PAPERS AND PROCEEDINGS OF THE ROYAL SOCIETY OF TASMANIA, VOLUME 89

The Orocline Concept in Geotectonics

PART I

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(WITH 22 TEXT FIGURES)

ABSTRACT

The face of the globe shows many areas where orogenic belts wheel in trend through large angles, sometimes as much as 180°. Such a form could have one of two origins. Either the orogenic zone had that shape from the beginning, or the bend represents an impressed strain (here defined as an *orocline*). Classical geology has always made the first assumption, explicitly or implicitly, using the concept of cratons around which the orogens were moulded. However, logical scientific analysis demands that we should also examine the consequences of making the second assumption. Twenty-five such cases occur on the face of the globe. In every case the major structures of the region not only agree with the assumption, but lesser compressional and tensional structures fall where they would be predicted by the impressed strain theory, and quite unexpected solutions of other major tectonic problems result. Six of these oroclines are worked out in detail in this paper. Six more are presented more briefly. When all such oroclines, together with other identifiable strains, are reversed, there appears a Laurasia substantially identical with that deduced by Du Toit on wholly different grounds.

INTRODUCTION

Sir James Hall first made the induction that observed contortions in strata were actual deformations of beds originally flat, and therewith structural geology began. A century and a half has seen much progress, but most of it has been towards increasing our understanding of the internal anatomy of orogens. Little has been done about the deformation of the orogenic belt as a whole. Again, with the outstanding exception of Suess and his disciple Argand, the bias of structural nomenclature is towards the deformation of the profile cross-section of the orogen, not its shape in plan. There are adequate terms for the deformation and dislocation of strata in the vertical plane, and even for the further deformation in the vertical plane of such folded structures but there is no term for deformation of structures in plan, and still less for the impressed bending of the orogenic belt itself, or for its longitudinal stretching. Yet in view of the horizontal compression involved in orogenesis, and its longitudinal variation, there must be substantial deformation in plan. This is emphasised by a consideration of the relative dimensions of an orogen and the physical limits of its possible deformation.

The order of the dimensions of a mountain system is 10^3 km. or more long by 10^2 km. wide by 10^1 km. deep. Reduced to a model we might think of it as a strip-lamina. Its plan and cross section are shown to scale in A of Fig. 1. When such an orogen is folded, deformation in the vertical direction is closely confined by gravity and isostasy. Before and after orogenesis the locus of the centre of gravity of elements of the strip departs little from a gravitational isopotential surface, and the cross-section of the deformation of the orogen is still contained wholly within the lens B. It is quite impossible for the orogen to be deformed into the form C. The dimensions of length and breadth, on the other hand, are not confined or limited. Alpine geologists speak in terms of 500 km., even 1200 km., of horizontal translation. Only 400 km. away on the strike of this compression is the central plateau of France where the Alpine compression is nil or negligible, and 400 km. away normal to the strike of the Alps the Apennines disclose strong compression in a quite different direction, of an amount which has not been closely estimated but would surely be of the order of 10^2 km. These facts are among the most certain data of field geology.

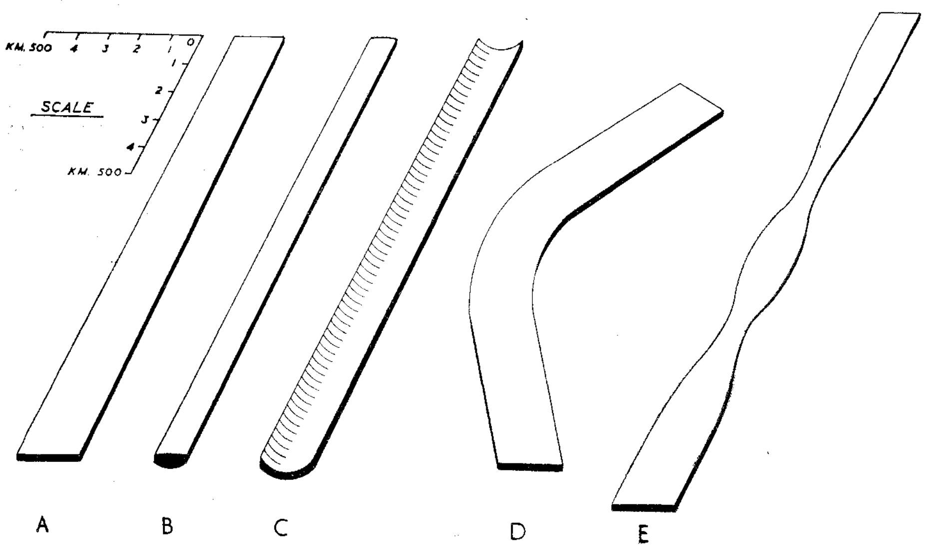

FIG. 1.—The relative dimensions of an orogen.

When such phenomena are closely analysed, it will be found that their geometry and plan relations can only mean strong movements in different directions *with differential rotation through large angles* in the plan view. It is impossible to escape the implication of great change of surface shape, bending, shrinking and stretching in the non-limited dimensions of length and breadth (that is in plan). This deformation might reasonably be far greater than the change of shape in the end section, and there seems no logical reason why deformation by bending in plan to the form D of Fig. 1 might not occur or stretching to the Form E.

It is reasonable to examine the surface pattern of the globe to see whether there are structures which could be of such kind. If this quest is successful, we should follow out the consequences of assuming that they are in fact deformations in plan, of straightening and restoring them to their implied former positions. This procedure has yielded surprising results.

Evidence is presented that such structures probably do exist and that, if they are herein correctly interpreted, they are in fact the most important structures of geotectonics, they provide the key to the understanding of the evolution of the continents, and integrate all the other structurel features of the earth into a coherent pattern. The concept opens a new vista of tectonic understanding quite as important and as fundamental as Hall's initial induction.

DEFINITIONS

For an orogenic system which has been flexed in plan to a horse-shoe or elbow shape, the name *orocline is proposed.* (Greek ορος, mountain, κλινο to bend.) Orocline replaces the term geoflex which has already been used for such structures in a preliminary note (Carey, 1954A) and in lectures given before the Geological Society of Australia, Geological Society of South Africa, and the Pan Indian Ocean Science Congress. However, orocline is more precise, in that it is specifically the orogen which is bent not the associated shields; in addition, geoflex is a hybrid.

For a mountain system which has been torn free from the continental shield to which it is genetically related, the name *diothesis* is proposed. (Greek, διωθεω, to tear away, pluck out. Diothesis, o long as in both, and accented.)

For a diothesis which has been stretched by significant fraction of its length, the name *orotath* is proposed. (Greek, ορος, mountain; ταθεις, to stretch.)

Examples interpreted as belonging to each of these categories will be given in turn, with evidence supporting such interpretation. It is intended that these terms should be reserved for the really major structures of the earth's surface—of the order of 1000 km. long. It is not proposed that they should be applied to structures less than 100 kilometres long. The term megashear has already been used for transcurrent faults of very large displacement. This term will be used herein where the displacement exceeds 100 km. Such a fault might be conceived, not as part of an orogen, but as a co-ranking structure which offsets the orogen as a whole.

THE ROTATION OF SPAIN

The Pyrenean Compression

The Pyrenees form a belt of intense compression folding and overthrusting, which is widest and strongest at the eastern end against the Gulf of Lyons and diminishes in width and intensity westwards to the head of the Bay of Biscay, where the main movements die out. Subordinate folds continue the trend along the north coast of Spain as far as Oviedo. The pattern of the late Mesozoic and Tertiary folding is shown in Fig. 2 in which the intensely compressed zones are hatched and cross-hatched; in the more moderately folded areas the principal anticlinal trends are shown in full lines and synclinal trends in broken lines.

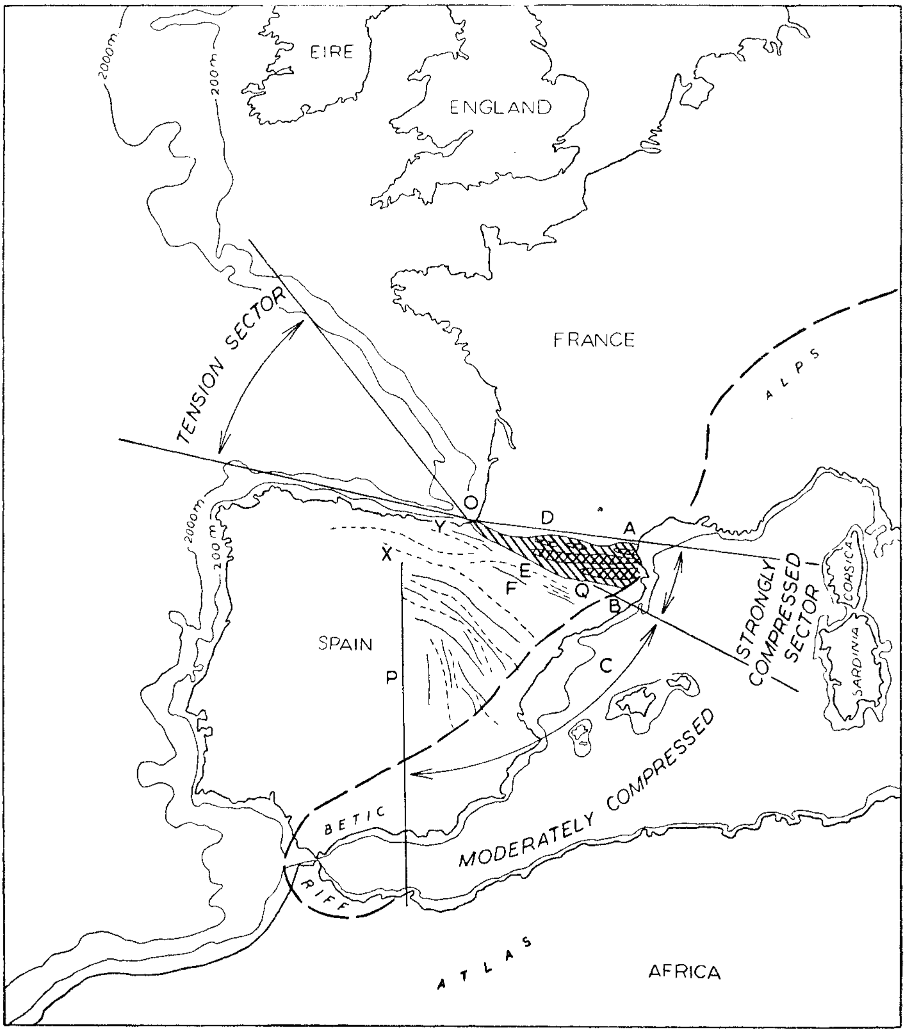

FIG. 2.—The Pyrenean compression.

Now a section drawn across the Pyrenean compressed belt along the line AB in Fig. 2 would show intense compression and shortening. If we consider only relative movement we may regard one side *A* as fixed. Then the shortened section indicates that before the folding the point *B* must have been at some point such as *C* on *AB* produced. A parallel section at *DE* would also show folding and shortening, but less in amount than at *AB*. Considering the relative movement of *D* and *E*, *E* must originally have occupied some point such as *F* on *DE* produced, *EF* being less than *BC* since the shortening is less. Finally, a third parallel section through *O* or a little west of it will show no folding, hence, no shortening, that is, the point *O* will not have been moved by the folding.

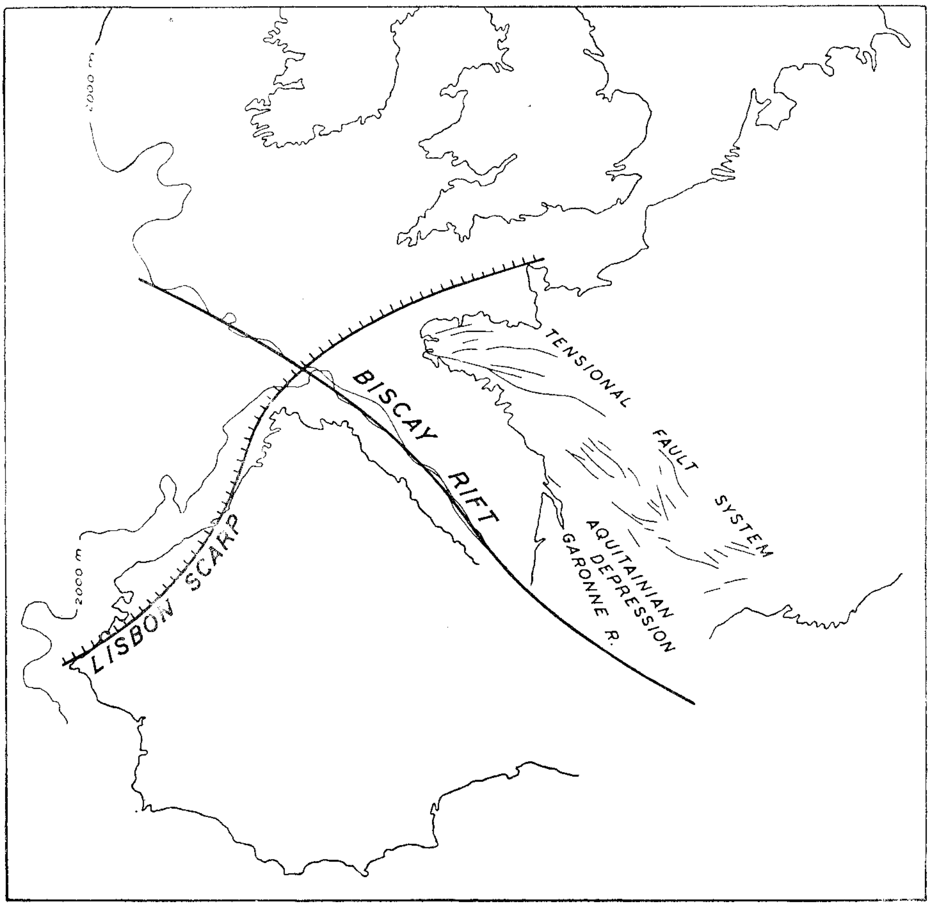

FIG. 3.—Tensional structures in the Pyrenean region.

