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The Instability of Folded Structures

Robert Del Mar

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By

Robert Del Mar

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ABSTRACT

Folded structures are not necessarily stable through geologic time. "Unfolding" is defined as the changes in attitude through which folded structures go subsequent to their creation by tectonic means, other than by faulting alone.

The principal types of unfolding, together with their causes, are: (1) the effect of gravity on isolated structures, and the effects of loading and unloading insofar as the gravitational force is concerned; (2) basining action and its effect on unfolding; (3) the action of vertical forces on folded structures; (4) migrating or "wave" folds in relation to unfolding.

It is concluded that unfolding is always a partial phenomenon.

The evidences supporting the unfolding concept include the dying-out of folds into a basin, certain types of bedding plane striations and slickensides, and certain types of fracture and fault patterns. The evidence for the migration of folds consists of measureable changes of altitude, the rising, sinking and tilting of islands, and possibly unconformable stratigraphic relationships.

In the section devoted to the practical implications of unfolding, the emphasis is upon the application of the concept to petroleum geology, in which branch of the science it is thought that the idea might prove to be the most useful.

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THE INSTABILITY OF FOLDED STRUCTURES

INTRODUCTION

The principal theme of this paper is that folded structures are not necessarily stable forms through geologic time. The purpose of the study is to consider the changes in attitude that may occur in folded structures subsequent to their principal deformation. The entire study is an attempt to develop an idea. As such, it is no more susceptible to proof than are the various theories and hypotheses concerned with the origin of earth, orogenesis, the origin of petroleum, etc.

Those changes in attitude of strata comprising folded structures which are caused by such phenomena as landslides, cavern collapse, or slump and creep are not considered. The object of this paper is to explore the possibility and nature of significant changes in the structural form of folded strata by the following means: (1) gravity acting upon a single fold such as an isolated dome, or a fold isolated from the rest of a series of folds by erosion; (2) smoothing out of anticlines and synclines by basining action; (3) migration of an undulation in the earth's crust.

For the sake of convenience, the term "unfolding" will be used in the balance of this discussion to mean one of the following things: (1) any previously folded strata which are now more or less horizontally disposed; (2) any previously folded strata in which there has been a significant lessening of the intensity of the fold, that is partial unfolding.

Refolding, meaning to fold again, may or may not contribute to the unfolding of pre-existing structures. The results of refolding relative to unfolding are dependent upon the direction of application of the causal forces of the second-cycle folding (the refolding) with regard to that of the first cycle of folding.

With the exception of the unfolding accomplished by undulatory movements of the earth's crust, which may be termed "wave folds" or "migrating folds", all other unfolding may be thought of as happening in place, that is, the trace of the axial plane of an anticline would appear in approximately the same position on a planimetric map both before the unfolding of the anticline and afterwards.

Owing to the nature of the evidence which would substantiate the hypotheses herein set forth, and to the writer's limitations, particularly with regard to breadth of experience in the field, an analytical approach has been selected. It is recognized that the necessary sequel to this study is sufficiently extensive field work to prove or disprove, point by point, the postulates upon which the hypotheses presented rest. This is largely a study of the possibilities of the proposed process and it would be difficult to test in the field, although some suggestions along this line are made.

It is not the purpose of this discussion to consider in detail the origin of the forces involved in the unfolding process. These forces will be assumed to have the same fundamental origin as those which produced folding in the first

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place, with added emphasis on the role of gravity insofar as the unfolding of arched structures is concerned. During the initial stages of this study, it was thought that the fundamental forces which produce folding in the earth's crust could be ignored. Further thought indicates that such is not the case. Unfolding on a major scale could well be a correlative of folding and therefore the product, at least in part, of the same forces. Two basic assumptions underlie many of the ideas expressed in this paper. They are: (1) major folds in the earth's crust may involve the total thickness of the crust or at least a considerable part thereof, and, (2) one of the primary forces operative in the formation of folds and in their subsequent unfolding is the subcrustal flowage which is required to effect the redistribution of mass which must take place in order to keep the system in balance.

It is thought that unfolding is a possible corollary to folding, that it may have occurred throughout geologic time, and that it may be continuing.

The earliest use of the term "unfolding" found in the literature occurs in a two-volume work entitled, "The Geology of Pennsylvania", published in 1858. (Rogers, p. 481). As may be seen in the following quotation, the term was not used in the same sense in which it is employed in this paper:

> "The Second and Third mountains include a deep, narrow, folded synclinal valley of higher Surgent slates and shales, and other soft rocks, which by the shallowing and unfolding (italics by the present writer) of the synclinal trough, come gently to a head, the two mountains forming but one, which is broad and level on its surface and still of synclinal structure---." (op. cit.)

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As interpreted by the present writer, Rogers referred to the dying out of the fold and did not mean to imply that a syncline with previously steeper limbs had been subjected to forces which subsequently flattened the limbs to produce a shallower syncline.

A careful search of the Gological Society of America publication, Bibliography and Index of Geology Exclusive of North America, for the years 1933 through 1953 was made. No mention of, or reference to, unfolding was found.

