Tilting of rock layers

The shape of the landscape is controlled by the differential weathering of rock units of differing resistance to weathering and the structural geometry of those rock units. In humid climates like eastern north America, fine grained sedimentary strata, such as shale, and carbonate units, such as limestone, are less resistant to weathering and form valleys. In the same climate, coarse grained clastic sedimentary units like sandstone and conglomerate are more resistant to weathering and form the ridges. In arid climates like the desert southwest limestone is resistant to weathering and forms cliffs just as sandstones do. Layered igneous rocks (flows and sills) are generally more resistant than sedimentary rocks because of their low porosity. Flat-lying Strata Sediments are laid down layer upon layer with the oldest on the bottom and the youngest on top. Since sedimentary layers are originally horizontal, in areas where the strata have not been disturbed it would theoretically be possible to find only one sedimentary formation exposed over a wide geographic area. However, streams erode through the younger strata, exposing the lower-lying older strata. In areas of flat-lying (undeformed) strata, the following characteristic landforms are found. dendritic drainage (also found in homogeneous crystalline rocks no structural control of the random headward erosion of a developing drainage network cliff and bench topography is well developed in arid climates cliff formers are resistant layers (sandstone, limestone [arid climate], lava flows & sills bench formers are typically non-resistant shales buttes and mesas are un-eroded remnants of a large scale cliff retreat buttes are taller than they are wide mesas are wider than they are tall In humid climates where bedrock is mantled by thick soil and vegetation there are few cliffs, only in the most resistant strata. We mostly find reversals of curvature of mantled slopes to indicate differences in resistance. Tilted Strata In areas where sedimentary strata have been deformed into folded or otherwise tilted structures, regular patterns of sedimentary rock layers are observed at the earth's surface. Valleys underlain by non-resistant strata like shale lie between ridges upheld by resistant strata like sandstone. Homoclinal ridges formed by the resistant beds are typically asymmetrical (if the strata don't dip too steeply) with a steep scarp slope and a more gentle dip slope. The dip slope lies at or less than the angle of dip of the beds while the scarp slope maintains a steep slope by undermining and mass wasting due to rapid weathering of a less resistant stratum below. Homoclinal ridges are called cuestas where bedding dip is gentle hogbacks where steep (>30-40 degree) An initial dendritic stream pattern will develop into a structurally controlled trellis pattern as streams drain the linear valleys. Folds Anticlines are folds with the sedimentary strata dipping away from the axis of the structure and the oldest strata exposed in the core. Synclines are folds with the sedimentary strata dipping toward the axis of the structure and the youngest strata exposed in the core. Anticlines and synclines show up as long linear parallel ridges and valleys. If the axis of a fold does not remain horizontal for long distances the fold tapers to an apex where the limbs meet, typically in a V-shape. Such features are called plunging anticlines and plunging synclines. Some large-scale folds are circular in outline. Domes are like circular anticlines with the oldest strata exposed in the middle. Basins are like round synclines, with the youngest strata exposed in the core. Anticlines, synclines, domes, and basins are terms that describe the exposure pattern of the sedimentary strata and not the surface topography. For example, the core of an anticline does not necessarily form a ridge and a structural basin is not necessarily a topographic low. The actual topography may be controlled by the symmetric patterns of the exposed strata, but the highs and lows are determined by which sedimentary units are more and which are less resistant to weathering (differential weathering). Faults - Geomorphic Expression and Evidence Fault scarps (escarpments) are common features of faults. However not all scarps are fault scarps. They may also form as a result of erosional processes, for example on steeply-dipping sedimentary strata, or by mass wasting, for example slumping or rock slides along steeply-inclined joints. Fault scarps may be modified by erosion. Streams flowing from hanging valleys on top of a scarp will cut down forming deeply-incised V-shaped valleys (wineglass structure) yielding and cutting the scarp into a series of triangular facets. Faults move in discrete events (earthquakes). So, periodic earthquakes in the vicinity of a major escarpment is good evidence that it is a fault scarp and that it is still actively uplifting. Fault offset in an earthquake may be very small (millimeters or centimeters) in scores of small earthquakes. But if large stresses build up on the