The pattern of the Pyrenean compression therefore implies that the line *OEB* was rotated about *O* relative to the line *ODA*, from some position such as *OFC*. The precise position could theoretically be re-established by a careful determination of the amount of shortening represented in the Pyrenees.

Such a compression of a sector by shortening through the angle *BOC* can only mean that within the circular area described by rotating *OB* about *O* there must be a complementary tensional area which has been stretched through a sector equal to *BOC*. If we go back round the arc looking for such a tensional area we come to the Bay of Biscay. The Bay of Biscay (as determined by the 200 metre isobath whence there is a steep slope to the floor) has a triangular shape opposed apex to apex to the Pyrenean compression. The floor of this area lies between

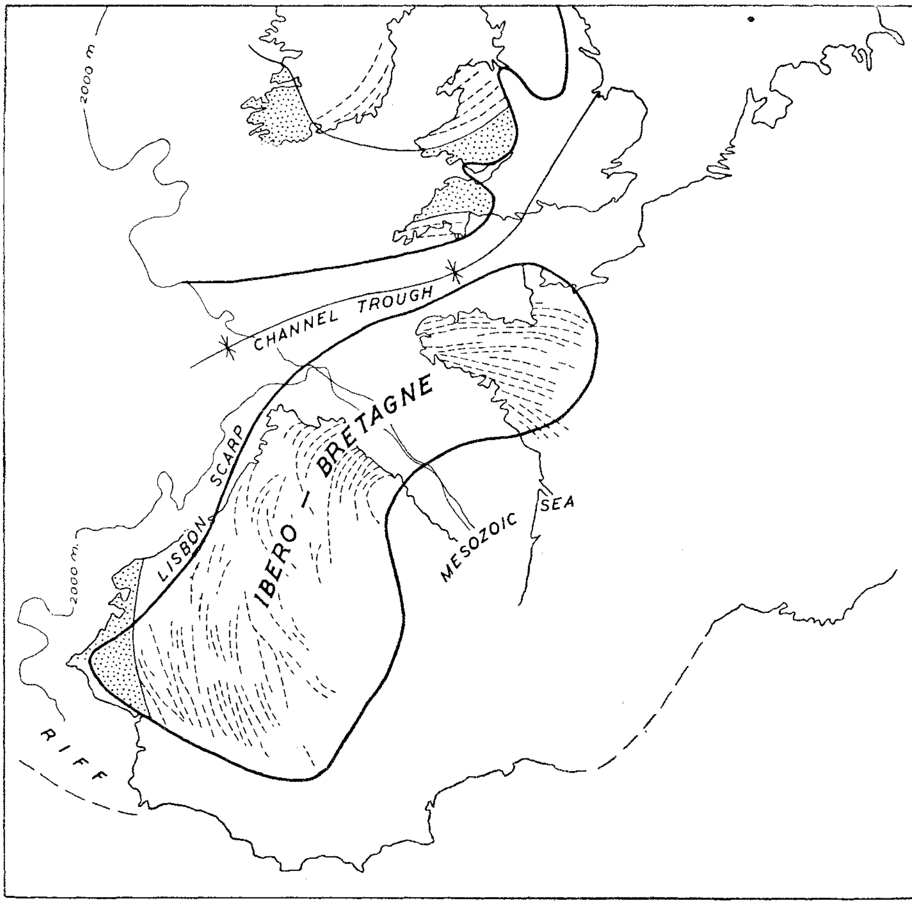

FIG. 4.—Matching of structures across the Biscay Rift.

3 and 5 km. below the platforms of France and Spain. This approximates the normal difference in level between continents and ocean floors of the Atlantic and Indian type. The Bay of Biscay should therefore be regarded as normal ocean floor. It could not be foundered continent, for to depress continental material to such a level would involve very large negative gravity anomalies across this area.* Further confirmation is given by submarine " seismic " spreads carried out by Bullard and Gaskell (1941) and Hill and Laughton (1954) which show that the steep continental slope running from south-west of Ireland to the head of the Bay of Biscay marks the boundary between typical continental and oceanic profiles with the Mohorovicic discontinuity rising from depths of 30 to 40 km. to very shallow depths.

* The only escape from this conclusion is the suggestion by Lees (1954, p. 402) that the Mohorovicic discontinuity is a paramorphic phase change, which, however, is incompatible with the very different depths of the discontinuity under continents and oceans respectively.

If the Pyrenean compression is smoothed out by rotation of *OB* about *O* away from *OA* the movement would (qualitatively) close the Bay of Biscay by bringing the Spanish continental shelf into contact with the shelf off Brittany. The simplest interpretation of the morphology of this region is therefore to regard the Bay of Biscay as the tensional rift demanded by the geometry of the Pyrenean compression, since there is no other feature in the region which has the required characteristics, and the magnitude of the tension called for is certainly great enough to have permanent physiographic expression. It seems therefore reasonable to conclude that the Spanish Peninsula was rotated through some 35° during the Pyrenean folding.

This should be capable of being checked geologically by studying second order strains. It would be surprising if a rotary compression of the magnitude indicated by the Pyrenees should occur without other evidence of rotary compression with the same general origin: likewise we might expect a rift on the scale of the Bay of Biscay to be accompanied by subsidiary tensional fractures parallel to the primary rift and with the same sense of movement. Such confirmatory strains are in fact present, and indeed, apart from the Pyrenees and the Biscay gulf, they are the dominating morphological features of the region.

Subsidiary Rotary Compression

It has already been mentioned that there are a number of folds in north-eastern Spain which appear to be related to the Pyrenean compression. These folds, the trends of which are shown on Fig. 2, have quite large dimensions, but represent much less intensity of compression than the Pyrenees. Their pattern also implies a rotation of the Iberian Peninsula in the same sense as the main Pyrenean compression and the Biscay rift. For, if we assume as a first approximation that each of the folds shown represents the same amount of shortening, then there is five times as much shortening between *P* and *Q* as there is between *X* and *Y*. This means that the line *PX* has been rotated towards the line *QY* during the folding. This also demands a complementary tensional sector. Hence, we may conclude that the tensional rift represented by the Bay of Biscay is the complement not only of the intense Pyrenean compression but also of this Ebro bundle of folds, the compression of the former being apparently appreciably greater than that of the latter.

The centre of the rotation implied by the Ebro folds seems offset somewhat to the west of the Pyrenean and Biscay centre. This should not be surprising, for it would require a very special distribution of forces to produce pure rotation of a non-pivoted tabular body. Rotation accompanied by some translation in the same sense is a much more probable type of movement. This seems to have occurred in the case of Spain.

The angle of the compressed sectors on Fig. 2 is not a measure of the angle through which rotation has taken place. These angles merely limit the distribution of compression effects, which theoretically could be distributed through the whole of the sector complementary to the tension sector, or be confined to one or more weak zones. The angle of compression could only be determined by measuring the whole shortening along an arc both for the Pyrenees and the smaller folds of the Ebro group and dividing the measured shortenings by the radical distances from the centre of the sector. These angles should add up approximately to the rift angle of the Bay of Biscay. Theoretically this offers a method of testing the hypothesis, but it would be tedious to carry out, and the limits for subjective interpretations in determining the amount of shortening in the Pyrenees are probably great enough to make the check only qualitative. Nevertheless, it would be useful to make the attempt.

Second Order Tension

A conspicuous feature of the geological map of France is the group of tension faults which trend south-easterly from Brittany almost to the mouth of the Rhone. This group of faults, shown on Fig. 3, was active during the Upper Mesozoic and Tertiary and was responsible for the development of the Aquitainian basin. It may also govern the present coastline from the mouth of the Garonne to the tip of Brittany. The outcropping faults of the system are distributed through a belt 100 kilometres wide and 700 kilometres long. Towards the south-west they become submerged under the younger sediments of the Garonne valley. It is not impossible that they may be present all the way to the Biscay Rift. This fault system is clearly a major tectonic feature of the region,

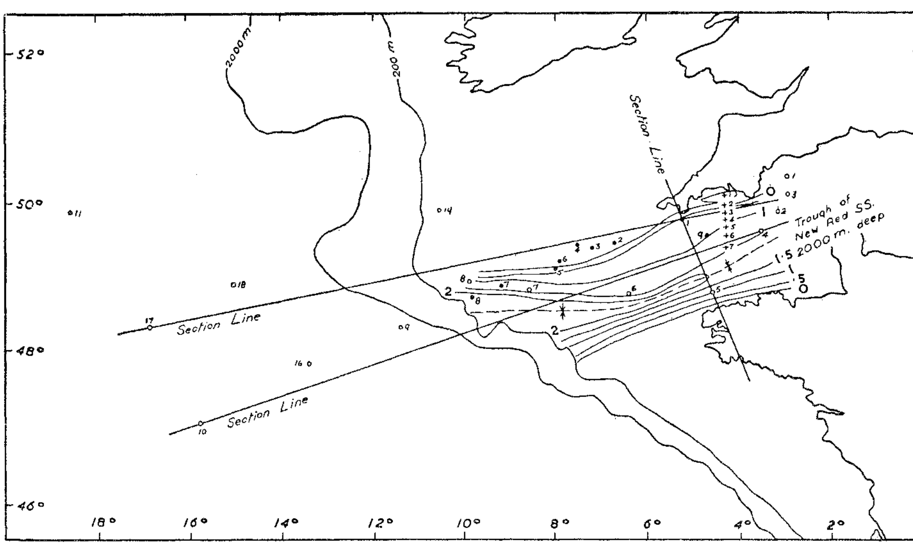

FIG. 5.—Trough of Mesozoic sediments revealed by submarine seismic investigations in the English Channel and Bay of Biscay. Open circles numbered 1 to 19 show the positions of seismic measurements by Hill and Laughton (1954), filled circles 1 to 8 those by Bullard and Gaskell (1941), and crosses 1 to 7 those by Hill and King (1953). Contours (in kms. below sea level) show the floor of the Channel Trough of Mesozoic sediments.