Acknowledgment

The original idea of "unfolding" was presented to the writer as a seminar discussion topic by Dr. V. C. Kelley. It is not an overstatement to say that were it not for Dr. Kelley's continued interest and assistance, this thesis would not have been written.

TYPES AND CAUSES OF UNFOLDING

General Statement

As noted in the introduction to this paper, unfolding is considered to be the product of one or more of the following: (1) gravity, (2) basining action, (3) vertical forces, and (4) migrating undulatory movements. Each of these four actions will be considered separately despite the fact that more than one may be operative in any given case of unfolding. The type of unfolding may be classified on the basis of the actions

that produced it. The classification of the types and causes of unfolding is an arbitrary one and to an extent it is artificial. The force of gravity is, of course, operative in all cases and at all times. It may constitute an integral part of basining action and is certainly a prime factor in the functioning of vertical forces with regard to the possibly resultant unfolding.

In view of demonstrated recurrent tectonic disturbances through geologic time, it seems logical to assume that after the first cycle of folding in any given area was accomplished, each succeeding period of crustal deformation dealt at least in part with strata that were already in attitudes other than the near horizontal and which were not plane surfaces. Consequently, since earliest Precambrian time there have been some parts of the earth's crust that were folded and therefore subject to being unfolded or refolded. Among the possible results to be expected from deformation subsequent to the original folding are: (1) if the second-cycle deformation (or any other period of deformation which occurs after the initial folding) consists essentially of tangentially applied forces that act in the same direction as the original forces, the pre-existing folds will be increased in severity, that is, an open fold might become closed and finally isoclinal; it has been refolded rather than unfolded; (2) if the tangential force is applied differently from the force which caused the pre-existing folds, part of the effect may be to unfold the

structure; (3) if a migrating or wave fold moves in a direction parallel to the strike of pre-existing folds, part of the effect may be to unfold the pre-existing structure; (4) if vertical forces are operative in an area of folded rocks, unfolding may result, that is, if vertical forces acting upward were concentrated beneath a basin, the result could be the uplifting of the basinal structure into relatively, and apparently, undeformed strata.

The reasons that all folds are not unfolded are many. Among the more important are: (1) the folds may be of insufficient magnitude to upset local crustal equilibrium so that there is no tendency to unfold, (2) if a sequence of folds are very sharply folded, the horizontal component of the force of gravity is too small to overcome frictional resistance or the buttressing effect of adjacent folds, (3) if a system of folds is opposed by a large rigid mass, the possibility for the lateral expansion of the folded strata which must accompany unfolding is greatly impeded.

The Work of Gravity in Unfolding

The force of gravity is considered to be one of the two most important elements involved in the unfolding process. In the case of an isolated arched structure, the ever present tendency from the inception of the fold is for the fold to flatten or collapse under its own weight, that is, under the influence of gravity. In order to unfold, the dome or

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anticline must have room for lateral expansion and be of great enough magnitude so that its weight acting through a long period of time will induce subcrustal flowage outward from the crest of the structure. In fact, the formation of a fold may be thought of as the result of a positive force, compression for example, overcoming temporarily, in a geologic sense, the opposing force of gravity. In this example, if the gravitational force exceeds the compressive force as it is relaxed, the tendency will be to unfold the structures just completed. Many factors enter into the consideration of how far the unfolding will proceed, such as the sharpness of the folds involved, the strength of the folded strata, the presence or absence of buttressing structures, which, if present, will tend to support adjacent folds, the depth of folding and the character of the substratum, the proximity to a major positive area, etc.

The strength of the rocks involved in a fold will have an important bearing on the amount and nature of the unfolding which may occur. Thick, competent strata such as quartzite or massive limestone may have sufficient strength to survive as unsupported arches whereas weak, thin-bedded strata such as shale or gypsum would not survive as folds were they not supported both laterally and from beneath.

If a fold is one of a number of adjoining anticlines and synclines, it will be less likely to unfold due to the mutually buttressing effect of the adjacent structures. The

cutting of valleys or canyons in the synclines which separate anticlines in a series of folds would tend partially to destroy the buttressing effect, thus facilitating the unfolding process by providing space for lateral movement of the flattening limbs of the anticline. The possibility of unfolding is greatly reduced where the folds abut a craton which serves as a permanent buttress, permitting unfolding movement in only one direction.

The character of the substratum and the depth of folding have an important bearing on the nature and quantity of unfolding which may occur. A decollement such as that represented in the Jura Mountains can be shown to have a definite "bottom" so far as the folding is concerned. Here the folding is thought to be the result of the sliding and crumpling of the Mesozoic and Tertiary formations along an inclined "plane" of crystalline Paleozoic rocks which are not folded. The depth of folding is limited to the thickness of the stratigraphic column above the Paleozoic rocks at the time of the decollement. The point may be made here that if folding can be accomplished by a series of strata breaking free from the underlying rocks and sliding down hill so to speak, it is possible that the folds so produced could be unfolded rather easily if the tilt of the plane down which the original sliding took place were removed or reversed. With regard to the character of the substratum, the decollement in the Jura Mountains is believed to have been facilitated by the presence

of relatively thin strata of salt, anhydrite, and shale which acted as lubricants for the overlying rocks sliding over the underlying unaffected Paleozoic rocks.

