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# SCALE MODEL REPRODUCTION OF TENSION FAULTS

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ABSTRACT. Normal or tension faults were produced in the laboratory and simulate those observed in basin and range structural regions. Apparatus was designed with due regard for scale modification of natural conditions. The structural patterns seem predetermined by the active side of the tensed region and by the load factor controlled by topographic slopes. Typical graben were not produced by any of the many variations, within scale limits, which were tried out and are believed to be due to some other sort of force than simple tension.

## INTRODUCTION

Tension faults were produced experimentally to determine the form assumed under specific and different conditions. The average strike of these simulated normal faults was perpendicular to the direction of greatest tension, i.e. strike-slip movement was not involved. Experiments were performed on a scale model, greatly reduced from nature. Conditions such as strength, thickness, rate of strain, and surface slope of strata were varied singly and collectively in succeeding tests.

A number of attempts have been made to reproduce deformation of the Earth's crust experimentally. In this, the work of Hans Cloos (1929-1930) is outstanding; his object was to reproduce normal faults, using a scale model. In order that the model simulate natural conditions, the strength of the material representing the rock strata had to be reduced to a degree commensurate with the small size of the model. Therefore Cloos used wet clay. too soft to stand and contained in a box with one end movable, the other fixed. Overlapping metal plates were attached to the fixed and movable ends. The ends were pulled outward, and a fault pattern occurred only above the overlap of the metal plates.

Our experiments were planned to allow the stress distribution within the simulated rock to control the strain surfaces, and avoided the artificial and arbitrary plate junction as an influence. It is recognized in natural settings that basement complex structures occasionally do guide or influence strain surfaces of subsequent deformations in superjacent strata but rarely to such extent as to hold movement or strain to one plane. Distribution of strain in our experimental procedure was attained by using an extensible basal surface rather than a rigid plate.

## SCALE SIMULATION

Scale simulation includes first, study of scale theory and second, devising methods to conform with the scale suggested.

### *General Scale Model Theory*

One of the fundamental problems of this experiment was construction of a dynamically correct model that would effectively simulate a portion of the Earth's crust under tensional stress. Hubbert (1937) outlined the essential mechanical properties of any model relative to the known properties of the original and given in terms of the three fundamental model ratios $\mu$, $\lambda$, and $\tau$ of mass, length, and time.

Definition of these model ratios follows.

$\mu$ is equal to the mass of the original divided by the mass of the model.

$\lambda$ is equal to the length of the original divided by the length of the model.

$\tau$ is the ratio of the time consumed in the original process to the time necessary to produce a similar process using a particular scale model.

Aside from these, a number of dependent model ratios are introduced later. As one example, the density ratio $\delta$ is equal to $\mu\lambda^{-3}$. It will be noticed that this relationship corresponds closely to the formula $d = m\,v^{-1}$ where d equals the density of a body, m its mass and v its volume (which is, after all, expressed in cube of length units).

Reynolds (1883) worked out the following equation applying to any fluid. Any characteristic length multiplied by a characteristic velocity $\eta$ divided by the kinematic viscosity (the viscosity $\Psi$ to density ratio) is equal to R, or Reynolds' number for a particular case. It follows that for a model dynamically similar to the original we get $R_2/R_1$ is equal to the product of the length and mass model ratios divided by the kinematic viscosity ratio, which is in turn equal to unity. That is:

$$\frac{R_2}{R_1} = \frac{\lambda\eta}{\Psi/\delta} = \frac{\lambda^2\ \tau^{-1}}{\lambda^2\ \tau^{-1}} = 1$$

Since Reynolds' number is taken from the ratio of the inertia to the resistive forces, it approaches zero when the inertia forces are negligible compared to the resistive forces. In such cases the restriction of the above equation may be violated, and dynamic similarity can still be obtained when the respective Reynolds' numbers are not equal, but both small.