fault, periodic large earthquakes can offset a fault up to 5 to 10 meters at a time. Faulted Landforms - Normal Faults Normal faults, which form in crustal extension, are high-angle (~60°) faults where the block lying on top of the steeply-dipping fault surface (the hanging wall block) slides down the fault surface. The other block (the footwall block) rises up because of the reduced weight as the hanging wall block is removed from it. The uplifted block forms a fault-block mountain or mountain range. A fault block mountain is also called a horst. In some areas of broad regional extension, a large number of normal faults cut the crust into a series of sub-parallel fault block mountain ranges with linear basins in between. The downdropped basins are also called grabens. A good example of this kind of faulting is found in the Basin and Range of the western United States. Most of the basins have internal drainage (no through-going streams), so the spring runoff forms playas (lakes) that evaporate in the arid heat. Over many years extensive salt flats form in these evaporating basins. In other extended regions, normal faulting is limited to a narrow belt(s). For example, in the East African Rift system and in the ancient Newark structural basin and other coeval rift basins of eastern North America, half-grabens have subsided and rotated downward along major border faults, single normal faults bounding just one side of the basin. The border faults are curved (listric faults); they are steep at the surface but flatten at depth. This allows the basin to tilt downward toward the fault. Rift lakes lie in the depression near the border fault. African rift lakes include Lake Malawi, Lake Tanganyka, Lake Turkana, and Lake Kivu. Volcanoes also develop in rift systems as the continental crust is thinned. Mt Kilimanjaro is the most famous of the African rift system volcanoes, but many others dot the African landscape, including Nyiragonga which erupted in January, 2002 sending lava flows through the city of Goma (eastern Congo) and into Lake Kivu. As the footwall block rises along the border fault it also tilts because only its free end is rising, yielding a tilted fault-block mountain. Inspection of a physical map of Africa will show that on the western side of the rift in this region of Africa stream drainage is westward, away from the tilted fault-block mountain that borders Lake Kivu and the region to the north and south of it. Streams to the east of the rift flow westward into the half-graben, toward the lakes and toward the border fault. Half-Graben Profile Half-Graben Map Faulted Landforms - Strike-Slip Faults Strike-slip fault are vertical faults that form as a result of shearing stress such as near transform plate boundaries. Offset streams, fences, roads, etc. are clear signs of active fault motion. For example, some streets in the San Francisco Bay area are being offset at a rate of more than an inch per year. The maximum displacement on the San Andreas Fault during the great 1906 earthquake was about 25 feet, which occurred in essentially one sudden motion. March 25, 2019 By Philip S. Prince, Virginia Division of Geology and Mineral Resources Tilted sedimentary layers along the edges of mountain belts offer a good opportunity to visualize geologic movement. One of my earliest recollections as a geology student was a discussion of the upturned sedimentary rocks in The Garden of the Gods at the eastern foot of the Rocky Mountain Front Range in Colorado. I distinctly remember hearing about the vertical movement of a large block of crust, which would ultimately produce the high mountains, tilting the overlying sedimentary layers out of its way as it rose. This basic narrative seems to match up fairly well with the layout of rock types and structures along the Front Range, as seen in the view towards distant Pikes Peak (underlain by rock from greater depth) across The Garden of the Gods (steeply tilted shallow sedimentary layers) below. Image from colorado.com. Upward movement of deeper rock units in the background tilted the fins of orange sandstone in the foreground towards the observer to vertical before they were uncovered and etched out by erosion…they didn’t rise out of the ground looking like this. The high mountains in the background are underlain by continental crustal rock that was once deeper in the earth than the sandstone prior to being tectonically “pushed up.” This post discusses the details of the upward movement of this once deeply buried rock and how it moved the sedimentary layers out of the way. In my mind, I visualized a geologically impossible scenario like the one illustrated in the block diagram below. Vertical movement of a block of crust meant just that to me–vertical movement–and sedimentary layers (tan) were pushed out of the way of the rising block to end up leaning against its edges. Erosion during and after movement etched out the peaks and gorges of the modern landscape, illustrated by the yellow line. The upturned sedimentary layers at the foot of the mountains would thus appear to be backed