An Analysis of Thrust Faults

University Undergraduate Fellows Program

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April 30, 1976

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Abstract

Part I. Through a literature search on the mechanics of thrust faulting, I have found that reduction of the effective downward stress component of the overburden pressure due to abnormal fluid pressures in the subsurface is the key theory in the geologist's current explanation of the mechanics of thrust faulting. I have found five possible mechanisms for developing abnormal pore pressure in the subsurface. The five theories are: (1) location of outcrop of formation up dip at a higher elevation than the surface where well was drilled; (2) rapid compaction and depositon; (3) tectonic compression of a water-saturated shale or clay; (4) Clay dehydration (Powers, 1967), a process in which montmorillonite is changed to illite releasing chemically bound water; and (5) Aquathermal pressuring, (Barker, 1972), a process in which an isolated volume of water-filled sediments is subjected to increased temperature. The expansion of the pore fluids due to increased temperature is greater than the expansion of the minerals of the rock, and this effectively generates an excess pressure.

I propose that clay dehydration and aquathermal pres-

suring are two steps involved in the sequence of deposition of sediments and the generation of abnormal pore pressure. After normal compaction of the shales occurs, at a depth of 6000 to 7000 feet, the montmorillonitic clays begin to dehydrate. With the effective permeability being very, very low, the release of this bound water is confined to this shale zone. After more subsidence and deposition of the basin, the temperature increases with depth. Normally the increased temperature would not generate an excess pressure, because some of the water could easily bleed off. But within this confined shale zone, the low permeability will not allow the pressure to equalize; rather it builds up due to expansion beyond that which is expected under a normal hydrostatic gradient.

I am of the opinion that the conditions of excess fluid pressure are present in a basin of deposition long before any tectonic event takes place. The pressures generated by aquathermal pressuring can produce pore-pressure to overburden-pressure ratios of 0.8 or 0.9 under ordinary geological conditions. Clay dehydration and aquathermal pressuring are two consecutive steps in the development of abnormal pore pressures capable of facilitating the development of large thrust faults.

Part II. My contribution to the pool of knowledge in the field of experimental tectonics is of a negative sort. The method I used to develop thrust faults needs some refinement. I attempted to model thrust faults using a horizontal-compression device and ordinary pottery clay, by trying to scale down the physical properties and dimensions of a large region, and treating the rock layers as a plastic, viscous sediment package. The variables that it was necessary to control in the device to generate different structural forms were: (1) the stiffness of the clay, (2) the thickness of each clay layer, (3) the plasticity of different clays, (4) the thickness of the total layered package, (5) the rate of deformation , and (6) the length-to-thickness ratios in general.

Control of the behavior of the variables was hard to achieve, and quantification of the variables was equally difficult. To be able to quantify the variables should result in a better reproducibility of results. Developing a way to control and evaluate the behavior of any variation in the physical properties is necessary so that one can see in what direction to proceed. A considerable time factor must be allotted to thoroughly investigate the physical and behavioral characteristics of the clay itself.

Other materials might be used in place of pottery clay such as soap, soft paraffin, or lard. Again the nature of the behavior of these materials must be investigated thoroughly before a complete understanding of how to relate the results to geology can be developed. The use of viscous, flexible materials rather than brittle materials for the experiment produces a much more realistic picture of how the rock layers behave on the surface of the earth.

Part I

Mechanics of Thrust Faulting

Introduction

Thrust faults are definitely among the geologic features that are most mechanically difficult to explain. " Overthrusts are spectacular geological features along which large masses of rock are displaced great distances. An overthrust may be defined as a thrust fault with an initial dip of ten degrees or less and a net slip measured in miles," (Hubbert and Rubey, 1959, p. 119). Thrust faults indicate a shortening of the rock layers in a zone of orogenic activity. One may recognize them in the field as repetitions of the sequence of rock layers either laterally or vertically. They are not new features to geologists, rather the structural and stratigraphic relationships of thrust-faulted areas have been investigated and described for 100 years. While the descriptive aspects are comparatively well known, the mechanics involved in generating such large features are still not completely understood. I have investigated the theories that have been proposed to explain the mechanics of overthrusting and the development of abnormal pore pressures. Abnormal pore pressure is believed to be necessary for the development of thrust faults.

