fault in Southern California. (b) Buried traces of the Wheeler Ridge fault and Los Lobos folds and topographic profile constructed along the crest of the west side of San Emigdio Canyon. Late Pleistocene gravels are faulted and folded over the Wheeler Ridge fault and Los Lobos folds. Modified from Keller, E.A., Seaver, D.B., Laduzinsky, D.L., Johnson, D.L., Ku, T.L., 2000. Tectonic geomorphology of active folding over buried reverse faults: San Emigdio Mountain front, southern San Joaquin Valley, California, 2000. Geological Society of America Bulletin 112(1), 86–97.

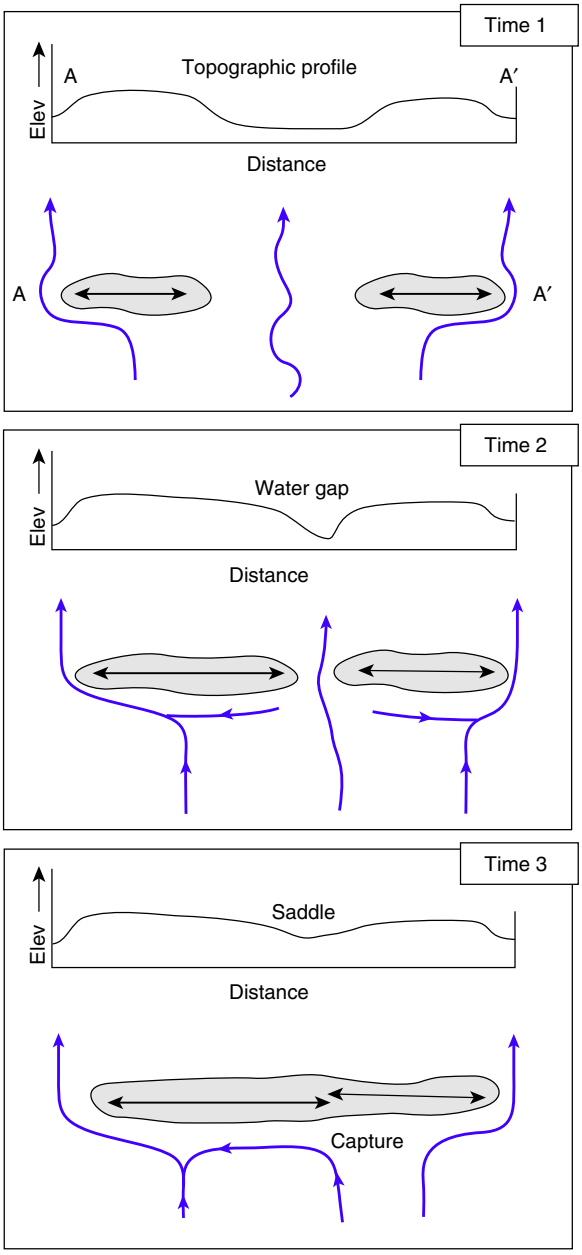


Figure 13 Idealized diagram showing the development of drainage as two fault segments with anticlines propagate laterally toward one another at 'Time 1.' At 'Time 2' the distance between the propagating folds narrows, and a water gap forms. With continued lateral propagation ('Time 3'), the two folds may become sutured, and the water gap is transformed into a topographic saddle. The result is a longer, continuous fold where streams are diverted to both ends where lateral propagation continues unimpeded.