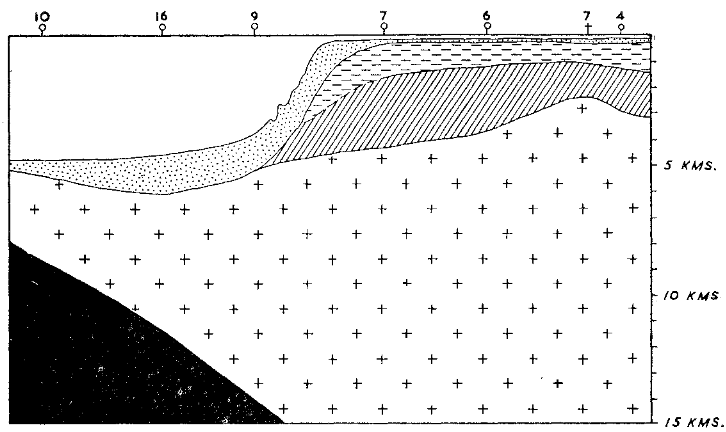

Figure 6 SECTION ALONG CHANNEL TROUGH

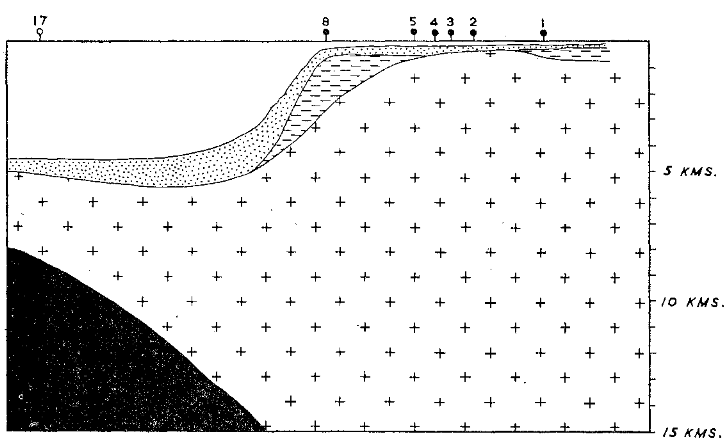

Figure 7 SECTION ALONG CORNWALL RIDGE

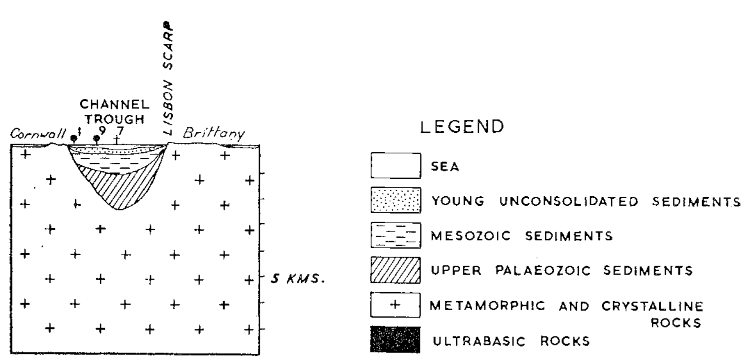

Figure 8
SECTION ACROSS CHANNEL TROUGH

FIGS. 6, 7 and 8.—Section through the Mesozoic trough of the English Channel along lines shown in Fig. 5. These sections are compiled from seismic results and published sections of Hill and Laughton and Bullard and Gaskell, together with known land outcrops and sub-channel core sampling of New Red Sandstone.

and since it parallels the postulated Biscay Rift the reality of tensional conditions with this trend at the required time is unequivocally established.

Matching of Structures Across the Biscay Rift

As a further geological check of the alleged rotation a comparison should be made of the structure and facies of the rocks on opposite sides of the Bay of Biscay, which would have been in close proximity prior to the movement. Attention may be drawn to the salient features which show up on the International Geological Map of Europe (1 : 1½ million). A tightly compressed bundle of Hercynian folds strikes north-westwards through Brittany, curving towards the west (Fig. 4). A similar tight knot of folds strikes south-south-east in north-western Spain, curving to south-eastwards through Spain and Portugal. Under the present configuration of the lands, these fold bundles are both chopped off and strike into featureless ocean which, as we have seen, cannot reasonably be regarded as consisting of such continental material. Under the reconstruction shown on Fig. 4 these fold bundles are the continuation of each other. The reversal of the rotation of Spain sets them end to end. The curvature of each bundle is in the same sense, and together they form a smooth continuous arc. Each segment has a core consisting of crystalline metamorphic rocks intensely injected by granites which also intrude an overlying sequence of strongly folded Cambrian, Silurian and Devonian strata.

This Ibero-Bretagne massif is cut off on the west by the Lisbon scarp, where crystalline and Palaeozoic rocks of the Meseta drop down to the coastal plain of Portugal. This scarp, or flexure, which seems very similar morphologically to the Darling Scarp of Western Australia, runs obliquely out to sea and strikes towards the rift gap of the Bay of Biscay. A similar sharp drop from the metamorphics of Brittany to a trough of Mesozoic sediments under the English Channel, has recently been proved by the submarine seismic investigations (see Figures 6, 7 and 8). The closing of the Biscay rift gap as shown on Fig. 4 places the Lisbon scarp end to end with the structural downthrow from Brittany to the Channel Trough, and thus gives further confirmation to the proposed reconstruction.*

Fig. 4 also shows the pattern of the Liassic transgression, which is representative of the broad basins of shallow epicontinental sedimentation that occurred behind the Alpine-Betic fold belt during the Mesozoic Era. The Liassic is chosen in order to confine the palaeogeographic map to a reasonably short time range. A comparable picture is given by other Mesozoic epochs. The Liassic boundary as reconstructed after closing the Bay of Biscay shows an eastward bulge in Brittany and westward bulge towards Oviedo, which fall in just the places expected from the relations of the sediments themselves. For in Brittany, where the Liassic sea transgressed the Palaeozoic folds, each series of the Mesozoic is overlapped in turn by the succeeding series, indicating a palaeogeographic promontory eastwards there, whereas in Oviedo the complete

* Professor King's paper (King, 1954) which has reached me while this manuscript was in press, adds much more detailed information regarding the post-Palaeozoic history of the English Channel. However the essential features here cited remain unaltered. Compare for example fig. 5 herewith with King's figs. 5 and 6.

Mesozoic sections indicate a complementary westward gulf. This pattern then also agrees with the proposed reconstruction.

To sum up, the following structural units all match up in order across the restored Biscay rift: the Liassic sea of southern France and eastern Spain, the Ibero-Bretagne fold bundles of Palaeozoic and crystalline rocks, the Lisbon Scarp and the submarine flexure off Brittany, and the Mesozoic sediments of the Channel trough and of the coastal plain of Portugal. Unless we close the Bay of Biscay we are faced with the problem of the continuation of these structures, for all eight broken ends run out to the Bay of Biscay which is demonstrably underlain by very different rock.

The Baluchistan Orocline

The Cretaceo-Tertiary fold-system of Persia has a south-east trend for 2000 km. from Asia Minor to the Hormuz Straits. Within the next

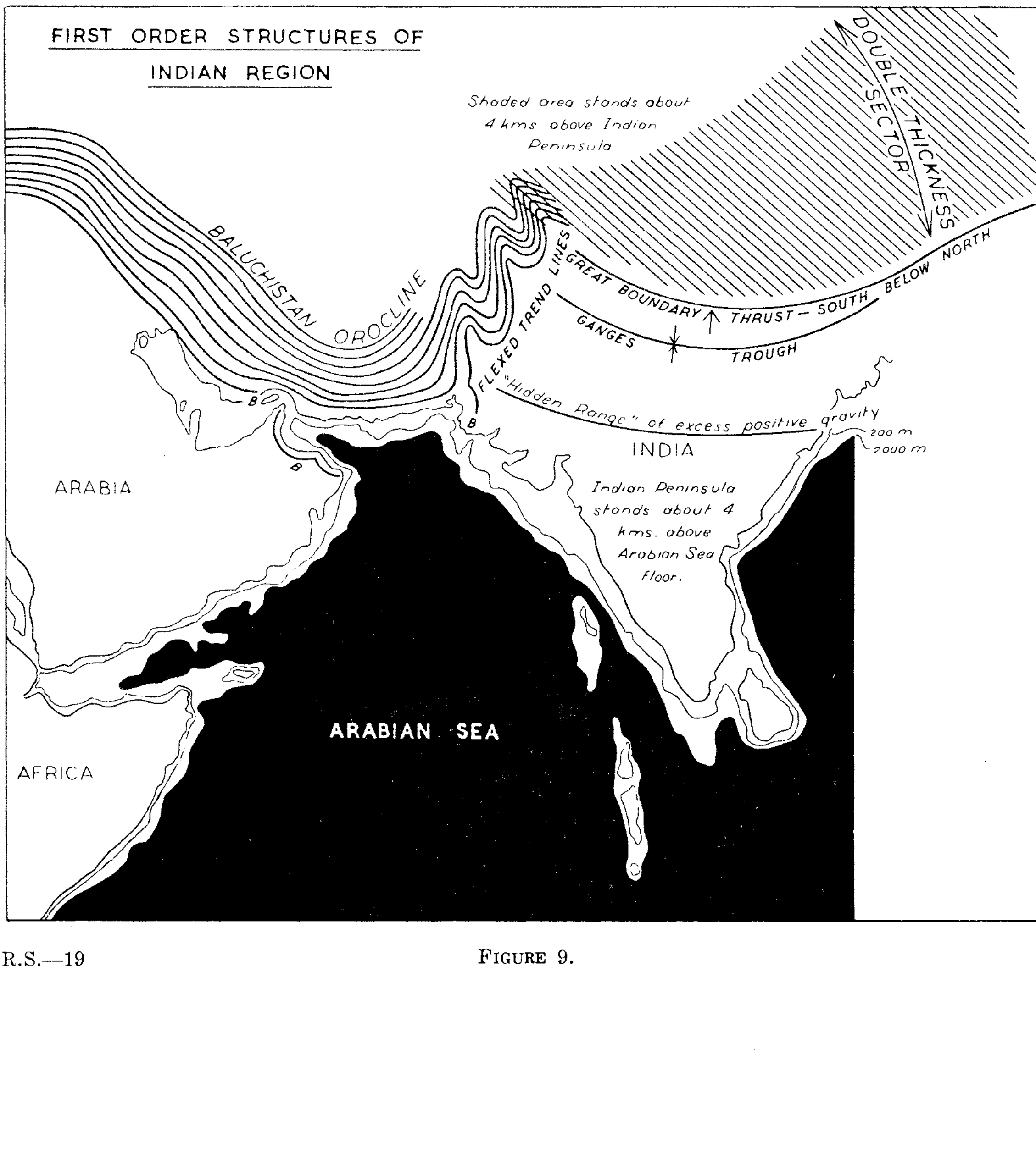

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FIGURE 9.

1000 km. the strike wheels through 120° to an almost northerly trend into Kashmir (Fig. 9). Here there is another wheel round the Punjab into the Himalaya. Let us consider first the bend in Baluchistan. There are two possible interpretations of such a structure. Either the mountain system developed in this shape from the beginning, or the 120° wheel is a superimposed strain due to the bending of an orogen in plan. Classical geology has consistently made the first assumption, using the theoretical concept of strong passive shields around which and between which the orogens were moulded. However, logical scientific analysis demands that we should also examine the consequence of making the second assumption; particularly we should examine the relations of such an orocline to the other first order structures of the region.

Consider first the Arabian sea, a triangular gap between the continental blocks of India and Arabia. Does not the shape of this area—apically opposed to the Baluchistan orocline—recall the relation of the Bay of Biscay to the Pyrenees? Straighten the suggested Baluchistan orocline and the Arabian Sea is closed (Figs. 9, 10 and 12). This pattern of orocline and apically opposed triangular rift will be found to repeat itself with impressive regularity on the face of the globe. The coasts of this gap are fault coasts, generally oblique to the trends of structures and stratigraphy. Yet the floor of this sea is certainly not foundered continent. The gravity observations indicate that although there is a regional negative anomaly in the northern Indian Ocean-Arabian Sea region, the departure from isostasy is small, which would not be the case if the floor consisted of a continental shield depressed 4 km. For the foundering of a block similar to the Deccan Peninsula through 4 km. would require the displacement laterally of 4 km. of material from beneath, which would result in a mass deficiency of three thousand million tons per square km. Irrespective of isostasy this would result in a gravity anomaly of several hundred milligals, which would show up in the free air anomalies even before any Bouguer or isostatic adjustment. Moreover, where seismic work has been done on such seas hitherto regarded as foundered continent, it has been found that the Mohorovicic discontinuity is not far below the sea bed, indicating, not foundered continent, but a gap between continent material (Hess and Maxwell, 1953 for the Carribbean, and Officer 1954 for the south-west Pacific).

Next consider the Tibetan Plateau, a region of post-Palaeozoic compression shown hatched on Fig. 9. Like the Pyrenees this tapers, from a width of some 1000 km. on the 100th meridan to less than 300 km. on the 70th meridan. Does this tapering of the width mean, as in the case of the Pyrenees, that there has been rotation about Y (Fig. 10)? Or are we to assume that the compression was much less concentrated in the east than the west?

The southern front of this Tibetan plateau is known to be intensely overthrust, the south side underlying the north side. The Siwaliks of the foothill region show at least as much compression as the Swiss Molasse, and although the high Himalaya has not received the intense study which has revealed the compression of the Alps, preliminary studies suggest that at least the same order of shortening has occurred—certainly of the order of hundreds of kilometres. Straighten the Baluchistan orocline and the Himalayan thrusting is also put back.

The Tibetan plateau stands about four km. above the level of the Indian peninsula and other continental regions generally. The latter, in turn, stand about four km. above the general level of the Arabian Sea and the ocean floors. It has often been pointed out that this implies that the Tibetan plateau is underlain by twice the normal thickness of continental material. For, if one floating tabular iceberg has twice the freeboard of another floating tubular iceberg, the first is twice as thick as the second, irrespective of the densities of ice and water. Likewise, a continental mass such as the Tibetan plateau, must be twice as thick as another continental mass such as the Indian peninsula which has only half the freeboard above the ocean floor. Restore the Baluchistan orocline, and the problem of the double continent is automatically solved, for the Indian mass is removed from beneath the Tibetan mass. The width of the double thickness area is a direct measure of the compression. If the volumes of material involved are considered, this will be seen to be true irrespective of whether one continent is pushed below the other, or the two continents are crumpled face to face until the thickness is doubled (Fig. 11). The tapering of the high plateau shown on Fig. 10 does then imply rotation, for the amount of compression involved in the Himalaya would be of the order of 1000 km. at the eastern and only two hundred km. in the west.