The immense size of thrust faults is indicated by the following dimensions: the thrust faults in the Scottish Highland thrust belt have lateral displacements of over 80 miles; in the Canadian Rockies the minimum lateral displacement for one thrust sheet is over 8 miles; a twenty-mile displacement is found on the Lewis overthrust along the international border between Canada and the United States; in Nevada, the Muddy Mountain overthrust has displaced a 25,000-foot thick section of rock fifteen miles. How can a block of rock two or three miles thick and hundreds of square miles in area move a horizontal distance of tens of miles without crushing the rock itself?

Early Theories

Hubbert and Rubey (1959, p. 122) developed the following ideas of the mechanics of thrust faulting: " The mechanical paradox of thrust faulting resulted in visualizing two distinct methods for sliding one plate over the other corresponding to the use of surface forces or body forces." Using surface forces involves shoving the block from the rear, whereas utilizing body forces involves gravity acting on the whole rock mass to generate motion down a slope. To understand the strength of the rock in relation to its size and the energy required to slide it, visualize a large wet noodle that is moved by pushing on one end of it. The noodle will most likely fold at the end near the applied force before it will move. Contrarily, most thrust-fault blocks show little or no internal deformation.

The idea of using a push from the rear of a thrust block was early refuted purely on the basis of the strength characteristics of the rock itself. The force required to move a body along a surface is given by the equation:

$$F=(abc)we\ ,$$

where abc= volume of rock mass (length, width, thickness)
w= weight per unit volume of rock material
e= coefficient of friction.

For example, if one used a coefficient of friction of 0.15 (iron on iron), a thrust-block length of 100 miles, and a granitic material, the pressure at the end of the block would be over seven times the crushing strength of the granitic material. Clearly there must be some other explanation for the mechanics of thrust faulting. The idea of using a body force such as gravity as a deformation force was developed into the idea of gravity sliding. Perhaps the block could be uplifted and then slide down an inclined plane. Utilizing the gravity-slide idea, if a coefficient of friction of 0.6, an inclined surface of 30°, and a crushing strength of 18,000 psi are used, a thrust block could be only 5 miles in length without having any internal deformation due to drag along the surface.

Both of these theories involve subjecting the rock mass to more stress than it can physically withstand in order to facilitate movement of thrust sheets comparable to the size seen in the field.

Relation of Abnormal Pore Pressure to Thrust Faulting

An equation that was developed in fracture experimentation defines the stress conditions present before fracture. The following equation:

$$T = T_o + \sigma_n \tan \phi$$

where T = total shear stress present at fracture

T_o = cohesive strength of the rock material

σ_n = is the effective normal stress acting on the plane of fracture

$\tan \phi$ = is the coefficient of friction along the plane of fracture defines how the normal stress adds to the shear stress along the plane of fracture. Since the coefficient of friction (tan ϕ) of rock materials is not easily reduced, another mechanism of shear-stress reduction must be found to reduce the shear stress necessary to fracture the rock. Hubbert and Rubey (1959) proposed that the shear stress might be decreased by the reduction of the normal stress (σ_n). Inasmuch as rocks in the subsurface are saturated with water, we can assume that the overburden is being supported jointly by the pore pressure and the grain-to-grain contacts of the minerals. The following equation demon--strates this idea:

$$P + \sigma_{zz} = S_{zz}$$

where P = pore pressure
σ_{zz} = residual grain-to-grain contact stress
S_{zz} = total stress developed by overburden

As "P" approaches the value of "S_{zz}", the grain-to-grain contact stress approaches zero. In effect, the overburden is almost in a state of flotation, being supported almost entirely by the pore pressure. The ratio of pore pressure to overburden pressure, λ, helps to quantify the idea, with λ ranging from 0 to 1. Hubbert and Rubey's (1959) calculations utilizing this flotation idea showed that a pore pressure that is 0.9 of the overburden pressure could facilitate the movement of an eight-kilometer thick block

