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THE ORIGIN OF LAND-FORMS THROUGH CRUST-TORSION.

By M. M. Ogilvie Gordon, D.Sc., Ph.D., ~~LL.D.~~

(*From 'The Geographical Journal' for October*, 1900.)

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Crust-torsion has already been recognized as a mode of crust-deformation associated with the superposition of different movements upon one another, either simultaneously or successively. But its appearances in the field had been referred more especially to cases of rectangular cross-movement, or, as some writers expressed it, to the action of end and side pressures.

In 1898, I demonstrated, by the field geology of Enneberg, that phenomena of crust-torsion were induced by *any combination of crust-pressures, not only by cross-movements crossing rectangularly, but also by cross-movements at any oblique angle.*

Without entering here into the original cause of crust-strains, it is within the experience of geologists and physicists that any deformation of a flexible sheet of material due to a lateral thrust or pressure will set up internal strains of warping traceable to some inequality in the strength of the material and to consequent local differences in the resistance offered to the deforming tangential strain.

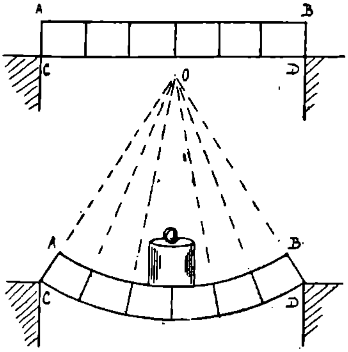


FIG. 1.—BENDING AND WARPING OF A LATH LOADED AT THE CENTRE WITH A WEIGHT.

The least complex case of differential movement can be illustrated by the behaviour of such a material as a wooden lath supported at both ends, and bent by being either loaded by a weight at the middle (Fig. 1), or by end thrusts directed along its length. As every one knows, the upper layers of the wood are subjected to compression, and the lower to tension; consequently we find that the uppermost surface, AB, of the lath is shortened in length, and the lowermost, CD, is increased in length.

Here the differential movements of the layers of a uniform material have given rise to a decrease of surface at one place, and an increase of surface at another.

The deformation of such a lath would correspond to the formation of a trough. A similarly deformed lath would, if inverted, correspond to the formation of an arch. Lines such as AC and BD, which were originally vertical, have got deviated into such a position that they would, if produced, meet in such a point as O (Fig. 2). Similarly, AC and EF would, if produced, meet in P. In short, points which were arranged in vertical parallel lines before the deformation of the lath would, after deformation, be arranged in lines which meet radially in such centres as O or P; such lines have therefore undergone a movement of rotation in a vertical plane. These laths are deformed in a vertical plane because they are weakest in that plane.

Continuing the lath illustration, suppose a lath turned on its side. Then, if its ends were subjected to compression, the lath would be deformed, but this time in a horizontal plane, because it is weakest in this direction. Such lines as AC and BD, which were horizontal and parallel before deformation, would get deviated in a horizontal plane into such a position that they would, if produced, meet in a point like O. Similarly AC and EF would, after deformation, meet in a point like P.

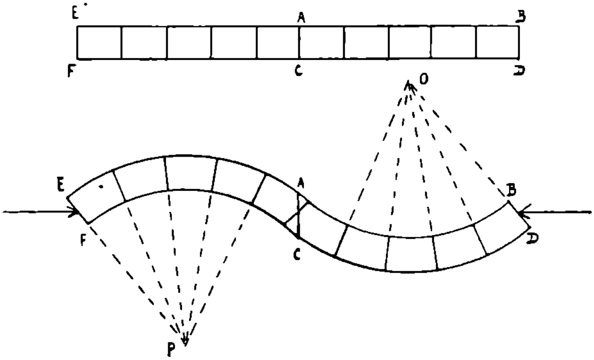


FIG. 2.—BENDING AND WARPING OF A LATH SUBJECTED TO END COMPRESSIONS.

If these two movements, the one a turn in the vertical and the other a turn in a horizontal plane, were combined, such lines as AC and BD would describe cones, and each point in these lines would be twisted or move in a spiral. When a sheet of material is built up of layers heterogeneous both in vertical succession and in horizontal extension, it is most certainly unequally strong in different directions. Whence, if subjected to horizontal compression in any one direction, the general movement of any one part of that sheet will consist of a combination of a horizontal and vertical turning movement—that is, *motion in a spiral.*

Since the Earth's crust is everywhere heterogeneous, the spiral is the fundamental mode of movement in the crust. Observe that this is independently of any repetition of folding. When, however, repetition of folding *does* take place, increased complexity in the spiral movements ensues. Any subsequent differential movements may be influenced by the development of local places of weakness due to a primary series of folds, thus rendering such movements more marked than would arise from heterogeneity alone.

