THE EFFECT OF EROSION/SEDIMENTATION ON MOUNTAIN BUILDING: AN EXPLANATION AND DEMONSTRATION OF LAZY MOUNTAINS

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Concepts: Tectonics
Mountain Building
Equilibrium
Work - Energy
Erosion
Disequilibrium – dynamic instability
Feedback mechanism

It is generally accepted that mountain ranges grow in size (length and elevation) at convergent margins toward a characteristic triangular profile (Fig.1). This profile is controlled by a dynamic interaction between forces. This means that changing one force in the system will require all the other forces to vary accordingly to regain equilibrium. Because there are relations between a force applied to a body and the way in which this body deforms, altering the forces will change the shape of the mountains as they grow to a new equilibrium.

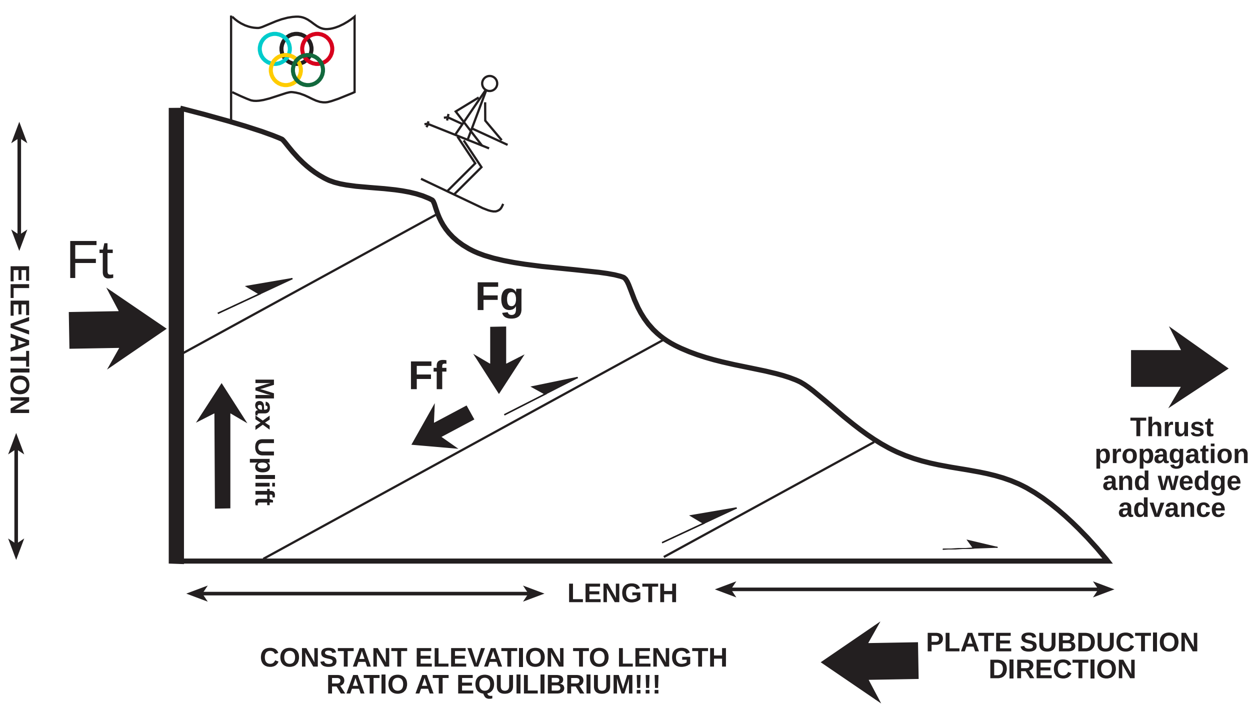

Figure 1

FORCES AND WORK

There are three main tectonic forces that govern the equilibrium of a growing mountain range (Fig. 2). These are:

TECTONIC FORCE (Ft) – It results from two plates converging/colliding one against the other. The convergence is responsible for large compressional forces that break the crust into large blocks bounded by thrust faults, which progressively pile up to build the mountain range. We will call this a positive force, as it favors the building process.

GRAVITATIONAL FORCE (Fg) – Mountain ranges, as any other body on the Earth surface, is subjected to gravity. This force is oriented vertically (Fig.2). As the mountain range grows under the effect of tectonic forces, greater and greater gravitational forces act within the mountain. As the mountain grows taller, it becomes more and more difficult to build it higher, as the mountain needs to be 'lifted' against the force of gravity. We will call gravity a negative force, as it works against the building process.

FRICTIONAL FORCE (Ff) – This force acts on the thrust faults between crustal blocks sliding over each other within the mountain. It is related to the gravitational force, being the product of the gravitational force times the friction on the sliding surface.

