# Geomorphic criteria to determine direction of lateral propagation of reverse faulting and folding


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## ABSTRACT

**Fault-related folds develop above active faults, and as these faults propagate laterally so do the folds they produce. Geomorphic criteria useful in evaluating rates and direction of lateral propagation of active folds in the direction of propagation are: (1) decrease in drainage density and degree of dissection; (2) decrease in elevation of wind gaps; (3) decrease in relief of the topographic profile along the crest; (4) development of characteristic drainage patterns; (5) deformation of progressively younger deposits or landforms; and (6) decrease in rotation and inclination of forelimb. All these criteria are consistent with lateral propagation, but do not prove it. The presence of more than one wind or water gap formed by the same stream, however, is strong evidence of lateral propagation. Rates of lateral propagation of folding may be several times the rate of uplift and fault slip. Lateral propagation of anticlinal folds allows for a new explanation of how drainage may develop across active fold belts. Development of drainage across an active fold belt is probably a function of relatively long structurally controlled drainage diversion parallel to fold axes and development of relatively short antecedent stream reaches, around the nose (plunge panel) of a fold. Water and/or wind gaps form as uplift, drainage diversion, and stream capture associated with fold growth continue.**


## INTRODUCTION

Lateral propagation of folds is a process in active tectonics that has been recognized since Shelton (1966), but only recently studied in detail (Jackson et al., 1996; Delcaillau et al., 1998; Keller et al., 1998). Determining the direction and rate of lateral propagation of folding has important implications for understanding deformation in contractile regimes, and for better understanding of the mechanics of folding and reverse faulting.

Folding in fold and thrust belts is intimately related with buried reverse faulting, and the bulk of evidence suggests that buried reverse faulting produces the observed folding (Davis, 1983; Namson and Davis, 1988; Stein and King, 1984; Yeats, 1986; Stein and Yeats, 1989; Medwedeff, 1992; Gurrola and Keller, 1997). It has been argued that as total fault displacement from repeated earthquakes increases, so does total fault length (Cowie and Scholz, 1992; Jackson et al., 1996) That is, faults propagate laterally as they accumulate slip. Although it is difficult to show from landscape evaluation that buried reverse faults propagate laterally, the folds these faults produce can provide an indication of the direction and rates of lateral propagation. The two processes of faulting and folding go hand in hand, and in many locations fold scarps (the scarp produced by active folding, a term suggested to us by James Dolan, 1997, personal commun.) have been mapped as faults. Evidence from many fold and thrust belts suggests that horizontal shortening produces reverse faults that cause hanging-wall deformation and the development of anticlines (Yeats, 1986).

The purpose of this paper is to introduce geomorphic criteria we believe are useful in evaluating direction and rate of lateral propagation. We illustrate several of the criteria from geomorphic evaluation of Wheeler Ridge at the southern end of the San Joaquin Valley, California, a well-studied anticlinal fold (Medwedeff, 1992; Keller et al., 1998). We apply the criteria to the Mission Ridge anticline at Santa Barbara, California, to suggest that the fold is propagating westward. Geomorphic evaluation at Wheeler Ridge reveals that the rate of lateral propagation of the anticline is ~3 cm/yr, which is ~10 times greater than the vertical uplift rate (Keller et al., 1998). This suggests that lateral propagation of folding may be one of the most rapid tectonic processes identified, on the order of several centimeters per year. To observe the process of lateral propagation, push a tablecloth with your finger tips, producing a fold in the material. Notice the rapid lateral propagation and what happens if the process starts near the edge of the table, simulating fold growth from a boundary.