The older system of folding and fracture may be regarded as a floor with lines and areas of weakness; any material which is laid down on the floor, is really laid on a foundation with strong and weak places. If now a new set of forces come into operation, the structure, consisting of floor and material resting on it, will yield readily at these places of weakness. Thus the material which has been laid down in the interval between the first and second foldings will have its movements determined by both foldings.

It is clear that in a region like the Alps, which has in its separate parts suffered from repeated folding movements, the complications due to cross-movements must be very involved.

In Enneberg, in South Tyrol, I regard the torsional phenomena as prominently developed, both because in that area the layers of the Permo-Triassic sheet of deposits offered strong contrasts in strength, and because the whole post-Permian series had been laid down upon an already folded and fractured floor, namely, that of the Permian Alps. I showed in Enneberg that the original horizontal, vertical, or oblique limits between groups of softer deposits and more rigid calcareous or dolomitic rock-masses had been pre-eminently planes of local differential movements during the regional Alpine movements, and were still, in many places, characterized by the continuance of crust-fractures, or by frequent surface-slips. Accordingly, the original distribution of the more rigid and the more plastic deposits was a matter of the utmost significance for the subsequent history of deformation and denudation.

The geological succession of the Upper Triassic deposits is remarkable in the Eastern Alps for the very great differences in the lithological character of contemporaneous sediments, and in the faunas comprised within them. The particular development within each geographical district is termed a particular local "facies," and the geographical district is termed a "province." In Enneberg, the local facies of deposits in the earlier eras of Upper Trias comprises a mixed series of volcanic tuffs and marls, shales, sandstones, together with limestone and Schlern dolomite. On the other hand, the facies of the contemporaneous deposits south of Enneberg is almost wholly calcareous or dolomitic, and is known as the "Schlern dolomite" facies in contradistinction to the tufaceous facies of Enneberg. Both these facies pass upward into various local developments of "Raibl" marls and shales, succeeded by the highest horizons of the Upper Trias, namely Dachstein dolomite. All groups of Triassic rock, both the less yielding and the more yielding, varied rapidly in thickness in Enneberg.

Another important intermixed series of deposits is the Liassic group, succeeding the massive and less yielding Dachstein dolomite of Upper Trias. During the post-Jurassic regional movements of Alpine upheaval, the harder masses exerted subordinate pressures on the softer. "The harder rocks of Schlern and Dachstein dolomite have sometimes been pushed into new positions over the slipping substratum of earthy rocks without in themselves undergoing much relative change of position or perceptible evidence of strain, except where complications are introduced by minor thrusting and faulting along the main planes" (*Geol. Mag.*, 1894, "Coral in the Dolomites").

Local differential movements had also been set up between Enneberg and the adjacent area on the south, which exhibited the calcareo-dolomitic facies, the northern area having sunk relatively to the southern. The mixed tufaceous facies of Enneberg extends along the north of an ancient zone of fracture, in which considerable masses of lava and tuff occur, partially of Triassic age, partially of the younger ages of Alpine movements. In addition to the existence of an old zone of crust-movement, the marked differences of the Triassic deposits on the north and on the south of it tended to make these contiguous areas of deposit act in a measure independently of one another during any future oncoming of movement.

The above examples of the modifying influence that may be exerted upon a regional movement by local strains due to local conditions are furnished upon personal evidence. A third example may be selected from the general literature of the Dolomites. It shows how the presence of the Permian quartz porphyry in the Bozen area affected adjacent areas during Alpine upheaval.

The general stratigraphical relations of the quartz porphyry are thus described by Prof. Suess: "Towards the south and towards the north, older formations appear below the porphyry; towards the east and towards the west, the porphyry descends below younger formations. . . . The younger deposits resting on the porphyry on the east side, form that part of South Tyrol famous for the beauty of its landscape, and which has been somewhat erroneously termed the "Dolomites." The western edge descends more steeply below a long and narrow fault-block of deposits, assuming in some parts the form of a flexure overcast towards the west. The fault-block of deposited material embraces *the whole succession from Permian to Middle Tertiary*, and is lowered into a great crust-trough between the flexure on the western edge of the porphyry and the Judicarian fault-line" ('Antlitz der Erde,' Bd. i. p. 330: the italics are mine).

The position of the porphyry relative to the older strata on the north and south indicates compression of this area from north and south, a compression which was shared by the adjoining areas of the Etsch valley and the Dolomites. On the other hand, the position of the porphyry relative to the younger strata on the east and west shows that differential movements took place locally in cross-directions at the limits between the hard porphyry mass and other less resisting rock-material next to it.