Frictional force = gravitational force * friction

The friction is a characteristic property of the material sliding and the conditions existing at the surface itself. If the surface is smooth it will have lower friction and be easy to slide than if the surface is rough. If the surfaces are being tightly squeezed together, such as by great gravitational forces, they will be more difficult to slide than if they are loosely squeezed. The frictional force is important at shallow levels in the crust (within the upper fifteen kilometers), where rocks break forming discrete faults. At deeper levels, where the pressure and temperature become higher, rocks tend to "flow", albeit very slowly, when subjected to forces. Other parameters are necessary to describe the rheology of rocks at those depths. As with the gravitational one, the frictional force is negative.

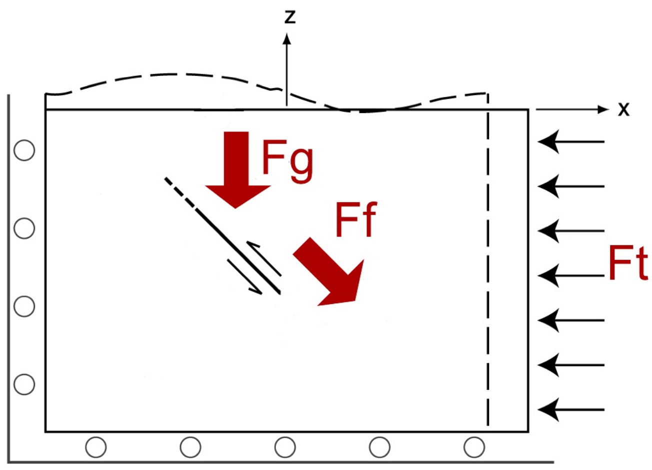

Figure 2

Another concept which is worth introducing at this point is that of work, which is a manifestation of energy (Fig. 3). When you add energy to a system it may move, the work done is the product of the force on the body and the displacement/deformation of the body.

Work = Force * movement

Any body can persist in a moving/deforming stage provided that energy is continuously fed into the system. As much as a mountain climber needs to eat to keep climbing, a mountain range needs energy to keep growing. The plate motion creates tectonic forces responsible for regenerating the energy a mountain range needs to grow. Meanwhile, work is consumed as the mountains grow higher against the force of gravity- the mountains tries to go up, but the gravity pulls it back down. Work is also consumed by work against friction forces as faults slip. If you rub your hands together quickly, they will become warm. Similarly as faults slip the sides become warm and the energy of mountain building is transferred to heat energy.

Positive work = Negative work

Tectonic work (Wt) = work against gravity (Wg) + work against friction (Wf)

Note that Wg and Wf act against the force of gravity (Fg) and friction (Ff). For this reason the work arrows in Figure 3 point in opposite directions as the force arrows in Figure 2.

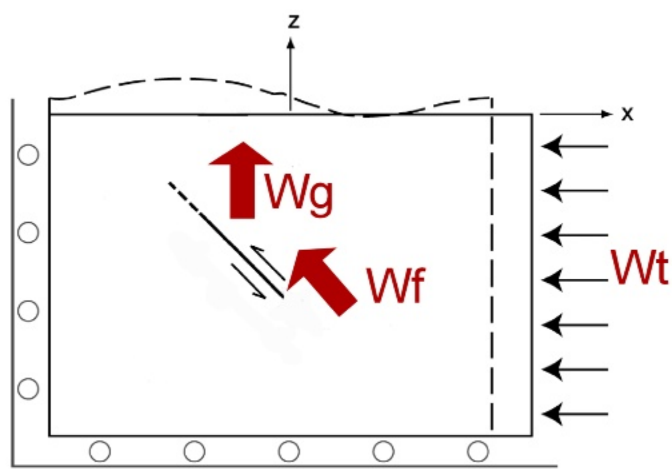

Figure 3

The question is: if you were a mountain climber would you plan ahead the easiest route to the top or would you climb up and down and all around randomly walking until you found the top? Remember that this would affect the amount and weight of food you need to store in your backpack. The answer is simple: you definitely want to reduce the energy you use to avoid carrying too much weight. A mountain range behaves exactly the same. This means that it “chooses” where to deform, what faults to activate, what deformation processes it needs in order to minimize the work required to accommodate the tectonic force. In other words, mountains are lazy.

The theory of work minimization predicts that the interaction between these three forces (tectonic, gravity and friction) will provide a critical mountain length to height aspect ratio that characterizes the mountain range at equilibrium. At equilibrium… that is the magic word! The concept of equilibrium is necessary to scientists to tackle such complicated problems, but of course it constitutes an approximation. The number of variables that must be taken into account is so large that the equilibrium of a deforming mountain range can be altered in many ways.