by a “wall” of deeper rock (the gray stuff) that was pushed upward. Don’t fall in love with this diagram…it can’t work for a variety of reasons. It shows the simplest way to visualize the deep igneous and metamorphic crustal rock (gray) moving upward and pushing the overlying sediment layers at its margins out of the way. Erosion during and after uplift would sculpt the high Rockies out of the gray rock and leave upturned sedimentary stubs at the foot of the mountains. This model puts all the parts in the right places, but big blocks of crust just don’t move in this way. My understanding is that models invoking this type of motion were once put forth for the Front Range, but they cannot be rectified with rock mechanics and various other aspects of tectonic movement as it is understood today, along with details of field observations. A 2019 Google search about Front Range geology will produce numerous newer models using predominately horizontal compression of the crust and angled thrust faults (in red, below) to accomplish upward movement of deep rock and tilting of the overlying sedimentary layers. Development of the “wall” of deep rock behind the upturned sedimentary layers is a bit tougher to visualize in this setup, but the right combination of angled faults makes it possible. Angled thrust faults resulting from compression are a geologically possible way to move big blocks upward and tilt overlying sediment layers. In the case of the Front Range, compression and a component of strike-slip motion are now regarded as the driver for uplift; the strike-slip component is not illustrated here for simplicity. With the right combination and orientation of angled thrust faults, the “wall of rock” geometry and tilted sedimentary layers can still develop. The Garden of the Gods is located has formed within the tilted sedimentary section. This sketch is based largely on Sterne (2006), which is an outstanding read. Focus on the forelimb of the pop-up…I didn’t take the time to re-draw the back limb. The sandbox model below provides a cross-section view of the general idea of the angled thrust diagram. The shallow red and white layers have indeed been pushed out of the way of the “wall” of deeper gray and white material, but this has occurred via movement on angled thrust faults (see the video link a few pictures down). Erosion down to the jagged black line would produce high mountains exposing rock from great depth and a zone of steeply tilted sedimentary layers at the foot of the mountains. Following the “wall” downward, it is easy to see it has been pushed over the green/white layer from left to right and not has not undergone purely vertical motion . Noteworthy is that the “wall” has not continued to push up and over the shallower layers. Instead, they have been able to slide up along the front of the wall and out of its way, compensating for its forward movement without being heavily faulted themselves. The wall itself has been able to rotate forward, tilting the lowest sedimentary layers (green and white) to vertical as well. This independent movement of the upper portion of the section relative to the deeper rock is key to many modern interpretations of structure at the eastern edge of the Front Range. This sand model developed angled thrusts from horizontal compression and produced a geometry like what is interpreted at the eastern foot of the Front Range. Note that “deep rock” means rock that originated at greater depth than the shallowest sedimentary layers. The gray material represents igneous and metamorphic continental crust, or basement; the white layer immediately atop it is the deepest sedimentary unit. The dark black line represents the modern mountainous land surface after long term uplift and erosion; individual peaks are greatly exaggerated for illustrative effect. Compare these two models. Upper sedimentary layers are pushed out of the way of the deeper rock at left, and they are run over by the deeper rock at right. The zone of vertically-tilted layers between the gray material and upper layers doesn’t exist in the model at right. Everything tilts in the direction of thrusting (to the right), and the layers are badly damaged and “smeared” by the overriding thrust sheet. The relative movements of the different layer horizons is not the easiest concept to capture in a still image, but the diagram below, presented by Christine Siddoway of Colorado College, does an excellent job (. This cross section, based on Sterne (2006), effectively communicates the idea of shallow layers (green) sliding up the front of a wedge of deeper rock (blue and pink) along a “roof thrust”. The green layers can thus be tilted all the way to vertical without actually being run over by the blue/pink wedge. They are indeed pushed out of the way as suggested by the faulty first block diagram, but the movement is accommodated on angled fault planes. This beautiful diagram drafted by Christine Siddoway at Colorado College really captures the motion style needed to push the shallow sedimentary layers out of the way of deeper rock moving