

12.113 Structural Geology
Part 4: Thrust tectonics

Fall 2005

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1 Reading assignment

Chapter 6 in Twiss and Moores is the relevant chapter. Make sure you understand and are familiar (i.e. you could write a caption and label them) with the figures in the chapter. Figures 6.11, 12, 15, and 19 are particularly germane to what you need to take away. Viz.: you should be familiar with the general geometry of thrust faults and their associated folds; the geometry of thrust belts; how that geometry is associated with various tectonic settings.

The material covered in the lab on fold and thrusts is obviously relevant.

2 Jargon

Make sure all these are familiar to you!

autochthonous – allochthonous – klippe – fenster/window – decollement – thick-skinned vs. thin-skinned thrusts – duplexes – vergence – tear faults – fault-propagation folds – fault bend folds – ramps – flats – foreland – hinterland – vergence – nappe – backthrust – admissible cross-section – accretionary prism – admissible and retrodeformable cross-sections.

3 Geometry, general characteristics

A thrust or a reverse fault is a dipping fault whose hanging-wall is translated up-dip. Generally, when the fault dips less than 45° , it's called a thrust fault, steeper faults are called reverse faults. This is not, however, a hard and fast distinction.

Thrusts are commonly low angle faults. According to mechanical models of faulting (where maximum compressive stress is at acute angles to fractures), these are associated with sub-horizontal σ_1 and sub-vertical σ_3 . In particular, thrust faults and thrust belts are associated with convergent margins (subduction zones, collision zones) and tectonic thickening of the crust.

Movement of the hangingwall up and over the footwall material creates the canonical stratigraphic signature of a thrust fault: older rocks are placed above younger rocks, stratigraphy is repeated. (What does this assume?). This characteristic signature of thrust faults is something that can be used to recognize thrust faults even if they have subsequently been folded or reactivated as normal faults.

Listric geometries are common, as are subhorizontal segments linked by short dipping segments. These last are referred to as "flats" and "ramps". Movement of material above ramps and flats requires deformation of the material in the hanging-wall of the thrust, in particular, ramp-flat geometries are associated with characteristic folds in the hangingwalls of thrusts called fault bend folds.

Folds are often associated with "blind" faults. Since a blind fault terminates in the middle of the rock mass, offset along the fault has to be transferred into more distributed (ductile?) strain past the buried fault tip: i.e. folds. Folds form at the tips of blind faults (characteristically, an anticline forms in the hangingwall and a syncline forms in the footwall). More generally, when the slip rate along a fault exceeds the rate that fault tip itself propagates, the fault will be blind for much of its history and fault propagation folds form.

Thrust faults and their folds can commonly occur during sedimentation. Growth stratal patterns then reflect the kinematics and geometry of the growing folds and slip on the thrust faults and permit placing tight time constraints on how the geometries evolved through time. This is exactly analogous to growth strata in extensional environments.

Fold and thrust belts are commonly associated with the deformation of layered sediments (especially passive margins). The sedimentary layering provides a pre-existing mechanical anisotropy along which faults propagate. That is, sedimentary layering provides ideal initial conditions for ramp-flat geometries.

In many fold and thrust belts, thrust faults dip in the same direction and all join together at a low-angle master fault at depth. This is the decollement. Fold and thrust belts where all the deformation occurs in the hangingwall of a shallow (i.e. upper 5 – 10 kms of the crust) decollement are known as a thin-skinned thrust belt. Conversely, thrust faults that penetrate into the middle crust (or deeper?) are called thick-skinned faults. Thin-skinned thrust belts generally occur during the deformation of horizontally layered sedimentary rocks and the deformation does not penetrate into the "basement" to those rocks (eg. crystalline rocks without horizontal mechanical anisotropy). Conversely, thrusts that involve crystalline basement are generally termed thick-skinned.