## GEOMORPHIC CRITERIA TO IDENTIFY DIRECTION OF LATERAL PROPAGATION OF FOLDING

Geomorphic relationships are a primary way to demonstrate lateral propagation of folds (Jackson et al., 1996). Geomorphic indicators of lateral fold propagation resulting from buried reverse faulting include (in direction of propagation): (1) decrease in drainage density and degree of dissection; (2) decrease in elevation of wind gaps; (3) decrease in relief of the topographic profile along the crest of the fold (i.e., a fold plunges in the direction of propagation); (4) development of characteristic drainage patterns; (5) deformation of progressively younger materials; and (6) decrease in rotation and inclination of the forelimb. As a result of style of folding and variable geomorphic response, all of the criteria may not be evident at a particular fold.

A drainage map of Wheeler Ridge is shown in Figure 1 along with several geomorphic indicators of lateral propagation. Criteria 2 and 4 have been established independently to demonstrate lateral propagation of folds in New Zealand (Jackson et al., 1996). To demonstrate lateral propagation of folding and to develop rates of propagation, several of the geomorphic criteria need to be evaluated, and the chronology of the deposits or landforms being folded needs to be established. For example, the ages of deposits (alluvial fan segments) at Wheeler Ridge, along with geographic position, were used to determine the rate of lateral propagation as about 3 cm/yr (Keller et al., 1998). Lateral propagation at Wheeler Ridge, according to Medwedeff (1992) and Mueller and Talling (1997), is a process characterized by occurrence of propagation events associated with development of


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tear faults. Subsurface data suggest that the position of major wind and water gaps at Wheeler Ridge coincide with tear faults (Medwedeff, 1988). Tear faults on Wheeler Ridge produce topographic scarps that face the direction of lateral propagation, helping establish stream position at the base of the scarp.

The six geomorphic criteria are consistent with but not proof of lateral propagation, because the criteria are consistent (given specific scenarios) with both fold propagation and fold rotation models of fold growth (Fig. 2). Criteria 4 and 5 are strong evidence of lateral propagation, and if there are at least two wind or wind and water gaps (from the same stream), then this is very strong evidence of lateral propagation. Assuming that the stream can only be in one place at a time, the model of rotation (Fig. 2B) is unlikely to produce two wind gaps or a wind and water gap at lower elevations in the direction of fold growth. There could be only one wind gap and one diversion. Once a stream is defeated by uplift in the rotation model it would be deflected to the nose of the fold (which is fixed in that model) and would not form another gap.

Specific methods employed to analyze lateral propagation of folds are keyed to the six geomorphic indicators. The first task is to make a detailed drainage map of the forelimb, backlimb, and plunge panel (or nose ramp) of specific folds, such as that shown for Wheeler Ridge in Figure 1. This is accomplished by using aerial photographs and detailed topographic maps. Drainage patterns are analyzed to evaluate drainage density and estimate the degree of dissection of the fold. Drainage density ($D_d$) is defined as the ratio of the sum of the total length of channel divided by the drainage basin area. Drainage density is an important spatial measure of the network geometry because it is an expression of the degree of dissection of the drainage basin by surface streams. As a result, drainage density is a link between the physical characteristics of the drainage basin and the processes that act upon it, related to material type, surface slope, and uplift (Knighton, 1998). In our studies of Wheeler Ridge (Keller et al., 1998) we found that a threshold hillslope angle is necessary to initiate the development of drainage and its subsequent evolution. Drainage density on the south flank of Wheeler Ridge (Fig. 1) decreases from about 15–18 $km^{-1}$ for surfaces older than about 100 ka to about 0.4 $km^{-1}$ for surfaces of 17–60 ka, and is nearly zero for Holocene surfaces.

Topographic profiles along the crest, profiles normal to the fold, and digital elevation models can help identify geomorphic parameters of folds. The elevations of wind gaps along an anticline are measured directly, and we postulate, as did Jackson et al. (1996), that these elevations are usually lower in the direction of propagation. The topographic profile along the crest of the fold may