In this case we have as our fundamental ratios: $\mu$ and $\lambda$, and $\lambda$ is independent of $\tau$ when inertial forces $\gamma$ are negligible, because the force of gravity is dominant here, and this force is quite independent of the model ratio of time used in a particular experiment. Furthermore $\gamma = 0$ and $\gamma_g$ (acceleration of gravity ratio) $= 1$ since both our model and the original are at the Earth's surface. The density ratio, $\delta = \mu\lambda^{-3}$, the force ratio $\Phi = \mu\ \gamma_g = \mu$, and the stress and strength ratios (which are the same), $\sigma = \Phi\ \lambda^{-2} = \mu\ \lambda^{-2} = \delta\ \lambda$.

*Model Ratios for This Experiment*

This model simulates an area of the Earth's crust about 100 to 150 km wide. Since the model is about 40 cm wide, $\lambda = 3 \times 10^5$. The Earth's crust is generally strong enough to support a column 10 to 20 kilometers high. The density of the crust is approximately 2.7 whereas the density of the model is approximately 1.5, giving $\delta = 1.8$. Thus the strength ratio $\sigma = 1.8 \times (3 \times 10^5)$, and the strength of the model material should stand as a column about 2 to 4 cm high. The value in Cloos' experiments was 2 to 4 cm. He described his clay as having "the consistency of thick cream." This experiment made use of wet clay because it is intermediate between plastic and brittle. The rocks composing the Earth's surface are generally brittle but do have plastic qualities under pressure. Furthermore, the stress necessary to produce plastic shear is very nearly independent of the rate of shear.

*Independence of Rate of Shear*

In theory, and for the purposes of this experiment, the time ratio ($\tau$) is almost an independent variable, which can be modified to suit the convenience of the experimenter. However, in experimental practice, various rates of strain gave varied experimental results. For example, 15 inches per hour rate of strain produced numerous small faults whereas 2.6 inches per hour strain gave larger and less numerous faults. Nevertheless, at 5 inches per hour faults were only slightly smaller than those produced at 2.6 inches per hour, and it is therefore suggested that a 1 inch per hour rate of strain would produce faults very little different in character from the 2.6 inches per hour sort. It is entirely possible that at approximately 1 to 2 inches per hour conditions approximate a critical value of $\tau$ beyond which further change in rate (i.e. further decrease in rate of strain) has little effect on experimental results.

## EXPERIMENTAL ARRANGEMENT

The apparatus is described below, and the essential controls to permit variation of conditions are outlined briefly.