Associated Tension

When the Baluchistan orocline is reversed the Indian peninsula is restored to a position such as that of Fig. 12. In the restored position the postulated Arabian Sea rift becomes an integral part of the greatest rift system of the globe. The tensional genesis of the African rift valley system has been hotly debated for several decades but there is no doubt concerning the normal fault margins of the Arabian block. Further, it was pointed out by the writer at the Pan Indian Ocean Science Congress at Bangalore in 1951 that the fault troughs which let down the Gondwana rocks into the shield of peninsular India have a radial pattern consistent with tensional strains associated with the postulated Baluchistan orocline (Fig. 12). Ahmad (1952), following Gee, has argued that these fault troughs are largely Upper Mesozoic in age.

Associated Transcurrent Displacement

It was pointed out in the discussion of the rotation of Spain that pure rotation of tectonic blocks is physically improbable, and that rotation would usually be accompanied by transcurrent displacement in the same sense as the rotation. This is in fact indicated by the offsetting of apparent centres of rotation X and Y (Fig. 10). Transcurrent displacement of India in the direction XY is also implied by the tensional opening of the Red Sea and the Persian Gulf, and by the double knee action of the Baluchistan and Punjab oroclines, which developed *pari passu,* and are straightened simultaneously when the Baluchistan orocline is restored (Fig. 12).

Palaeogeography

The broad geology of the coasts thus brought together is similar. Extreme caution is necessary, however, in drawing positive conclusions concerning the former juxtaposition of continents by such evidence alone. The writer has found it possible to present separate cases for matching pairs of coasts, with general geological similarities and even striking parallels, but wherein the correlations were mutually exclusive. If one such case is certainly wrong, other similar cases become suspect. This is particularly true in correlation of areal distributions as distinct from linear features such as orogens and facies changes.

In the Indo-Arabian case the Deccan peninsula, the Arabian block, and Somaliland are all old stable Pre-Cambrian shields with overlying basins of Jurassic and Cretaceous rocks. Towards the north these shields slope gently under increasing thicknesses of Tertiary and Mesozoic strata which overlie marine Palaeozoic sediments of shallow shelf facies. There are no structures striking transverse to the coasts which are not reasonably

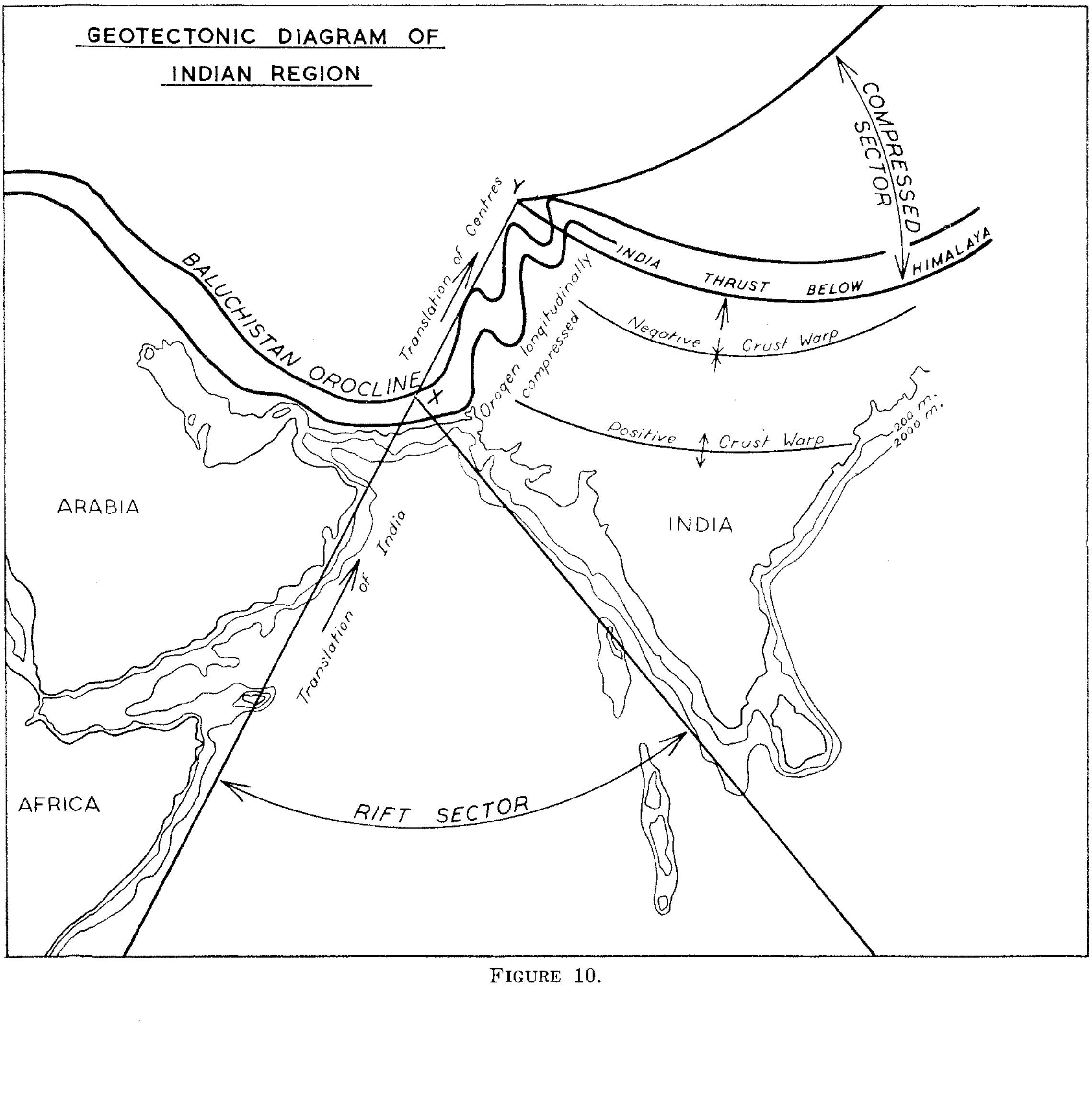


FIGURE 10.

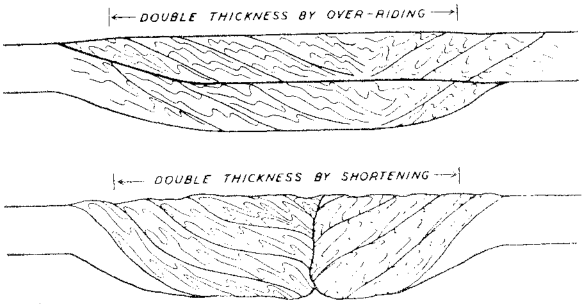


FIG. 11.—Diagram showing amount of compression implied by double continental thickness.

matched on the coast set in apposition to it. It is reasonable to conclude that whereas the geology of the opposed coasts may not, on available evidence, *prove* their former juxtaposition in the manner proposed from the study of the first order strains, the geology as known is quite consistent with this interpretation, and forms a coherent palaeogeographical picture. This has been studied in some detail by Ahmad (1952).

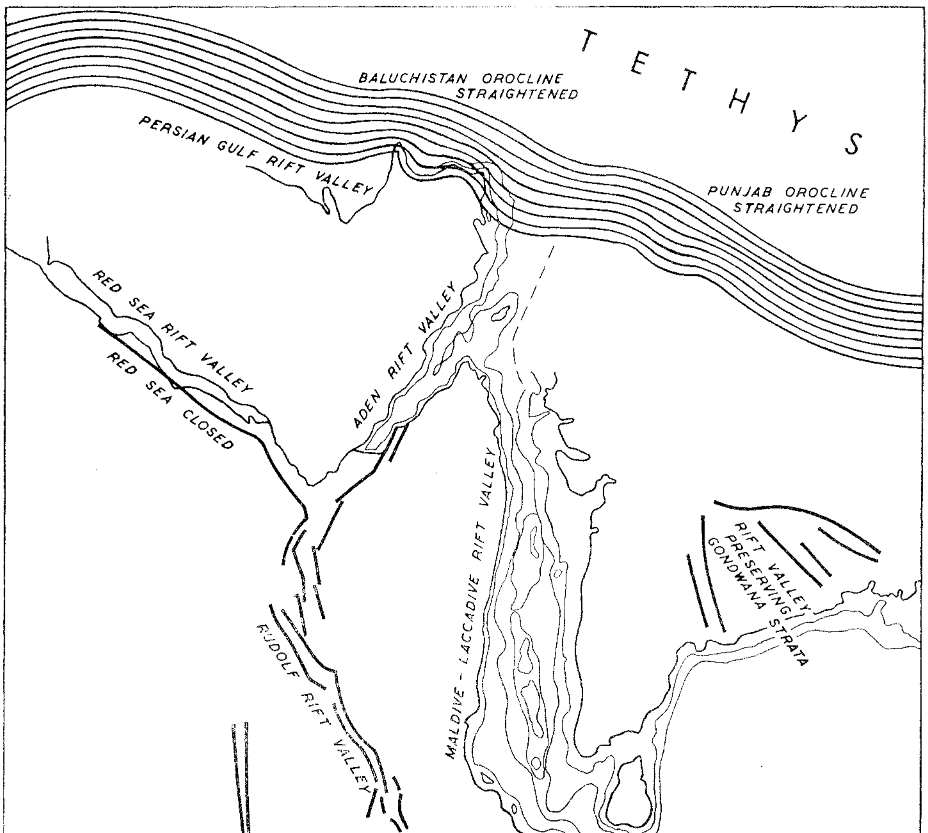


FIG. 12.—The Baluchistan Orocline restored.
[NOTE: For "Rift Valley" on India, read "Rift Valleys".]

The Case for the Baluchistan Orocline

To sum up, the induction that the wheel of the mountain systems through 120° in Baluchistan is an orocline simultaneously explains all the other first order structures of the region and is consistent with the smaller structures. Reverse the Baluchistan orocline and the Himalayan overthrusting is also reversed, the Indian Peninsula comes out from beneath the Tibetan Plateau, the triangular rift of the Arabian Sea is closed, and the problem of the missing fault block solved. Whether the new orocline induction be right or wrong, it must be conceded that it integrates in one act all the great geomorphological features of this region.

The Alaskan Orocline

When the Rocky Mountains are followed northwards through Canada into Alaska, the fold trends wheel through about 75° (Fig. 13). A good deal of this bending however is very local and is recovered in complementary inflections, but viewed regionally there is a deflection in the trends of about 30°. As in the other cases already discussed, there is a triangular tension rift sector (the Arctic Ocean basin) apically opposed to the centre of the wheel in strike. This wheel in trends then has the

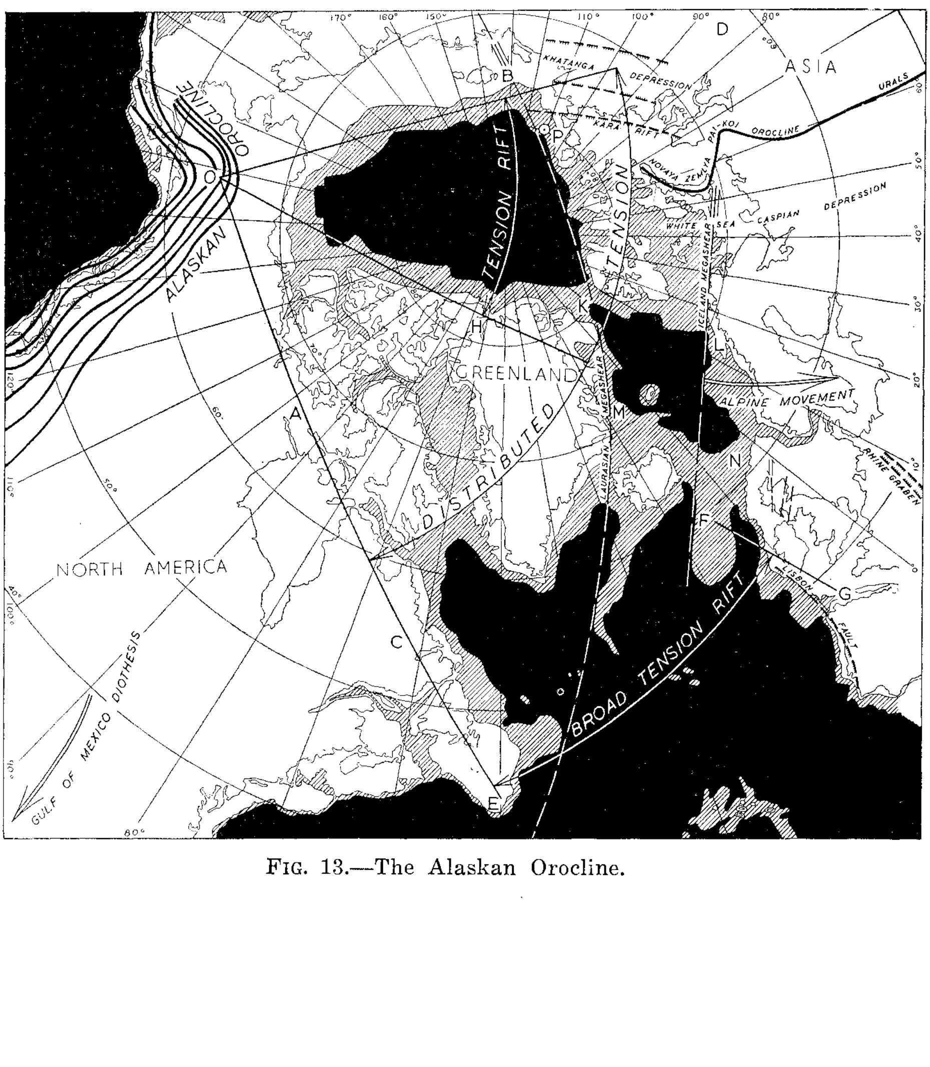
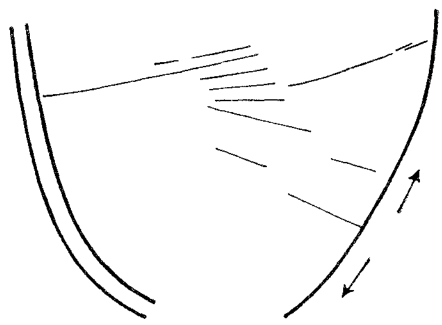


FIG. 13.—The Alaskan Orocline.