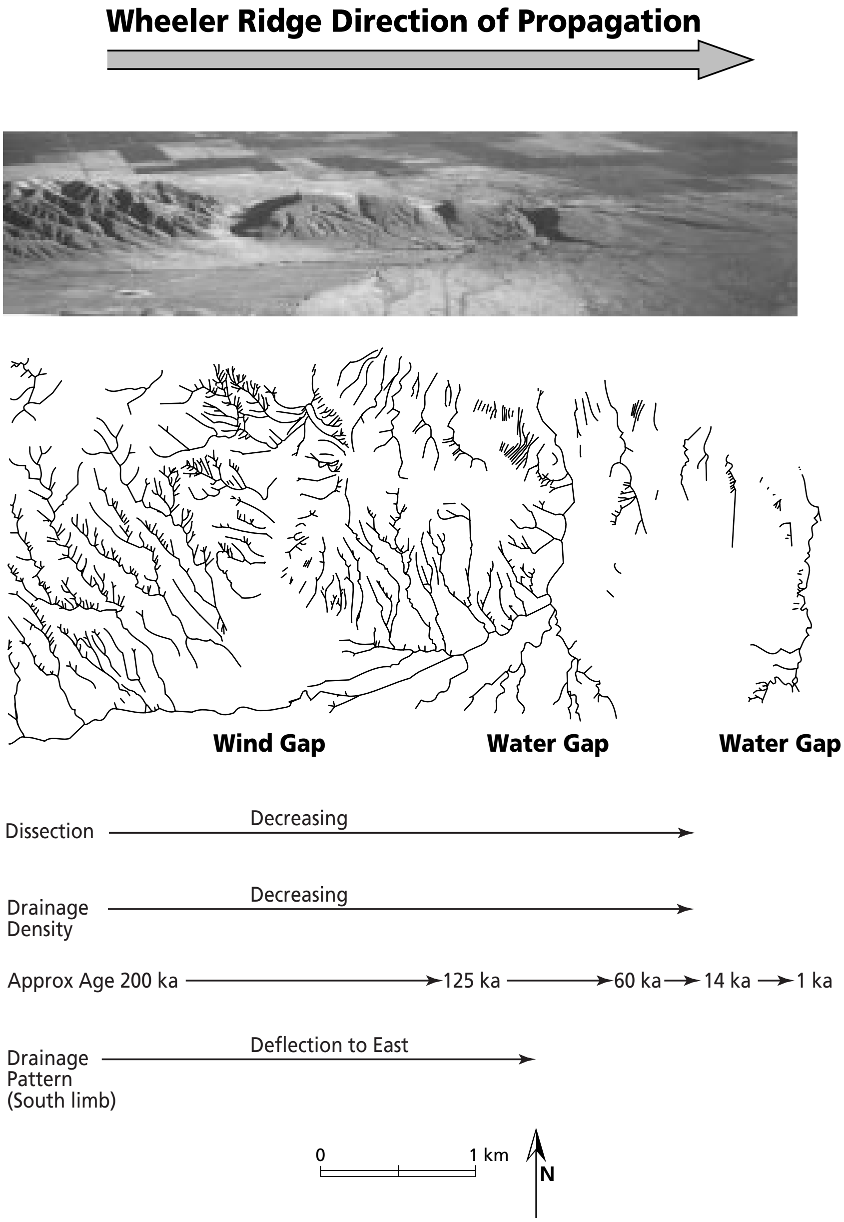


**Figure 1. Aerial photograph (courtesy of John S. Shelton), and drainage map of Wheeler Ridge, southern San Joaquin Valley, California (after Keller et al., 1998), illustrating several geomorphic indicators of lateral propagation present at ridge.**