The decollement separates undeformed material in its footwall from the system of "imbricate" (meaning stacked like shingles) thrust faults that deform and thicken the hangingwall material. The decollement also serves as the fault along which the entire fold and thrust belt is translated towards the undeformed material in front of the fold and thrust belt (the foreland). The general uniformity of fault dip and sense of translation (i.e. material is being translated towards the foreland) leads to the concept of vergence. Vergence is just the name for a structural geometry that suggests or implies a sense of tectonic transport. Dipping thrust faults are said to verge towards the foreland; overturned fold nappes also have vergence (here vergence is

indicated by "the sense of overturn" or the asymmetry of the fold). Not all thrusts in a thrust belt have uniform vergence (i.e. dip): thrust faults that have a vergence opposite to the rest of the faults in the belt are called backthrusts.

A common structural association in thrust belts is duplex structure. At its simplest, a duplex consists of two or more dipping thrusts that are bound above and below by sub-horizontal faults. These are called the floor and roof thrusts. The actual mechanism by which duplexes can form varies, but generally involves (1) an initial ramp flat geometry; (2) breaking of a new ramp fault. If the new ramp fault breaks in front (i.e. towards the direction of transport), then the old ramp is now in the hangingwall of the thrust and is subject to being deformed into hangingwall fault bend anticlines and synclines. If the new fault breaks behind the initial ramp, the initial ramp is now in the footwall of the thrust and is not subsequently deformed.

4 Restoration of balanced cross-sections

Line and area-balancing of cross-sections are techniques that are particularly applicable to fold and thrust belts. Generally, a cross-section is said to be balanced when it is admissible (i.e. it contains no glaring geological impossibilities or inconsistencies) and retro-deformable (it is possible to undo the deformation, moving rocks back to their initial, pre-deformational configuration). Fold and thrust belts are particularly suitable for this because retro-deforming a cross-section assumes that there has been no movement of material in or out of the plane of section. Since fold and thrust belts are often characterized by consistent foreland translation of rock, it is possible to draw a cross-section parallel to this direction of tectonic transport. Moreover, thin-skinned fold and thrust belts are particularly suited to retrodeforming (or restoring) since deformation occurs in the upper 5-20 kilometers of the crust. Therefore most of the deformation is accomplished by faults which are expected to brittle and sharp; folds are likely to be concentric or kink-band folds, with little ductile flow of material from limbs to hinges and so forth.

5 Sandboxes and critical taper theory

5.1

The sandbox experiment performed in class is an attempt to make a scale analog model of thin-skinned fold and thrust belts. The box was constructed of plexiglass, which is rigid and transparent. In this box, layers of sand and coffee were laid down on a sheet of mylar paper resting on an inclined ramp. The starting thickness of the sand was around 4cm, and the ramp was inclined at 4°. To simulate the transport of material in a thrust belt towards the foreland, the mylar sheet was pulled underneath the sediment, translating the "foreland" towards the back wall ("backstop") of the box. Very quickly, a stable wedge of sand was formed. This wedge was two-sided: towards the foreland, the top of the wedge formed a 6° angle. Towards the backstop, an early formed backthrust and backfold made a steeper (25°) angle. This geometry was basically stable: even as more material was incorporated into the wedge by continued pulling on the mylar sheet, the wedge grew, but maintained a reasonably constant angle.

Deviations from a perfect wedge resulted from the top surface being deformed about folds verging towards the foreland. Viewed from the top, at the end of deformation, five or six major structures dominated the top surface. Most of the shortening structures were folds, although these were presumably cored by faults. In one instance, material from the middle layer broke the surface.

The presence of a plexiglass sidewall created some edge effects, in that frictional drag along the wall resulted in less shortening. Another edge effect was the abrupt



Figure 1: Table top fold and thrust belt produced in a sandbox. Wedge was sectioned, revealing a classic thin skinned fold and thrust deformational style, albeit on a smaller scale than, say, the Canadian Rockies.

thinning of the original package of sediment. Numerous tear faults formed were the sediment package thinned laterally.

Most of the deformation was localized in the toe of the wedge: once folds and faults had formed in the back of the wedge, there was little or no continued deformation. Thus, most of the structures were developed "in sequence", with the youngest structures closest to the foreland and vice versa.

We tested the idea that significant erosion can affect the wedge deformation dynamics by removing a large portion of the wedge top material. Upon continued shortening, the original back thrust and back fold was reactivated, presumably in an attempt to restore the original stable wedge geometry.

