ART. XXXI.—*On the Origin and Hade of Normal Faults*; by
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FAULTS may be either *normal* or *reversed*; i. e., may hade to either down-throw or up-throw. Both classes are probably developed by movements relieving radial strain (either simple or differential), tangential thrust, tangential tension, or a combination of these stresses, in the terrestrial crust. Only those due to radial strain in its essential combinations are here considered.

Let contiguous areas of a homogeneous rigid tract resting on a mobile sub-stratum (which may be either the gaseous, fluid or *quasi*-solid terrestrial nucleus, or a yielding layer any where within the exterior shell) be in unstable equilibrium, such as might arise from transference of sediment, and let all initial stresses save those immediately due to the disturbed equilibrium be at first supposed eliminated. In such case the tract will suffer differential radial strain culminating in the plane of coincidence of the unstable areas.

* Read before the Iowa Academy of Science, May 31st, 1883.

Now manifestly, before fracture supervene the strain will be distributed over a considerable horizontal zone, and will be propagated vertically through the tract; whence the resultant of stresses at any point in the plane of imminent faulting will bisect a parallelogram similar to that whose base and perpendicular are respectively the width of the stressed zone and the thickness of the homogeneous tract. Make such parallelogram equilateral; denote base and perpendicular by $2n$ and $2m$ respectively; and let BC be the depressed side. The strain will then be resolved into stresses of opposite sign acting in the directions of the diagonals.

If now fracture relieve tensile strain only, it will occur at right angles to the tension-diagonal AC, or in BD; and the fault will hade to the up-throw. Such indeed is the direction actually taken by ice-stream crevasses (to which the diagram will equally apply) as shown by Hopkins;* for in slowly moving ice the crushing strength must be nearly *nil* and the compressive-elasticity infinite, while tensile stress probably increases rigidity and brittleness, and thus diminishes the tensile elasticity.† And were the antithesis of ice existent its fracture under the like stresses would occur at right angles to the compression-diagonal, or in AC, and its fault would hade to the down-throw.

But the materials of faulted tracts possess both tensile and crushing strengths, and also tensile and compressive elasticities. Denoting these in their order by t , c , t' and c' , the values $t \times t'$ and $c \times c'$ are obtained for the moments of fracture orthogonally to the diagonals AC and BD respectively; which values may be represented by a and b , whose sum is proportional to $2n$. Obviously, if a and b be equal, the fracture will bisect the angle of the diagonals in nO ; but if a be in defect (as in crystalline solids generally) the hade will ever be to the up-throw in the angle y , whose tangent is $(n-a)m$. From this expression the hade of fault in any greatly attenuated tract of determinate stress-parallelogram and known strength and elasticity might be readily computed.

If the case be modified by the introduction of initial tangential stress, such stress will operate through mO with intensity i , and tend to produce fracture in nO . If the stress be tensile it must be less than a , and will at once relieve BD and strain AC proportionally to its intensity by the cosine of the angle formed by its direction and that of the latter diagonal, and thus (denoting such angle by θ) reduce a by $i \cos \theta n$; when the expression for hade will become $\tan y = (n - a - i \cos \theta n)m$,

* *Trans. Camb. Phil. Soc.*, viii, (pt. ii, 1844, 163-7.)

† *Vide* "On Maximum Synchronous Glaciation, III, 1, 2; *Proc. A. A. A. S.*, xxix, 1880, 497.

and the hade will ever diverge from the normal. Conversely, if the stress be compressive the relation will become $\tan y = (n - a + i \cos \theta n)m$ or $\tan x = (n - b - i \cos \theta n)m$ as the case may

be, and the hade will ever approach the normal; but if it become normal the tendency to movement will be counteracted and a disposition to produce

dragged fault or flexure will be engendered; since the development of normal faults demands that the lateral extent of the faulted tract shall increase from T to $T + (\tan h \times d)$ where h is angle of hade and d the vertical displacement.

(The case in which tangential thrust is predominant, and the tendency hence toward ordinary reversed faults, complex folding and tumefaction, falls beyond the scope of this discussion.)

It thus appears that the general disposition of differential radial strain, either singly or combined with tangential strains, is to form reversed faults.

Let the case be farther modified by the introduction of simple vertical stress apart from those due to the unstable equilibrium. Were the stress tensile, its effect would be analogous to that of tangential tension; but since general vertical tension without predominant tangential thrust is inconceivable (whence the sum of tensile vertical stresses is always in defect), and since local vertical tension must equally react on adjacent *couches*, the effect of such stress is nugatory. But if the stress be compressive it will equally relieve AC and strain BD , and thus diminish b ; and since within the crushing strength of the material of the tract there is no limit to this stress, b will be reduced to $b - v \cos \theta m$, where v is such vertical stress, and the original expression for hade will become $\tan x = (n - b - v \cos \theta m)m$; when the fault may hade strongly to the down-throw.