Hence this example is in harmony with one of the writer's conclusions in Enneberg, that local torsional effects arising from cross-movements between dissimilar masses of strata or unequally yielding areas have, in the Alps, been superinduced upon fundamental east-and-west or "regional" axes of deformation. It is a separate question in how far the local strains were synchronous with the more general movement, or if the local strains were earlier or later.

Such a question can only be decided on the merits of each individual case; in the case of the Bozen area, an index of the age of the cross-movements is given in the lowering of middle Tertiary strata within the trough west of the porphyry; since, at whatever time the local differential movements may have begun, they have been in progress since the deposition of middle Tertiary rocks. In the case of Enneberg, there is clear evidence that a general east-and-west folding and faulting of the strata has taken place subsequently to the deposition of all the Mesozoic horizons of rock exposed there. The whole series also shows the folding and dislocating effects of cross-strains, mainly from west-north-west and east-south-east, while the results of more local horizontal, oblique, and vertical differential movements are variously exhibited in the different horizons of rock. It follows that there has been in Enneberg compression and cross-compression. Upon mechanical principles, the resultant effect of superinduced strains is the same, whether the several strains develop simultaneously, or successively, or intermittently, and it has been explained above how superinduced crust-strains in different directions would inevitably cause resultant displacements in the same sense as would be effected by twisting or "torsion" of rock-layers and rock-particles.

It may probably be regarded as true of any wide region upheaved by a folding-movement and afterwards submerged, that old crust-forms and crust-fractures, especially such as allow occasional intrusion and outlet of volcanic material, are determining factors in the distribution of the subsequent deposits. They largely determine the irregularities of the sea-floor, the varying depths of adjacent basins, the local deflections of oceanic currents and the distribution of warmer and colder water, the wash of breakers, and other local conditions which influence the distribution of pelagic faunas (cf. Sir John Murray, *Geogr. Journ.*, July, 1899). And in this way, by local demarcation of lithological and faunal facies, local idiosyncrasies having reference to older surface-forms are imprinted upon a region for all time.

With the oncoming of another movement of upheaval from the same direction as the earlier movement, or from any other direction, the boundaries of facies laid down in that region during the previous ages of deposit are specially liable to become zones or planes of differential movements, although the individual facies can only exert local modifying influences. Hence incidents of folding and faulting, of intrusion of igneous rock, of subaërial and submarine denudation associated with an earlier upheaval are the basis directly and indirectly of subordinate or local systems of crust-strains which interfere with the main system of strains governing a later upheaval, and are concentrated along old depositional and structural limits.

During the progress of the new regional movement, the new axes of deformation determine new boundaries of facies, and these new boundaries of different deposits or of intrusive and sedimentary rocks offer additional planes of differential movement that take effect as the movement progresses.

For example, the Cretaceous epoch is regarded as the second great mountain-forming period in Alpine history, and during it both longitudinal and cross-faults are said to have been developed, more especially in the Eastern Alps. Austrian geologists are of opinion that the deposition of Upper Cretaceous rocks in certain parts of North Tyrol was localized in accordance with the previous development of important Cretaceous fault-lines, also that these faults were afterwards zones of marked deformation during the farther upheaval of the "limestone and dolomite" region of North Tyrol. This case offers analogy with certain points that I demonstrated in Enneberg, (1) in respect of the localization of facies in the vicinity of Triassic faults; (2) in respect of the tendency of any later movements in the same region to be influenced by the old lines of fault.

But still other agencies have to be considered besides these of sedimentation during the new movement. For as the Cretaceous and Tertiary lands emerged in the Alps, they were subject to the processes of denudation and to subsidiary movements of crust-adjustment following upon these. The complications of cross-movement were therefore bound to increase as the history of upheaval and denudation went on side by side, and the actual crust-forms shaped during the Cretaceous and Tertiary epochs could not be other than complex resultant forms, combining effects of differential movements accomplished in virtue both of older and newer boundaries of deposits, directions of crust-weakness, and influences of surface-erosion.

As early as 1894 I had pointed out that the Cretaceous-Tertiary movements only in so far followed the main lines of the Triassic movements, that they also crossed these at various angles. Further examination and mapping showed me that radiating dykes were associated with characteristic "bundles" of faults and with curvatures of the strike developed in the Cretaceous-Tertiary epochs. The complications corresponded in essential features to the structure which Prof. Lossen had worked out in the Harz, and had there attributed to torsional crust-movement. Many other complexities in Enneberg, such as the minor thrusting in oblique directions across a main overthrust, the disposition of the outcrops of rock-horizons in sigmoidal or S-shaped curves, and in whirl-shaped figures generally, the gradations of strike in diverging fault-blocks, the rapid variation in the angle of inclination of fault-planes, and frequent forking and intersection of faults, indicated a solution based upon principles of crust-torsion.