5.2 What sets the angle of the wedge?

The geometry of a wedge is set by the strength of the material deforming within it, and the frictional resistance of the decollement upon which the wedge forms. In particular, the weaker the decollement, the lower the wedge angle; strong wedge material has the same effect. In a material like sand, these parameters can be captured by the internal friction angles of loose sand and sand on mylar. In thin-skinned fold and thrust belts, rocks presumably deform according to the Mohr-Coulomb criterion so sand is not a horrible choice as an analog material.

5.3 If wedges grow self-similarly, can they grow forever?

This section asks you to take the concept of self-similar wedge growth to an absurd level. If the wedge angle remains at 5° , and the wedge tip remains at sea level, self-similar growth to a 180km long wedge suggests that the top of the wedge be at elevations in excess of 15.5 kilometers. This is three times higher than the highest regions of the Earth today (individual peaks in the Himalaya reach 8km, but the average elevation at the crest of the range is a bit over 5km).

This analysis neglects several important parameters. First, isostatic compensation is neglected. We know that for every 1km of topography, there is a corresponding 6 or 7 kilometers of crust present as a "root", much like most of the volume of an iceberg is below the ocean. So we might expect that isostatic subsidence would take care of most of our 15km high wedge. Second, critical wedge theory assumes constant strength, but we know that the strength of rocks varies considerably with depth. While the increase in strength with depth due to increasing pressure is accounted for by appealing to Mohr-Coulomb rheology, above certain temperatures, rocks deform ductilely and according to viscous or viscous-plastic flow laws. Finally, since we expect that erosion to scale – at least to a first order – with average slope and therefore elevation, the higher we make mountains, we expect erosion rates to increase as well. It could be that geomorphology, and not crustal strength is the real limit for the height of mountains on Earth.

5.4 What is the backstop anyways?

The backstop in the sandbox experiment is probably the most unsatisfying part of the whole set-up. What, in nature, corresponds to a vertical, unyielding wall? Early papers on critically tapered wedges had cartoons showing bulldozers pushing wedges in front of them, but this is surely just trading one suspect metaphor for another.

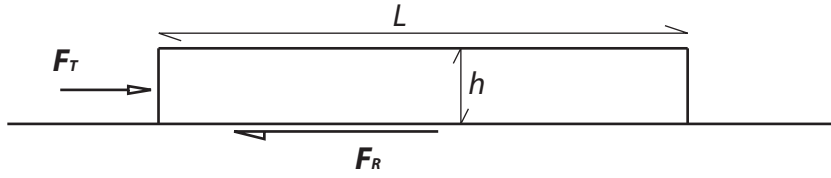
One thing to realize is that the critical taper models and sandbox experiments are meant to simulate or describe fold and thrust belts or accretionary prisms. That is, they are models of a small part of the anatomy of an entire mountain range, in particular, the exterior parts. The backstop then, is just the interior (hinterland) of the mountain range, and all the model requires is that this part of the mountain range consists of thicker crust and higher elevations. How that part of the range became thickened and whether sandbox experiments shed any light into this is beside the point.

Alternatively, smaller ranges might be described as two Coulomb wedges back to back. Along these lines, our experiment yielded a clue as to what the backstop was all about. Recall that the crest of the wedge did not occur at the backstop. Instead, one of the earliest structures was a back thrust / back fold. The wedge we created was a two-sided wedge, one with a gentle foreland dipping angle of about 5° , the other with a hinterland / backstop dipping angle of about 20° . In essence, there were two wedges, backing up against one another. Each wedge forms the backstop to the other. In some experiments, researchers have pulled the underlying mylar sheet through a slit in the middle of the original pile of sediment. What happens is very similar to what happened in our experiment: two wedges form, each making the backstop to the other. A often-cited example of a double-sided mountain belt is the island of Taiwan, which has been described as two thin-skinned wedges verging in opposite directions on either flank of the mountain range.

6 Mechanical paradox of overthrusts

References: Price, R. (1988) The mechanical paradox of large overthrusts, GSA Bull., v. 100: 1898 – 1908.

