Cleavage fronts and fans as reflections of orogen stress and kinematics in Taiwan

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ABSTRACT

Recent observations of cleavage patterns, strain histories, and kinematics across the Taiwan mountain belt depict systematic orogen-scale variations with respect to the synorogenic divide and suggest that the pattern of cleavage development is a predictable consequence of orogen stresses and kinematics. In Taiwan, continental crust within the collision is accreted in the prowedge facing Asia, but is advected eastward into the east-verging retrowedge, where the most deeply exhumed rocks are exposed. Wedge mechanics predict a reversal in the direction of plunge of the principal compressive stress at the topographic divide between the opposing wedges. The observation of a single cleavage in western Taiwan suggests that the cleavage in the prowedge remains stable with respect to the stress orientation. In contrast, the existence of a second crenulation cleavage in the retrowedge is evidence for an abrupt change in stress orientation and unstable buckling of preexisting prowedge fabrics. Advection of a fabric across a topographic divide in a doubly vergent wedge provides an explanation for the occurrence of cleavage fronts and fans in natural systems such as Taiwan.

Keywords: cleavage fan, cleavage front, Taiwan, slaty cleavage, incremental strain.

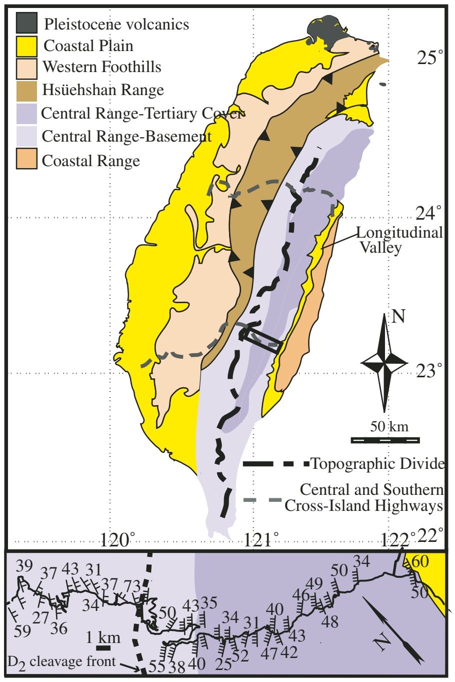

Figure 1. Top: Geologic map of Taiwan showing major tectonostratigraphic units, position of two cross-island transects, and drainage divide for Taiwan. Bottom inset shows map of cleavage orientations for Southern Cross Island Highway (two and four tick marks for slaty and crenulation cleavage, respectively).

INTRODUCTION

Deformation fabrics are systematically distributed across many active and ancient orogenic belts. At the scale of a mountain belt such as the Pyrenees (Choukroune, 1976) or Taiwan (Stanley et al., 1981; Fisher et al., 2002), cleavage patterns can take the form of a cleavage fan, fabrics on opposing sides of the mountain belt dipping toward an axial zone where cleavage is near vertical. Cleavage first appears in the foreland thrust belt along a front (Fourmarier, 1923, Holl and Anastasio, 1995), in some cases on each side of a mountain belt (Choukroune, 1976). The initial cleavage can be overprinted in the interior of the orogenic belt, resulting in a crenulation cleavage front (e.g., the Taconic allochthon; Chan et al., 2000). A cleavage orientation reflects specific stress and deformational conditions, and the common occurrence of regional-scale cleavage fans and cleavage fronts provides an important insight into orogenic stresses and kinematics of rock advection through the stress field.

In this paper we describe cleavage patterns across the Taiwan mountain belt, an active arc-continent collision where numerous studies have documented formation of multiple cleavages and fanning cleavage orientation across the mountain belt (Stanley et al., 1981; Fisher, 1999; Fisher et al., 2002) (Fig. 1). The Taiwan mountain belt is an active collision with convergence rates of 8.2 cm/yr (Yu et al., 1997) and erosion rates of 4–6 mm/yr (Willett et al., 2003; Dadson et al., 2003); there is widespread exposure of fabrics formed and exhumed since onset of collision in the Pliocene, thus permitting comparison to the modern tectonic context.

The mature north-central region of the Taiwan mountain belt is likely close to topographic steady state, where flux of material into the system by offscraping and underplating of continental crust is balanced by erosional removal of material from the surface of the orogen (Willett et al., 2003). In such a system, topography at long wavelength remains steady (Suppe, 1981; Willett and Brandon, 2002), permitting comparison between deformational fabrics and syntectonic topography. Based on this comparison, we argue that the cleavage forms in response to stresses consistent with topography, and that the fanning pattern and occurrence of a crenulation cleavage are reflections of kinematic motion of rock through this stress field.