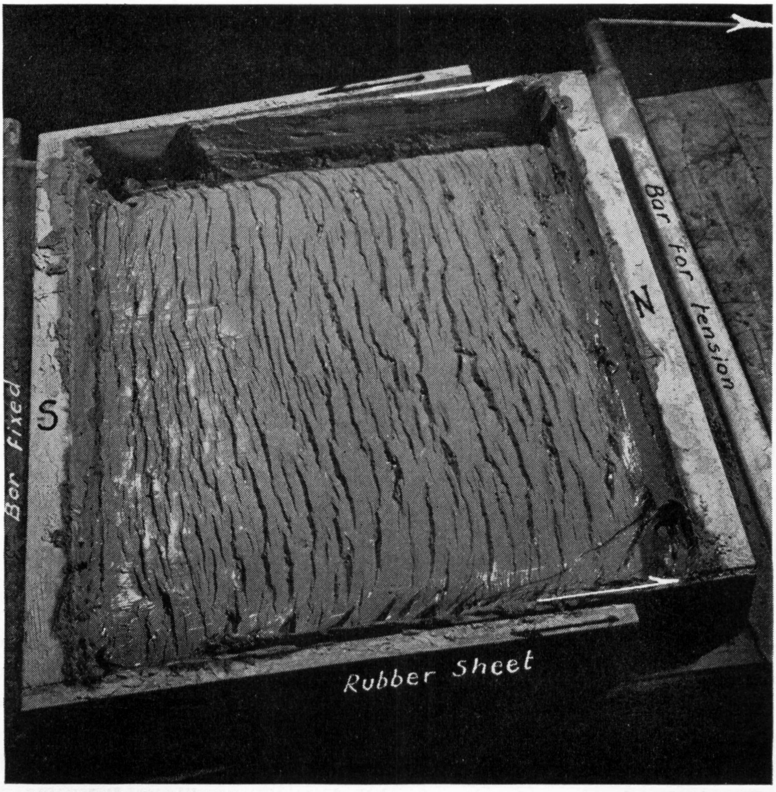


Fig. 1. Photograph showing the extensible container and deformed clay.

### *Description of Apparatus*

The simulated strata, built on a rubber sheet which could be elongated at various uniform rates, were composed of a stiff, creamy, clay-water mixture. The rubber sheet base served as a means of applying a generalized tensional stress to the strata, and a small electric motor provided the motive power.

The arrangement was prepared as follows: A thin rubber sheet of size 2 feet by 2.5 feet was stripped of talc on the top side to cause adhesion of overlying clay to the rubber during the experimental work. The sheet was attached along the longer edges to 3-foot lengths of 1-inch pipes and laid out on a table. A wire was passed through one of the pipes and used to anchor the south end of the sheet. A length of rope passed through the north end pipe, and each end of the rope ran over a pulley to a winding system driven by a 1/20 H.P. gear reduction electric motor. This winding system was the source for a uniform rate of strain. A framework contained the clay and was constructed of two sections, each resembling a box with the bottom and one side missing. The north end of one "semibox" was slightly shorter than the end of the other semibox and formed a sliding fit inside it (fig. 1). This enabled the sides to slide freely, as strain was induced by the motor, yet still retain the clay. Generally, the south end remained fixed during stretching of the clay. Wet clay of the proper consistency was poured into this framework until it occupied a space 26 inches wide, 17 inches along the length of the table and 2.5 centimeters deep. Operation of the motor applied stress to cause uniform rate of strain in the clay.

### *Control of Rate of Strain*

The electric motor ran at 43 r.p.m., and its speed was reduced by worm gears and a cone pulley system. The belt connections in the cone pulleys were used to vary rate of strain. The fastest rate of strain was 12 inches per hour, while the slowest rate was 2.6 inches per hour.

### *Control of Competency of Strata*

Indirect control of clay consistency or competency was accomplished by specific gravity determinations. If the specific gravity in one experimental run was 1.43 and a comparable consistency was desired in a later experiment, the clay could be allowed to dry if too wet, or water could be added and stirred in if too dry, until density was 1.43. Clay was used at specific gravities, varying from 1.398 to 1.467 during the experiments.

## FORM OF FAULTS

The average angle of inclination, the direction of inclination and the size of faults varied with thickness and strength of strata, and with the duration and rate of application of stress. The faults assumed a steep dip during the early stages of development but were rotated to angles of less than 45° with continued application of stress. Size of faults increased within limits with increase in thickness and/or strength of strata and decreased with increase in rate of stress application.

### *Development of Faults under "Normal" Conditions*

The faults developed under simplified or "normal" conditions are described first. The clay had 1.44 sp.gr., was 2.5 cm deep, its surface was horizontal, and the rate of strain was 2.6 inches per hour.

Minute shears began to appear at the north or mobile side after stress had been applied for about 20 minutes. Strike of these shears, as well as those that developed later, was essentially E-W and perpendicular to the stress axis in the rubber sheet. However, figure 1 shows that the strike is not a straight line and is modified further where stress is transmitted from the sides of the restraining "semiboxes." Similar departures from linear form appear also in actual fault forms. The early shears or faults grew larger as stress was applied uniformly to the rubber sheet and new minute faults began to form. Appearance of initial shears at the north side is attributed to friction between the rubber sheet and the table, aggravated by the pressure of the clay on top of the sheet. This concept is appreciated if one presses down on a rubber band with the palm of one hand, and pulls out an end with the other hand. It will be noticed that the band slips first and is extended under the side of the palm nearest the stress.