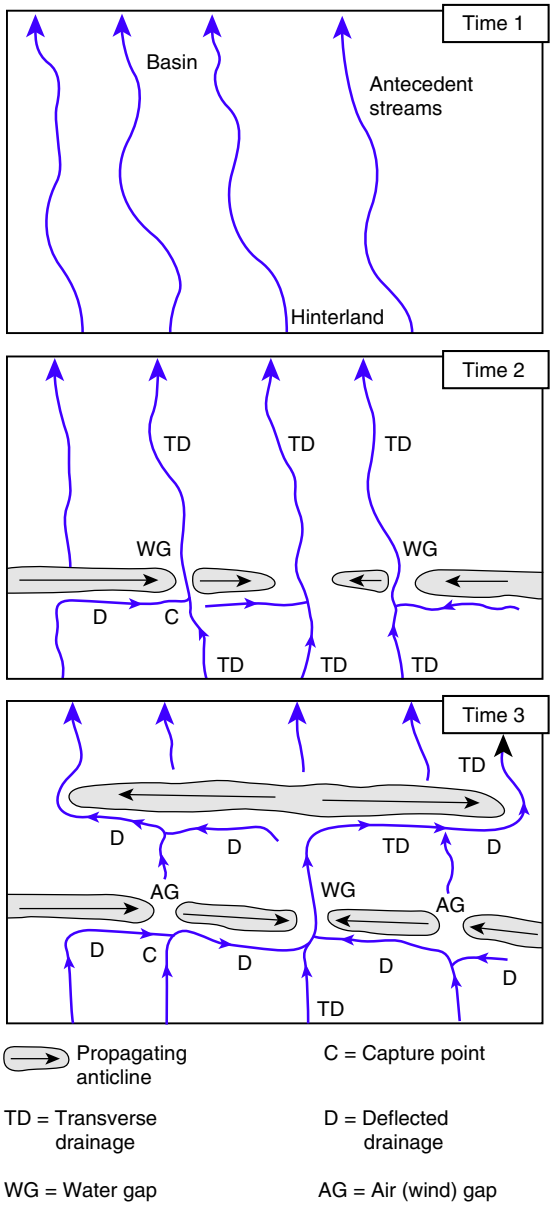


Figure 14 Idealized diagram showing drainage that has developed across a fold belt where most of the folds are propagating laterally. This is only one possible scenario that might occur with complex changes developing as folds propagate laterally and from the hinterland into a basin. Through a series of antecedent positioning of streams and of lateral deflections with stream capture, the drainage works its way through a fold belt.

5.7.8 Directivity of Earthquake Energy and Lateral Fold Propagation: A Hypothesis of Tectonic Extrusion

An earthquake may be considered as a process of rupture that starts from an initial point on the fault plane (called the focus). Fault rupture does not occur instantaneously, and it does not proceed in a uniform manner along the fault plane. For example, during the Northridge (ca. M_w 6.7) event, the earthquake ruptured the fault plane for ~8 s, and the average slip across the plane was about 1 m. During the earthquake, the rupture propagated across the fault plane in a northwesterly direction at a speed of ~3 km s^{-1}. However, the

propagation was not uniform; and some parts of the fault plane experienced little or no slip, whereas others experienced more than 3 m.

Directivity of seismic waves parallel to the rupture direction along the fault results in wave amplification when the amplitude of seismic wave increases in the direction of fault rupture. The direction in which the rupture occurs can greatly affect the intensity of seismic shaking (strong ground motion) (Benioff, 1955; Boore and Joyner, 1978). This principle is illustrated in **Figure 15**, which shows that in the direction of propagation of fault rupture the amplitude of the resultant wave may be as high as 10 times the amplitude of the waves in the reverse direction. This suggests that damages from seismic shaking may be much greater in the direction of fault rupture than in the opposite direction. For example, the 1994 Northridge earthquake, in the Western Transverse Ranges of California, was up (north) and to the west, resulting in stronger ground motion from seismic shaking to the northwest. The stronger ground motion to the northwest is believed to be the result of the movement (fault rupture during the earthquake) of a block of Earth moving upward and to the northwest (US Geological Survey, 1996).

