



Mechanics of thrust belts and the weak-fault/strong-crust problem

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Abstract: The mechanics of thrust belts and accretionary wedges ultimately concerns the strength of the basal detachment relative to the internal strength of the overlying deforming wedge. We show that detachments are typically very weak absolutely ($\mu \leq 0.1$ or $\sigma_{\tau} \leq 0.1 \rho g z$) and an order of magnitude weaker than the overlying wedge ($\sigma_1 \approx 1.5$ to $2 \rho g z$), which itself may contain weak thrust ramps. A variety of non-classical mechanisms, including those activated in large earthquakes, may control the strengths of major faults in thrust belts. A likely locus of wedge strength is at fault bends, where bulk rock of the thrust sheets must continually deform.

Keywords: thrust belts, critical-taper wedge mechanics, fault strength, crustal strength, thrust mechanics.

Mechanics of intact thrust sheets

Hubbert and Rubey (1959) treated the problem of mechanics of thrust faulting using the familiar physics-lab friction experiment of pushing a rigid block across a table, showing that if long thin thrust sheets are to be pushed without internal deformation they must be very strong internally relative to their base. They asked the question, “What is the greatest length a thrust sheet can have without breaking up?” The answer is about 20 km for normal laboratory rock strengths and frictions if the block is 5-10 km thick. In contrast, it can be easily shown that the Glarus thrust sheet in the Swiss Alps was at least 80 km long, on the order of 10 km thick and largely intact when it moved. The presently active Hotian thrust sheet in western China is >200 km long, about 5 km thick and is internally essentially undeformed. Therefore, the thrust fault problem can be thought of

as the “strong-crust/weak-fault problem”, which is a central theme of this paper.

Hubbert and Rubey (1959) suggested several compelling solutions to the problem of frictionally weak thrust sheets, one of which has become classic, that of high pore-fluid pressures. They showed that the fault strength or effective friction is reduced by the pore-fluid pressure by a factor $(1-\lambda)$:

$$F = (1-\lambda)\mu \quad (1),$$

where $\lambda = P_f/\rho g z$ is the depth-normalized pore-fluid pressure (fault strength is more generally $F = \sigma_{\tau}/\rho g z$, regardless of the mechanism). Pore fluid pressures on the order of $\lambda = 0.9$ are required to give effective coefficients of friction that are an order of magnitude less than typical laboratory friction measurements of $\mu = 0.85$ (Byerlee, 1978). Hubbert and Rubey showed some bore-

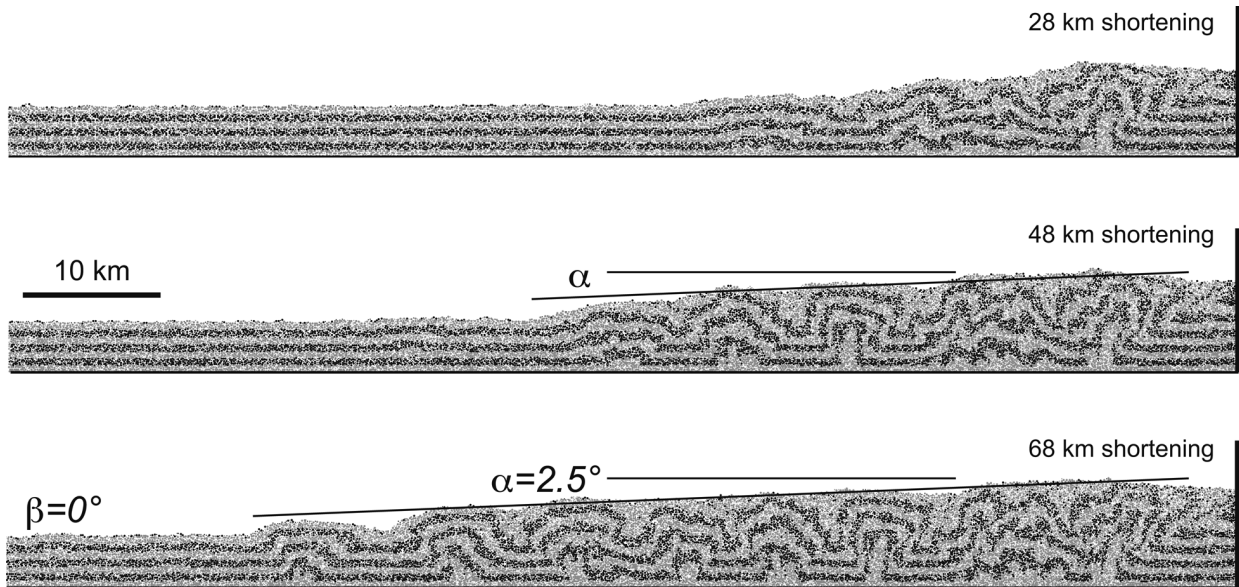


Figure 1. A distinct-element numerical model of a brittle accretionary wedge that is pushed from the right. A region of steady homogeneous taper ($\alpha+\beta$) develops at large deformation, which represents a region of homogeneous wedge and detachment strength.