DOUBLY VERGENT WEDGE TECTONICS IN TAIWAN

The Taiwan mountain belt can be described in the context of doubly vergent orogenic wedge models, in which crust from the continental plate is accreted into an orogenic wedge, which overlies a subducting plate (Willett et al., 1993) (Fig. 2A). Such an orogenic wedge develops a characteristic geometry in which the wedge tapers in both directions, reflecting a balance between gravitational stresses and basal traction from the underthrusting plates (Davis et al., 1983). Deformation associated with the accretionary flux maintains a low-taper prowedge verging toward the subducting plate, and a higher tapered retrowedge verging in the opposite direction. The crest of the mountain belt represents the transition between these opposing wedges. The topography of Taiwan is consistent with this model, with an asymmetric drainage divide that separates a northwest-facing, narrowly tapered prowedge from a southeast-facing, steeply tapered retrowedge. Crustal structure based on wide-angle seismic data across the Hengchun Peninsula in southern Taiwan shows the doubly vergent wedge structure of the young collision zone (McIntosh et al., 2005). Seismic profiles just south of Taiwan show active backthrusting of the accretionary wedge over the forearc basin (Reed et al., 1992), and seismic tomography based on teleseismic data shows evidence for a subducting Asian slab in central Taiwan (Lallemand et al., 2001; Lin, 2002). In

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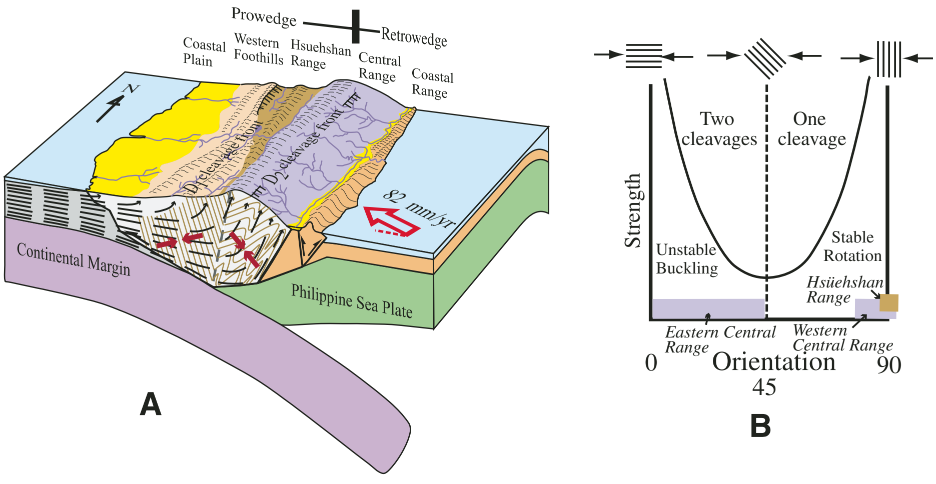

Figure 2. A: Block model depicting trajectory of Asian crust relative to Philippine Sea plate in context of doubly vergent wedge model (dashed black curves). Also shown are S_1 cleavage trace in cross section, orientation of maximum principal stress (red arrows), plate motion vector for Philippine Sea plate relative to Asia, and locations of D_1 and D_2 cleavage fronts. B: Parabolic relationship between yield stress and orientation of maximum principal shortening direction relative to cleavage (ϑ) for frictionless foliated material. ϑ is assumed to be approximately equal to φ, the orientation of maximum compressive stress (σ_1) relative to cleavage. ϑ values shown for prowedge in Taiwan are based on incremental strain data (see text). ϑ values for retrowedge are shown schematically to reflect observation that slaty cleavage is crenulated along cleavage front to east of divide.

east-central Taiwan, bathymetry data are consistent with backthrusting at the base of the slope at the boundary between the Coast Range and the Philippine Sea plate (Malavieille et al., 2002). In northern Taiwan, the tectonic setting is complicated by the change from suturing to separation that occurs at the intersection with the Ryukyu plate boundary (Shyu et al., 2005), so our analysis is limited to the southern two-thirds of Taiwan.