137 kilometers long without any internal deformation. Any pore pressure that exceeds that which is expected at a certain depth using a normal hydrostatic gradient is termed abnormal pore pressure. Calculations by Hubbert and Rubey (1959) also show that with a tilted surface of one degree, a pore-pressure to overburden-pressure ratio of 0.9, and using a force from the rear, a six-kilometer-thick thrust block could be 163 kilometers in length without crushing internally. It must be stated that this process does not reduce the coefficient of friction; rather it reduces the normal effective stress which correspondingly reduces the critical value of shear required to produce sliding. It is possible to understand the mechanics of the development of thrust sheets of the magnitude that are seen in nature if much of the overburden is supported by the pore pressure.

The bearings on the Mt. Palomar telescope operate on this same principle. While the structure weighs one million pounds, the bearings are hydraulically pressured with oil so as to eliminate any metal-to-metal contact. Thus, the whole structure can be rotated by a one-twelvth horsepower electric motor, (Hubbert and Rubey, 1959).

Due to the impact of Hubbert and Rubey's papers on the role of fluid pressure in the mechanics of overthrust faulting, abnormal pore pressure has been accepted by many geologists as the main mechanism for facilitating the development of thrust faults.

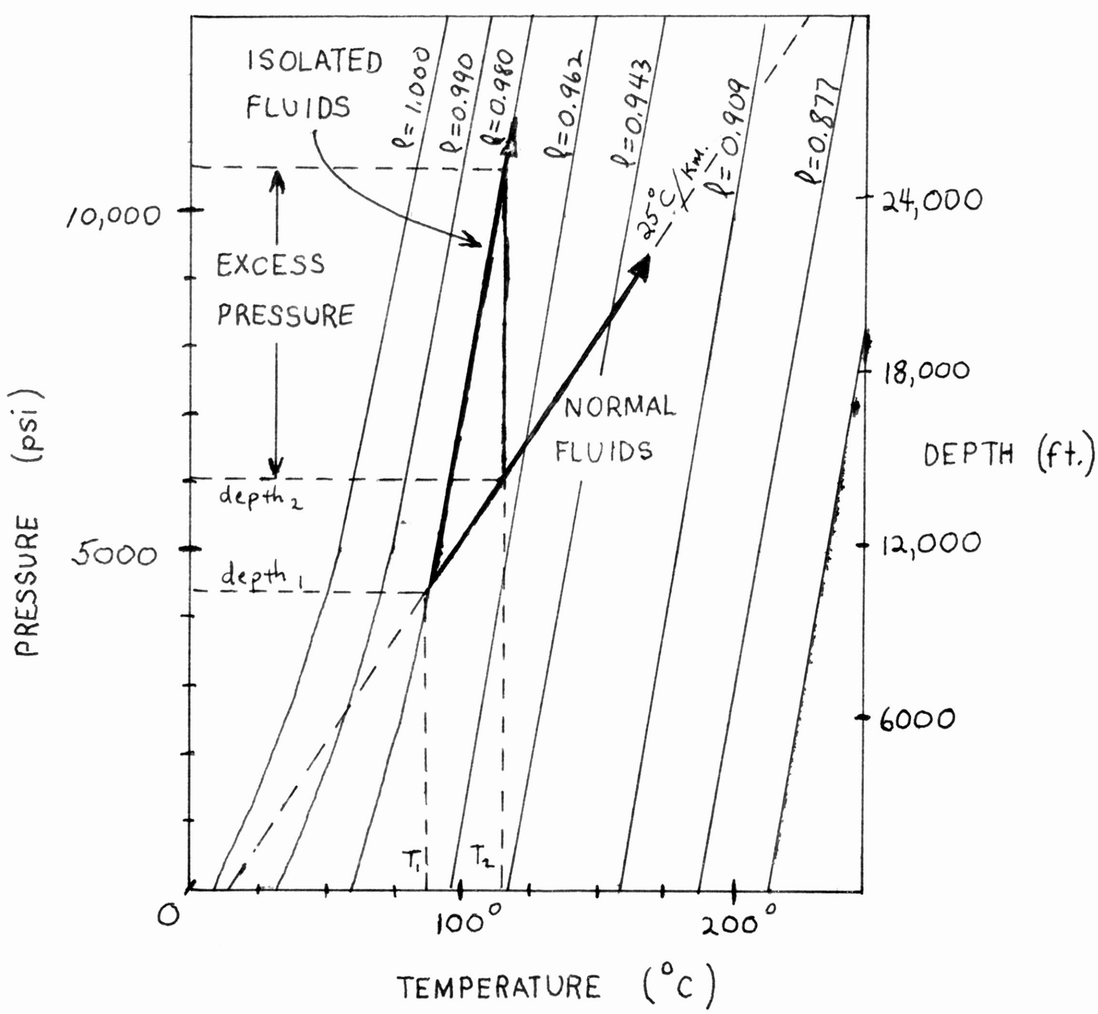
Development of Abnormal Fluid Pressures

Abnormal pore pressures in the subsurface are locally isolated zones in which the pore pressure is higher than that generated by an average hydrostatic gradient from the surface to that depth. Several articles have been published on possible causes of abnormally high fluid pressures, and how these causes are related to the geologic history of a depositional basin before it is structurally deformed.

First of all, a high-pressure zone requires a layer to act as a seal or to confine and isolate the pore fluids. Otherwise, the high pressure could easily dissipate. One method of generating excess pore pressures is through rapid compaction with rapid deposition of low permeability sediment such as clay. This creates a situation in which the added load of the sediment is being supported in part by the pore fluids because they cannot escape rapidly enough through the low permeability shales. Tectonic compression of the fine-grained, low permeability rocks would also generate abnormal pore pressures by causing the pore fluids to support the increased stress placed on the formation due to tectonic forces. The low permeability of the water-saturated clays would require a long time for the pressure to "bleed" off after comparatively short intervals of deformation.