Washington, P. and R. Price (1990) The mechanical paradox of large overthrusts; alternative interpretation and reply, GSA Bull., v. 102: 529-532.



$$\begin{aligned}\sigma_{xx} &= \frac{F_T}{h} \Rightarrow F_T = \sigma_{xx}h \\ F_R &= \sigma_{yx}L \\ \sigma_{yx} &= \mu\sigma_{yy} = \mu\rho gh \quad (= \tan\phi\rho gh) \\ \text{if } F_R &= F_L \\ \sigma_{xx} &= \frac{\sigma_{yx}L}{h} = \mu\rho gh\end{aligned}$$

Supposing a horizontal tectonic stress of 100MPa, $\mu = 0.038$. In terms of the angle of internal friction, $\phi \sim 2^\circ$. Price (1988) cites a value for μ of 0.577 and $\phi = 30^\circ$ for typical values of rock strength known from rock deformation experiments. Twiss and Moores (page 171, eg.) describe results from the deformation of sandstone samples that yield $\phi = 28.7 \pm 7.4$. In other words, our analysis seems to predict much, much weaker faults than we expect from experimental results.

Supposing we assume a far more reasonable value for $\mu = 0.6$. Then, to initiate sliding along the base of the rigid block, we require $\sigma_{xx} \sim 1.6$ GPa. Twiss and Moores (p. 207) cite 250 MPa as being a maximum value of stress based on the stress required to fracture rock. The actual value will depend on the confining pressure (and hence the height of the block), but 250 MPa is a very permissive number. (TM discuss this problem in terms of the maximum length of block that you can push from behind, using 250MPa as a maximum stress. They get 17km.)

Hubbert and Rubey get around the apparent paradox by appealing to a mechanism that will greatly reduce the effective frictional resistance at the base. In particular, the expression for frictional resistance, modified for pore fluid pressure, becomes:

$$\sigma_{yx} = \mu\sigma_{yy}^* = \mu(1 - \lambda)\rho gh$$

where λ is the pore fluid factor, the ratio between the pore fluid pressure p and the lithostatic pressure ρgh . Even hydrostatic pore fluid pressure (i.e. $p = \rho_w gh$, where ρ_w is the density of water) greatly reduces the frictional resistance along the base of the fault ($\lambda \sim 0.4$). If pore fluid pressures approach lithostatic pressures, then $\lambda \sim 1$ and the frictional resistance approaches zero.

The question then becomes: do we have evidence of such high pore fluid pressures in nature. Certainly, in some environments, very high pore fluid pressures exist. On the other hand, field observations of many faults suggest that this cannot be a general mechanism. In particular, in class, we looked at a few slides of the Keystone Thrust in Nevada where field evidence clearly indicated that the thrust sheet was emplaced over a subaerially exposed erosion surface. The Keystone thrust sheet rode over deposits of stream gravels and unconsolidated alluvial deposits, which are not the sorts of rocks that could sustain near-lithostatic fluid pressures.

Price (1988) suggests that the main problem to the so-called "mechanical paradox of large overthrusts" is that the model description is at fault. That is, its only a paradox to the extent that we buy into a specific mechanical description (a model) of how large thrust sheets are emplaced. Price argues that if we go out and look at real thrust faults, both ancient (such as faults in the Canadian Rockies) and active (such as the great Alaska earthquake of 1964), we would realize that this mechanical

description was entirely inappropriate. Toss out the model and you also get rid of the paradox. (At some level, the existence of the mechanical paradox of thrust faults should have alerted us to the possibility that the model was deeply flawed).

In particular, the mechanical model assumes that thrust sheets move (1) entirely rigidly; (2) are pushed from behind; (3) slip along the base of the thrust sheet occurs simultaneously over the entire fault surface. Price points out that all three assumptions are ruled out by observations of real faults in nature. Thrust sheets are not rigid: deformation – folding and fracturing – occurs throughout the entire thrust sheet and the amount of slip along the fault is variable both along strike and in the direction of motion. More to the point, slip along thrust faults takes place by the addition of many small slip events that affect only a small amount of the fault at any one time. Even in one slip event, rupture does not take place simultaneously, but instead propagates at rates that scale with shear wave velocity. He quotes Oldow: "thrusts did not move simultaneously over the whole of their extent, but partially, first in one part then in another ... the movement would not be like that of a sledge, pushed bodily forward over the ground, but more akin to the crawl of a caterpillar which advances one part of its body at a time, and all parts in succession".