With the exception of the type of folding noted above, very little is known about the actual total depth of folding beyond the empirical data derived from drill holes, which rarely penetrate the entire stratigraphic column. In most cases, if not all, it is not known whether the basement rocks are involved in the folding or not, but evidence from numerous deep oil wells or tests indicates that the depth to which folds extend is very considerable and that in most instances the intensity of folding increases, rather than decreases, with depth, particularly in parallel folding.

As interpreted by the writer, a decollement and the resulting folding are a product of the force of gravity. It has been suggested that if the tilt of the surface upon which the shearing took place were removed or reversed, unfolding would be a likely consequence.

The force of gravity is responsible for other tectonic effects. Harrison and Falcon (1934, p. 303) had the following to say with regard to structures produced by gravity:

> "In parts of South-West Persia the rocks were thrown into large simple anticlinal folds during the Alpine orogeny. Later, these rocks, comprising massive limestones separated and succeeded by considerable thicknesses of incompetent strata, were subjected to differential erosion, which has unroofed the limestones and removed their support in places. The action of gravity upon the folded rigid rocks has produced strikingly abnormal large-scale structures, varying according to the attitude of the

> limestones. The structures include cascading dips, overturned flaps on the edges of the synclines, large recumbent folds, slip-faulted blocks, 'roof and wall' folds, etc. Similar features are liable to have been formed in the Laramide, Hercynian and Caledonian Revolutions--whenever, in fact, orogenesis had thrown the rocks of the earth's crust into folds of large amplitude. Bailey has produced evidence of rare structures caused by steep topography in submarine earthquake zones, and Jefferies has indicated the fundamental instability of towering piles of rock and their inherent tendency to flatten under the influence of gravity. The evidence examined by the authors shows that this process tends to occur when the surface relief is of the order of 2,000 feet or more in limestone fold-mountains. Formerly such structures have been imputed to the action of tangential or rotational forces only."

The loading and unloading of the earth's crust may be considered logically under the heading of the function of gravity in the unfolding process. Loading may be accomplished by means of sedimentation, glaciation, or the extrusion of molten rock matter and pyroclastics. Unloading is essentially a function of gradational agencies.

Two of the principal assumptions which must be made in postulating quantitatively significant unfolding of domal or anticlinal structures by loading, unloading, or any other means are; (1) that the material under the crest of the structure at depth can be displaced, and, (2) that there is sufficient void space, most likely intergranular, left at depth during the original deformation so that complete displacement of the substratal material is not required. The main possibility in the second case is for compaction of a sufficient vertical extent to compensate for the downward

settling or unfolding of the anticlinal structure. The assumption here is that the anticline will tend to settle according to the principle of isostasy, whereas the syncline would tend to rise in order to achieve isostatic balance, hence compaction would occur mainly in the region under the up-arched structure. In this connection, Willis' concept is pertinent. In his paper on Appalachian structure, Willis (1893, p. 246 ff.) implied that a competent stratum can lift the entire load from the beds beneath it during the formation of the anticline. This does not mean, according to the present writer's interpretation, that the anticline forms an arch over the underlying beds with an interval of void space between the lowest stratum of the anticlinal arch and the material beneath, but rather that the underlying beds do not support the upward fold during the time of its creation, and while the creating forces are operative, the anticlinal arch is self-supporting. If the compressive forces relax, or the buttressing effects of adjacent structures are destroyed by erosion, the arch would tend to settle under the force of gravity, compacting the underlying material or displacing it.

The problem of displacement of material at depth during the process of unfolding is best solved by the concepts of rock flowage and plastic deformation. The idea that an anticlinal structure can act as an unsupported arch is acceptable only on a very limited time basis. If plastic rock flowage can be the means by which the material beneath the crest of

an upwarped structure can be displaced upon unfolding, it can also be the means by which any void space left by the creation of an unsupported arch can and will be filled. The creation of a zone of lessened pressure under an arch of strong rock would tend to initiate plastic flowage inward under the limbs of the structure and upward under its crest. With the occurrence of conditions favoring unfolding, the force of gravity acting downward would tend to initiate plastic flowage downward and outward, displacing the material under the arch and permitting the whole anticlinal structure gradually to unfold. (Fig. 1). The reversal of the direction of plastic flowage is the result of relative pressure conditions existing in the region beneath the anticlinal crest. If the structure is assumed to be more or less self-supporting, a low pressure zone should exist under the arch. With the relaxation of compressive forces, or for other reasons, the arch will no longer be self-supporting, and the force of gravity acting upon the structure will create a zone of higher pressure under the anticline, initiating flowage away from the structure.