Two theories that seem very important in understanding the generation of abnormal pore pressure within an undeformed depositional basin have been described during the past eight years. The theory developed by Powers, (1967), involves a thermal, chemical dehydration of montmorillonite clays to illite clays at a certain depth in the subsurface. He proposed that the clays that are buried within a basin of deposition go through a diagenetic process that includes not only compaction and mechanical squeezing of the pore fluids out of the formation, but also a thermal, chemical dewatering of the clay minerals. In montmorillonitic clays, there are four molecular layers of water chemically bound to the clay mineral. His theory follows four steps, one of which is deposition and burial of the clay layer to about 3000 feet. At this depth through normal compaction, most of the free interstitial water should be compressed and expelled out of the formation. The chemically bound water still constitutes about fifty percent of the total volume of the clay layer. At 3000 feet as subsidence and deposition continue, effective porosity and permeability are reduced and approach zero, while bulk density of the clay layer increases. Since clay dehydration is a temperature phenomenon, the chemical alteration of the montmorillonite to illite does not begin until the layer is buried to a depth of about 6000 feet at which depth the temperature is around 70°C. At 6000 feet below the surface, the montmorillonite converts to illite with the chemical release of the fresh water of hydration. This process continues to a depth of about 9000 feet, at which the last molecular layers of water are released. The water, now free as water molecules, expands and accumulates in the interparticle locations reducing the bulk density and decreasing the strength while increasing the plasticity of the clay. With permeability so low and confining pressure so great, there is no place for the water to go or the pressure to dissipate. Effectively, an isolated, sealed, potentially high-pressure zone has been generated. This volume of isolated rock and pore fluid could be acted on to produce abnormal fluid pressures. The observed properties of a high-pressured zone can be explained by this theory. The abrupt reduction in salinities as an abnormally pressured zone is penetrated are explained by the release of the fresh water of hydration. Bulk densities are lower than expected, and the rock layers appear undercompacted. These enigmas can be explained by the expansion of this released molecular water into the small pore spaces. In effect, a smaller mineral, illite, is formed while the rest of the original montmorillonite volume is occupied by the water of hydration.