Washington's reply is actually fairly subtle. He doesn't want to rescue the Hubbert and Rubey model, but doesn't like Price's explanation either. In particular, he dismisses Price's explanation that the fact that fault motion occurs non-simultaneously over the whole surface resolves the paradox. This is a subtle point: he doesn't dispute – for example – the observations that Price summarizes from the 1964 Alaska earthquake. He just argues that the fact that slip occurs non-simultaneously makes no difference to the paradox. His claim is that fault slip and earthquakes are simply the release of elastic strain built up along a fault; that at any given time, the built-up elastic strains are such that the pre-failure shear stresses along an active fault are generally at or near the stresses required for failure. He argues, therefore, that the need to explain how the entire fault surface comes to this point of critical balance is essentially the same thing as the Hubbert and Rubey problem of balancing the basal resistance with the tectonic driving stress at the back of the thrust sheet. His solution to the paradox also involves tossing out a basic part of the model, but what he tosses out is the conceptualization that thrust sheets move as tabular bodies being pushed from behind.

Washington appeals to the general wedge geometry of thrust belts. Thrust belts can be translated along the basal decollement because the area of surface across which the driving stresses are applied increase towards the back of the wedge. Individual thrust sheets move along with the entire wedge, so a large part of the motion of any given thrust sheet might be due to drag along the upper surface of the thrust sheet. What Washington seems to be saying, in effect, is that part of the problem is considering a thrust sheet in isolation. Thrust belts consist of series of faults, stacked shingle-like. Thrust sheets move along a fault at their base, but typically also have another thrust bounding the top of the sheet, whose motion may contribute importantly to transmitting the appropriate stresses down to the base of the sheet. (*Note: when I first read this paper, I thought that Washington was simply off-base. Upon re-reading it a few times, I now think that there is a lot more to his argument than I first gave him credit for. I do think that his argument could be re-stated much more clearly.*)

Price's response is two-fold. First, he disputes Washington's assertion that active thrust faults are everywhere near failure (a claim that Washington provided without much in the way of evidence). The point stands: if thrusts do not slip simultaneously along their entire surface, then there is no need to balance a resisting force that is in large part a function of the surface area. It is true, however, that having demolished this model of a thrust sheet, Price fails to explain how stresses are transmitted across thrust sheets, or what the origin of those stresses are. Price resolves the paradox by eliminating the model, but provides no alternative model.

Second, Price takes Washington to task for his appeal to critical wedges as a model that can explain fault motion. Critical wedge models (sandbox models) are idealized as a penetratively deforming mass of material that slip along their base. Price is correct that, apart from the basal decollement, there are no faults in these models. Washington's figure 1 certainly appears a little *ad hoc*, and it's easy to see why Price, a geologist who had spent over 30 years looking at thrust faults in the field, would have nothing but disdain for this totally unrealistic cartoon of a thrust sheet. But what Washington is actually trying to do is show that there is another source of stress driving individual thrust sheets that has to do with their being located in a larger deforming mass (something like a critically tapered wedge). At least he provides some hand-waving in the direction of a model (whose details are, at a minimum, a bit unclear).

7 Review questions

1. How and why are thrust belts associated with crustal thickening and mountain-building?
2. Fig. 6.15 in TM shows a cross-section of a duplex structure from the Canadian Rockies. Is this section balanced? How does balancing a section provide a test of geological interpretation (which most any cross section surely is).
3. Consider two thrust belts that deform identical rocks (i.e. same mechanical properties, eg.), with identical tectonic boundary conditions (i.e. convergence rates of the foreland to the thrust belt are the same). One of these is located such that it receives strong monsoonal precipitation; the other is located in a continental interior in the rain-shadow of a large mountain range and so received very little rain. Speculate how the evolution of the two thrust belts might differ, esp. in terms of the width of the thrust belt, the sequence of thrusting, and other possible differences.