EROSION

Erosion can be a very effective tool to knock the system out of equilibrium so that the system changes. We call this a dynamic instability. For example, over millions of years, erosional processes will have the time to remove rocks as the mountains grow, thus altering its gravitational and frictional balance. Of course, neither the tectonic forces growing the mountains are constant over time nor it is granted that erosional processes are fast enough to remove sufficient material in order to destabilize such a large deforming body (the growing mountain). All this is the subject of a great effort by researchers belonging to many disciplines of the geosciences, who try to reconcile the geological record offered by rocks in the real world (the clue is always hidden by a several million years lasting history!) with both numerical and physical models which are becoming more and more refined interpreting tools (the clue is hidden by the yet inadequacy of the boundary conditions and equations available to the researchers!). This subject of research is called dynamic mountain building.

Erosion is a continuous process that shapes the Earth surface. Water, either in its liquid or solid state (rivers and glaciers, respectively) constantly moves downhill towards the oceans, which is defined as the base level. In doing so, the flowing water must attain an equilibrium profile, i.e. a steady-state upward concave profile (Figure 4) that results from interplay of erosion and sedimentation. The rivers profile is controlled by many factors. Tectonic uplift is one of these. As the mountains grow, they constantly uplift the rivers bottoms, increasing the vertical distance between the flowing water and the base level. This provides the river with further energy to invigorate the erosional process (Fig. 4).

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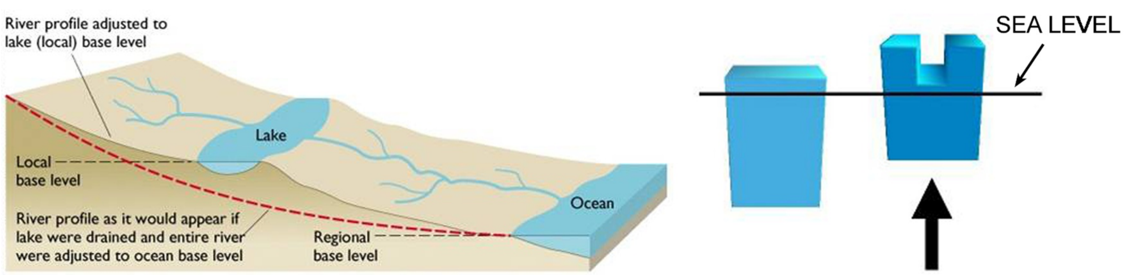

Figure 4

The river profile is composed of many segments moving from the mountains to the sea. Within the mountain range, where slopes are steeper, water flows faster. As a consequence, rivers are usually very powerful (Fig. 5, A) and are able to effectively erode the rock substratum. As the water flows towards lower segments of the river course that are less steep, it slows down. The transported rocks eroded from upstream are re-deposited where the slope becomes gentle enough for the river to loose its transport capacity. As a consequence, the sediment load is dropped at the rivers' mouth (this segment of the river is called delta). In this way the river itself builds its own bottom and extends seaward, by a process that geologists call river progradation into the ocean. Depending on the river size and the extent of the drainage area, the deltas can be of variable size. Sometimes they are very large, as is the case of the Mississippi river delta in the United States, the Nile and Niger rivers in Africa or the Indus river in India. This last one rises in the Himalaya region and erodes this mountain range. It flows towards the South and it releases its entire sediment load in the Indian ocean, building a very large delta at its mouth (Fig. 5, B).