Shortening across the Western Transverse Ranges is the result of right-slip and contraction in the vicinity of the 'Big Bend' of the San Andreas fault system (SAF). Right-slip along the Big Bend produces (north and south of the SAF) parallel to subparallel faults with predominantly left-lateral strike-slip faults and left-oblique-slip reverse faults (if they have a component of strike-slip). Major folds and (buried) faults tend to propagate laterally to the west, south of the SAF, and propagate to the east, north of the SAF. The authors hypothesize that the lateral propagation of fault rupture during earthquakes tend to be to the west, south of the SAF; and to the east, north of the SAF (**Figure 16**). At the north and south of the extrusion zone, the plate bounding deformation terminates, and this may coincide with the left-lateral, Santa Cruz Island and White Wolf faults, respectively (Keller et al., 2000).

The concept of tectonic extrusion has been used in a variety of tectonic settings, including the Mediterranean region (McKenzie, 1972), Asia (Tapponnier et al., 1982), and the Los Angeles Region (Walls et al., 1998). The driving mechanisms for each of these locations are somewhat different, depending upon specifics of the regional tectonic framework. In the case of the Big Bend of the SAF, the extrusion is evidently driven by the contraction produced by the bend in conjunction with the orientation of left-lateral strike-slip faults, such as the White Wolf, Santa Ynez, and Santa Cruz Island faults. An analogy that has sometimes been drawn is the squeezing of a watermelon seed between the thumb and index finger until it pops laterally. In the case of the Big Bend, we might envision two watermelons seeds being squeezed, with one extruding to the east, north of the fault, and the second to the west, south of the fault.

In order for a fault to propagate laterally, it must rupture and displace new ground in the direction of propagation. Thus, earthquake ruptures would hypothetically tend to propagate in the same direction as the growth of the fault and associated folds. The hypothesis that direction of rupture during earthquakes would tend to be the same as the direction of propagation of the fault that produced the earthquake is highly speculative. This leads to the question: Can we predict, using geologic or geomorphic criteria, lateral direction of earthquake rupture propagation? The answer to this question is possibly 'yes' in specific instances for buried reverse faults that have produced an anticline with surficial expression for which a single direction of lateral propagation may be determined. In other cases, a fold may propagate laterally in two directions, and some earthquakes may rupture laterally in a direction opposite to the direction of the propagation of the fold. Nevertheless, we hypothesize that the dominant direction of lateral propagation of rupture during moderate

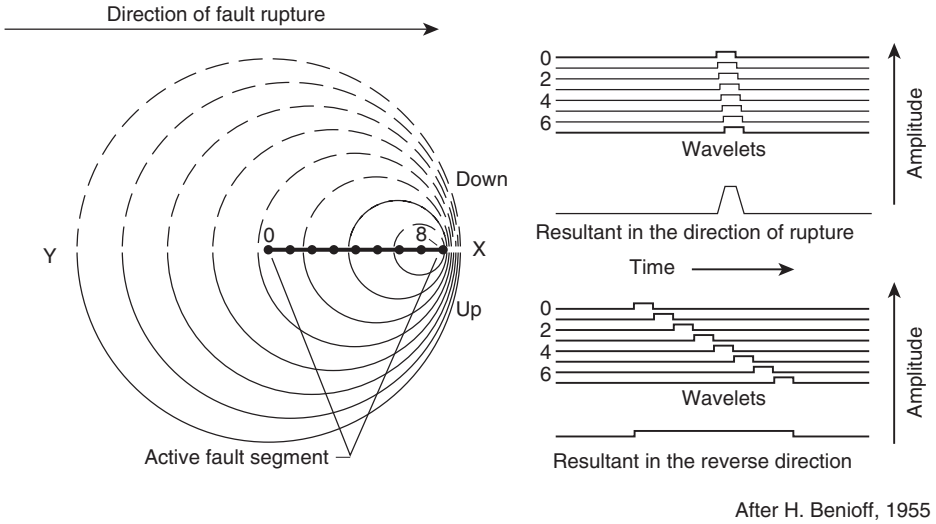


Figure 15 Concept of directivity increasing the amplitude of seismic waves and the direction of rupture propagation. Modified from Benioff, H., 1955. Mechanism and strain characteristics of the White Wolf fault as indicated by the aftershock sequence. In: Oakeshott, G.B. (Ed.), Earthquakes in Kern County, California during 1952. Division of Mines Bulletin, California, vol. 171, pp. 199–202.