The other theory of generating abnormal pore pressures was proposed by Barker, (1972). It concerns the role of thermal expansion of the pore fluids within a confined volume to develop excess pore pressures. He states that, in order for a zone to be abnormally pressured, it must be confined, isolated, and sealed from any pressure dissipation. Therefore, as an isolated clay zone such as mentioned above subsides to greater depths and the thermal gradient gradually increases the temperature, the thermal expansion of the pore fluids would develop pressures above that which would develop if the pressure were to "bleed" off and equalize. Barker labeled this theory aquathermal pressuring. The following diagram showing pressure-temperature-density relationships for water as "normal" and as "isolated" fluids including a superimposed geothermal gradient of 25°C/ kilometer shows what he has developed. For example, he chose a fluid at a pressure of 4500 psi and a temperature of 95°C and imposed a 25°C temperature increase resulting from one additional kilometer of burial. The normal pressure at the new depth would be 6000 psi, but if the fluid had been isolated at a depth where the pressure was equal to 4500 psi, that 25°C increase in temperature would develop a pressure of 10,400 psi at the new depth. In other words, an excess pressure of 4400 psi would be developed if the



Pressure-temperature-density diagram for water with superimposed geothermal gradient of 25°C/km. showing P-T relation for normal and isolated fluids as temperature rises.

Modified from Barker, (1972, p. 2068).

fluid were truly isolated from any pressure dissipation. It appears that "aquathermal pressuring," as Barker calls it, is a very probable explanation for abnormal pressures that have been encountered. A 25°C temperature increase requires about 3500 feet more burial. Since the pore fluids are isolated, the excess pressure can only force the minerals slightly apart, therefore decreasing bulk density and increasing the plasticity of high-pressured shales.

The two theories, clay dehydration and aquathermal pressuring, explain many of the anomalies that we see in high-pressured formations in the subsurface. Low bulk densities, the undercompacted nature, low salinities, and high pressures are all explained by the combination of these two ideas.

Relation of Development of Abnormal Fluid Pressures to the Geologic History of a Deformed Basin

I would like to propose a sequence of geological events that seem to fit into the pattern and evidence we can observe and that leads to the generation of thrust faults. Suppose we select a layer of montmorillonite clay to begin the sequence. The first step is the deposition of the unit in a basin similar to that along the Gulf Coast with sedimentation rates similar to those in the vicinity of the Mississippi delta. After deposition and subsidence, normal compaction takes place with the expulsion of the free water out of the clays. According to Powers, at a depth of around 3000 feet, most of the water should be squeezed out. Continued subsidence and deposition depresses the clay to a depth of about 6000 feet, where the proceeess of clay dehydration takes place. The process continues to a depth of about 9000 feet, at which depth almost all the chemically bound water is released. The temperature at this depth is approximately 100°C. With continued subsidence to 12,000 feet, the temperature is raised to 120°C. With the isolated volume of fluid trapped within this dehydrated clay layer, this temperature increase develops a pressure of about 10,500 psi. That constitutes a pore-pressure to overburden-pressure ratio of 0.85. An excess-pressure zone has been developed in a subsiding basin at about 11,000 to 12,000 feet of depth. After subsidence of the basin ceases, either the margin or center of the basin is uplifted to expose the rock layers. Tectonic forces then tilt the rock layers to develop gravity-slide thrust faulted or imbricated fault sections. With a pore-pressure to overburden-pressure ratio of 0.85, an angle of only 5° can result in a gravity-slide thrust-fault sequence.

Thus, I have presented a sequence of geological events involved in the development of one isolated instance of gravity-slide thrust faulting.

The aspect that I would like to stress is the incorporation of clay dehydration and aquathermal pressuring as consecutive mechanisms in the development of abnormal fluid pressures. Both theories are geologically sound and seem to fit the field evidence. Thus I feel that they play an active role in many basins in routinely generating the conditions of abnormal fluid pressure favorable to thrust faulting. Essentially, the rock layers, following the general sequence I have presented, have developed favorable conditions for thrust faulting even before the first orogenic activity begins.