FRACTURE PATTERN OF NORTH ATLANTIC
(*BEFORE PARTING*)

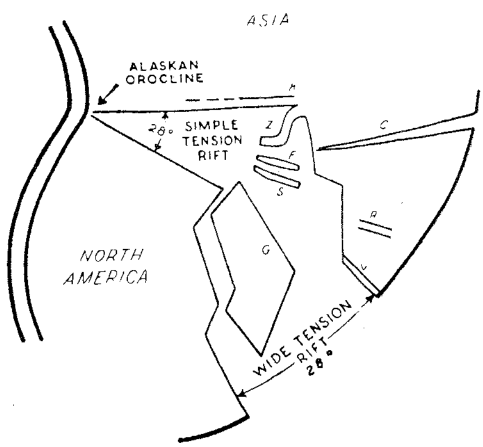


FIG. 14.—Diagram illustrating fracture pattern of Alaskan Orocline.

C. Caspian—White Sea depression.
F. Frans Joseph Land.
G. Greenland.
K. Khatanga Rift.
L. Lisbon Fault valley.
R. Rhine Rift valley.
S. Spitzbergen.
Z. Novaya Zemlya Oroclines.

morphology of an orocline and to be consistent we should follow out our induction and examine the consequences of assuming this bend to be an impressed strain. According to the agreed assumption of this investigation the orocline should be straightened and the rift sector closed. This act closes not only the Arctic basin but also the North Atlantic Ocean, for the gap between Newfoundland and Ireland also subtends 28° *at the centre of the orocline* (*ECO, GFO,* Fig. 13). The pattern is made clear by comparing the map in Fig. 13 and the diagram, Fig. 14. Three zones complementary to the Alaskan orocline may be distinguished in the tensional rift. The inner zone, *HOB,* is a simple tension rift sector of about 28° opening, quite similar to the Bay of Biscay and the Arabian Sea. The outer zone is the sector annulus *CEFG* where there is again simple rift tension, which again subtends an angle of about 28° at the origin. These inner and outer simple rifts are connected *en echelon* through a wider embracing zone of distributed tension (the sector annulus *ABCD*) where the tension is distributed through 80° but may be presumed to add up to about 28°.

This distributed tension zone is expressed by the Greenland, Barents and Kara Seas, and the Khatanga, Davis Strait and Baffin Bay troughs. Many authors have argued that there is a large transcurrent fault along Robeson channel along which Greenland is displaced relative to Canada, thereby causing a tensional depression now expressed by Davis Strait and Baffin Bay (e.g., Wegener 1924, p. 58; Taylor 1928, Fig. 1; Bucher 1933, Fig. 99; Du Toit 1937, p. 135).

The East Greenland Basin is trapezoidal in shape. The sides, *KL* and *MN*, of the trapezoid are radial from the centre of the Alaskan

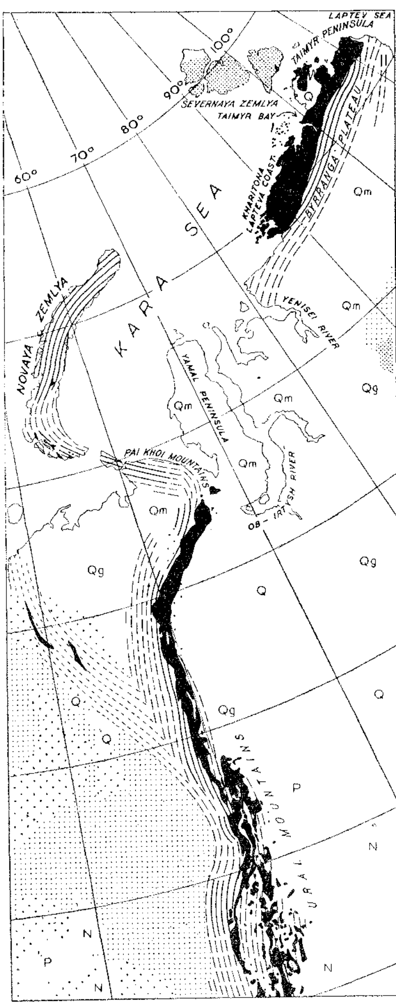


FIG. 15.—Novaya Zemlya and Pai Khoi Oroclines.

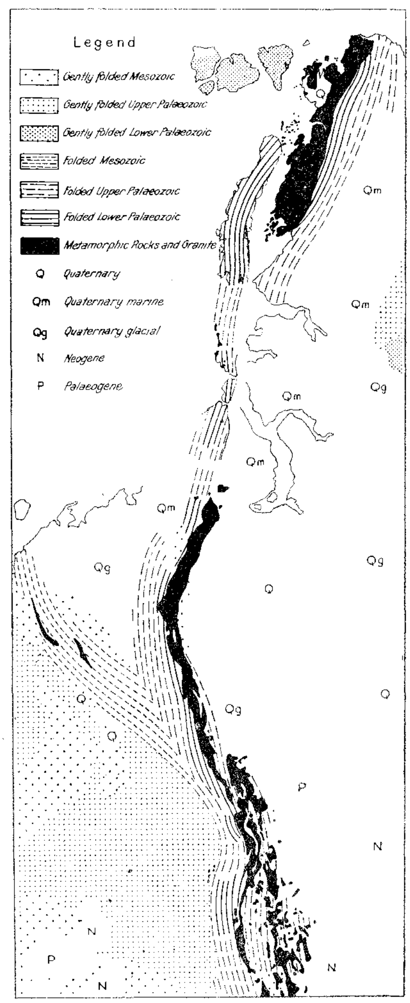


FIG. 16.—Novaya Zemlya Oroclines restored.

orocline, and show a convergence towards that point (see Fig. 13). The angle subtended at the orocline is 13°. It will be found presently that the Kara Rift subtends about 6°, leaving about 9° to be accounted for by the Barents Sea, the Khatanga depression and Davis Strait. This would seem to be of the right order of magnitude. It will be shown later that the north and south sides of the East Greenland depression are lines of strong transcurrent displacement (the northern boundary is De Geer's Line of Wegmann, 1948). The writer will show elsewhere that this trapezoidal shape with two opposing tension boundaries and two complementary transcurrent boundaries, is a characteristic form of disjunctive basin, and that this pattern recurs many times on the earth's surface.

In order to recognise the tensional opening of the Kara Sea, it is first necessary to examine the Novaya Zemlya and Pai Khoi oroclines, which will be found to be part of the larger pattern of the Alaskan orocline.

Novaya Zemlya and Pai Khoi Oroclines

The northern continuation of the Urals makes a right-angled elbow bend to the north-west into the Pai Khoi mountains for 400 km. into

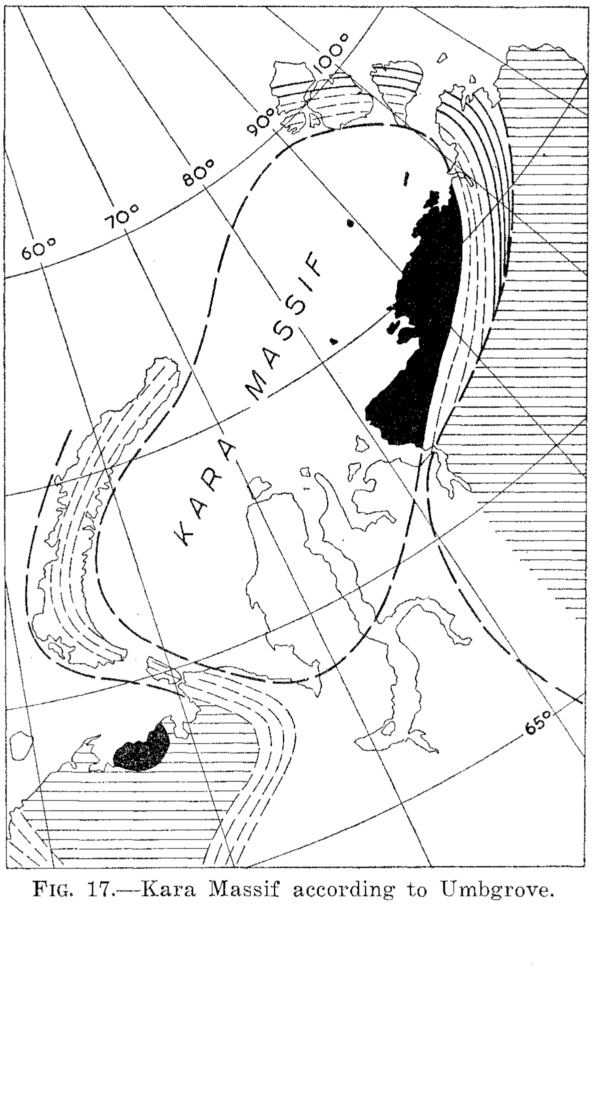


FIG. 17.—Kara Massif according to Umbgrove.

Novaya Zemlya. Here there is a further right-angled elbow to the north-east, a trend which continues thence for 400 km. Fig. 15 shows the structure of this region as traced from the one to five million Geological Map of the U.S.S.R. prepared for the International Geological Congress (1937). These inflections fall within the morphological category and are of the dimensions of structures to be tested as oroclines.

Fig. 16 shows the picture as it would be if the two elbow bends were straightened. The mere unbending, of course, produces a simpler tectonic picture. But the Novaya Zemlya link now reveals the crystalline rocks and Upper Palaeozoic folds of the Byrranga Mountains and Taimyr Peninsula as the direct continuation of the Urals. The resulting greater Urals would sweep in a simple bow from the Aral Sea to the Laptev Sea, a distance double their present length.

This raises the question of what underlies the Kara Sea. According to the orocline interpretation the Kara Sea should be a simatic basin, the tension rift due to the double orocline and morphologically similar to the Bay of Biscay and Arabian Sea, though modified in shape owing to the second orocline. However, Umbgrove (1947, plate 5) has postulated a Kara Massif of crystalline rocks, now foundered, to account for the rim ranges of the Pai Khoi, Novaya Zemlya, and the Taimyr Peninsula (Fig. 17). But there is no real evidence for a Kara massif, and his rim ranges are in part contrary to fact. For the arc of Caledonian and Hercynian folds shown by Umbgrove to swing from the Byrranga mountains northwards and north-westwards into the islands of Severnaya Zemlya is not in agreement with the geological map. Umbgrove seems to follow Leuchs, whose reconstruction is in agreement with old topographic maps (Bartholomew 1931, p. 53); but this topography is revised in later maps (Bartholomew 1950, p. 63). Moreover, the trends given by Umbgrove cut across the trends on the U.S.S.R. 1 : 5,000,000 geological map. The old crystalline rocks, shown by Umbgrove along the Kharitona Lapteva coast only as far as Taimyr Bay, in fact continue eastward without change of trend to Cape Pyretra, and the Hercynian folds south of these crystalline rocks, also continue eastwards without break to the Laptev Sea. (Compare Figs. 15 and 17.)