hole fluid-pressure data from Pakistan with fluid pressures reaching $\lambda \approx 0.9$, making their hypothesis plausible. We will evaluate the viability of this hypothesis by looking at pore-fluid pressures in specific active thrust belts.

Hubbert and Rubey (1959) also suggested that thrust sheets might move by either being pushed or by slid-

ing downhill driven by gravity. In their application to the western United States (Rubey and Hubbert, 1959) they clearly favored gravity sliding as the solution to the thrust fault problem, which is understandable given the unpopularity of tectonic shortening in the United States in the decades before plate tectonics. Nevertheless, gravity sliding and low-angle nor-

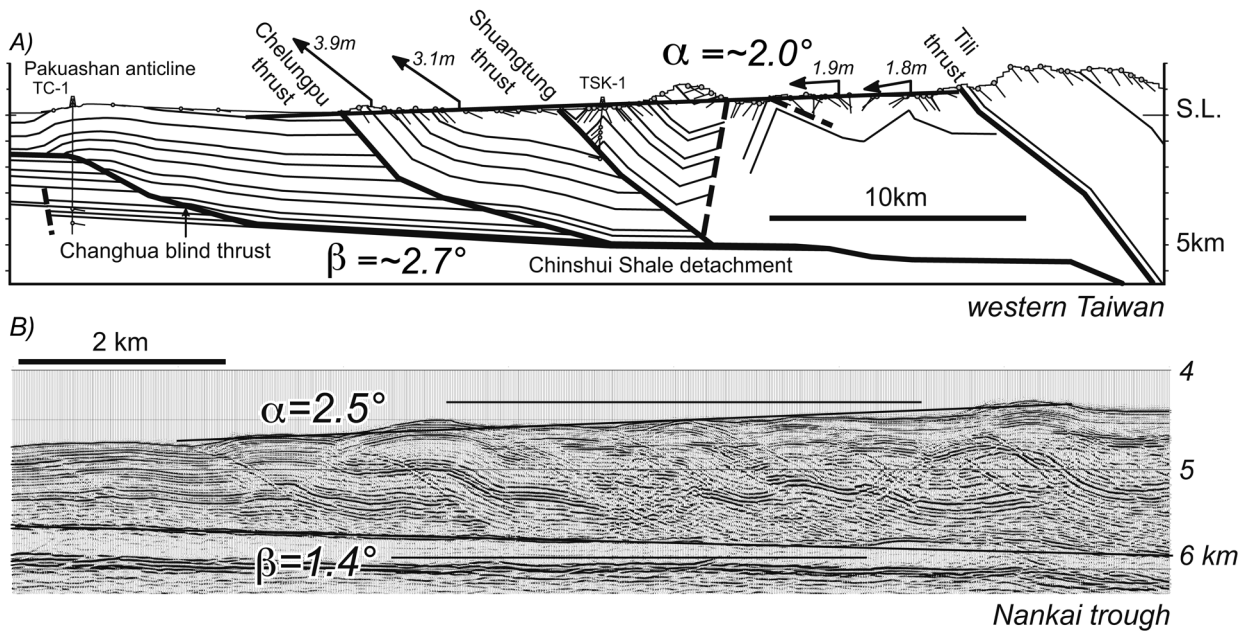


Figure 2. Two active critical-taper wedges: a) western Taiwan with the coseismic displacements from the Chi-Chi earthquake on the Chelungpu thrust (after Yue *et al.*, 2005), and b) the Nankai trough accretionary wedge (Moore *et al.*, 1990).