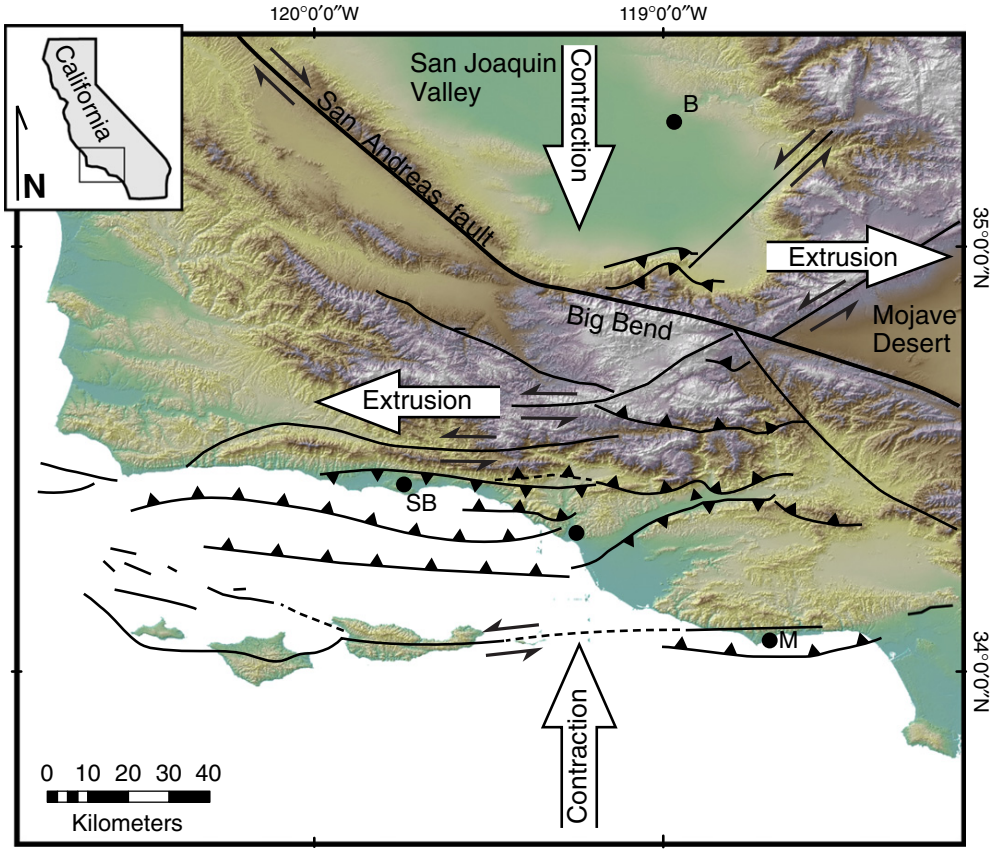


Figure 16 Model of tectonic extrusion away from the Big Bend in the San Andreas fault (SAF). South of the SAF folds are propagating to the west, whereas, north of the fault folds are propagating eastward. B, Bakersfield; M, Malibu; SB, Santa Barbara; V, Ventura. See text for explanation. Modified from Keller, E., Gurrola, L., 2000. Earthquake hazard of the Santa Barbara fold belt. Final Report to the US Geological Survey, NEHRP Award 527726, 78 pp. http://www.scec.org/research/98research/98gurrolakeller.pdf

to large earthquakes will be in the direction of the fold propagation.

Although a very limited dataset exists with which to test this hypothesis of lateral propagation of faulting and folding, as well as rupture during earthquake, **Table 1** provides some examples from southern California earthquakes. The table lists earthquakes and locations relative to the SAF, direction of lateral propagation of rupture, and the lateral component of displacement. Also indicated is whether a particular event supports the hypothesis of westward propagation of structure and rupture during earthquake, as well as the predicted left-oblique component of displacement.