Although the Kara Sea is for the most part very shallow, it is difficult to avoid the conclusion that it consists largely of a thick delta of Tertiary and Recent sediments. This would also apply to the greater part of the Yamal Peninsula. The only outcrops in this area are marine Quarternary sediments; moreover, this area is the only outlet for the Ob-Irtysh and Yensei river systems which together drain all the country between the Urals, the Altai, and Lake Baikal, an area approximately twice as large as the Mississippi catchment. It would indeed be surprising if there is not an accumulation of sediments in the Kara Sea at least equal to that about the mouth of the Mississippi.

The assumption that the Kara Sea basin then consists of young sediments resting on deep ocean bottom is in agreement with the morphology of the region, and all available geological data. The interpretation of the Pai Khoi-Novaya Zemlya inflections as a double orocline is therefore consistent with everything that is known about this region, and greatly simplifies the tectonic picture. The complementary relation of the Pai Khoi and Novaya Zemlya oroclines repeats the relation of

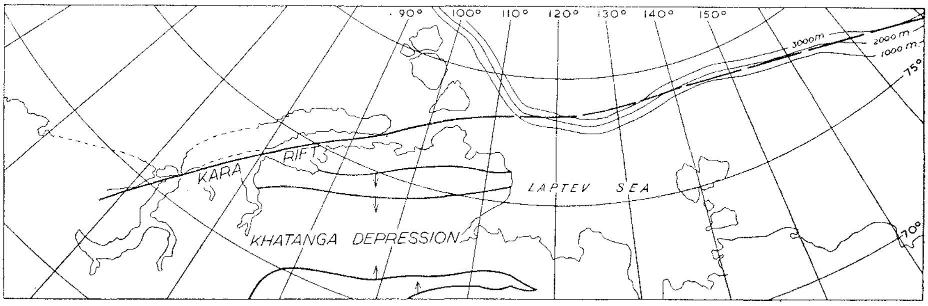


FIG. 18.—Tension structures associated with the Kara Rift.

the Baluchistan and Punjab oroclines. Each pair has produced a crank-like pattern and the two must be restored *pari passu.*

As in the previous examples discussed, there is ample evidence of second order tension with the same direction as the alleged Kara rift (Fig. 18). The Khatanga depression is a fault trough let down into old shield rocks of the Siberian platform thereby separating off the Taimyr Peninsula. Parallel faults are shown on the one to five million geological map along the south side of Taimyr block. The Khatanga depression is largely occupied by marine Quaternary sediments, but the faulting seems to have been active since the Mesozoic. The Kara rift is collinear with the northern edge of the continental shelf of eastern Siberia (compare Figs. 14 and 18), and the southern side of the Khatanga depression is collinear with the general trend of the North Siberian coast. This would seem to be a fault coast because old fold belts strike directly into it.

If these interpretations are correct the Kara Sea is a tensional rift behind the Novaya Zemlya diothesis, and is part of the distributed tension zone associated with the Alaskan orocline. This raises the question of the age of the double orocline in the Novaya Zemlya belt. The Alaskan orocline is presumably Mesozoic and early Tertiary; the Urals are Late Variscan, and so presumably are the Novaya Zemlya folds. But, according to the above interpretation, the *flexing* at least of the Novaya Zemlya trends would scarcely be older than early Mesozoic. However, another possibility is that the Alaskan orocline has been moving since the Palaeozoic (see the discussion below of the relation of the Alaskan transcurrent movement and the Glen Fault of Scotland). For comparison, the San Andreas fault of California has been moving consistently since the Jurassic (Hill and Dibblee 1952) and any earlier movement is not recognisable owing to lack of reference points.

Summary of Primary Tension Complementary to the Alaskan Orocline

Reverting to Figs. 13 and 14 it is now clear that the simple 30° tension rift sector of the Arctic basin and the North Atlantic Ocean, together with distributed tensional rifts of Baffin Bay, and the Greenland, Barents and Kara seas, are geometrically complementary to and radial from the Alaskan orocline and constitute the primary tension demanded by the geometry of that great bend.

It is not surprising that a rift as large as that which formed the Arctic and North Atlantic oceans should not be a single simple fracture.

The distribution of tension is unlikely to have been uniform over such an area. More important here, perhaps, was the lack of uniformity of the continental material. For the fractures seem to have followed largely the weak zones of earlier Palaeozoic fold belts, and as these did not run exactly in the line of maximum tension, echelon splinter fractures resulted (Fig. 14).

Second Order Tension Associated with the Alaskan Orocline

In the cases of the Pyrenean and Baluchistan oroclines, there were clear cut subsidiary tension structures, particularly on the larger continental block. The same is true of the Alaskan orocline, though here the echelon splinter pattern of the main rift indicates that the subsidiary tension fractures tend to merge with the primary fractures.

Thus, the Khatanga rift valley may be regarded as the expression of subsidiary tension on the larger block (compare Figs. 13 and 14). The Lisbon fault (Figs. 3, 11 and 12) is clearly of this type. The Rhine Graben (Figs. 11 and 12) is also radial from the Alaskan orocline and integrates perfectly with this great tension system. Many writers have referred to the East Russian depression between the White and Caspian Seas as a belt of stretching of the continent. This has the position and character of a radial tension sag associated with the Alaskan orocline and the opening of the North Atlantic ocean. There can be no doubt then that there were in fact tensional conditions both major and minor on the trends and at the time required by the orocline interpretation of the Alaskan bend.

Transcurrent Displacement Associated with the Alaskan Orocline

The Pyrenean and Baluchistan oroclines were found to be associated with transcurrent movement in the same sense as the rotation. Similar evidence is present in the case of the Alaskan orocline. I shall discuss elsewhere the whole question of this and other megashears. It will then be shown that this megashear follows the south-eastern side of the Greenland block, and the northern edge of the Barents-Kara shelf from Spitsbergen to the Tamyr Peninsula, then continues across east Siberia to the *Fossa magna* of Honshu thence on to the Mariannas (see Fig. 13). This will be found to be the principal line of slippage between the Asian and North American masses. Meanwhile I wish to confine the present discussion to the orocline concept, and to resist the temptation to dwell on the cognate structures. Suffice it to point out that the relative displacement of the American block has the same sense with respect to Asia as its rotation about the Alaskan orocline, as is required by physical theory.

Parallel to this primary Laurasian megashear there are other major transcurrent faults. The Iceland megashear springs from the Pai Khoi-Novaya Zemlya oroclines and from the south-eastern boundary of the East Greenland disjunctive basin (see Fig. 13). Intense transcurrent displacement believed to be of Upper Palaeozoic age has been established in the northern British Isles (Kennedy 1946, and Leedal and Walker, 1954). The Glen fault is believed to have been moved 65 miles and the Barnsmore faults have throws of two or three miles. It is perhaps significant that the trend and sense of movement of these mapped faults agree with the Iceland Megashear.

Restoration of the Alaskan Orocline

In order to reverse the strains implied by the Alaskan orocline, it is necessary to carry out the following operations concurrently:—

(i) Reverse the transcurrent displacement of about 1000 km. along the Laurasian megashear.

(ii) Close up the distributed tension of the East Greenland basin, the Kara Sea, Davis Strait, the Barents Sea, and the associated subsidiary stretchings.

(iii) Close the primary rift sector by rotating America through 28° about the Alaskan orocline.

The result is shown in Fig. 19. Thus, the reversal of the visible strains of the earth's crust reproduces Du Toit's Laurasia without Schuchert's North-Atlantic misfit and without Wegener's dilemna of widening the Bering Strait as he moved America towards Europe. The palaeogeographic arguments used by Du Toit to build his Laurasia have not been used in the present synthesis. The palaeogeographic and tectonic analyses stand therefore as independent corroborative testimonies.

By comparing figures 13 and 19, it will be found that each block is assumed to extend out to the 2000 m. isobath. The boundary rifts and megashears follow this line closely. Statistical grounds for adopting the 2000 m. isobath as arbitrary boundary of continental blocks are given elsewhere (Carey 1955).

The shape of the deep sea basin between Newfoundland Banks and Greenland (Fig. 13) suggests that the Greenland block may originally have fitted against the Labrador shelf with Cape Farewell against the northern re-entrant of the Banks east of St. John. However, this would in turn imply the existence of a megashear along the north coast of Baffin Island and along Lancaster Sound, Barrow Strait and McClure Strait. Whereas this might be so, there is no published evidence of it, so this first draft of the restoration of the Alaskan orocline omits it. But it should be borne in mind that even if the Alaskan orocline is valid, more data are necessary before all details of its associated fractures and displacements could be finally reconstructed.

Case for the Alaskan Orocline

The case for the reality of the Alaskan orocline may be summarised as follows:—

(1) There is a major change of direction of the trends of the marginal orogenic zone of North America. This bowed form must either have developed as such from the beginning or be an impressed strain.

(2) The Arctic basin is a triangular gap in the continental material; this gap is apical to the centre of the bend in the orogen. The gap is geometrically where it would be if the wheel is in fact an impressed strain. The angle of the gap agrees with the angle of change of trend.

(3) There exists clear evidence of tension on a continental scale, the tensional fractures being approximately radial to the centre of the alleged orocline. The tension is geometrically where it should be if the wheel in trends is in fact an impressed strain.

(4) There is evidence of transcurrent movement on a continental scale, of a kind which would probably be present if the alleged orocline is in fact an impressed strain.

(5) The palaeogeography of the parts presents a coherent whole under this interpretation. There is nothing in the palaeogeography on the negative side to contradict the configuration which results from the assumption that the wheel in trends is in fact an orocline—on the contrary the integrated palaeogeography gives this solution very strong support.

(6) The adoption of the orocline alternative and the restoration which is implied, *ipso facto* result in comprehensive and unexpected integration of diverse facts. Structures such as the Rhine Graben, Lisbon Fault, White Sea-Caspian depression, the inflections of Novaya Zemlya, Khatanga

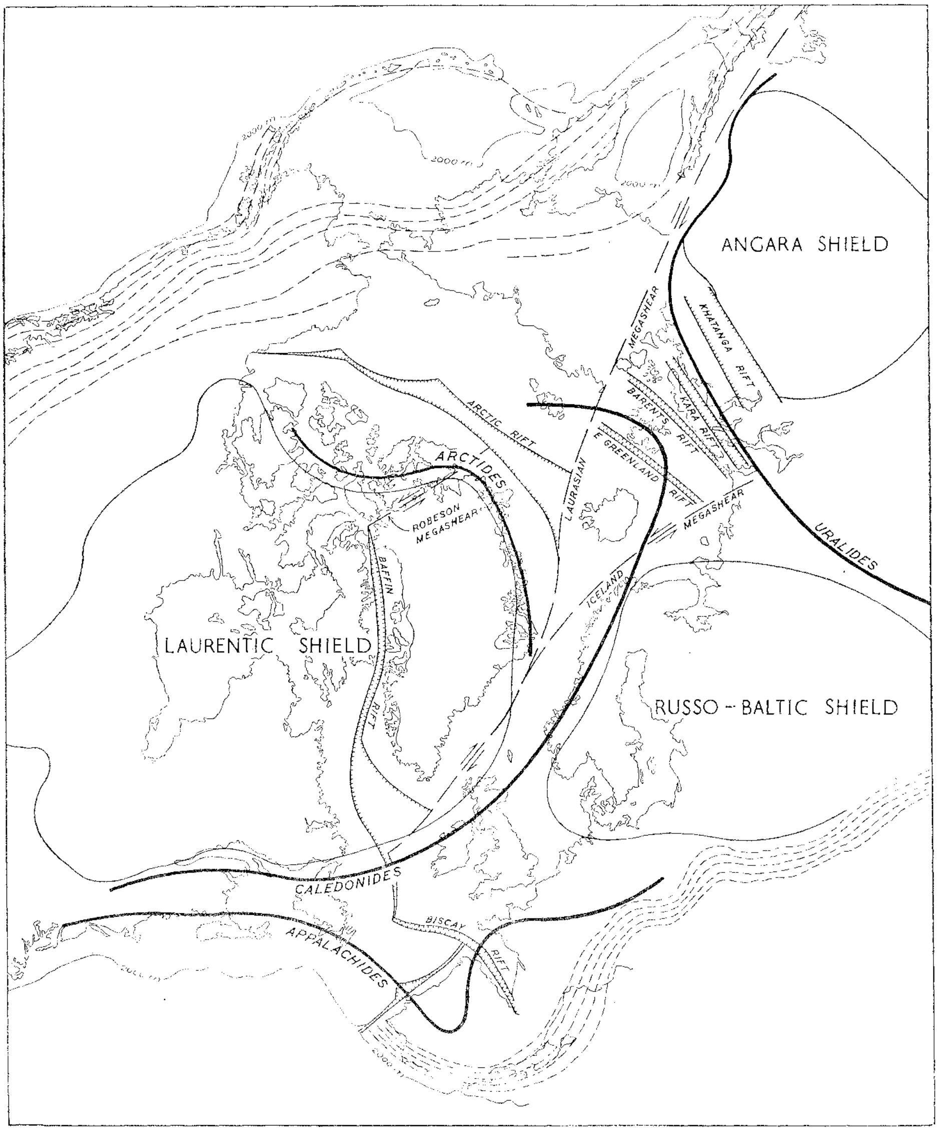


FIG. 19.—The Alaskan Orocline restored.

rift valley, the Arctic and North Atlantic basins, and the Robeson Channel megashear, all become integrated as parts of a single movement. The Urals become part of a structure twice as large. Shuchert's two classic criticisms of this part of the Wegener hypothesis, the " Atlantic misfit ", and the objection that if America is moved closer to Europe the Bering Strait must be widened equally, both vanish.