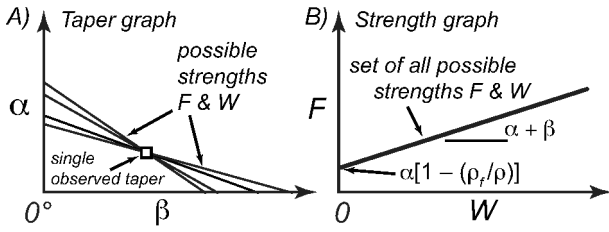


Figure 3. Relationships between a) homogeneous wedge taper ($\alpha + \beta$), and b) wedge and fault strength (W , F). The set of all homogeneous fault and wedge strengths that are consistent with a single homogeneous taper is a line in the strength graph. After Suppe (2007).

mal faulting is the most extreme version of the weak-fault problem, because gravity is the driving stress ($\sigma_1 = \rho g z$) rather than some horizontal compression that will be greater than the gravitational load ($\sigma_1 = W + \rho g z$) by an amount that is equal to the strength of the thrust sheet W :

$$W = (\sigma_1 - \sigma_3) / \rho g z = (1 - \lambda) K \quad (2),$$

where K is the intrinsic crustal strength, analogous to the *earth-pressure coefficient* of soil mechanics. Ignoring cohesion, K is a simple function of angle of internal friction φ , which describes the brittle pressure dependence of the strength $K = 2 \sin \varphi / (1 \pm \sin \varphi)$ in

extension and compression. Both tectonic and gravity-driven solutions to the mechanics of thrust faulting are interesting, because fully developed fold-and-thrust belts are now well known in both plate tectonic mountain belts and in passive margin settings. Their mechanical distinctions, however, are subtle and in need of research (cf. Xiao *et al.*, 1991).

Mechanics of fold-and-thrust belts and accretionary wedges

Modelling the thrust-fault problem as a rigid-block pushed across a table is somewhat misleading because long-thin intact thrust sheets are in fact the exception rather than the rule. Typically, thrust sheets have broken up by thrust imbrication and folding to produce fold-and-thrust belts and accretionary wedges (Figs. 1 and 2). Their mechanics can be described as a critical-taper wedge that is regionally at failure throughout its interior and along its base (Davis *et al.*, 1983; Dahlen, 1990). The taper is described as $\alpha + \beta$ where α is the regional surface slope and β is the dip of the detachment. The wedge deforms until it reaches a critical surface slope that is determined by a combination of the strength of the wedge W and the effective friction on the base F . In the case of a mechanically homogeneous wedge, such as the region of homogeneous taper in figure 1, we have (Suppe, 2007):

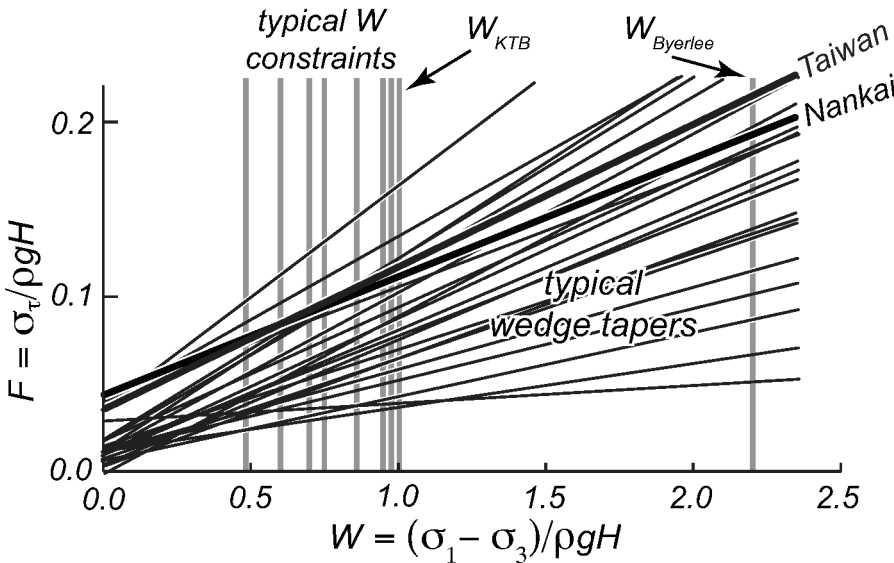


Figure 4. Graph showing the possible homogeneous wedge and fault strengths (W , F) that are consistent with the observed homogeneous tapers ($\alpha + \beta$) for western Taiwan and Nankai trough (Fig. 2) and a number of typical active accretionary wedges. Independent constraints on wedge strength W from Taiwan and elsewhere (Suppe, 2007) suggest that typically $W \leq 1$, indicating that basal detachments are typically very weak $F \leq 0.1$ or $\sigma_\tau \leq 0.1 \rho g z$, and an order of magnitude less than wedge strengths ($\sigma_1 \approx 1.5$ to $2 \rho g z$). For comparison $W_{Byerlee}$ is shown, which is Byerlee's law internal friction ($\mu = 0.85$) with hydrostatic pore-fluid pressure, and W_{KTB} which is stress data to 8 km depth from the German KTB borehole. Data from Flueh *et al.* (1998), Park *et al.* (2002) and compilation of Lallemand *et al.* (1994).