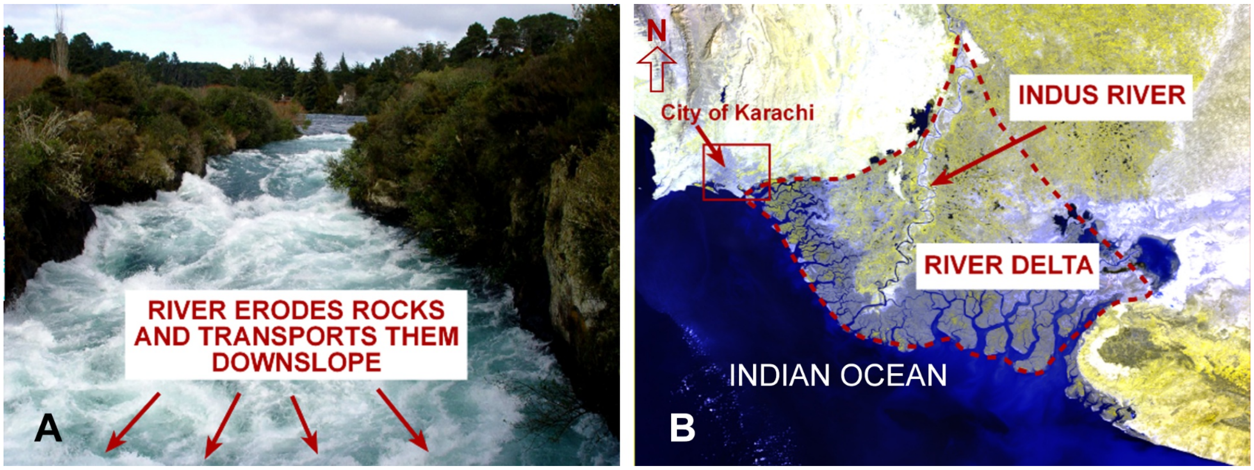

Figure 5

The delta is several tens of thousands Km^2 large at the surface (as a reference, the city of Karachi in the box on the left is of the order of 1300 Km^2) and it covers an even larger surface below the sea table. The maximum thickness of the sediments has been evaluated in the order of 5 Kms. This gives the idea of the incredibly large rock mass that has been eroded away from the Himalaya and transported in the ocean. The same is true for the Mississippi which has for millions of years carried sediments from the Rocky Mountains and Appalachians Mountains.

Glaciers behave much the same way. They flow slowly down mountain slopes (Fig. 6).

Figure 6

As this time it is ice that flows and not water, glaciers are capable of transporting large quantities of rocks even if they move very slowly. The way a glacier flows, erodes and transports is indicated in figure 7. At higher elevation, the glacier is continuously renovated where new snow accumulates and freezes. From the area of accumulation, the ice flow down slope. Because of this movement, friction grows between the ice and the rock substratum, both at the glacier bottom and flanks. Chunks of rocks are torn off and become mixed with the moving ice and are transported away. At the same time, on the flanks of the glacier, rock falls from the surrounding mountain slope accumulate large quantities of debris on the glacier top that can be too transported away from the mountain highest elevations (we call these moraines)

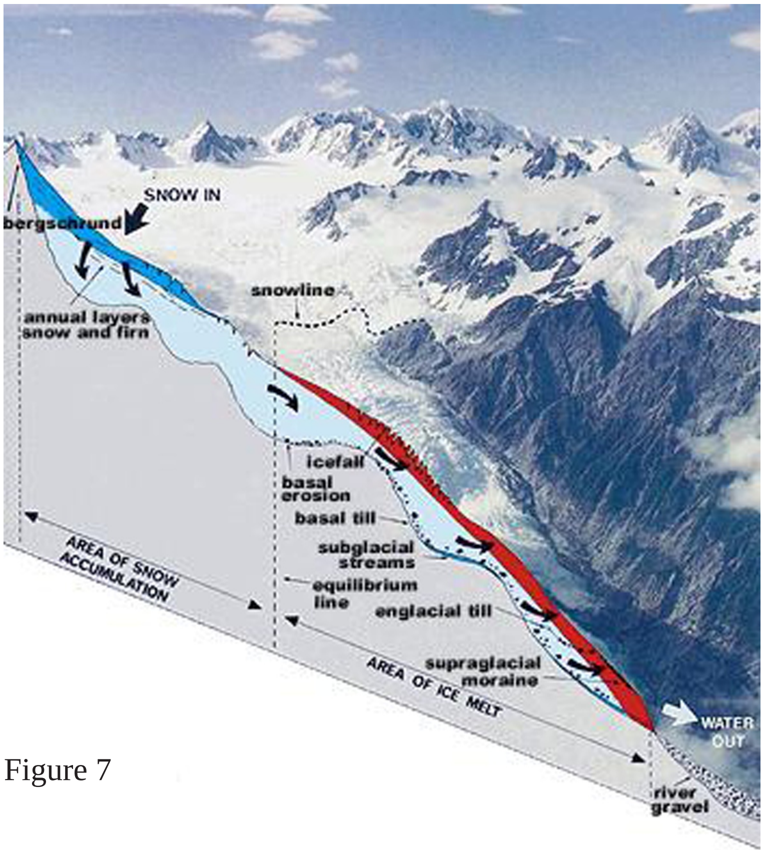

Figure 7

It may seem strange that ice flows, but that is what happens everyday. The movement is so slow that we are not capable of perceiving it by the naked eye, but it does leave some traces. Glaciers flow is particularly evident when they are observed from aerial photographs. The flow lines can be easily reconstructed by the mixing of ice (whitish) and moraines (Fig. 8, A). At the same time, they also leave traces of their past existence at those locations where old glaciers have been completely melted. Because of their motion and rock off scraping, glaciers produce some characteristic structures, like grooves and striae (Fig. 8, B), that geologists use to both locate ancient ice covering the Earth surface and the direction of flow.