The natural case favorable to profound faulting arises in such an unstable tract as has been assumed within which exist vertical stresses due to its own weight and sufficient initial tension to admit of free lateral movement as rupture occurs. In such case the strain in BD and the disposition to give way in AC will progressively increase downward until the crushing strength of the material is reached; whence *the fault due to radial strain must originate with normal hade in a deep-seated hypogeal couche, and (since rupture in each couche will throw the strain on the next higher) must be propagated upward with progressively diminishing hade, which may eventually become nothing or even reversed; while below the couche of origin the fracture*

must give place to plastic flexure. The full expression for moment of fracture and angle of hade in this case is $\tan \alpha = (n - b - v \cos \theta m + i \cos \theta n) m$; and since the several factors may be approximately evaluated it follows that the regimen of faults formed under given conditions, and conversely the conditions giving rise to faults of known regimen, are roughly determinate.

Below the couche of origin the substance of the tract must be in the condition of ice in a Brahma press or of lead in a pipe machine; and for the purposes of the present discussion, as for the purposes of physical geology generally, it is immaterial whether the mobility be molar or molecular. Obviously such substratum would be equivalent in effect to the quasi-solid terrestrial nucleus assumed at the outset.

If the unstable equilibrium were due to transference of sediment, the sub-surface strata would be compressed beneath the loaded area and allowed to expand under the lightened area, and the throw, as measured by corresponding strata, would consequently increase toward the surface.

In profound faulting, such as is here considered, minor departures of the plane of fracture from the plane of maximum stress may be neglected, since (1) the irregularities would be relatively slight, and since (2) incipient movement would tend to eliminate all such irregularities.

Fractures of the origin and character here contemplated may be denominated *Normal Faults of the First Order*.

Let a homogeneous rigid tract be subjected to simple vertical compressive stress due to its own weight. Within the limits of its elasticity, resulting vertical compression will be relieved by lateral extension; but beyond such limits lateral stress will be in defect, and fracture may occur in each prism of the stratum of imminent crushing just as if it were independent and unsupported laterally. Now as shown by Hodgkinson,* fracture in crushed prisms of crystalline texture occurs diagonally to the direction of stress and separates the prism into wedge-shaped segments; whence the stratum of incipient crushing may develop a series of diagonal fractures each bisecting a prism of height equal to the thickness of the stratum and of width determined by the constitution and texture of the material fractured. Only so much movement of the pyramidal segments can occur as will serve to equalize vertical and lateral stresses: the hade will ever be normal; and from the center of each plane of fracture the throw will progressively increase upward and downward to the apices of the contiguous segments. Such may be termed *Normal Faults of the second order*.

* Cited by Rankine, "Civil Engineering," 4th ed., 1865, 235.

Let a homogeneous rigid tract resting on a mobile substratum, or a tract consisting of alternate rigid and yielding strata, be subjected to vertical compressive stress due to its own weight; and let the rigid portion be traversed by oblique planes of fracture or of weakness due to any cause. Each rigid pyramid, prism or wedge bounded by such planes will then seek a hydrostatic equilibrium and will sink into or be upraised by the mobile substratum to a degree determined by the area of its base and its mass, and the initial planes of fracture or weakness will become faults of normal hade. As in faults of the first order, beneath the *couche* in which pressure equals crushing strength fracture will give place to flexure; and, since the behavior of any yielding stratum will simulate that of the mobile substratum, if there be alternations of rigid and yielding strata, or if all strata be imperfectly rigid, the throw will increase toward the surface.

Dislocations of this character may be designated *Normal Faults of the Third Order*. The principles involved in their development were long ago pointed out by Hopkins,* and are now too generally recognized to require thorough analysis.

Except in the last case the influence of joints in determining the regimen of faults may be neglected; for joints are known to be superficial, while faults are deep-seated.

Since the movements contemplated in the second case must be confined to strata of limited thickness, while in the third case the assumption of profound initial fractures or planes of weakness is unwarranted, the grander faults of the globe must be referred to other causes; and since differential radial strain is an adequate cause, while the phenomena of profound normal faults are collectively such as differential radial strain tends to produce, the hypothesis that these faults are due to such strains is warranted, and is here enounced.

If the hypothesis be valid, it will afford the means of coördinating faults and flexures; it will at once sustain the suggestion of Gilbert† that Appalachian flexures and Cordilleran fractures are but diverse manifestations of identical movements, and render the amount of denudation which the former region has suffered roughly determinate; it will go far toward demonstrating that, whatever be the condition of its interior, the terrestrial crust is—as already indicated by Dutton‡—in hydrostatic equilibrium; and it will afford a new vantage-point from which many of the complex problems of orology and terrestrial physics may be approached.

Salt Lake City, Utah, March 23d, 1883.

* "Researches in Physical Geology," *Phil. Trans. Roy. Soc.*, 1842, i, 53.

† "U. S. Geog. and Geol. Surveys West of the 100th Meridian," III, Geology, 1875, 62.

‡ Notice of Fisher's "Physics of the Earth's Crust," this Journal, xxiii, 1882, 288.