I then formulated certain definite principles of crust-torsion which seemed to explain the present complicated structural relations in Enneberg—the leading principle being that in Enneberg we have not a simple lateral thrust to deal with, but the resultant effects of different lateral thrusts differing in intensity and crossing one another.

It had been hitherto accepted in Alpine geological literature that the lateral pressure which led to the upheaval of the Alps in Cretaceous and Tertiary time came from one direction, mainly from the south, and caused upfolding of Alpine territories in a general system of east-and-west folds, associated with gigantic crust-creep of overthrust masses, more especially towards the north on the northern edge of the Central Alpine chain, and in less degree towards the south on the southern edge of the Alps; the whole structure had also been dislocated by longitudinal and transverse faults, some of which were older, others younger, than the folds and overthrusts.

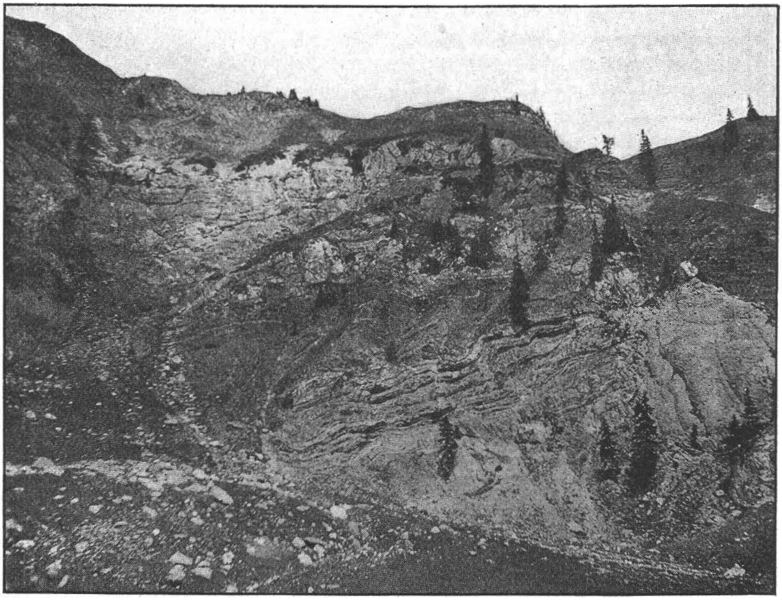


FIG. 3.—WEDGES OF LOWER AND MIDDLE TRIAS ABOVE THE PLANE OF OVERTHRUST IN BUCHENSTEIN VALLEY, VIEWED FROM THE SOUTH.

In agreement with this, I found that *all* the rock-deposits in the Alpine district which I examined had been subjected to compression from north and south, and folded in a general fundamental system of east-and-west folds. But I also found that this system had been crossed by a transverse or slightly oblique system of anticlines and synclines, and subjected to extreme deformation and distortion from cross-directions. The longitudinal folds had been steeply tilted, or "overcast," *i.e.* laid over into more horizontal positions, or fractured, and the parts carried into different oblique directions. Associated with the cross-compression new folds had formed, and overthrust masses had travelled in transverse and various oblique directions. Within the Dolomites, where I worked, I found that in several cases overthrust slices had crept obliquely across the smaller folds and crumples of intensely-crushed underlaid masses, which had been dragged out and tilted slantingly upon one another in wedge-like fragments, representing subsidiary overthrusts accompanying the major overthrust.

An example of such oblique shearing is given in the photograph of an outcrop in the "Buchenstein" overthrust south of Enneberg, in the Dolomites (Fig. 3), which is interesting also in showing igneous rock-material injected into these planes of fracture and shearing.

The photograph Fig. 4 shows a highly characteristic effect of cross-compression upon the dolomite rocks. The cliff in the photograph is composed of dolomitic strata which form part of a longitudinal arch, the strata being tilted so that the planes of bedding incline at an angle of about 20° to the north. Far more apparent than the planes of bedding are the planes of separation which cut the bedding planes almost vertically, and extend in north-north-west—south-south-east direction, indicating the action of lateral pressures along east-north-east and west-south-west direction.