up on angled thrust faults. Note the physical scale. When comparing this to the sand model above, keep in mind that this diagram shows the modern land surface after prolonged erosion. It should match up reasonably well with what is underneath the jagged black land surface line on the sand model. I think comparison to the “cow catcher” on an old steam locomotive is an odd but potentially useful way to visualize the movement in this diagram. The angled cow catcher wedges under the cow, driving it up the front of the locomotive and (dynamically) pushing it out of the way. This still ends badly for the cow, but presumably leaves it much less messed up than being completely run over! Visualizing an inanimate obstacle on the track may be preferable… The front of the locomotive is the “wall,” and the tilted cow represents upturned sedimentary strata. Seeing this style of motion in a sandbox model is admittedly much more nuanced than a train hitting things, but keep the above visuals in mind and watch for the red and white layers moving independently of deeper layers in the video: In addition to providing a geologic context for iconic landforms, the roof thrust model is a good example of how the right combination and orientation of faults can explain seemingly impossible structural arrangements (Sterne (2006) is highly recommended). The model shown below illustrates how a very unusual geometry is explained using a floor thrust-roof thrust combination. The deeper gray and white material has been thrust up and to the right a considerable distance. The overlying red and white layers don’t show the same movement, but they must have somehow responded to the motion of gray/white. They did so by moving on a roof thrust above the gray/white wedge. The cow catcher perspective works well here; the red and white layers have slid up along the front of gray/white as it moved left to right. Yellow thrust faults are ugly, but black lines are invisible in the wedge zone. As gray/white thrusts towards the right, the red/white layers slide up and in front of it on a roof thrust. The cow catcher is at work again… These sand models have a number of shortcomings, particularly their inability to accommodate for crustal flexure due to the thrust loading. Even so, they do a reasonable job of illustrating the roof thrust concept with some attention to geometry of the overall system. The figure below is from Sterne (2006), and shows just how small the roof thrust system and overall Front Range topography is in terms of subsurface structures. The model displays a comparable overall shape, although the main thrust should continue to greater depth and warp downward due to loading. It is also important to remember that the the rocks seen at the surface today were still buried under kilometers of additional rock when thrust faulting ended; subsequent regional uplift and erosion have “unburied” them to produce the landscape seen today (Pazzaglia and Kelley (1998) is a good read). The large-scale cross section at the top matches the model fairly well. Note that the scale of the basement structures (gray stuff) completely dwarfs the upturned sedimentary zone at the right edge. The cross section offers some suggestion of how much rock has been eroded away in this system to ultimately expose the modern landscape…up to 4 or 5 km along the crest of the Front Range (see Pazzaglia and Kelley (1998) among others). I ran several trials of this model setup and ended up with some results that resemble interpretations presented in Sterne (2006). Note in these sections that both the layers above the roof thrust and the deepest sedimentary units on the “wall” can both produce fins or hogbacks at the foot of the higher mountains. In the sand models, this means that the blue and white layers as well as the lowest red and white layers could both conceivably be producing dramatic topographic fins. Sedimentary layers are tilted vertically. Note in the top cross section that forethrusts have offset an earlier roof thrust. Here, the white layer just above blue as well as the red and white layers could all appear as upturned fins of sedimentary rock in the landscape. In this model, the cow catcher wedge consists of two thrust “slices.” In this model, the heavy black line shows how deeply the model should be eroded to match the Sterne (2006) section above. All of these models used the same setup and produced subtly different results, each of which involves a roof thrust to separate shallow sedimentary layers from deeper crustal rock during movement. Roof thrusts also develop in models using a more “thin-skin” type of setup when glide horizons step upward to produce a ramp anticline. If the forelimb of the anticline tilts and bends sufficiently, the tightening is accommodated by a roof thrust. Collectively, these features can be regarded as “out-of-syncline” thrusts and represent an interesting way to explain how everything fits together in certain thrust systems. This post was originally published on The Geo Model blog.

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