An effective means with which to accomplish unfolding by loading and unloading would be continental glaciation. A continental glacier has not only the enormous weight required, but also progressive movement which would tend to iron-out gently to moderately folded structures which stood in the path of the advancing ice. That the force of an ice

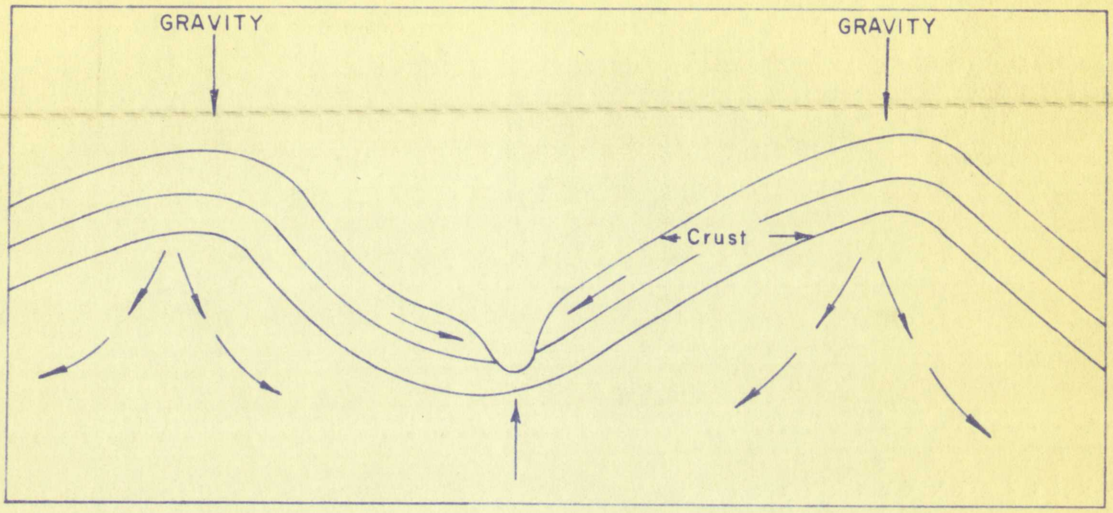

Figure 1. Diagram showing the effect of gravity on folded structures and the resultant displacement of subcrustal material by flowage.

The arrows in the subcrustal region indicate flowage away from the crests of the anticlines, with a resulting component exerting an upward pressure in the synclinal area. Space for lateral expansion of the strata as they flatten may be provided for in part by erosional breaching of the beds, thus destroying the mutually supporting roles played by adjacent anticlines and synclines.

sheet's outward, more or less horizontal thrust action is very great can not be gainsaid, and that the downward pressure due to its enormous weight is likewise very great is attested to by the fact that some 500 feet of vertical elevation resulting from plastic return of material at depth can be demonstrated in the Labrador area and 1250 feet or more at Hudson Bay. (Daly, 1926, p. 194-5). Considering that there have been at least three major periods of extensive continental glaciation; in Precambrian, Permian, and Pleistocene times, the very extensive amount of unfolding which could have been accomplished by this means may be significant.

Volcanic action is one of the principal means by which loading of the crust is accomplished. The burying of pre-existing structures by pyroclastics and extrusives will not be considered here in detail although loading by extensive, thick lava flows must have its effect in the alteration of the structures over which the extrusives are deposited.

The extrusion of basaltic lavas on the scale exemplified by the Columbia River Plateau basalts necessitates a major readjustment of the crust over a very considerable area. That some part of this adjustment of the crust to the new conditions arising from the redistribution of exceedingly large quantities of subcrustal material will result in substantial changes in the form and attitude of existing structures seems very likely. Among these changes, the unfolding of pre-existing structures appears to be one of the more

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probable adjustments. In such a situation there are two possibilities for unfolding. First, there is the subsidence which occurs when there is a withdrawal of large amounts of molten material from depth. Secondly, the deposition of this material in sufficient thickness would promote the subsidence of the area over which the lava is deposited. In both cases, local basining action could be expected to take place and, as will be shown in the next section of this paper, basining action, with its production of tension or stretching, is an important means of unfolding structures which existed prior to volcanism.

The following observation by Nevin (1950, p. 102) is considered applicable at this point:

> "Subsidence of the crust, on a large scale, is a common event in regions where the volume of extruded rock has been great. Of still more restricted significance, but of the same general class, are the small faults formed by removing the surface support during mining operations and in the drainage of certain types of oil reservoirs."

Basining Action

The formation of basins of considerable areal extent is considered to be one of the means by which unfolding may be accomplished. Whether the basining action consists of a subsiding central area surrounded by a relatively fixed rim or a relatively stable central portion being surrounded by rimming uplifts or a combination of the two modes of formation is immaterial to the point under consideration. In any

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case, part of the effect will be to set up a tensional stress system within the basin itself and in the flanks of the bounding "uplifts." If it be assumed that the area in which the basin forms consists wholly or partially of folded strata, the effect of the tensional stress set up by the basining action would be to stretch-out or unfold the structures present to a greater or lesser extent. It should be pointed out, however, that the effect of basining action could well be twofold, i.e., the upper part of the stratigraphic section affected may be subjected to some compression while the lower part is subjected to tensional stresses. It is thought that the net effect will be primarily tensional and that unfolding will be one of the results of the basining process. In the case of a basin formed by actively rising peripheral uplifts, the unfolding action can readily be visualized. However, in the case of a basin formed by the subsidence of the central area, more special conditions must prevail in order that unfolding may proceed. Assuming again that the area involved consists of folded strata, it may be seen that the initial subsidence of the basin will serve only to intensify the existing folds. In order that unfolding may occur, it is necessary that the subsidence be of sufficiently great magnitude so that when basining action or subsidence stops, the profile distance on any line across the basin is greater than it was, on the same line, prior to the beginning of basin formation. (Fig. 2). Otherwise, no "stretching" has