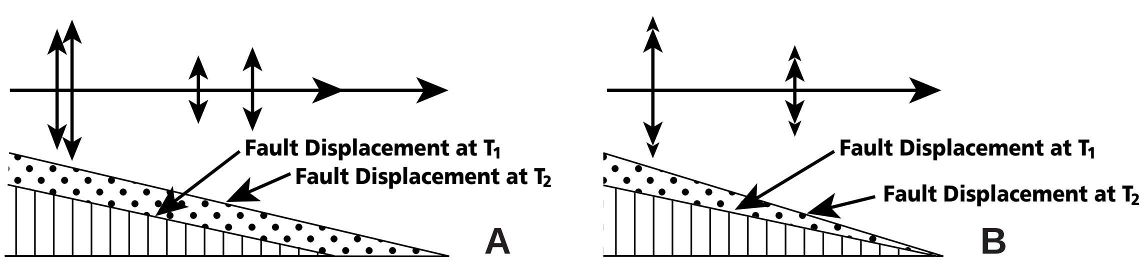


**Figure 2. Two models of fold growth. A: Lateral propagation where fault length grows. B: Rotation, where end points of buried fault are fixed. Drawing courtesy of D. Medwedeff.**

reveal the direction of fold plunge. This relationship is shown for Wheeler Ridge (Keller et al., 1998) and for the apparent westward propagation of Mission Ridge at Santa Barbara, California (Fig. 3). Jackson et al. (1996) argued that drainage parallel to a fold will likely be diverted in the direction of propagation. As the diversion develops, streams are captured and the drainage basin area increases until there is sufficient stream power to temporarily maintain a channel at the nose of a fold, where propagation has not yet occurred. As fold propagation continues, this area becomes a water gap, and eventually may become a new wind gap if the channel is defeated by uplift or stream capture. If this occurs, the channel is diverted again in the direction of propagation and may make several passes around the fold as the drainage develops. In some folds there may be several wind gaps produced in this manner, and the major drainage will be repeatedly diverted around the nose of the fold. In this sense, the streams are antecedent where they cross an active fold as their position is established at the nose of the fold before folding and uplift propagates through the area. These relationships are clearly shown for Wheeler Ridge (Fig. 1; Keller et al., 1998) and are suggested for Mission Ridge (Fig. 3). In both cases, streams are diverted in the direction of propagation; with Mission Ridge, there are two wind gaps of Mission Creek and the elevation of the gaps decreases in the direction of propagation. This is strong evidence that the ridge is propagating westward. Dissection of the fold decreases to the west, as does limb rotation (Fig. 3).