Small faults tended to join together as they enlarged and produce one fault where originally two or more had started. Also some faults joined even when they were initiated on different planes slightly offset from each other (fig. 2). Ofttimes the trace of a fault lying northward from a second one joined in with the southerly one producing a single fault with "steps" or angles in its trace and scarp. This phenomenon has been observed also in the field.

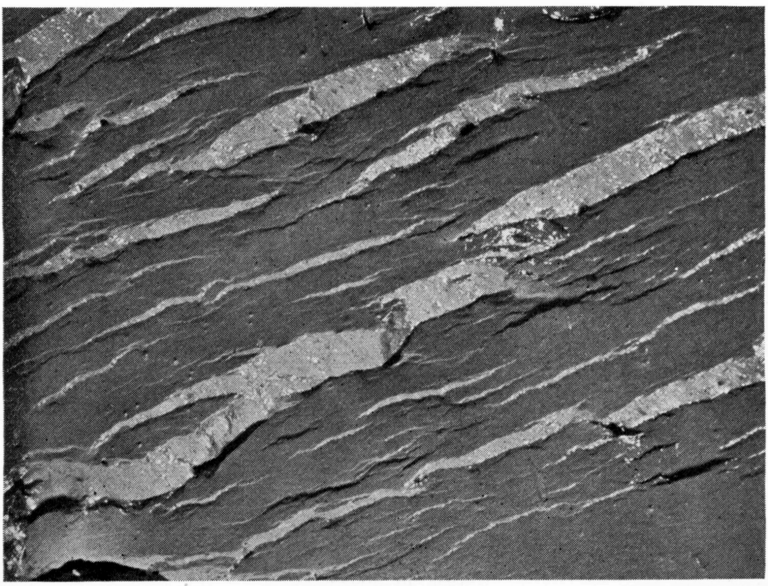

Fig. 2. Photograph showing steps, terminations and offsets in tension faults.

### *Description of Fault Patterns and Individual Faults*

Detailed observations were made of the fault patterns, and the form of faults in the pattern, and close watch was kept for development of graben. Typical graben and horsts did not form as persistent structures under the conditions of the experiments.

*Fault patterns.*—A definite pattern of faults was obvious after two hours of applied tension which caused 5.2 inches of strain; the features are shown on figure 1. Multiple faults had joined up in many instances; size varied from less than 1 inch long and less than 1 mm high to 10 inches long and throw exceeding even 1/4 inch. The faults dipped about 30° after two hours of stress application, and actual maximum dip-slip was about 1/2 inch. The larger faults were about 0.5 to 1 inch apart, but a number of smaller faults with throw of 1/8 inch generally lay between them. Toward the eastern and western edges of the clay the fault traces swung away from the stress direction in the rubber sheet. This effect was due to stress transmission from the box sides.

The general pattern of the simulated faults corresponds closely to actual basin and range structure. Like the actual case, it lacks numerous graben and horsts which appear in so many idealized representations of this sort of structural province. Experimentally, tensional stress divided the "crust" into blocks separated by uniformly dipping normal faults. Rotation of these blocks, downward on one side and upward on the other, formed "ranges" and "intermontane basins." Initially the faults dipped steeply at about 70°; (this figure is only approximate since the early small faults could not be measured accurately). However, after an hour, the dip of faults was measurable by using a clinometer. Rotation took place as time passed, and the average dip was only