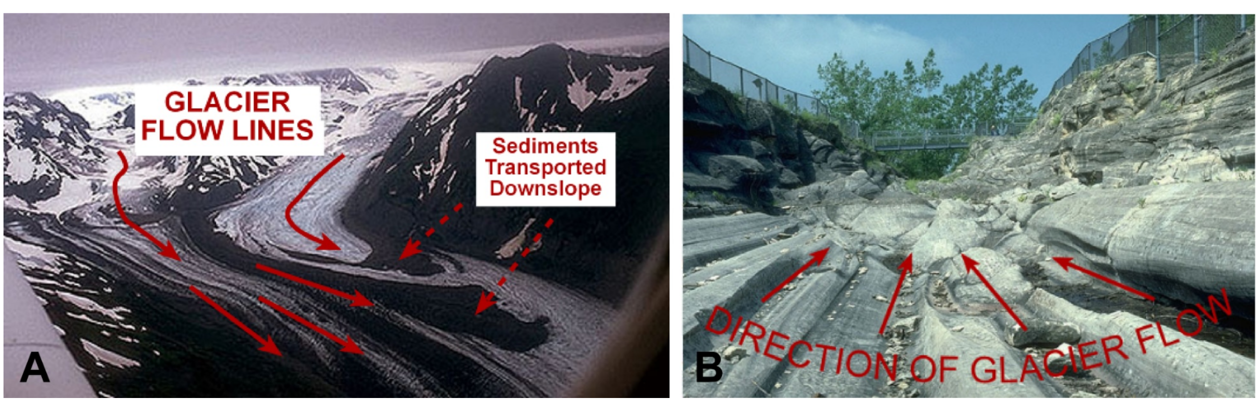

Figure 8

INTERPLAY OF EROSION AND MOUNTAIN BUILDING

So far, we have described some erosional mechanisms that reshape the Earth surface. What should be now clear is that erosion is responsible from taking rocks from one place and bringing them somewhere else. The way erosion interacts with mountain building is intuitively simple. It redistributes mass across the mountain range as it is deforming. Erosion competes against the tectonic processes. As higher topography is created by continuous stacking of crustal blocks, rivers and glaciers are at the same time eroding and removing rocks from the highest elevations of the mountain range and transporting them towards lower elevations where they are deposited again.

The rock removal process means that the weight of the mountain range is decreased. Given that the gravitational force and indirectly the frictional force are dependant on the weight, erosion is decreasing their negative effect, thus it is favoring again the mountain growth. We will say that erosion causes a positive feedback on the mountain building process. In other words, if we erode and reduce the gravitational and frictional forces, there will be less work required by the mountain range to grow by reactivating old faults and/or create new faults. Conversely, a negative feedback will occur where all the eroded material is re-deposited again, because weight there will be added and the tectonic forces are resisted. Therefore, re-sedimentation increases the negative effect of gravity and friction.

As a consequence of erosion and deposition the length to height aspect ratio will change from the critical value measured for the non-eroding mountain range, because the balance of forces is not in equilibrium. The mountain range will adjust to the renewed conditions trying to regain its equilibrium once again.

These concepts are more easily understood if described in two dimensions, i.e. on any vertical cross section cut perpendicular to a mountain range strike. However, the aforementioned reasoning holds true also when the mountain range is analyzed in its entirety. Erosion is seldom uniform across the mountain range. How a river drainage distributes sediments and where it concentrates, or how a glacier grows and where it flows are dynamic processes themselves. As a consequence, there will be sectors that might undergo more erosion compared to others. Similarly, the re-sedimentation processes might transport the eroded rocks great distances parallel to the mountain range. This gives way to a combination of scenarios that is difficult to predict. The result is always the same: the mountain range is always striving to attain its equilibrium. How does it achieve that? This subject of research is called Dynamic Mountain Building and it will be the goal of your next series of experiments!

POSSIBLE EXPERIMENTS TO BE PERFORMED BY THE STUDENTS

Depending on the time available for lab work, the students might do the following series of experiments. For experiments simulating both erosion and deposition of the sand wedge, no special equipment is needed. If you want to investigate erosion only (no deposition) or you want to be extra careful about the erosion, all you need is a vacuum cleaner or dust buster. Care must be taken to do this as the sand is very light and the vacuum can suck a large amount of it. Before running an experiment, the students can practice with a mound of sand in order to optimize the distance between the vacuum hose and the sand surface. This will help them slowly removing the right amount of sand during a real experiment.

CROSS-SECTION VIEW

1) No erosion (Fig. 9): An initial standard experiment without erosion is recommended. The kinematics of the wedge observed during this experiment can be compared to that of the wedges affected by erosion. Students can measure and document the critical ratio of edge length (measured across the wedge in the cross-section) to wedge height (measured as the wedge top to the starting uniform height of the sand layer).