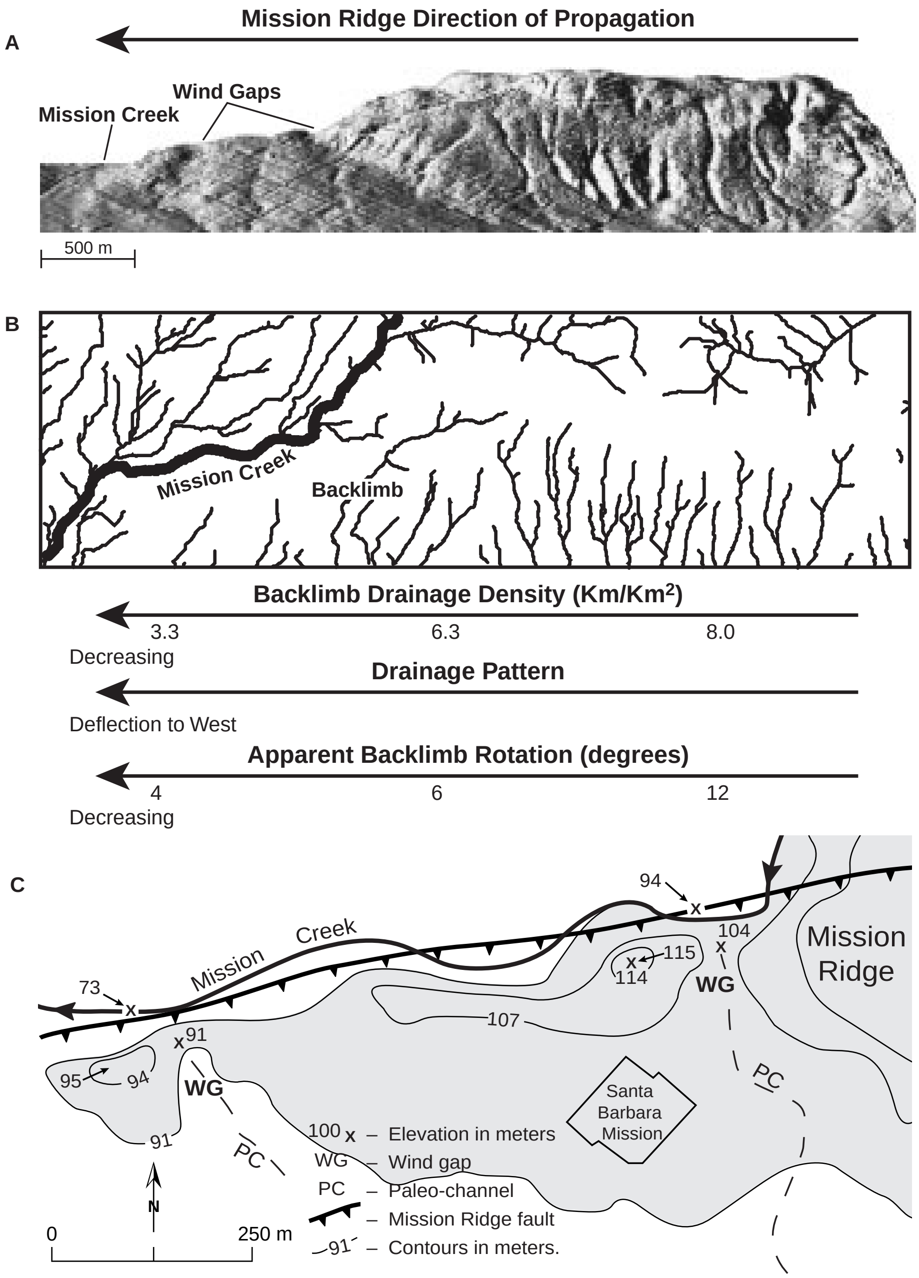


**Figure 3. Mission Ridge, east-west anticlinal uplift just north of the center of Santa Barbara, California. Dissection decreases to west. Ridge is (A) apparently propagating west, (B) deflecting Mission Creek about 1 km to the west, and (C) in process, forming two wind gaps (with associated paleochannels) at elevations that are lower in direction of propagation. Digital elevation model (A) is based on 3 m grid and 1 m elevation control. Oblique view is to north; vertical exaggeration is 2×. Grid pattern is city streets.**

## DISCUSSION

Careful evaluation of drainage patterns may reveal that some folds are propagating in two directions, that adjacent folds are propagating toward each other, or that younger folds are propagating parallel to and toward or against older folds in a fold belt (e.g., see Jackson et al., 1996). The position of the fold relative to an adjacent basin may also be important. A propagating anticline in which the forelimb (fold scarp) is facing upstream and deflected parallel to the fold axis may be more easily eroded by the deflected drainage than the backlimb. This occurs because the forelimb is normally much steeper than the backlimb in a fault-propagated, asymmetric fold; as a result the streams from the mountains that are diverted may erode vigorously into the steeper escarpment, perhaps producing a series of meandering scars along the forelimb. In some cases, for example the Mesa anticline at Santa Barbara, California, the forelimb has been nearly removed by erosion and meander scars are present (Gurrola et al., 1998).

The range of rates of lateral propagation of folds will remain poorly constrained until more data, i.e., the age control of materials being folded, are obtained from other folds. We speculate that the rates, when determined, will be several times the rate of uplift, and will be some of the most rapid of tectonic rates yet identified.