(7) The Pyrenean, Baluchistan and Alaskan oroclines each independently reproduces parallel phenomena—an inflection in the orogens, apical rift sector, consistent major and minor tension phenomena, transcurrent displacement in the same sense, coherent palaeogeography, integration of all regional structures large and small, and automatic unexpected solution of diverse anomalies. It is surely in the highest degree improbable that any one such concurrence should be fortuitous. The triple repetition of such concurrences is surely strong ground for accepting the induction that all three bends are in fact oroclines.

Six European Oroclines

Excluding the Pyrenees and Ebro folds already discussed, the pattern of the fold systems of Alpine age is shown in Fig. 20. This pattern immediately discloses six great loops in the fold trends; the Riff, Sicilian, Ligurian, Carpathian, and Transylvanian loops, each of which causes a bend in the fold trends of about 180°, and the Hellenic bend through about a right angle. In accordance with the stated purpose of this investigation let us see the consequences of assuming that these bends are all oroclines—impressed strains due to folding in plan. Fig. 21 shows the pattern which results. Nothing has been done in going from Fig. 20 to Fig. 21 except straighten the six loops on the assumption that they are impressed strains. The trend plan allows two solutions according as the Apennines are interpreted as a continuation of the Atlas through the Sicilian orocline or of the Alps through the Ligurian orocline. Whichever be adopted, there can be no doubt that this is a greatly more probable picture than the existing twisted tangle, whether we look at it from the point of view of palaeogeography or of tectonics and the implied stress systems.

Tectonic Pattern in the Alpine Belt

The present distribution of the directions of compression and intense shortening gives a hopelessly chaotic pattern, quite impossible to resolve into any rational stress system. Consider for example the Riff arc, which wheels through 180°. The 1 : 1,000,000 Geological map of Spain (1951) shows clearly that the directions of the fold axes and the two structural zones of the Alpine geosyncline continue smoothly right round the loop. To form this structure *in situ* demands an intense local system of forces acting radially through two quadrants from a point in the Mediterranean some 70 km. east of Gibraltar, or an equally improbable centripetal system. An even more local and intense centre of forces is demanded in the plains of Milan, the centre of the Ligurian orocline, and another in the Tyrrhenian Sea and still another in the Hungarian plain. In addition, other bilateral compressive forces, equally intense, are demanded to account for the various straight connecting belts, which have trends which box the compass (e.g., the Apennine trend is at right

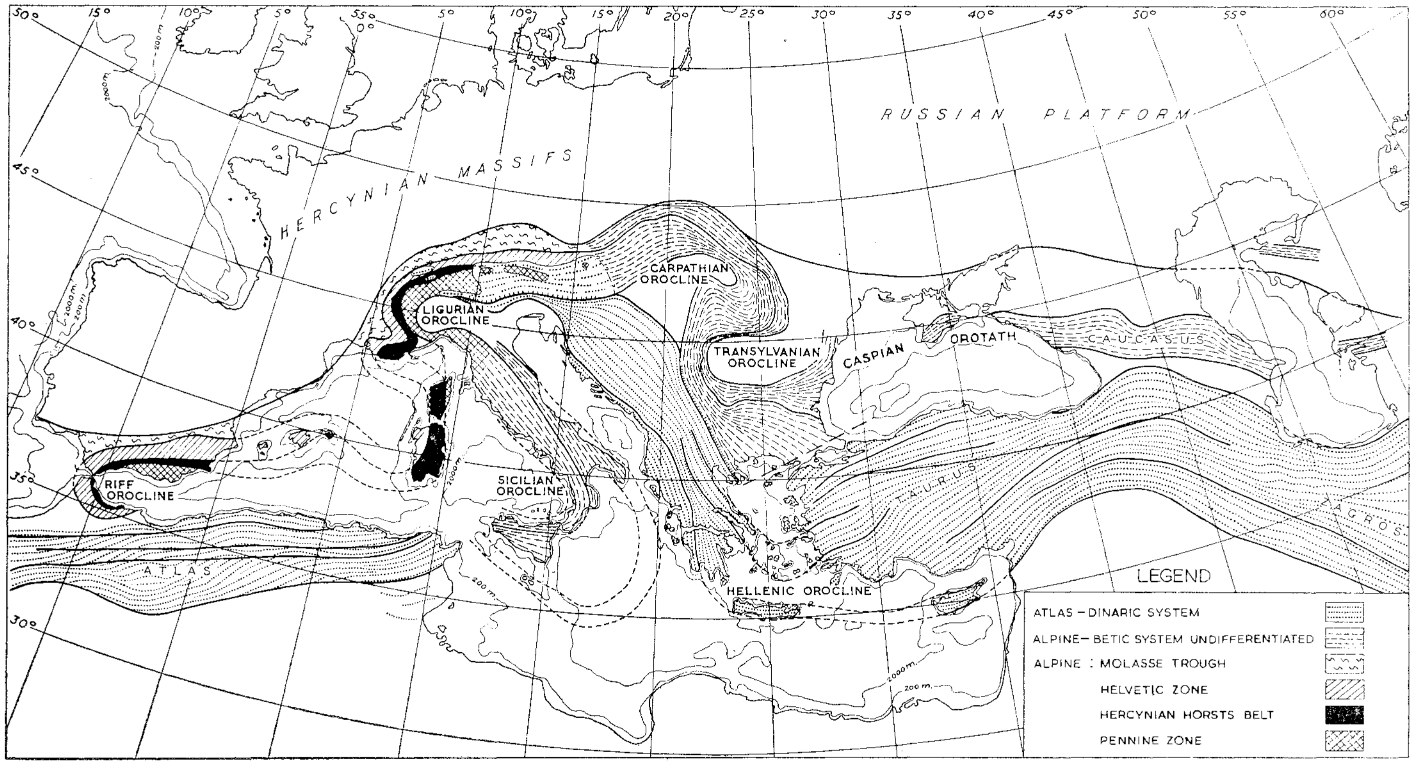


FIG. 20.—Orogenic pattern of Europe.

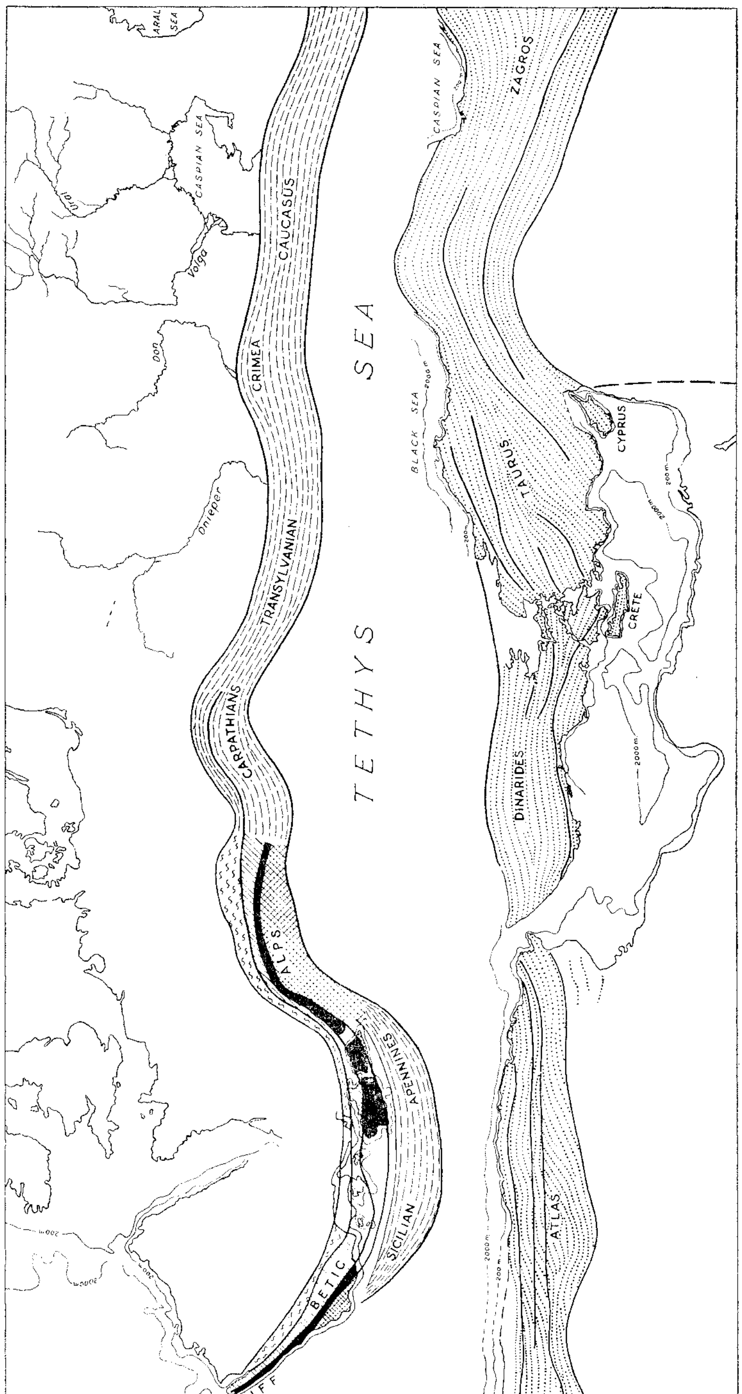


FIG. 21.—Result of restoring the six oroclines of Europe.

angles to the Alpine trend). It is difficult or impossible to offer any coherent stress system at all, still more so to relate such a confused tangle to any global tectonic pattern. Yet these foldings were clearly part of a revolution which expressed itself in every quarter of the globe.

Once the oroclines are straightened, however, the strain pattern becomes extremely simple—two marginal orogenic belts facing each other across the Tethys. Observe (Fig. 21) how the great Tethys emerges unsought from the orocline restoration! The Tethys was the first world-scale palaeogeographic conception ever to be recognised by geologists. What a complicated business it is to reconstruct it from the tangle of trends and cross-trends all the way from Spain to Burma! Yet, if one makes the single induction that the visible bends in the great orogenic belts are impressed strains, undo them, and there *is* the Tethy's, simple and entire! It seems that wherever an orocline is restored an unexpected and unsought solution to a problem of greater scale is granted.

Facies Distribution in Alpine Belt

Let us review first the palaeogeography of the Alpine geosyncline in the Western Mediterranean where the orocline concept implies that it has been intensely disrupted by large scale diotheses. In the type area the Alpine orogen has been divided into distinctive zones from north-west to south-east:—

(*a*) The Hercynian shelf, the stable mass against which the Alps are folded.

(*b*) The Molasse zone—the lowland of the Swiss plain which consists of a trough of Neogene sediments.

(*c*) The Helvetic zone—a synclinorial belt of fold and thrust mountains made up from the intense compression of marine shelf deposits on the northern side of the main geosyncline.

(*d*) The Horst zone—an anticlinorial belt exposing horsts of the pre-Mesozoic basement, which are thrust across the Helvetic zone.

(*e*) The Pennine zone—fold and thrust mountains made up from the shortening of the sediments of geosynclinal facies.

(*f*) The Dinaric zones, which in the eastern Alps are thrust across the top of the horst and Pennine zones.

As the fold belts are approached from the north-west the Molasse zone, which is marked by wavy broken lines on Fig. 20, is the first continuous structure with an Alpine trend. From the Swiss plain it extends eastwards along the Upper Danube valley to Vienna, and thence round the Carpathian arc where its northern margin becomes less clearly defined. South-westwards from Geneva this lowland continues down the lower Rhone Valley to the sea. It is again clearly recognisable as the Guadalquivir trough from Valencia to Seville.

North-westwards from this boundary trough emerge the Palaeozoic platforms of Western Europe—the Spanish Meseta, the central massif of France, Ardennes, Vosges, Black Forest, and the Harz and Bohemian Mountains—the whole showing a swell and basin pattern. The structures in these massifs are characteristically oblique to the Alpine trend and they successively strike into it. In some places local elements with Alpine trend appear on the northern margin of the Molasse trough, such as, for example, the Jura Mountains, though even here a branch of the Neogene lowland runs up the Saone valley behind the Jura.