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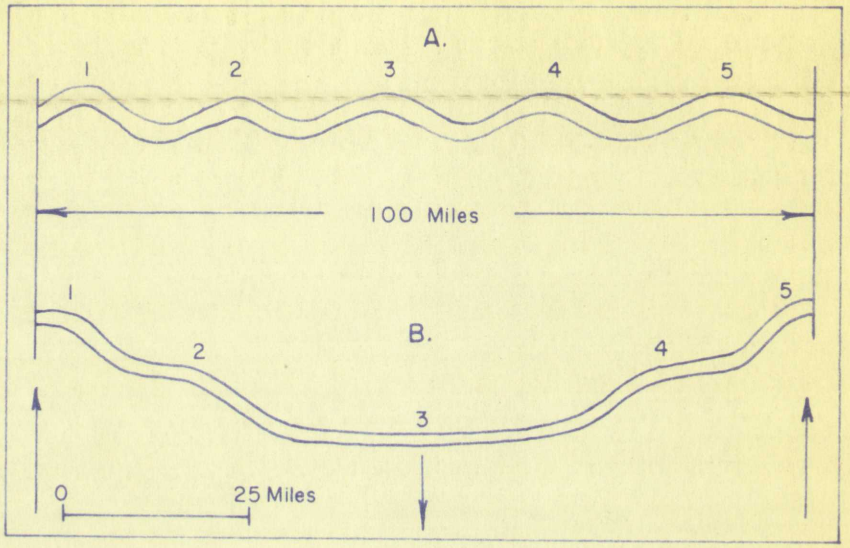

Figure 2. Diagram showing unfolding by basining action.

Part A represents a series of folds of approximately the same elevation.

Part B shows the stretching and consequent unfolding to which the folds in A are subjected when a basin is formed, either by uplift of the marginal areas, subsidence of the central part of the basin, or both.

At the scale shown, the length of the folded strata in A is approximately 107 miles, in B, 112 miles.

taken place with the consequence that unfolding could not have occurred.

For that school of thought which holds that basins are frequently the product of compressive forces, the preceding discussion is of little value. It is difficult, if not impossible, to make a case for unfolding, based on the hypothesis that basins are compression features. However, viewed as a secondary result, unfolding may be demonstrated. Regarding the post-compression period, Nevin (1950, p. 102) had this to say:

> "After the folding and smashing of an area by compressive forces, relaxation may set in and give major high-angle normal faults. Some of this settling may be the result of carrying the fold too far. *That is, the folds are unstable without the support of active compression.* (Italics by the present writer.) More probably, as the compressive forces diminish, the rocks, because of their elasticity and resilience, compensate partially for the previous crustal shortening by active extension, vertical relaxation, and normal faulting."

It should be noted that Nevin's phrases, "active extension" and "vertical relaxation" appearing in the last sentence quoted above, if taken together constitute nothing less than partial unfolding. His statement that folds are unstable is, of course, the fundamental theme of this paper. However, it is thought that there are important supports for unstable folds other than active compression. Considered from a regional point of view, adjacent folds and eventually perhaps even a craton will serve to buttress the fold and when erosion or faulting serve to destroy the buttress, the folds may become unstable and begin to unfold.

Lockett (1947, p. 429) presented an interesting analysis of the development of structure in basin areas. His main theme is that the tensions set up by the subsidence of basin areas adjacent to and lapping upon a tectonically stable element such as an arch, anticline or dome, sets up tensional stress which is in turn responsible for the deformation of the subsiding sediments.

Domes, arches, and anticlines are not necessarily stable elements. Tectonic stability is a relative thing and it should be kept in mind that unfolding is thought to be a very slow and long-continuing process. With regard to the deformation of the subsiding sediments by tensional stress, it is hoped that the foregoing discussion of basining action has made it clear that one of the principal effects will be to unfold to a greater or lesser extent the pre-existing structures which may have been present.

The Action of Vertical Forces

The concept involved here is a relatively simple one. If a basin or syncline under consideration is of small areal extent, that is, an individual basin or syncline, and vertical forces acting upward are localized under the structure, the effect will be to unfold the syncline or basin. In most cases, the probability is that the unfolding will be partial in both degree and extent for it would be fortuitous indeed to have the locus and extent of upward-acting forces coincide exactly with the trend and extent of a local basin or syncline.

Locate [illegible] of the development [illegible] the [illegible] ground [illegible] areas adjacent to [illegible] element such [illegible] stream which is [illegible] the subsiding sediments.

Other, [illegible] elements. [illegible] should be [illegible] the [illegible] tion of the [illegible] hoped that the [illegible] made it clear [illegible] unfold to [illegible] terms which may have been [illegible].