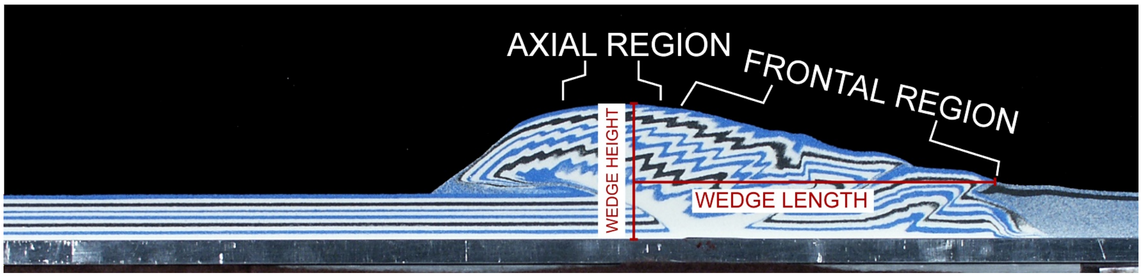

Figure 9

2) Erosion of the wedge axial region (Fig. 10) – In this experiment students will 1) grow a wedge, then 2) erode the top of the wedge and then 3) continue with contraction to see how erosion influences subsequent wedge deformation. To make sure that you have enough room for two episodes of contraction, start with the moveable wall far back within the sandbox (crank arm sticking out far). Also limit initial sand thickness to 3cm of sand so that the wedge develops quickly. Have students document the deformation during the first stage by measuring the growing wedge height and width and making sketches (every 20 turns or so). The measurements should be similar to that of no erosion at this point. You can also set up the sandbox so that half the sandbox remains 'normal' for the whole experiment while the other half will be eroded. When a nice wedge is developed but you still have lots of room for the second stage of contraction you are ready to erode.

You will see the greatest erosional effect if you erode the wedge and deposit the sediments in front of the wedge at the same time. This is sketched in the figure below with half the box remaining in normal conditions. For this set up, you can just sweep sand with your hand or a trowel from the wedge to the region in front of the wedge. If the new slope from the top of the wedge to the new toe of the wedge is constant then you have eroded maximum erosion at the top of the wedge and maximum deposition at the toe of the old wedge – just like nature. Make sure that the newly eroded and deposited areas are smooth so that the new faults show up clearly when they disrupt the surface. We brushed ours with a straight edge.
Students should document the length and height of the wedge upon continued contraction (every 10 turns or so). Students can also make sketches to document how and where faulting is happening. Are the new faults developing the same places within the eroded wedge as within the normal wedge? We recommend using red pencil to show active faults in each sketch and blue for faults that aren't slipping at the time of the sketch. The erosion and deposition has decreased the ratio of wedge height to width. The wedge system responds to this by growing in height in order to return to the equilibrium ratio. How does it grow?

By faulting! Upon resumed contraction, you should see faults now develop not in front of the wedge as with the normal experiments, but within the old wedge as this wedge tries to grow taller to reach equilibrium. Essentially, the erosion has lowered the work done against gravity by faulting in the wedge. Meanwhile deposition in front of the wedge has increased work against friction along the frontal thrust. The weight of the added sand on top of the fontal thrust pushes down on the thrust and prevents it from slipping. Under such conditions, it is easier for the wedge to accommodate contraction by slipping along old faults back within with wedge than along the frontal thrust. The weight of overlying sand on the old faults is reduced and weight on the new faults is increased. At all times the wedge is lazy and wants to grow along the easiest path.