$$\alpha+\beta = \frac{\beta[1-(\rho_f/\rho)]+F}{[1-(\rho_f/\rho)]+W} \quad (3),$$

which contains the ratio of the density of the overlying fluid (air or seawater) to rock, therefore $[1-(\rho_f/\rho)]$ is 1 for thrust belts on land and 0.6 for under water. Equation (3) is a very simple relationship that can be used to constrain wedge and fault strengths (W , F) based on observations of wedge taper ($\alpha+\beta$), as explained by Suppe (2007) using examples from sand-box models, the Niger Delta and Taiwan (Fig. 2a).

In the case in which the observed taper ($\alpha+\beta$) is constant it constrains the set of all possible strength (W , F) to lie along a line (Fig. 3). For example the Taiwan and Nankai trough wedge tapers in figure 2 correspond to two lines in figure 4. If we have independent constraints on the range of possible wedge strengths W , for example from borehole stress measurements, we can constrain the detachment strength F . Observed values of W are typically ≤ 1 , suggesting that the basal detachment is very weak $F \leq 0.1$. Observed tapers from a number of typical growing accretionary wedges give similar results (Fig. 4).

Discussion

The observations summarized in figure 4 indicate strong wedge strength and weak detachments. In the Taiwan case $F = 0.04-0.1$ on both the detachment and the Chelungpu fault ramp that slipped in the 1999 Chi-Chi earthquake, whereas the wedge is strong $W = 0.6-1$ (Suppe, 2007). In this case the observed pore-fluid pressures are entirely hydrostatic, therefore the classic Hubbert-Rubey fluid-pressure hypothesis fails in this case, as well as in the Nankai trough (Fig. 2). This opens up a Pandora's Box of proposed mechanisms of fault weakening, many of which are dynamical processes activated in large earthquakes (e.g. Sone *et al.*, 2007; Sone and Shimamoto, 2008). Given the extreme weakness of major faults, a likely locus of wedge strength is at fault bends, where bulk rock of

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the thrust sheets must continually deform, as shown in figure 5. This deformation typically occurs during large earthquakes on the master fault and involves propagation and slip on small faults within the hinge zone that are both bed-parallel and bed crossing. These faults are too small to undergo the dynamical weakening processes of the large master fault. This sort of coseismic folding occurred during the 1999 Chi-Chi earthquake, causing destruction of buildings and deaths (Chen *et al.*, 2007).

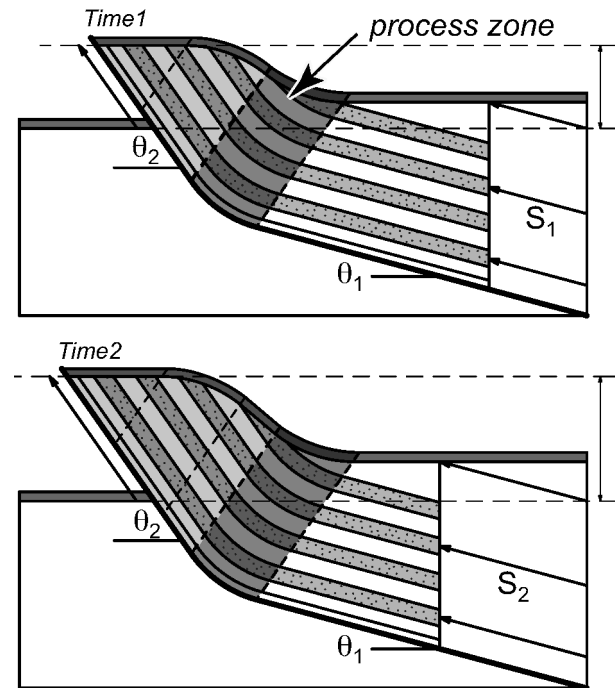


Figure 5. Given the extreme weakness of major faults a likely locus of wedge strength is at fault bends where bulk rock of the thrust sheets must continually deform. This deformation typically occurs during large earthquakes on the master fault and involves propagation and slip on small faults within the hinge zone that are both bed-parallel and bed crossing. These faults are too small to undergo the dynamical weakening processes of the large master fault. This sort of coseismic folding occurred during the 1999 Chi-Chi earthquake, causing destruction of buildings and deaths (Chen *et al.*, 2007).

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