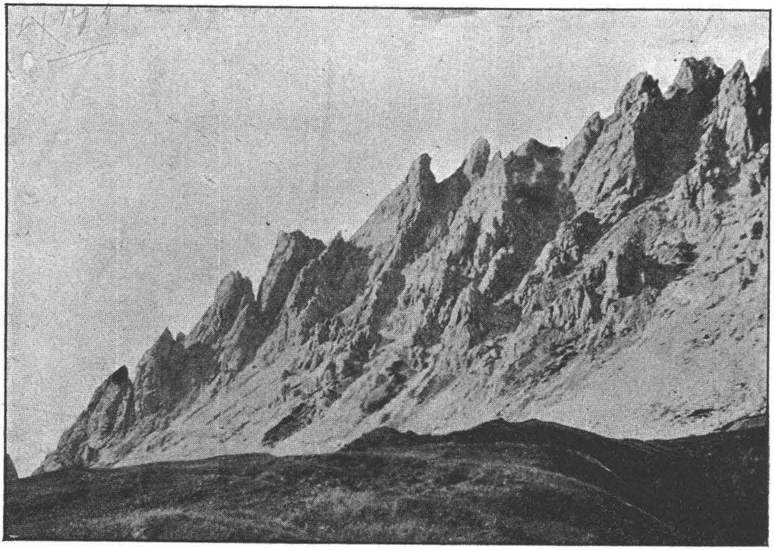


FIG. 4.—SLABS IN SCHLERN DOLOMITE ROCK, PRODUCED BY CROSS-PRESSURES: SPITZKOFL GROUP FROM GRÖDEN PASS.

The photograph Fig. 5 represents a small part of the eastern transverse arch of the mountain massive of Sella, in Enneberg; this arch comprises several *transverse* folds and fractures, indicating the action of lateral pressures transversely across the east-and-west systems. The western transverse arch of Sella faces Langkofl mountain, so well known to climbers; it shows nearly undisturbed horizontal stratification, being part of a wide arch deeply cleft and jointed (Fig. 6).

These are only a few examples of the simpler observations that can be made on cross-movements in the Dolomites. The difficulty that attends the elucidation of the complex resultant system of folds and overthrusts is due to the presence of a network of fault-planes, highly inclined or vertical, that have dislocated the series of folds and overthrusts, and displaced them in vertical and horizontal senses. The Sella mountain has subsided in several "fault-blocks" since the epoch of overthrusting, so that in its case faulting and erosion have only left incomplete remnants of the structural forms that were assumed by the upper horizons of the rock-series in the Dolomites. It is therefore chiefly in the lower horizons of the series exposed in valleys and high meadowlands that we have to seek fulness of detail; both at Gröden pass and in Buchenstein valley convincing evidence may be observed of the action of differently directed movements in the course of Alpine upheaval (cf. "The Torsion Structure of the Dolomites," 1899, *Q.J.G.S.*).

The leading faults of adjustment are of wide extent, continuing beyond the limits of the district examined; several of these converge in the interesting "eruptive centre" of Predazzo. The faults associated with the local subsidences and surface-slips more especially attest the influence of local differences in the character of the contiguous rocks, *either those which were originally next one another, or those which had been brought by the previous complex movements of bending and thrusting into juxtaposition with one another.* It would not be accurate to describe even the leading faults simply as a system of longitudinal faults crossed by transverse faults; they present varied arrangements in fault-bundles and fault-polygons, and, like the joints and the greater and finer separation-planes through the rock, intersect each other, or subdivide into forking branches of less importance.

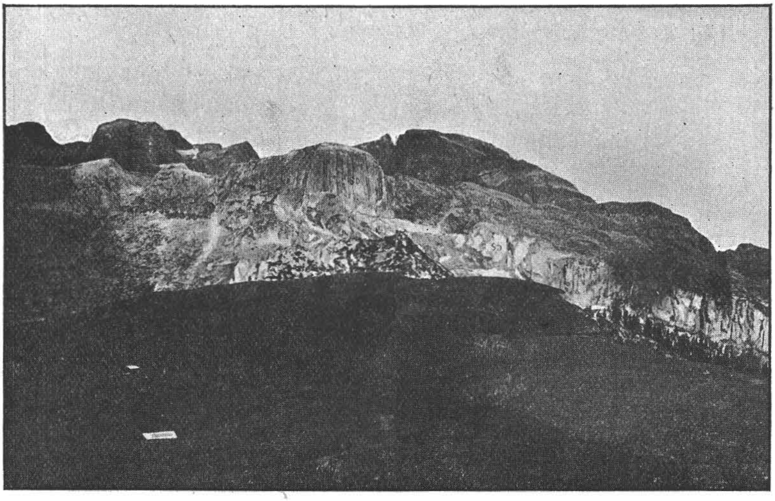


FIG. 5.—PORTION OF THE EASTERN TRANSVERSE ARCH OF SELLA MOUNTAIN IN THE DOLOMITES, VIEWED FROM THE EAST ON CAMPOLUNGO PASS. SD = SCHLERN DOLOMITE.

The general effect of these adjusting movements in the Dolomites has been to depress the whole region, cutting it up into numerous fault-blocks, some more, some less depressed. Thus we have evidence that during the chief epochs of folding and overthrusting in the "Dolomites" the whole region stood much higher, and now represents a sunken and fragmented Alpine "central massive."