Erosion of an accreting orogenic wedge produces a distinctive kinematic pattern reflecting the asymmetry in particle paths with material exhumed in the retrowedge following a deep path, passing through the prowedge to reach the surface (Willett and Brandon, 2002) (Fig. 2A). Taiwan exhibits this asymmetry with a progressive increase in metamorphic grade and depth of burial from the sedimentary cover of the thrust belt into the slate belt of the Hsüehshan and western Central Range and, finally to the metamorphosed basement rocks of the eastern Central Range (Suppe, 1981).

The deep exhumation of Taiwan has provided evidence for extensive pressure solution deformation and formation of distinct cleavages throughout the slate belt and metamorphic Central Range (Figs. 1 and 2A). A prowedge cleavage front in central and northern Taiwan occurs near the boundary between the Western Foothills and Hsüehshan Range (Fig. 2A). A second northwest-facing cleavage front in eastern Taiwan (~10 km east of the divide) is related to a northwest-dipping crenulation fabric that, in areas of greatest intensity, completely transposes the early slaty fabric (Figs. 1 and 2A). Given time-for-space equivalence along the mountain belt due to the obliquity of the Manila trench and the Asian passive continental margin (Suppe, 1981), the deformation related to these fabrics occurred early in the collision and is comparable to the current mountain belt architecture in southern Taiwan. We argue that the formation of these cleavage fronts and the fan structure is a natural consequence of the wedge kinematics and stability of anisotropic fabrics.

ANISOTROPY, RHEOLOGY, AND CLEAVAGE DEVELOPMENT

Donath (1961, 1964) and Patterson and Weiss (1966) showed experimentally that slates or foliated rocks have a strength that depends strongly on orientation of maximum compressive stress, σ_1, relative to the foliation (φ), a value we assume to be approximated by orientation of maximum incremental shortening relative to the foliation (ϑ). The strength as a function of orientation can be defined by a parabolic-shaped function, with high strength when the foliation is perpendicular or parallel to σ_1 and low strength when the material is inclined relative to σ_1 (Fig. 2B). The orientation of the minimum strength is dependent on the friction angle. In experiments at room temperature, the minimum strength occurs at an angle of 30°, but at higher temperature, the deformation is more likely frictionless and the minimum strength occurs at 45° (Mares and Kronenberg, 1993; Kronenberg et al., 1990). Deformation experiments are inherently limited by the apparatus, but the cleaved micaceous slates and phyllites that dominate the core of the Taiwan mountain belt are pervasively deformed, continuous, and compositionally uniform at the scale of a thin section and are thus likely to exhibit this anisotropic behavior.

Cleavage development and subsequent rotation depends on the evolution of its orientation with respect to the principal stresses. When cleavage is oriented at >45° from σ_1, an increment of strain will produce stable rotation of the existing foliation, so the rock retains a single cleavage, although that cleavage may rotate in time as stress orientation changes. When the cleavage is oriented at an angle of <45° to σ_1, an increment of deformation results in buckling instabilities that drive gradients in chemical potential that ultimately lead to crenulation cleavage development (Robin, 1979). A near-instantaneous change in the orientation of the principal stretching directions of 45° or more is observed to be sufficient for development of crenulations in slates (Fisher, 1990), suggesting an angle of internal friction of 0° and $\varphi = 45°$ for the boundary between stable and unstable behavior. Regardless of the complexity of the orientation history or number of discrete deformation events, there will only be one foliation as long as that foliation remains in the field of stable rotation. Only a dramatic change in orientation of the foliation relative to the principal stresses can result in buckling of existing fabrics and overprinting of a new cleavage fabric.

CLEAVAGE FAN FORMATION IN AN OROGENIC WEDGE

A critical orogenic wedge has a stress field that is determined by the topographic gradient of its upper surface and the orientation and strength of its basal décollement. In a cohesionless Coulomb plastic material, the stress field has a constant orientation within the wedge (Dahlen, 1984) and the orientation of the maximum compressive stress, σ_1, forms an angle, ψ, of <45° with the basal décollement (Fig. 2). The stress orientation of the retrowedge is ambiguous, because it may take either a minimum taper or maximum taper solution (Willett et al., 1993), but in either case, the maximum compressive stress must be oriented at an angle of <45° from the décollement. In general, this implies a change in orientation of the principal stress at the divide between prowedge and retrowedge. Following Davis et al. (1983), the change in stress orientation between back-to-back minimum-taper wedges with the same internal and basal friction angles, ϕ and ϕ_b, respectively, but prowedge and retrowedge décollement dips of β_p and β_r, respectively, is:

$$\theta = \frac{\pi}{2} + \beta_p + \beta_r - \sin^{-1}\left(\frac{\sin \phi_b'}{\sin \phi}\right) - \frac{\phi_b'}{2} \quad (1)$$

where the prime denotes an effective value taking into account fluid pressure (Dahlen, 1984). Although there are combinations of parameters for equation 1 that give $\theta = 0$, for typical values (e.g., Wang and Hu, 2006), θ will be close to $\pi/4$, implying a large transition in stress orientation at the wedge divide. Cohesive or viscous materials produce a more complex stress field, and there will be some stress rotation near weak faults and the Earth's surface, but the principle that stress orientation will be nearly uniform within the wedge and forms an acute angle with the décollement is still valid (Buck and Sokoutis, 1994; Willett, 1999).

Consideration of material kinematics through this stress field provides a specific prediction of deformational fabric. Accreted material enters the prowedge and moves progressively toward the retrowedge (Fig. 2A). In the prowedge, cleavage development is initiated with σ_1 plunging gently toward the wedge toe. Material rotations are small and slow, so the fabric remains in the stable field (Fig. 2B). There should thus be a single cleavage in the prowedge that dips into the mountain belt. In contrast, most material in the retrowedge is initially accreted into the prowedge, but is subsequently transported across the divide prior to its deformation and exhumation in the retrowedge. Cleavage developed in the prowedge is likely to be unstable when subjected to this new retrowedge stress orientation. The consequence is a crenulation fabric with a new cleavage dipping into the range interior.

CLEAVAGE PATTERNS AND STRAIN HISTORIES IN TAIWAN

Cleavage patterns can be used to test this wedge kinematic model, particularly when supplemented by incremental strain analysis from syntectonic fibers in pressure shadows (e.g., Fisher and Byrne, 1992; Fisher et al., 2002). Incremental strain histories from the prowedge slate belt have been measured on both the Central and Southern Cross Island Highways (Clark et al., 1993; Clark and Fisher, 1995) (Fig. 2B). Throughout the prowedge slate belt, pressure shadows indicate plane strain with downdip extension and little longitudinal strain parallel to strike. In the Hsüehshan Range, the strain history is coaxial and the final orientation of ε_1 (i.e., σ_3) is near vertical, reflecting the nature of the Hsüehshan Range as an anomalous pop-up structure squeezed between basement highs during the collision of the passive margin with the Luzon volcanic arc (Clark et al., 1993). In the western Central Range, 151 strain histories from 17 samples indicate that the final orientation of incremental elongation relative to cleavage (θ_f) is generally slightly steeper than the slaty cleavage (Clark, 1994; Clark and Fisher, 1995) (i.e., $\theta_f = -5.1° \pm 10°$; method of Durney and Ramsay, 1973). Given moderate cleavage dips to the southeast, the orientation of incremental shortening ($\sim\sigma_1$) plunges 20°–40° toward the foreland, with ϑ = 70°–90°. Syntectonic fibers in pressure shadows indicate noncoaxial deformation consistent with plane strain and a component of simple shear related to northwest-directed thrusting.

This strain pattern is consistent with macroscale structures and associated cleavages. The western Central Range is typified by northwest-vergent folds, with moderately southeast dipping axial planes and northeast-trending fold axes. Folds are tight to isoclinal, and a near-axial planar cleavage dips 30°–60° southeast and is associated with a downdip stretching lineation. The eastern Central Range consists of continental basement and the early Tertiary cover that by necessity passed through the prowedge prior to exhumation in the retrowedge. The basement is represented by multiply deformed metasediments, marbles, and granites interpreted as Eurasian continental basement (Ho, 1988). In contrast with the slate belt and western Central Range, the retrowedge is dominated by a strong northwest-dipping crenulation cleavage and southeast-vergent folds that crosscut the penetrative schistosity. The associated crenulation cleavage front is observed ~10 km southeast of the divide along the Central and Southern Cross-Island Highways (Fig. 1). The crenulation cleavage strengthens to the southeast away from the cleavage front across the eastern Central Range to the boundary with the Longitudinal Valley. South of the Southern Cross-Island Highway, the northwest-dipping crenulation cleavage in Eocene rocks weakens and the southeast-dipping cleavage dominates and is not transposed by the later deformation event. Farther south, Miocene rocks are less strongly cleaved and anisotropic mechanical behavior may no longer apply. Thus, the strain patterns related to anisotropic rheological behavior are restricted to Eocene rocks and basement rocks that exhibit higher temperature deformation. The main schistosity and associated stretching lineation do not change orientation across the basement-cover contact (Fisher, 1999), so the fabric history in the basement is dominated by effects of the arc-continent collision, and not Mesozoic tectonics that preceded development of the Asian passive continental margin.