The majority of earthquakes for which data are available regarding direction of propagation of rupture and sense of lateral displacement, generally supports the hypothesis that fault rupture during moderate to large earthquakes tends to have a westward component of propagation south of the SAF, and an eastward component, north of the SAF. The evidence is particularly good for the 1952 M_w7.5 Kern County earthquake, which is north of the SAF and had left-oblique displacement during the event – the rupture propagated to the northeast, as indicated by the pattern of aftershocks. The 1971 San Fernando *M*w6.6 earthquake had a left-lateral component of slip, which apparently increased from east to west (Palmer and Henyey, 1971), but the direction of propagation of the rupture was up and to the southeast. The 1978 Santa Barbara earthquake was characterized by left-oblique displacement, and evidence from the aftershock locations indicate that the direction of propagation of the rupture was to the northwest (Corbett and Johnson, 1982; Yeats and Olson, 1984). Finally, the 1994 Northridge M_w6.7 demonstrated a component of northwest direction of lateral propagation of rupture based upon aftershock locations (US Geological Survey, 1996). Thus, the earthquakes of 1952, 1978, and 1994 (for which data exists concerning the direction of propagation of rupture) support the hypothesis that there is a tendency for rupture propagation to have an eastward component north of the SAF and a westward component south of the fault.

This hypothesis has important ramifications for earthquake hazards because earthquake damage is generally most severe in the direction of a propagating rupture (Benioff, 1955; US Geological Survey, 1996) (**Figure 16**). Anticipating potential direction of rupture during earthquakes will allow for better modeling of potential damages to human structures as a result of seismic shaking.

Table 1 Selected examples of Southern California earthquakes

Earthquake	*Approximate magnitude*	*Location relative to San Andreas fault*	*Direction of lateral propagation of rupture*	*Aftershock locations*	*Lateral component of displacement*	*Supports hypothesis? Yes (Y), No (N)*	*Comments references*
1925 Santa Barbara	6.3	South	West (?)	Not known	Probably left-oblique		Many uncertainties
1952 Kern Co.	7.5	North	Northeast	All northeast	Left-oblique	Y (displacement)	Oakeshott (1955)
1971 San Fernando	6.6	South	Probably to southeast	Mostly southeast	Left-oblique	Y (displacement) N (propagation)	Left-lateral component of slip apparently increases east to west (Palmer and Henyey, 1971)
1978 Santa Barbara	5.9	South	Northwest	Northwest	Left-oblique	Y	Corbett and Johnson (1982), Yeats and Olson (1984)
1994 Northridge	6.7	South	Northwest	Mostly northwest	Not known	Y	US Geological Survey (1996)

5.7.9 Conclusions

Study of the tectonic geomorphology of active faults and folds from various locations across the world allows us to come to the the following conclusions:

1. Investigations of the active tectonics of fold growth suggests that folds may propagate laterally in one direction or two; twofolds may propagate toward each other, producing a suture zone with a longer segmented structure; and folds may also propagate past each other to form en echelon patterns.
2. A major challenge in the understanding of fold growth is to establish the chronology that defines rates of lateral propagation and incision of streams across growing folds.
3. Geomorphic criteria to recognize lateral propagation of folding are straightforward, and several criteria are useful. However, geomorphic criteria, although necessary to demonstrate lateral fold propagation, are not sufficient to prove the propagation. The strongest geomorphic evidence to support lateral propagation includes the presence of inherited drainage in the landscape that fans out from the flanks and noses of actively growing, laterally propagating folds. The presence of a series of wind gaps and water gaps in the direction of lateral propagation that result from the same stream being diverted laterally is strong evidence for lateral propagation.
4. The development of transverse drainage across active folds and fold belts is a complex process that involves the interaction of several variables, including rate of uplift, resistance of the rocks, unit stream power, and the nature and extent of preexisting drainage.
5. A simple model for development of transverse drainage is that a stream may establish a channel across the path of a propagating fold before the fold arrives through lateral propagation. That stream reach can be considered antecedent to the uplift. As fold growth continues, a water gap may form which will either persist or eventually be defeated. Thus, drainages are established across the developing fold by a series of captures, diversions, and antecedent positioning.
6. Understanding lateral propagation hypothetically may have implications for better understanding the earthquake hazard. If earthquake ruptures have a preferred direction of propagation, then variability of seismic shaking and increase in shaking in the direction of propagation may be better predicted. The hypothesis of tectonic extrusion states that in the Big Bend area of the SAF, faults and folds tend to propagate west, south of the fault, and to the east, north of the fault.