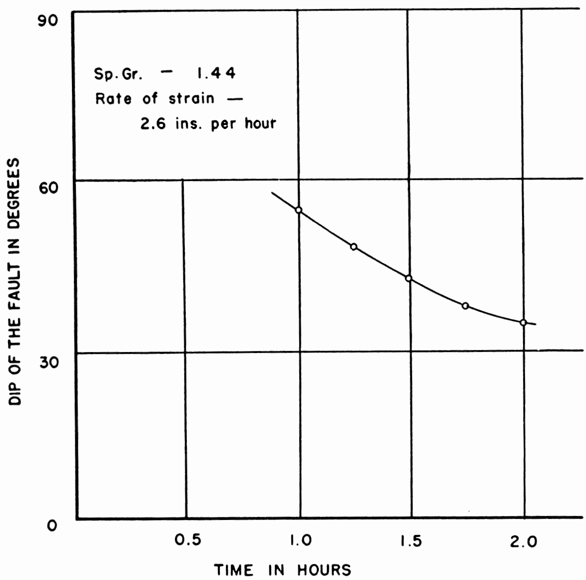


Fig. 3. Graph showing change in fault inclination relative to time or strain increase.

35° after two hours of stress at 2.6 inches per hour (fig. 3). This meant that the reverse slopes of the fault blocks inclined in a direction opposite to the fault dips, giving the basin and range topographic form to the structure.

*Fault forms.*—Individual simulated faults showed forms that have field counterparts. Displacement of the strata diminished both laterally and in depth during early stages of development. Dip probably changed with depth, although no direct observations were possible beneath the clay surface. However, variation of dip from place to place along the trace of individual faults was measured; one fault 8 inches long had 38° average dip; measurements at 1-inch intervals along the trace gave dips of 36°, 30°, 32°, 25°, 40°, 50°, 54°, showing lowest inclination near the center of the shear.

The faults died out laterally and displacement was not uniform along any given fault, either in direction or magnitude. Indeed strike, dip, and net shift varied along any one fault, exhibiting a condition observed in natural forms.

Slickensides or flutings caused by the movement of the hangingwall against the footwall were obvious on the scarps of the simulated faults. They appeared to be quite similar to slickensides found on the scarps of natural faults.

*Graben.*—At the outset of the experimental work, it was hoped that the horst and graben type of basin and range structure might be simulated in model form. Generally this did not happen, and the faults all tended to dip in the same direction. However, graben were produced in the early stages of stress when the surface of the clay was essentially horizontal.

The graben development in this model took the following patterns: Twenty minutes of stress application initiated small faults dipping in the same direction. As the hangingwall of each fault began to move downward relative to the footwall, the clay surface of the hangingwall block was rotated slightly and dipped toward the fault scarp. Usually fault planes tend to incline in the same direction as the surface of the strata; often a secondary fault developed in the hangingwall within 1/4 inch from the main fault and dipped toward the latter.

These miniature graben did not continue to enlarge under continued stress application; the original fault of the pair increased in size, whereas the secondary fault grew scarcely at all. Initially, the simulated faults do not extend down to the rubber sheet but extend their surface down gradually as strain increases. Thus the original fault of the pair making the graben extends deeper than the secondary faults at any given time and cuts off the secondary one which terminates against the moving block. Thus only the primary fault continues to grow larger.

## EFFECTS DUE TO CHANGE OF VARIABLES

Water content controlling competency, rate of strain, and slope of the surface were varied to determine their effect and, by analogy with field cases, suggest the potential application of experiment to interpretation of structural history.

### *Water Content*

Varying the water content of the clay gave different experimental measurements. A high proportion of water in the clay reduced both specific gravity and strength or competency. Low strength modified the form and spacing of faults from corresponding features encountered in higher strength clay. At the lowest specific gravity used (about 1.40), the faults had low net displacement, and net shift was less than one-fourth that on faults in clay of sp.gr. 1.45. Also dip was less and shear planes were spaced more closely. However, the length of the trace of a fault averaged about the same for any clay density. Thus the height to length ratio was 1/80 at sp.gr. 1.40 and 1/20 at sp.gr. 1.45.