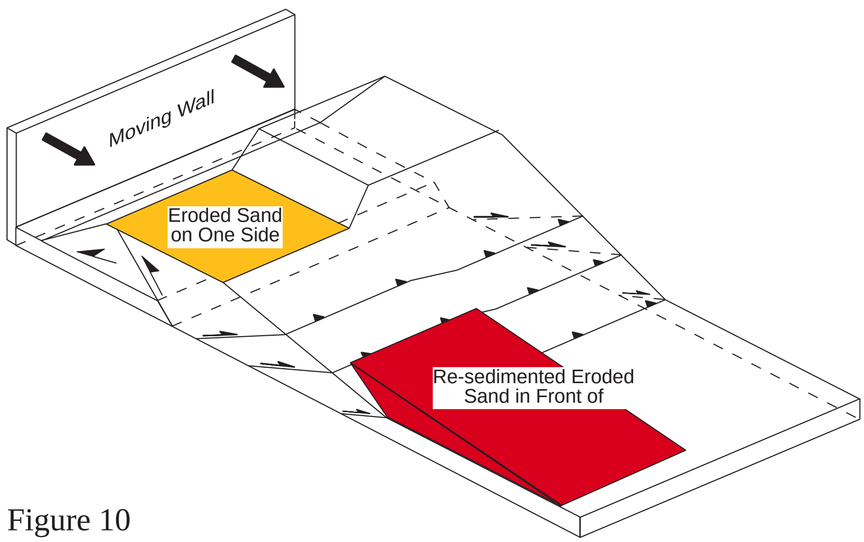

Figure 10

3) Erosion of the wedge axial region (Fig. 11). If you have a vacuum then you can do some fancy experiments where you only erode parts of the wedge.. Denudation (erosion) is performed on the top of the wedge in the early stages of deformation. The axial region is forced into a horizontal surface throughout the wedge deformation history (Fig. 10). Upon continued contraction, the students can sketch and measure changes to the wedge profile every 10 turns or so. How does the height and length change compared to the overall wedge profile of the basic-setup (non-erosional) experiment? How does it change from the experiment with erosion and deposition? Students can also make observations on how and where faulting is happening. Are the new faults developing the same places within the eroded wedge as within the normal wedge?

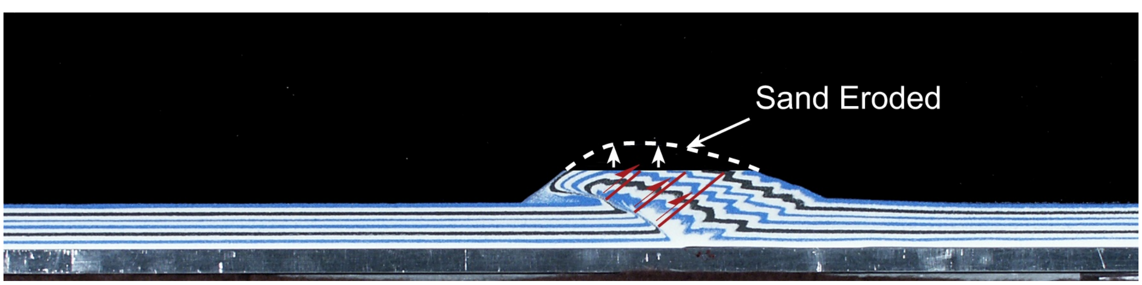

Figure 11

4) Erosion of the wedge frontal region (Fig. 12) – After the wedge attains a mature stage, the angle of the frontal slope can be decreased of a few degrees by vacuuming off some sand. !!Note that by lowering the slope of the frontal region, the axial region may be eroded too!! The students should be able to see that the wedge stops deforming at its front (frontal accretion stops) and reactivates inner thrusts, which were previously abandoned (out-of-sequence thrusting). In-sequence thrusting is when the newest faults form at the front of the wedge.

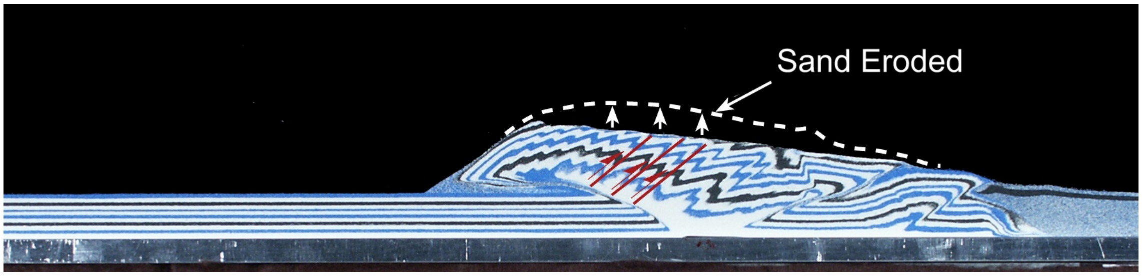

Figure 12

!!The students could draw on an acetate sheet a triangle with the desired lower angle of the frontal region slope. This can be attached on the Plexiglas wall to be used as a reference during erosion!!

OVERHEAD VIEW

3) Localized erosion (Fig. 13, A) – In this case, students will test the effect of variation of erosion rates along the strike of the mountain range. During the experiment, only one half of the model axial region will be affected by erosion. Students can observe how the wedge behaves when different growth rates are distributed along strike. Some parts of the mountain range will advance more than others leaving a curved mountain front.

5) Coupled Localized erosion and sedimentation (Fig. 13, B) – The experiment will reproduce a complete case, where localized erosion on one side of the axial region of the wedge (as in the previous one) is accompanied by sedimentation at the front of the deforming wedge, but on the opposite side. Figure 12 shows experiments performed in conditions of oblique convergence (my PhD work). They are slightly different from the ones student will perform, which are supposed to be run under orthogonal convergence. However, they are useful to see how localized erosion and sedimentation can be applied.