Through my analysis of the mechanics of thrust faulting, the above mentioned sequence may be helpful in deciphering the geologic history of a tectonically disturbed basin of deposition. Either surface forces or body forces could produce thrust faults because the favorable abnormal-pore-pressure conditions are present to reduce the effective normal stress produced by the overburden pressure.

Part II

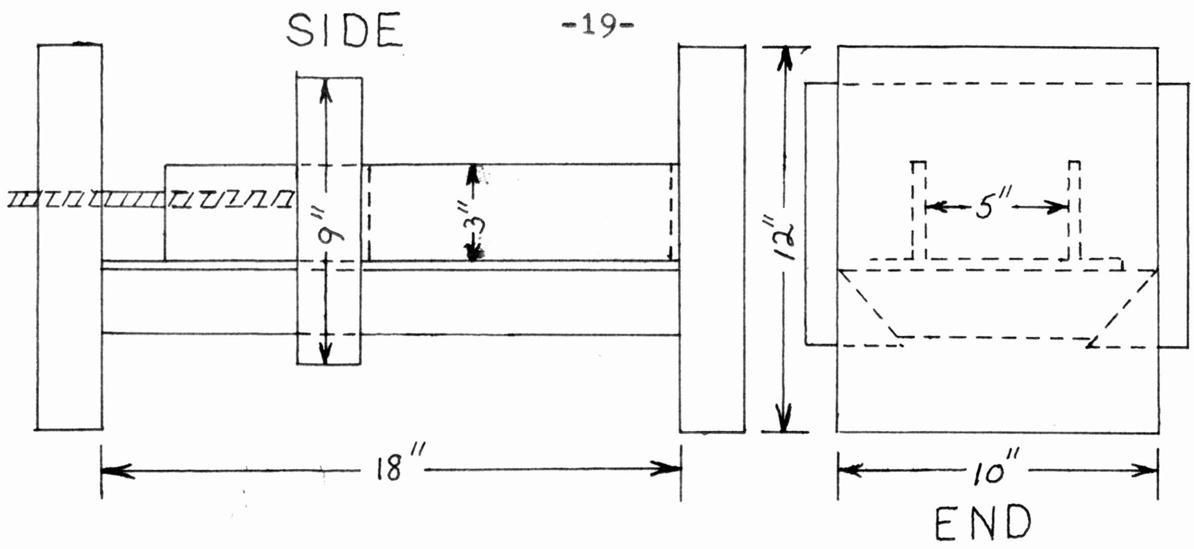
Experimental Tectonics

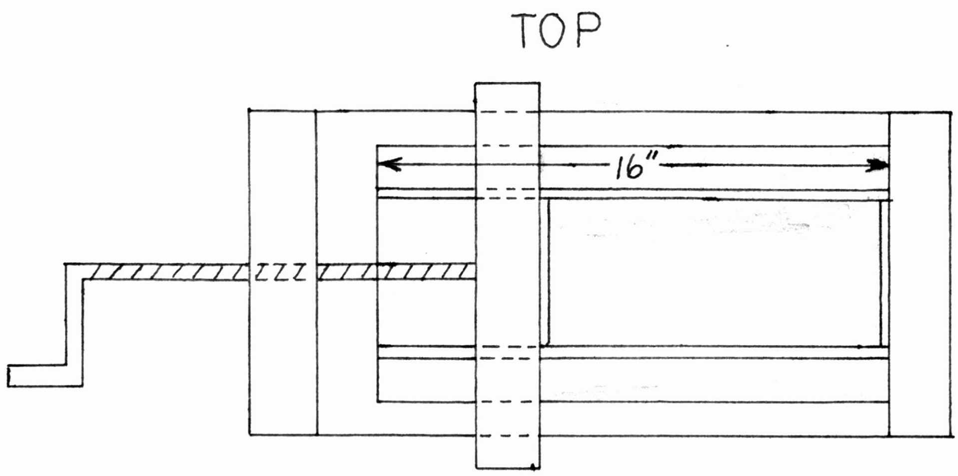
Purpose

My purpose for the experimental study was to analyze the development of thrust faults under horizontal compression. Knowledge of the development of thrust faults, structural trends within a deformed sequence, percent deformation necessary to generate thrust faults, fracture patterns in layers overlying thrust faults, and sequences of thrusting were all results that I wished to obtain from this experimental investigation.