The transverse and oblique folding and overthrust movements have affected Eocene and even Oligocene strata within South Tyrol, and must therefore have been in progress during the Oligocene and Miocene geological epochs; while the faults that have displaced the folds and overthrusts may have originated at various periods, but certainly must have been also later than these epochs of overthrusting.

We seem, therefore, bound to refer these displacements and adjustments at the earliest to the Miocene eras, when the loading and unloading of rocks that had been in process both by dynamic and subaerial agencies of denudation had considerably altered the earlier conformation of the uplifted system. From the evidence of the subsidences in the Dolomites, it is particularly to this adjustment phase that we may refer the *relative downthrow of the limestone and dolomite ranges, and the relative uplift of the central massives and central chain of the Alps generally.* The subsidence of the lateral chains enabled the outward creep of masses of rock to take place from the central chain over the limestone and dolomite chains, and further overthrusting movements from areas of uplift over troughs both within the Alps and on the outer zones, in which Oligocene and Miocene deposits had already gathered. Thus it is necessary to decipher one set of movements superposed upon another again and again in the long history of the Alpine upheaval, and the actual relations that we now see are *resultant* relations.

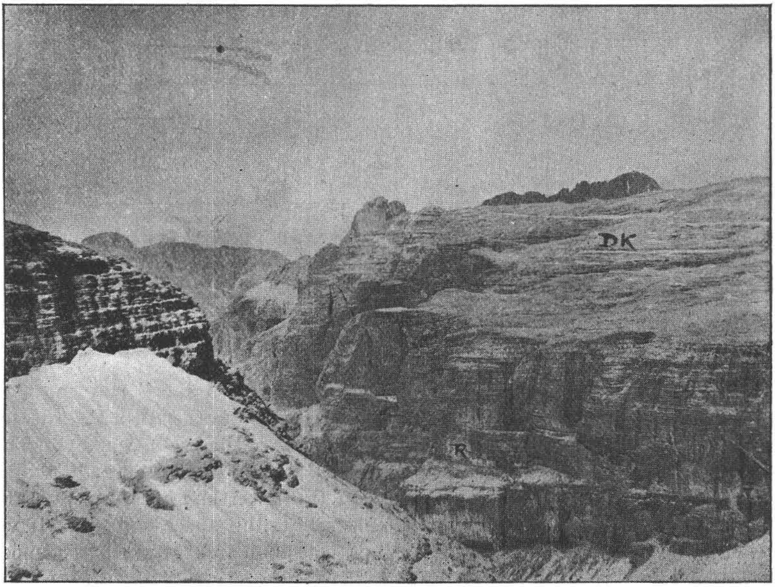
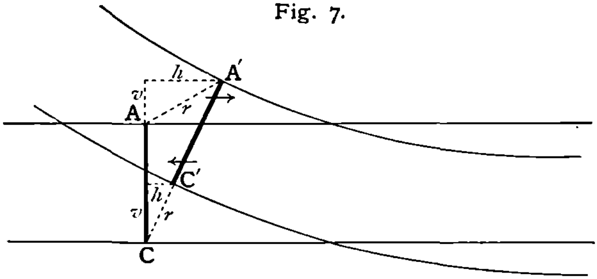


FIG. 6.—PORTION OF THE WESTERN TRANSVERSE ARCH OF SELLA MOUNTAIN, IN THE DOLOMITES (TOWARDS VAL DELLA STRIES). DK = DACHSTEIN LIMESTONE OR DOLOMITE. R = RAIBL STRATA. VIEWED FROM THE EAST, NEAR THE BAMBERG SHELTER HUT BELOW BOE SUMMITS.

This undoubtedly presents the most involved picture of the Alpine upheaval which has yet been given, but it may seem simpler if analyzed with the aid of the above illustration of the compression of a lath in different directions, and the effects of cross-warping that inevitably ensue. Let us suppose, instead of the lath, a series of sedimentary deposits of uniform character subjected to lateral pressure from a certain direction. Then, with the beginning of compression, the tendency is for the layers to be least disturbed in their relative position at the "crests" of arches and the "kernels" or hollows of troughs, and to assume a tilted position in the "middle limb," or intermediate part between an arch and a trough. The tilting of the series implies that, accompanying the vertical translation, there is a lateral displacement in rotatory sense of any vertical row of particles composing the several layers, the particles being displaced relatively to their own original position and relatively to one another.