The Action of Vertical Sorting

The [illegible] If a basin or [illegible] extent, then [illegible] forces acting [illegible] effect will be [illegible] the probability [illegible] degree and [illegible] the limits and extent of [illegible] with the trend and [illegible]

Still considering the matter on a small scale, a similar case may be made for vertical forces acting downward, in which case if the downward forces were concentrated beneath an upward-arched structure such as an anticline or dome, the effect would again be one of unfolding.

In the case of localized vertical forces, basement faulting may be the immediate cause of the upward and downward movements so that it could be expected that these movements will occur as couples and the unfolding which results will depend upon the geographic distribution of surface structures in relation to the trend and magnitude of the basement faulting.

Considered from a regional point of view, vertical uplift may be thought of as epeirogeny and the result, with reference to unfolding, is analogous to that produced by basining action, although opposite in direction. The gentle up-arching of a folded region would tend to stretch out the folds, thereby lessening the sharpness of folding and would also provide a subsurface gradient which might facilitate the action of gravity in the unfolding process by providing a downward-sloping "plane" upon which the folded sediments could move laterally.

Migrating or "Wave" Folds

The next consideration is the unfolding which may result from undulatory movements of the earth's crust. The results of such progressive undulations have been referred to in the

Still considering the [illegible]
case may be made [illegible]
even if the [illegible]
[illegible]
effect would [illegible]

In the case of [illegible]
ing may be [illegible]
movements so that it would [illegible]
will occur as [illegible]
demand upon the [illegible]
in relation to the [illegible]

Considering these [illegible]
may be thought of as [illegible]
to stability is [illegible]
although opposite [illegible]
folded angle [illegible]
Assuming the [illegible]
somewhere [illegible]
gravity [illegible]
sloping "plane" [illegible]
laterally.

Hypothesis on "Wave" [illegible]

The [illegible]
from [illegible]
of which [illegible]

literature as migrating anticlines, synclines, geosynclines, etc., depending upon the form and the scale of the feature under consideration.

The Dutch and, to a lesser extent, the German geologists appear to be the leading exponents of crustal undulation as a geologic phenomenon. The reader is referred to the works of Tromp (1937) and van Bemmelen (1933) for the somewhat involved theoretical considerations which enter into their explanations of the physical causes for undulatory movements of the crust.

That rhythmic undulations of the crust have occurred in the geologic past appears to be an established fact. It is highly probable that the phenomenon is of a more or less continuous nature and that the earth's crust is undergoing undulatory movement at the present time.

Whether such undulations are of sufficient magnitude and duration to be considered as permanent structures is not altogether certain, but it seems likely that they may be. The critical points involved here are the speed with which the undulations move over the surface of the earth and the amplitude of the waves. If the amplitude is small and the speed relatively great, one is dealing with a motion rather than a structure, as is the case with water waves. Conversely, if the amplitude is great and the progressive forward motion is very slow, then an undulation or earth wave is a structure. Now obviously a structure which moves, however slowly, across the face of the earth gives rise to folding followed by

literature on [illegible], [illegible], etc., [illegible] under consideration.

The [illegible] appear [illegible] geologic phenomena. [illegible] Trepp (1937) and [illegible] theoretical [illegible] of the [illegible].

[illegible] the geologic [illegible] highly probable that [illegible] [illegible] that [illegible].

[illegible] duration [illegible] critical points [illegible] undulations [illegible] ends of the [illegible] relatively [illegible] structure, [illegible] the amplitude [illegible] very [illegible] how [illegible] the form of the [illegible]

unfolding, for if we consider the case of a single wave moving from east to west at the rate of 5 centimeters per year through horizontal strata, at a given moment in time a point on the crest of the wave, structurally an anticline, will have a precise geographic location, with flat-lying strata to the east and west. At the postulated rate of movement, during a period of 10,000 years, the wave or anticline will have moved westward a distance of 500 meters, leaving unfolded strata at the location to the east where the crest of the moving structure had been 10,000 years before. (Fig. 3A).

Possibly the best explanation of the cause or origin of crustal undulations is the convection hypothesis advanced by Griggs (1939) as an explanation of mountain building. A cyclic current flowing beneath the crust could very conceivably give rise to undulations of the crust, regardless of whether or not the application of the theory to the genesis of mountains is valid.

If the existence of convection currents in the mantle is accepted as a valid concept, the drag exerted upon the under side of the crust by the moving current could serve effectively to smooth out or unfold the structures of the region beneath which it was passing, particularly in the area where the current begins to make its downward turn toward the center of the earth. In this area, a severe tensional stress is being exerted on the crust, lengthening it and possibly dragging it downward to form a root, as suggested by Griggs