Methods

I decided to use clay to represent rock layers in the study because in viewing structural regions from a spacecraft, rock layers appear to behave somewhat like a thin, plastic, viscous-sediment package. A diagram of the device in which the clay was deformed is shown on the next page. It is an 18-inch long by 10-inch wide H-shaped device with a sliding partition between the two fixed ends. A large, glass plate was installed on the flat portion, and glass sides and end sections were used for containing the clay layers. The wooden vertical section was moved by turning the threaded rod to give a smooth, not jerky or uneven, horizontal motion. One fixed end was made removeable so that loading the apparatus was easier and cleaning up was less time consuming and more efficient. The glass plates were used for reducing the friction between the clay and the wood and for facilitating the cleaning of the apparatus.





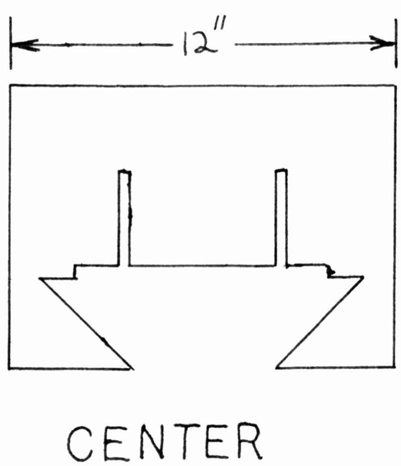


DIAGRAM OF DEFORMATION MECHANISM

All wood is 2" thick

SCALE : 1" = 6"

= GLASS

As for the clay, it was standard pottery clay, and came in more than one color. The colors were necessary to differentiate beds when the deformed mass was cut for cross-sectional analysis. The clay stiffness was altered by kneading in water much like kneading bread dough. The clay originally contains about 23% water by weight, whereas the stiffness necessary for development of thrust faults within a single layer was as high as 32% water by weight. The kneading process must be thorough so as to remove any lumps. Five pounds of clay could be kneaded well enough in about 30 minutes, and letting it set overnight in a closed plastic bag would allow the water to thoroughly distribute itself throughout the clay mass.

In making the layers, 12 x 12 inch plastic sheets were cut and oiled with mineral oil to aid in handling the clay layer. A lump of clay was placed on the sheet and smoothed with wet fingers to about 1/4 inch thickness. A bread-loaf pan or some similar device was then used to cut out the shape of the layer much like a cookie cutter is used. The device that I used made layers that were 10 x 5 inches. After cutting, the excess clay around the edge was removed, and the cutter lifted off. The plastic sheet could then be moved around with the clay layer sticking to it. All the layers were made at once.

In making the sediment package, first all glass surfaces were oiled with mineral oil to reduce drag between the glass and the clay. The first layer was placed on the removeable bottom glass plate, plastic sheet up. The plastic sheet was then carefully peeled away. The next layer was placed on top of the first, also plastic sheet up, and so on. The layers were of two colors that were alternated in the stack. I frequently used four layers, but I feel that a thicker package might be more effective in generating thrust faults.

After the package of layers was built, the basal glass plate, with the layered package, was placed on the device; next the side walls were installed into the slots in the moveable piston portion of the unit. The end plates were installed, and finally, the removeable end of the unit was put back.

Deformation was produced by turning the crank. I typically stopped at between 30% and 50% shortening of the original package length.

After a package was deformed, it had to be dried to a "cold butter" consistency in order to be able to cut cross-sections. Use of an oven fractured the clay because the drying process was so rapid. Natural drying was most effective, but took 3 to 4 days. Cutting the cross-sections required only a good stiff blade (spatula or concrete trowel). Cutting through the section slightly smeared the layers, but the smear could be removed by careful rubbing of the surface under a running faucett. The clay did not absorb water fast enough to create a problem of weakening the clay and consequently re-deforming the layers.