In Fig. 7, let the points A and C in the vertical line AC represent the original position of the uppermost and lowermost particles, and let A′ and C′ be the altered positions of the points after some period of lateral compression. At first, before the series is much shortened in its horizontal extent, the point A turns to the right, C to the left of their original positions; but with increased compression and subsequent farther shortening of the series, both the points A and C may move to the right of their original position, A, however, relatively farther than C. Clearly under compression there is relative differential movement between A and C. The horizontal components (*h*) and the vertical components (*v*) of the resultant displacement (*r*) are different for the particles in the upper and lower horizons, the lower horizons in Fig. 7 being retarded relatively to the upper horizons. If we turn the figure upside down, it represents then part of an arch in which the upper horizons have been retarded relatively to the lower.

Fig. 7.



AC. *original position*
A′C′. *altered position*
h. *horizontal, v. vertical, r. resultant, displacements*
⇄ *differential strains*

As compression continues (cf. Fig. 2), the tendency will be for the upper horizons to keep slipping partially over one another and accumulating in the trough or inthrow area; and with increased intensity of lateral pressure, the chief crush effects in the upper horizons would be within the trough, the chief crush effects in the lower horizons would be in the body of the arch, while in the intermediate area between arch and trough, the sliding, shearing, and overthrust effects would be chiefly presented. At the same time, the chief stretching and rending effects would be in the upper horizon of a series in the crest, and in the lower horizons of the same series in the trough. There faults might form, and in some cases igneous intrusions might become intermixed with deposits and crush-breccias. On account of the differential strains along each vertical line (Fig. 7), there is the tendency for inclined fault-planes to form through the midway points, therefore to hade inward to the trough, and to intersect more steeply inclined or vertical fault-planes passing through the intermediate area between arch and trough.

If the horizontal compression becomes very great, one or both arch-crests on opposite sides of a trough may bend back above the trough at the intermediate area. Then more complex results are obtained; inclined fault-planes with downthrow towards one trough may be parallel with reverse fault-planes upon which a portion of an arch has moved backward over an adjacent trough; oppositely directed reverse fault-planes may form, or an earlier series of arches and troughs may be cut by later reverse planes and the advance of overthrust rock-masses. It follows that these groups of intersecting planes of fault must be presented with which geologists are familiar in the sections of highly disturbed regions.

In accordance with the lath illustration, let the sheet of deposit be subjected afterwards to lateral compression from any other direction, let the conditions of strain be varied in any appreciable degree, so that we have a resultant system of displacements combining different systems that have acted over the whole sheet of deposit. Under such conditions of regional cross-compression, the most striking effect obtained—even upon theoretical grounds—would be that of centralization, since all the possibilities that arise under intense lateral compression from one direction are also true for the effects of lateral compression from the oblique and transverse directions.

So long as Alpine geology was based upon the principle of lateral pressure acting from one direction, no sufficient structural explanation of an Alpine central massive was forthcoming. Accepting the principles of cross-compression, the "fan-shaped structure" of the central massives, and generally the "whirl-shaped" figures in the conformation of the Alps and in the conformation of the mountain systems round crust depressions of Southern Europe, find as natural an explanation as the whirl-shaped forms in the region of the "Dolomites" which I examined.

The same modes of deformation that are accomplished on a grand scale by the action of varying cross-strains due to regional causes and acting over wide regions, are accomplished on a smaller scale by the local action of these subsidiary cross-strains arising from differences of resistance exerted in different directions with a sheet of heterogeneous rock-material. The combination of any subsidiary with any major movement produces a resultant local deformation, and the proportional intensity of different strains must be subject to all manner of local variations during the progress of regional movement. In short, consistently with what I have seen in the Dolomites, I am of opinion that all crust-deformation due to lateral compression is accompanied either locally or over wide regions by cross-movements, and presents corresponding resultant displacements of rock-masses, layers, and particles.

In a paper read at the Dover Meeting of the British Association (September, 1899), I compared the superposition of subsidiary crust-movements upon greater crust-movements, or generally of two or more different movements upon one another, with the familiar case of "Harmonics" in physics. As that paper has not been published, the following passage is quoted:—

"The fundamental structural form of the Gröden pass is that of an arch, while the fundamental form of the opposite mountain massives is that of a reciprocal trough on either side of the Gröden pass arch. The distortion of the fundamental forms has been caused by the tendency to the superposition upon the major forms of other subordinate or cross-forms due to subordinate or cross-strains; so that the present conformation of the surface on that area may be described as a *resultant* conformation. Similarly, what is designated a Central Massive in the Alpine mountain-system bears upon it numerous subordinate crust-forms due to subordinate movements, and a major trough or 'basin' in the Alpine system comprises numerous subordinate arches and troughs. The 'dolomite' district of South Tyrol, for example, is a crust-basin, which is incorporated in the Peri-Adriatic area of subsidence, but itself comprises numerous local areas of subsidence (such as Sella Massive and Sett Sass), demarcated by local areas of uprise (such as Gröden pass and Campolungo pass).