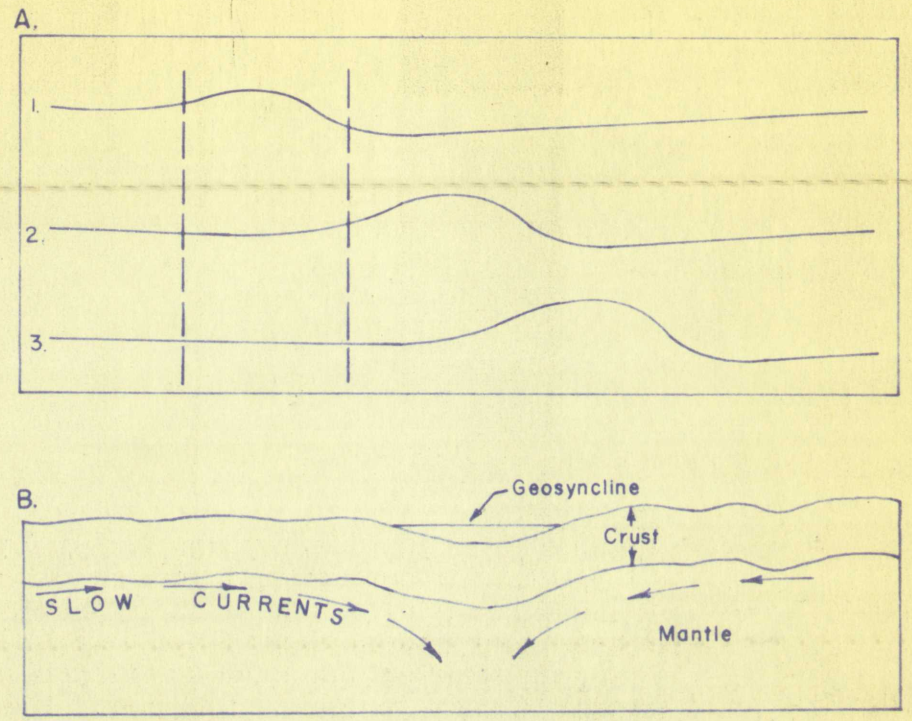

Figure 3. Diagram showing the suggested origin of migrating folds and the unfolding produced by such folds.

A. Fold migrating from left to right. Note that in the area between the vertical lines, the anticline in section 1 has been completely unfolded in section 3. The profile of No. 1 might be early Pliocene, that of No. 3, late Pliocene.

B. The action of a convection cell in the deformation of the earth's crust, possibly the means by which migrating folds are originated. After Griggs, 1939, p. 644.

(1939, p. 645). This tension set up by the convection current as well as the unstable base for crustal structures which the current provides would seem to set the stage for widespread unfolding. (Fig. 3B).

Unfortunately, there are no data on either the size of the cells set up by convection currents or the speed of flow of the current itself. Various workers have postulated the breadth of a cell as ranging from 100 to 8700 km and the speed of the current has been estimated at from a few mm per year to as much as 70 cm per year.

The long-accepted concept of isostatic adjustment may be extended in its application to provide another explanation for undulatory movements of the crust and consequent unfolding of previously formed structures.

The concept of subcrustal flowage, as developed in the isostatic adjustment theory, is thought to be a primary force in both folding and unfolding. Assuming that major folding may include the entire thickness of the crust, or at least a significant proportion of the total thickness, it follows that subcrustal flowage will impinge with greater force against the downfolded or synclinal areas, thereby tending to lift and unfold them. This would be the case particularly where the folding was gentle. Conversely, such flowage could be interpreted as increasing the intensity of pre-existing folds by means of the dragging action exerted against their bases or troughs. There is, however, an additional point

(1939, p. 643). These [illegible]
as well as the [illegible]
current processes [illegible]
unfolding. (Fig. 14). [illegible]

Unfortunately, [illegible]
the cells [illegible]
of the current [illegible]
breadth of a [illegible]
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be extended in [illegible]
tion for [illegible]
unfolding of [illegible]

The concept of [illegible]
[illegible]
in both [illegible]
may include the [illegible]
significant proportion of [illegible]
that subcortical [illegible]
against the [illegible]
to lift and unfold [illegible]
where the folding was [illegible]
be interpreted as [illegible]
folds by means of [illegible]
bases or troughs. [illegible]

for the affirmative argument, i.e., the uplift created by flowage from an ocean basin toward the continent would tend to create tension in the crust, which together with local lifting action resulting from impingement of subcrustal flowage against the troughs of downwarped areas would tend to unfold the previously existing structure. If this concept be accepted, it becomes mandatory that folding and subsequent unfolding be considered as parts of an alternating cycle. The cyclic nature of major deformational periods in the earth's history has long been accepted. It is only necessary to add here that it is possible that a subsequent cycle of deformation may just as well partially undo the work of its predecessor as it may augment that work.

There follows a hypothetical example of how such cyclic deformation might operate with regard to unfolding:

1. Assume a primeval earth with continents, seas, and a crust of unequal thickness, the latter possibly the result of differential density. Assume further that it is a dynamically balanced system, which is logical if the earth solidified from a molten state.

2. Beginning with the first rain and wind, material will be transported from the continents into the ocean basins. In time, sufficient mass will be moved from the continents to the ocean basins so that the balance of the system will be disturbed. Two basic possibilities now arise: (a) the distribution of mass on the earth will

for the affirmative [illegible]

Change from [illegible]

to create [illegible]

[illegible]

[illegible]

unfold the [illegible]

accept, [illegible]

[illegible]

The cyclic nature [illegible]

[illegible]

to add here that [illegible]

[illegible]

[illegible]

There follows [illegible]

deformation [illegible]

1. Assume [illegible]

a drift of [illegible]

of differential [illegible]

[illegible]

fied from a [illegible]

2. [illegible]

will be [illegible]

[illegible]

combined [illegible]

system will be [illegible]

[illegible]

become more and more unequal and the spinning globe will ultimately rack itself to pieces or, (b) flowage in the zone underlying the rigid crust will effect a redistribution of mass so as to keep the system in balance. Possibly some of the great paroxysms which have rent and torn the earth's crust in the past have resulted from the time lag existing between the conditions postulated in (a) and (b) above.