Recognition of the process of lateral propagation of folds is useful in better understanding the geomorphic problem of identifying processes that result in stream development transverse to structures such as fold belts (Oberlander, 1985). Streams that are transverse, i.e., cut across, active folds are usually thought to have been superposed across structure by erosion of an overlying cover mass, or to have formed antecedent to the uplift (downcutting of the channel with uplift). It has also been suggested that transverse drainage may form by headward extension of drainage, and by stream erosion related to local stratigraphy and structural control (Oberlander, 1985). Recognizing lateral propagation of folds allows some relatively short reaches of streams that cross a fold to be antecedent, while adjacent, relatively longer, reaches are parallel to fold axes. Hypothetical development of a major stream across an actively developing fold belt is shown in Figure 4. A stream establishes a channel across the path of a propagating fold before it arrives,

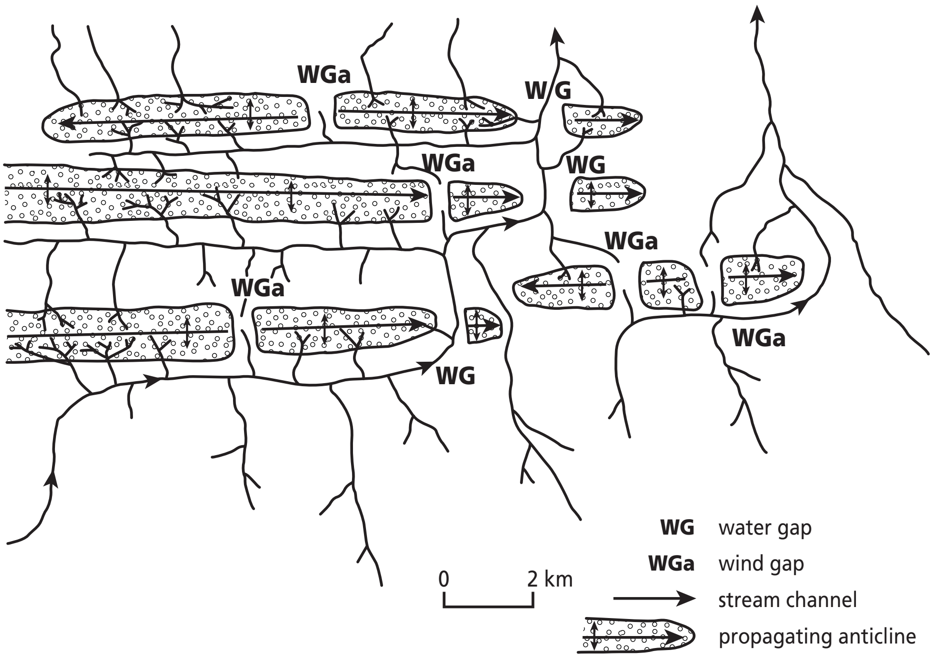


**Figure 4. Idealized diagram illustrating how drainage transverse to active fold belt deforming surface topography might develop by series of diversions, with short antecedent reaches across folds and longer reaches parallel to fold axes.**

and that stream reach is antecedent to the uplift. As fold growth continues, a water gap forms. If there is sufficient stream power, the water gap is maintained as the fold continues to grow vertically by uplift and laterally by lateral propagation (Jackson et al., 1996).

The processes that result in a water gap being transformed into a wind gap may be complex, and at least two hypotheses are reasonable. (1) Uplift of the fold may block the channel in the water gap, forcing a diversion in the direction of lower topography, which is most likely the direction the fold is propagating. (2) A channel crossing the nose of the fold has a tributary on the mountain side of the fold that erodes headward parallel to the axis of the fold. Extension of the drainage captures the drainage feeding the water gap. In reality, a wind gap probably forms by a combination of both tectonic and fluvial processes (uplift diversion and capture of drainage). With this model, drainage is established across a developing fold belt by a series of captures, diversions, and antecedent positioning.

## CONCLUSIONS

The six geomorphic indicators of lateral propagation of folding presented here are useful in analyzing lateral growth of individual folds. They may also be useful in unraveling complex topographic relationships between several folds. Folds may grow in more than one direction, toward one another, or away from one another. The existence of more than one gap produced by the same stream is positive evidence for lateral propagation.

Recognition of lateral propagation of folds provides a potential new explanation of how drainage may develop transverse to structure. 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 axes.

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