“Again, the great Alpine massives and Alpine basins are themselves component parts of the *regional* uprise represented by the mountains of Southern Europe as a whole in their relation to adjacent areas of relative depression.

“This aspect of the structure of any great mountain crest or system presents a suggestive resemblance to a diagram of the condition of a medium transmitting a complex sound, such as that of a musical note with several harmonics (cf. Fig. 8 from Fourier). . . . Indeed, the complications of geological structure that may result from successive or simultaneous applications of simple lateral pressure are such as in the end to produce a map as little suggestive of simple anticlines and synclines as the diagram of the medium transmitting a musical chord is of several diagrams representing the effects of the constituent notes.

“We have, in studying the Alpine system of crust-forms, to keep well in view the ‘interference’ of smaller movements with greater; the tendency to the superposition of movements affecting any two subjacent layers or horizons of the crust upon folds affecting greater thicknesses of the crust or complete crust-blocks; likewise the tendency to superinduce folds within a small area upon folds extending over a wider area; more generally, the tendency to superinduce cross-folds at various angles upon longitudinal folds, or any different series upon one another; and the consequent development in the crust of characteristic series of torsional phenomena varying in accordance with the complexities of the cross-movements.

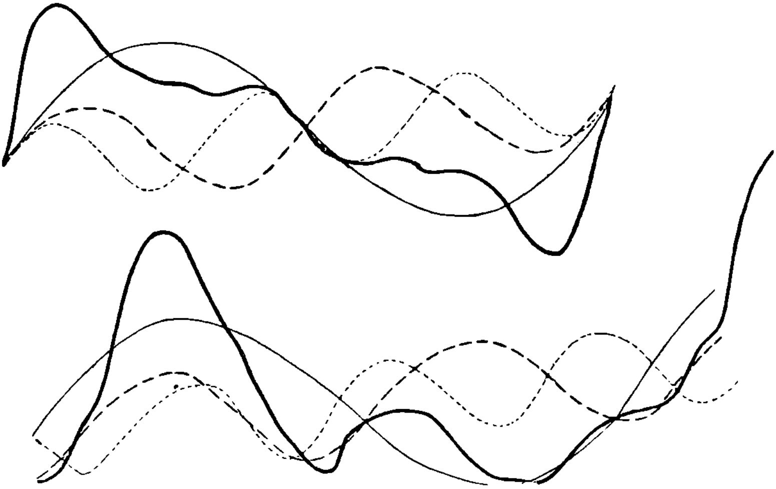


FIG. 8.—RESULTANT WAVE-FORM.

▬▬ resultant. ········ vibr. 2 } partial tones or overtones.
——— vibr. 1. - - - - - vibr. 3

Actual resultant wave formed during the simultaneous propagation of the simple waves corresponding to a note, its octave, and its twelfth (two phases shown).

“In case any one should question if cross-folds can tend to form simultaneously, I shall merely indicate the line a reply would take. We have to remember that at any one locality there may be a fundamental folding movement taking place in virtue of a great regional set of earth-pressures, and at the same time subsidiary folding, sliding, and shearing movements taking place in virtue of local pressures. It is true that any territory folded in such a way would indicate folding around definite centres, and bring us back to one of the most famous theories of Alpine upheaval. The better appreciation, however, of the 'resultant' of differential strains in any part of the Earth's crust undergoing deformation brings us in these days back to the general conception upon a more precise physical basis."

Those who are familiar with the mechanics of a wave, compounding two or more simple harmonic motions, will at once realize how many different forms of spiral and elliptical paths of movement might be described by earth-particles under the influence of superposed and intersecting movements; farther, how the directions of such paths might be related to one another as positive and negative, and the resultant strain in some places be a neutral strain, in others a positive strain, in others a negative strain.

Hence two of the results of the writer's observations in Enneberg, namely, that *torsional displacements have been performed in relative, positive, and negative directions with reference to local foci, and that these displacements have taken place in virtue of superposed movements*, conjointly verify for dynamic movements in the Earth's crust the general conception of phenomena of "interference."

To sum up, each rock-particle in the Earth's crust, when under the strains of lateral compression, behaves (1) as an individual bearing dynamic relations to neighbour individuals; (2) as an integral part of a rock-layer, facies, or mass bearing dynamic relations to adjacent and subjacent rock-layers, facies, or masses respectively; (3) as an integral part of a locality or region of the Earth's lithosphere bearing definite dynamic relations to the localities or regions next it; (4) as an integral part of a superstructure whose floor is in many places molten, and therefore plastic.

A disturbance in any one of these dynamic correlations carries with it a disturbance in the others. The action of a simple lateral thrust over a wide region during regional crust-compression is scarcely conceivable under these complex conditions of correlation.

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