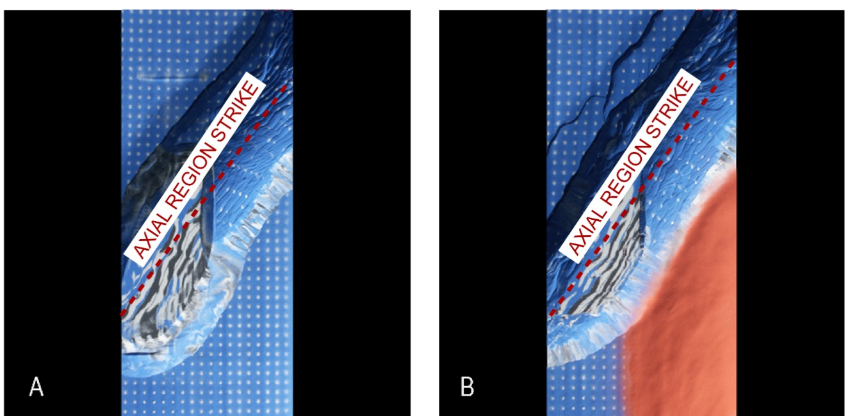

Figure 13

In the following 3D sketch, you can see how you can remove sand from one side of the wedge axial region (yellow colored sector) and redeposit it (red colored sector) at the front of the deforming wedge. You choose to redeposit it just in front of the eroded sector (Fig. 14) or on the opposite side (Fig. 15). If you'll do both the experiments, you can compare the results and evaluate the differences in the pattern of deformation. You do not need to move the same amounts of sand from one sector of the wedge to the other (you could do it, but you need high precision balance). Feel free to remove as much sand as you want from the axial region and add as much as you want at the front.

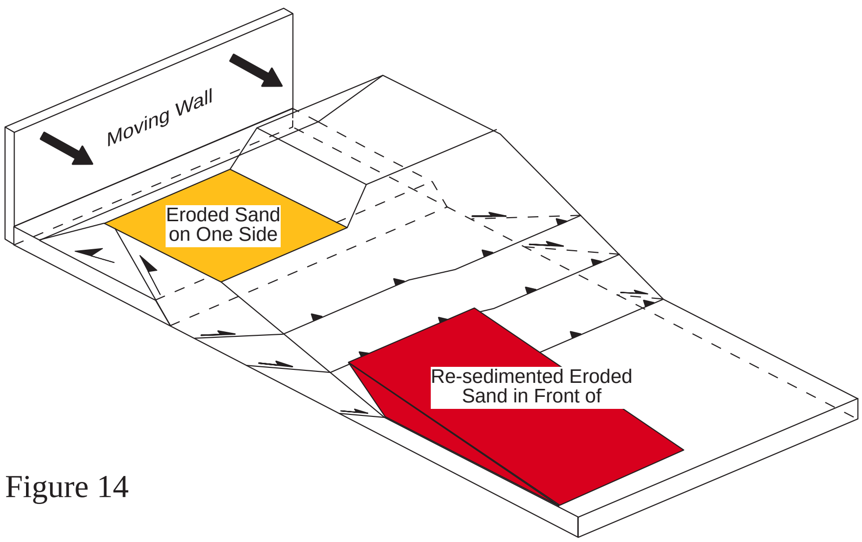

Figure 14

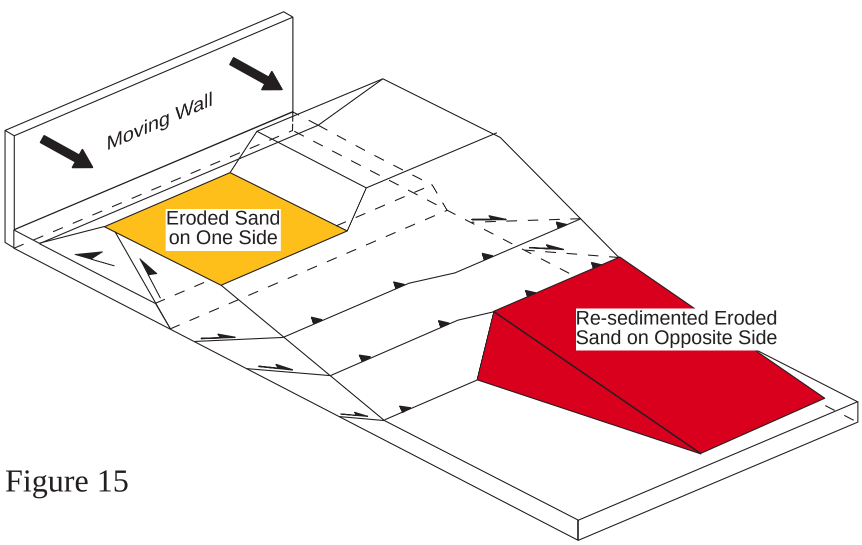

Figure 15