DISCUSSION

Development of an Orogen-Scale Cleavage Fan

The hypothesis that cleavage in the prowedge forms and remains in a stable orientation with respect to principal stresses is supported by the observation of a single cleavage and absence of a pervasive crenulation cleavage throughout the slate belt and the western Central Range. Buckling of the fabric at the crenulation cleavage front implies that either orientation of the fabric or orientation of the principal stresses rotate instantaneously to produce an unstable relationship between cleavage and σ_1. There is no evidence for changes in orientation of slaty cleavage as the crenulation cleavage front is approached from the prowedge side, but in the doubly vergent wedge model, stresses should change abruptly beneath the divide due to a reversal in topographic slope and basal shear stress.

The variation from southeast-dipping fabric in northwestern Taiwan to northwest-dipping fabric in southeastern Taiwan defines an orogen-scale cleavage fan. We emphasize that fabric that dips to the northwest is a crenulation cleavage axial planar to southeast-vergent meso-scale to macro-scale folds of the slaty cleavage. Given a steady position of the divide in the Central Range, the occurrence of the cleavage front associated with this transposition fabric at ~10 km southeast of the divide along both the Central and Southern Cross Island Highways is consistent with a change of stress orientation as material is advected from the prowedge into the retrowedge. The relationship between the orogen-scale cleavage patterns and this cleavage front is likely to be particularly significant in Taiwan, where the basement rocks are to a large extent composed of schists and phyllites that exhibit strong anisotropy and thus have a distinct transition from stable to unstable behavior.

This mechanism for formation of a cleavage fan is general insofar as orogenic belts are described by wedge mechanics such that stress orientation and regional topographic slope are genetically coupled. Cleavage fans and fronts that are common to many ancient orogenic belts may reflect a similar change in stress beneath a paleodivide. In such a case, the distribution of cleavages and cleavage orientations could define a synorogenic topographic divide that is obscured by postorogenic erosion.

Complications to the simple application of this model arise from a number of sources. Because cleavages reflect finite strain and stress at any instant in time, the relationship between cleavage fronts and topography could be more complicated for a mountain belt that is not in steady state. In a mountain belt where maximum principal stress orientation changes gradually from prowedge to retrowedge or in the case where the change is <45°, prowedge cleavage could rotate stably in response to changing stresses and fanning of a single cleavage would occur. This would still be a distinctive pattern and reflect the stresses associated with topography, but no crenulation cleavage would develop. In most orogenic belts, some material is accreted at the toe of the retrowedge as the orogen overthrusts the upper plate (e.g., accretion of the

Luzon arc; Fig. 1). If deformation associated with this accretion is ductile, the fabric records the retrowedge stress field, resulting in a single cleavage dipping toward the mountain belt interior, again a distinctive fanning cleavage structure, but without a crenulation fabric.

SUMMARY AND CONCLUSIONS

A doubly vergent orogenic wedge has two stress regimes that are distinct in space and reflect the synorogenic topographic gradient of an active mountain belt. Combined with kinematic rock motion defined by crustal accretion and erosion, this model provides a mechanism for the formation of cleavage fronts and regional-scale cleavage fans in ductilely deformed orogenic rocks. Implicit to this mechanism is the fact that a cleavage fabric has a strength anisotropy that implies stable deformation and a single fabric for small rotations of the material relative to the principal stress orientation, but unstable buckling and the formation of a crenulation fabric if the same anisotropic material undergoes a rapid and large change in stress orientation. Advection of a fabric across a topographic divide in a doubly vergent wedge is a mechanism to produce an abrupt change in stress orientation and is an explanation for occurrence of cleavage fronts and fans in natural systems such as Taiwan.

ACKNOWLEDGMENTS

This research was supported by National Science Foundation grants EAR-03-37455 to Fisher and EAR-03-37782 to Willett. We thank S. Carena, D. Wiltschko, and two anonymous reviewers for their constructive comments.

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Manuscript received 17 April 2006
Revised manuscript received 23 August 2006
Manuscript accepted 28 August 2006

Printed in USA