### *Rate of Strain*

Varying the rate of strain had definite effects except when diminished to approach 2.6 inches per hour. Rate of strain at about 15 inches per hour produced faults that had average net shifts appreciably less than those of faults produced in clay of the same competency and at a 2.6 inches per hour strain rate. However, faults produced at 5 inches of strain per hour were only slightly smaller than those produced more slowly. Thus it seemed that the time ratio could be distorted if the rate of strain was slow enough. At speeds appreciably greater than 2.6 inches per hour, faults had smaller net shifts, were more closely spaced, but were nearly as long as slow speed faults. Moreover, many clays of higher competency, producing only tension cracks under fast stress application, sheared instead if the rate of application was reduced adequately.

### *Slope of Clay Surface*

Some of the more interesting phenomena observed in the present experimental work were correlated with slope to the clay surface. Conspicuous slope of the entire clay surface toward the north or toward the south was attended by development of faults under tension which likewise dipped northward (if the surface dipped north) or southward (if the surface dipped south). This behavior recurred regardless of whether the stress itself was applied from the north or from the south. Since this principle operates for a dynamically correct scale model, it should be expected to have some bearing upon interpretation of the record for a sequence of events in a part of the Earth's surface which has been deformed under tensional stress.

It was hoped that by inclining the northern half of the clay toward the south and the southern half toward the north faults would be produced which had dips following their respective slopes, thereby producing graben in the central section. The experimental results were quite different. It has been pointed out already that faults develop first in that part of the clay nearest the side of stress application because of friction effects somewhat comparable to "viscosity" of flow in the so-called asthenosphere. Application of stress to the above "flattened V"-shaped arrangement was attended by appearance of initial faults on the northern (southward-dipping) slope and with fault surfaces inclined to southward. Extension of the faulted zone to southward into the area of northward-inclined clay witnessed production of shear surfaces which continued to dip southward. The direction of dip of the earliest faults had set a precedent strong enough to cause later faults to dip in the same direction even where the surface slope effect would tend to direct dip in the other direction. The cause for this effect is essentially the same as the one offered to explain why the small graben, which were produced in the model, did not grow into large graben under continued stress. The earlier south-dipping faults were able to block off any attempt by northward-dipping faults to penetrate to depth.

Another arrangement was made in an attempt to produce graben under tensile stress; the possibility of this condition being duplicated in nature suggests to us that graben are produced only rarely by tensile stress. Clay was arranged near the north side of the apparatus to dip gently southward for not more than one-fifth of the total surface area. The other four-fifths of the clay surface dipped northward at almost 20°. The anticipated southward-dipping faults appeared on the gentle slope as stress was applied. However, northward-dipping faults soon began to appear on the steeper northward-dipping slope and soon these became dominant. The original southward-dipping faults increased in size hardly at all and new shears dipping southward appeared on the gentle slope!

These observations suggest that, in the case of a doubly sloping land surface, the dip of all faults will follow the direction of inclination of the slope nearest the stress unless the more distant slope is much steeper and more extensive.

## SUMMARY AND CONCLUSIONS

The present experiment used a model somewhat similar to that of Cloos. The overlapping metal plates were replaced by a rubber sheet in order to distribute the strain. Regional basin and range structure, comprised of many individual tension faults, was reproduced by using a clay-water mixture.

Specific conclusions include:

1. Under tensional stress, the clay strata sheared to produce normal faults.
2. A normal, that is, a line perpendicular to any shear surface, inclines downward and outward towards the actively moving side or base of the clay except when the clay thickness was varied systematically as outlined under conclusion 7.
3. Tension cracks resulted when the clay was too strong (dry) and/or when stress was applied too rapidly.
4. Relatively slow rates of strain (2.6 to 5.0 in./hr. produced the largest faults.
5. Initial faults were nearest the source of stress.
6. Faults were steep during early development and rotated to a lesser inclination with continued application of stress.
7. Faults dipped southward or northward (side of stress direction) depending on direction to slope of the clay surface when the *thickness*

was varied systematically. In general, faults dipped in the same direction as the clay surface.

8. Distributed tensional stress produced graben of small size and only in rare instances.

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