Results

The attempts to develop thrust faults resulted in some thrust faults, but in most runs only asymmetric and symmetric folding along with thinning of layers occurred. Numerous experiments were made simply to investigate the behavior of the different variables that apparently affected the final form. The variables that seemed to be most dominant in determining form were (1) stiffness of layers, (2) deformation rate, and (3) thickness of total layered package.

Very stiff layers simply folded and separated from each other without thinning at crests and troughs. No asymmetry was present in stiff layer runs, where as weak layer packages definitely showed asymmetrical folding in upper layers and sometimes thrust faulting in the lower portion.

The deformation rate, another variable, was significant in determining the overall form of the layers. Slow rates caused gradual deformation across the package, whereas fast rates caused a high build up of material at the piston end end very little deformation throughout the rest of the package. A "slow" rate was on the order of 5 inches per minute, while a "fast" rate was about 2 to 5 inches per second. Slow rates produced a more asymmetrical fold pattern, while fast rates formed a high anticline at the piston end with the dying out of anticlinal forms toward the fixed end.

Thickness of the total package was one of the other main variables. In buckling theory, length-to-thickness ratios determine whether a beam will buckle or shear. This may be one area in which additional investigation is needed. I constantly got folding in thin layers, and only in thicker (6 layers) packages did I find any thrust faults.

The results of the experiment are negative. Trial and error attempts to isolate the behavior of each variable used up more of the allotted time than I had anticipated. Development of thrust-faulted sections was infrequent, and reproducibility was almost nil. The variables were so sensitive and my techniques so lacking in refinement that duplications were not possible due to slight differences in the make-up of each clay-layer section.

Conclusions

The conclusion that I reached is that the technique needs some mechanical refinement and a method to quantify clay stiffness, deformation rates, and the plasticity of the clay so as to increase reproducibility. Closer observation of how the layers behave throughout the deformation will be necessary in order to determine what to change. In its present state, I do not feel that the experimental results can be functionally related to geologic events. I do feel that the technique has promise as an experimental method if one initially evaluates the way in which the results could be related to our understanding of thrust faults. Investigation into how the results could apply to field work and/or our understanding of the complete deformational process in thrust-faulting should be done prior to experimentation. Also a more thorough behavioral study of the clay itself should be undertaken prior to designing the final apparatus.

Construction of a larger unit could be done so that gravity-slide behavior could be studied. Using a thicker layered package would make a difference in the behavior. One note to be made is that abnormal pore pressure could not be introduced or controlled, although lubrication between layers might serve the purpose. The behavior of the clay in relation to rigidity, viscosity, plasticity, and thickness must be well understood before attempting to work with a complete layered section. Otherwise, the results could end up exactly as mine did. The physical properties and behavior of the clay must be quantified so that when the desired result is obtained, one can then set up the system the same way as before. The success of this experimental tectonic device will lie in the ability to control the variables.

In contrast to Hubbert's (Hubbert, 1951) sand experiments, the clay does not shear as easily as dry sand. It is more plastic and viscous and responds as one layer rather than a very large number of individual sand grains shearing according to stress orientations. It appears that the difference between the sand experiments and my clay experiments is that the sand deforms almost entirely by shear failure, whereas the clay seems to behave in a more ductile fashion.

Possibly the pottery clay is <u>too</u> viscous, ductile and plastic and simply cannot demonstrate adequate shear behavior. Other materials such as soft paraffin, soap, or lard could be experimented with. These all possess a brittle yet plastic or viscous behavior. Again, behavioral characteristics would definitely need to be studied for any material used for the layers.

To study the deformational behavior of a regional area, the rock layers must simply be treated as ductile rather than brittle materials. I feel that the ductile behavior rather than the brittle behavior of rock layers seems to give geologists a much better concept of how the rock layers behave under the influence of tectonic forces on the surface of the earth.

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