The Helvetic zone hatched on Fig. 20 is clearly defined in the Western Alps, and continues to the sea near Toulon and Marseilles. Rocks of this facies without basement horsts also occur in the north-west corner of Sardinia, and in the north-eastern belt of the Betic Cordillera of Spain, whence they continue across the Straits of Gibraltar around the Riff arc. In the Balearic Islands, the north-eastern belt of Majorca and Ibiza may well belong here.

The anticlinorial zone of basement horsts is shown in solid black in Fig. 20. The black zone is the strip in which they occur, for they are not continuous. In the Alps the horsts are represented in the Aar, St. Gotthard, Aiguilles Rouge, Mont Blanc, and Grenoble massifs, the core of the Maritime Alps, and the Maures massif between Cannes and Toulon. Corsica and Sardinia are largely made up of granite and Palaeozoic rocks whose tectonic characters fit in with this zone. So in part do the Balearic islands, especially Minorca, which exposes inliers of Carboniferous rocks. The Spanish Coastal belt between Gibraltar and Cartagena including the Sierra Nevada is largely composed of basement rocks, mainly Pre-Cambrian crystallines of the Estrado Series, Silurian strata, and granites. However, much of this is allochthonous, and represents the cores of nappe sheets of the Pennine zone. The belts are much more complex in detail than is suggested by Fig. 20, but the regional distribution pattern which is significant to the present discussion is not affected by this complexity. This belt of pre-Triassic rocks continues across the Straits of Gibraltar round the coastal front of the Riff loop as far as the Bay of Alhucemas.

The Pennine zone of the Alps, shown cross-hatched in Fig. 20, with its lustrous schist facies and ophiolites, continues without interruption round the Ligurian loop past Genoa, Spezia and Leghorn into Tuscany. The north-eastern corner of Corsica, and much of the Betic Cordillera of Spain also belongs to this facies.

The Dinaric zone, shown in stipple in Fig. 20, is entirely allochthonous in the Alps proper. Its roots are in a tightly squeezed zone which extends eastwards from near Turin and the Lombardy foothills. It lies like a crumpled blanket over the eastern Alps with outlying remnants on the western Alps; the Dent Blanche nappe and the Pre-Alps on the shores of Lake Geneva may belong here. The Pennine zone shows through this sheet in the Engadine, High Tauern, and possibly the Semmering windows. The eastern boundary of the allochthonous Dinaric sheet has not been clearly identified.

Thus far I have summarized the distribution of the facies elements of the Alpine geosyncline as they exist to-day. As such, they make a hopelessly chaotic picture—palaeogeographically and diastrophically. If any facies is followed there are offsets, trend changes and wide gaps occupied by deep sea, which could scarcely be regarded as containing the same facies. These gaps have mild positive gravity anomalies, not strong negative ones as they would have if they were foundered segments. Once the oroclines are restored, the Alpine geosyncline from the Carpathians to the Riff becomes a normal geosyncline with its foreland, foreland depression, miogeosynclinal belt with calcareous facies, geanticlinal ridge of basement inliers, and deep eugeosynclinal trough with greywacke facies, ophiolites, younger granites, and absence of limestones. The north-west corner of Sardinia has close facies resemblance to the north-east corner of Spain against which the restoration places it. Indeed so close is this resemblance that the Sardinian rocks are commonly classified as " Andalusian " facies. It should be emphasised that this integration is achieved without any selective placing of the fragments. Merely straighten the oroclines where they fall, closing the triangular rift gaps of the Ligurian and Tyrrhenian Seas (compare their morphology in Fig. 20 with the Bay of Biscay and the Arabian Sea), and the disrupted Alpine geosyncline goes together again into a comprehensible unity. This integration becomes thus an independent confirmation of the probable validity of the orocline induction.

Relation of European Oroclines to the Cratons

The six European oroclines differ from the Alaskan and Baluchistan oroclines in that they are developed on diotheses. Where an orogen remains in contact with the associated craton any orocline developed in it must be convex towards the craton, and it is accompanied by a triangular rift gap radial from the orocline. However, where a diothesis has occurred and the orogen has been pulled free from the craton with a disjunctive basin between the orogen and the craton, oroclines may be either convex or concave towards the craton, and they may not be accompanied by rupture of the craton. Orotaths are, however, likely under these circumstances. Such free orogens are analogous to allochthonous folds of vertical sections. The European oroclines are of this type, and many more examples will be found, commonly with associated orotaths. These will be described in due course.

Welding of the Riff Orocline

Let us examine those places where the orocline interpretation implies the welding of masses formerly widely separated—the Riff zone to North Africa, and the Dinaric belt to the Alps and the south-eastern Carpathians.

Consider first the Riff zone. Enough is known of the geology on either side of the Straits of Gibraltar to make it certain that the fold belts of the Spanish Sierra Nevada and Betic Cordillera continue across the Straits of Gibraltar and wheel round eastwards as the Riff Cordillera of Spanish Morocco. This was recognised by Habernicht (1881) and adopted by Suess (1885), and, as Bailey (1953) points out, although various contrary opinions have been put forward (e.g., Kober, Staub, *et al.*), " increasing knowledge has proved them unacceptable ". The 1 : 1,000,000 geological map of Spain (1951) shows clearly that the directions of the fold axes and two zones of the Alpine geosyncline (the Helvetic and geanticlinal horst zones) wheel continuously and smoothly round the loop, and Bailey (*loc. cit*) has recently repeated that the intense horizontal displacements and nappes are similarly developed around the arc.

The structural continuity of the Betic and Riff Cordillera implies that the Riff, now part of North Africa, must have taken part in any rotation of Spain and that its welding to Africa could not be older than early Tertiary. Just where the join is to be looked for is not established on the information available. However, it would be at least as far inland as an arc through Larache, Alcazarquivir and Uazan, thence continuing parallel to the Riff fold trends to emerge on the Mediterranean on the western side of Cape Tres Forcas. Morphologically this whole Riff arc, which is so closely related to the Betic arc, is like a graft stuck on the Atlas orogen. It has therefore been treated as part of Spain and separated from Africa when the rotation of the Iberian Peninsula was reversed. This leaves the Atlas as a simple normal fold belt (Fig. 21).

Welding of the Dinaric Belt

The line from the foothills of Lombardy near Milan to near the junction of the Mura and Drava Rivers north-east of Zagreb, which marks the weld of the Dinaric belt to the Alps proper, is one of the most tightly compressed zones of thrusting in the Alpine region. In addition, nappes which spring from this confused part of the Dinaric zone are described as having been thrust over the eastern Alps, concealing the Helvetic and Pennine nappes of the Alps proper, except where they may be seen through the Engadine and High Tauern windows. Likewise, the implied weld between the southern Dinarides and the Stara Planina Ranges of Bulgaria is marked by a zone of strong overthrusting which runs from near Belgrade to near Salonika. These facts are in agreement with the proposed reconstruction though they might agree also with other hypotheses. They are recorded merely as checks rather than as supporting evidence.

The Hellenic orocline is a right-angled bend rather than a continuous loop, and the fact that it is interrupted by the sea, some of it fairly deep, suggests that there has been radial tensional stretching as well as bending. When this is straightened and closed up, and combined with the

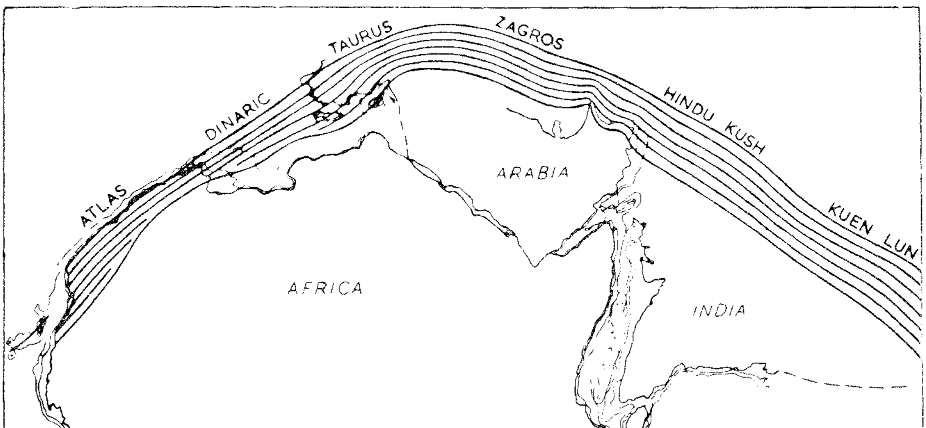


FIG. 22.—Tethyan portion of Gondwanaland resulting from reversing European and Baluchistan oroclines.

Baluchistan orocline movements, the Atlas, Dinarides, Taurus, Zagros, and Himalayas form a simple continuous belt to the Shan States—one hundred degrees of arc or 7000 miles (Fig. 22). This integration is another independent achievement of the orocline concept.

Dobrudja, Crimea, and Caucasus

The very extensive Neogene and Quaternary sedimentation of the northern parts of the Caspian and Black Seas obscures the relation of the Crimea and Caucasus to the Russian foreland. However, the gaps between the Dobrudja, Crimea, Caucasus, and the Aklal Tekke mountains across the Caspian, suggest that this is an orotath or stretched orogen which would be closed up by the straightening of the Carpathian and Transylvanian oroclines. This interpretation has been adopted provisionally in Fig. 21. This would imply that the Russian platform does not extend much further south than Odessa, Rostov, and the Magyshlak Peninsula, and that the alluvial plains further south conceal a former disjunctive sea as deep as the Black Sea, which formerly linked the Black and Caspian Seas north of the Caucasus.

Criticisms of the European Reconstruction

Although the simple assumption that all the great bends are oroclines clearly succeeds to an astonishing degree, there are anomalies. In the first place correlations have been made between the Apennines and both the Atlas and the southern Dinarides. On the other hand it is of course wholly possible that such resemblances are fortuitous and express similar facies rather than identity. Again, the Apennines are reported to be overthrust towards the north-east, which is contrary in sense to the Alpine and Betic thrusts with respect to the restored orogen.

The solution to these anomalies may lie in the interpretation of the Apennines as the continuation of the Atlas and not of the Ligurian arc. The continuity of the southern orogen would then be: Atlas, tensional gap, Sicily, Sicilian Orocline, Apennines, an attenuated orotath round the Po valley to the Dinarides. The northern orogen would be Alps, Ligurian orocline into the Tuscan Apennines, thence with several tensional gaps via Elba, Corsica, Sardinia, Balearides to the Betic and Riff zones. This picture is close to Stille's synthesis and is quite reconcilable to the orocline concept. However, in making the initial test of the orocline induction the writer deliberately followed out what seemed to be the simplest interpretation of the morphology of the trends to discover where the induction might lead.

Summary of the European Oroclines

The single induction that the six great wheels in the trend lines of Europe are impressed strains produces tectonic coherence from tectonic chaos. The Alpine structures fall logically into a grander structure which involves the whole of Asia. The Alpine geosyncline makes palaeogeographic sense for the first time. The great Tethys emerges from the straightened Alpine folds, as indeed it must, for nothing is more certain than that the reversal of Alpine movements should reproduce the Tethys.

Role of The Orocline Concept in Geotectonics

The present paper is but the beginning of a new approach to geotectonics. A few examples of oroclines have been discussed in some detail. Several more have been sketched more briefly. Altogether, twelve oroclines have been depicted in the diagrams. There are 25 such major bends of orogenic belts on the face of the globe, all with more than 30° of deviation. Not one of them yields contradictory results or improbable palaeogeography if it be assumed that the bend is in fact an orocline. In every case there is evidence supporting the orocline interpretation, and, as in the cases herein discussed, unexpected solutions to other problems appear.

In spite of the universality of this result, there seems to be no *a priori* reason to assume that all orogenic belts were necessarily straight or only gently curved. Each orocline must justify itself on its own internal evidence.

At the outset of this discussion it was pointed out (Fig. 1, &c.) that deformation in plan of large amount should be expected in all orogenic terrains. There is no logical reason why orogenic movements should only (or even commonly) involve purely parallel movements, as has been implicitly assumed in current tectonic thinking. The orocline is one possible type of such deformation in plan. But there are others, such as stretching, disjunctive rifting, and transcurrent displacement. Logically all of these should be looked for, with magnitudes of displacement comparable with orogenic shortenings, i.e., hundreds of km. The writer has followed up this induction, and has found that there is evidence, as convincing as that presented herein in regard to the orocline, indicating that structures of each of these types, and of the magnitudes stated, do in fact exist, and that with the oroclines, they are the first order structures of the globe. This evidence will be presented in due course.

Acknowledgments

This work was carried out partly in the University of Tasmania and partly in the Research School of Physical Sciences, Australian National University. The writer wishes to thank Professors Marcus Oliphant, J. C. Jaeger, Arthur Holmes, and Dr. W. R. Browne, for advice and helpful criticism. Thanks are also due to the Australian National University for meeting the cost of the blocks.

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