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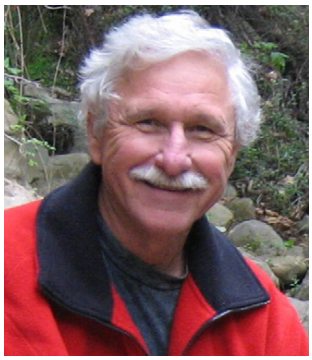
Biographical Sketch



Edward A Keller is a professor, researcher, writer, mentor, and teacher to undergraduate and graduate students. Currently, Keller's students are working on earthquake hazards, forms and processes of small coastal lagoons, and geologic controls on habitat of the endangered southern steelhead trout. He was born and raised in California (Bachelor's degrees in Geology and Mathematics from California State University at Fresno, Master's degree in Geology from the University of California at Davis); it was while pursuing his PhD in Geology from Purdue University in 1973 that Ed wrote the first edition of *Environmental Geology*, a text now in the Ninth edition that became the foundation of an environmental geology curriculum in many universities and colleges. Other widely used textbooks include Active Tectonics with Nicholas Pinter, Second edition, 2002; Introduction to Environmental Geology Fifth ed., 2012; and Environmental Science, Eighth edition with Daniel Botkin, 2011. Keller joined the faculty of the University of California at Santa Barbara in 1976 and has been there since, serving multiple times as the chair of both the Environmental Studies and Hydrologic Science programs. During that time, he authored more than 130 articles, books, and reports, including seminal works on pool-riffle dynamics in alluvial and bedrock channels, role of large woody debris on stream channel form and process, and tectonic geomorphology of active fold growth. Keller's academic honors include the Don J Easterbrook Distinguished Scientist Award, Geological Society of America (2004), the Quatercentenary Fellowship from Cambridge University, England (2000), two Outstanding Alumnus Awards from Purdue University (1994, 1996), a Distinguished Alumnus Award from California State University at Fresno (1998), and the Outstanding Outreach Award from the Southern California Earthquake Center (1999).

Duane DeVecchio is adjunct faculty at the City College of San Francisco and is an Assistant Researcher at the Earth Research Institute at the University of California Santa Barbara, where he earned his PhD in geology. DeVecchio has a broad field-based background in the Earth sciences and likes to relate his experience of living in trailers in the middle of nowhere mapping rocks. For his Masters Degree and post-Masters research, he conducted structural and stratigraphic analysis, as well as numerical dating of upper plate volcanic and volcaniclastic rocks in southeast Idaho and the central Mojave Desert of California, which record the Miocene extensional histories of these regions. His PhD research was aimed at resolving fault slip rates and quantifying the earthquake hazard presented by several active fault-related folds growing beneath urbanized Southern California. DeVecchio's current research interests focus on the timing and rates of change of Earth's surface due to depositional and erosional processes that result from climate change and tectonics. Since commencing his graduate education, Duane has devoted a significant amount of time to becoming an effective communicator of science to today's students. He is a passionate teacher and feels strongly that students need to develop the ability to critically evaluate data presented in numerous forms from various sources. He believes this is particularly important in today's world where the internet offers accessibility to vast amounts of information, yet the validity of this information is often questionable or misleading. When DeVecchio is not conducting research or teaching, he enjoys whitewater rafting, rock climbing, snowboarding, and camping with his partner, Christy.