3. At a certain critical point, subcrustal flowage will be initiated. In postulate (1) it was assumed that the original crust was of unequal thickness. This being so, a current of subcrustal material would impinge with varying degrees of force along the under side of the crust. Differential drag and uplift would be created which would in turn produce deformation of the crust, some of which would be folding. Theoretically, when the mass lost by transport of sediments from the continents is replaced by subcrustal flowage from beneath the ocean basins, flowage should stop until the critical point of unbalance is again reached. Probably it does not, at least not immediately. This excess of subcrustal material moving under the continents is possibly the reason for the culmination of orogenic cycles in great mountain-building periods.

4. The cycle now repeats itself through the first three stages, with one critically important difference. In addition to having a crust of unequal thickness upon which subcrustal currents impinge, there are now downfolded parts of the

because more [illegible] and [illegible] ultimately [illegible] underlying the [illegible] crust [illegible] made so as to [illegible]. [illegible] the [illegible] extent in the past [illegible] between the [illegible] in (a) and (b) [illegible]

3. At a certain [illegible] will be initiated. [illegible] (a) [illegible] the original [illegible] a current of [illegible] degrees of [illegible] the [illegible] produce [illegible] folding. [illegible] sediments from the [illegible] flowage from [illegible] until the [illegible] Probably 2 degrees [illegible] of subcrustal material [illegible] the present [illegible] downbuilding period [illegible]

4. The [illegible] stage, with [illegible] to having [illegible] currents [illegible]

crust which were formed in the previous cycle. Several possibilities are inherent in this new situation: (a) the downfolded or synclinal parts of the crust will be lifted, i.e., unfolded, by the pressure exerted upon them by the subcrustal flowage (this is most likely if the folds are gentle); (b) the force of the current will tend to increase the severity of the synclinal fold, particularly if the fold is a sharp one; (c) the downfold, if both deep and sharply folded, may be sheared off or dragged until the limbs are more or less parallel with the overlying crust, a structural situation, which, when exposed by subsequent erosion, might be interpreted as an overthrust.

As it would probably require more force to increase the severity of a fold or to shear it off than it would to uplift it to the mean level of the crust, it is thought that unfolding of major proportions could result from the sequence above postulated. It is realized that there are many variables that would alter the results to be anticipated from a slowly moving but nearly irresistable force applied against the downward projecting parts of the "rigid" crust. It does not seem unlikely, however, that more or less unfolding of the synclinal parts of the crust would be one of the expected results.

EVIDENCES OF UNFOLDING

General Statement

It is important that the nature of the evidence upon which hypotheses such as those herein advanced are based be fully recognized. Although from a logical standpoint unfolding appears to be a necessary corollary to folding, and therefore a phase of tectonic activity which must be of widespread occurrence, the results of unfolding are very difficult features to demonstrate. This is true because the problem resolves itself into one of proving the existence of a fold which either no longer exists as such, or one whose form has been greatly changed by being partially unfolded. As is the case with many aspects of geology, it appears as though evidence to support the hypothesis presented here must of necessity be more or less circumstantial.

Dying-out of Folds into a Basin

One of the possible indications of unfolding is that provided by the dying-out of folds toward the central part of large basins. It is recognized that there are other explanations for this phenomenon, as, for example, the obvious possibility that the folds are present but have been buried by post-deformation sediments. It is thought, however, that the unfolding process may be a factor in some places in explaining the absence or paucity of folds in the central

and southern Rocky Mountain region.

Kelley (1950, p. 105) stated his views on the results of basinal downwarping as follows:

> "One of the principal secondary forces set up during basinal downwarp is tangential to the rim and it results in shrinkage of the perimeter of the basin. As downwarping proceeds the outer parts of the beds are "pulled" toward the center of the basin and therefore must occupy a smaller area. One would expect radial fold axes from this action; and they are indeed present, especially in basins that approach circularity, such as the San Juan. On the other hand, tangential fold axes (parallel to the rim) result from either a push from a rising and expanding uplift or from differential confinement of the strata in the flanks of the uplift area. Both may work together. Upthrusts of basement or other competent masses may furnish an abutment against which basin sedimentary units move differentially up the flanks of the basin with respect to the underlying units. If an upthrust confinement is formed, the differential movement in the sedimentary units tends to fold the upper units somewhat more than the lower ones. Theoretically at least, the differential movement results in a decollement and the formation of allochthonous folds which terminate abruptly on a lower unit or "floor" of less crowded and possibly more competent rock."

It is difficult for the writer to visualize the stratified rocks in an area of incipient basin formation as having sufficient tensile strength to "pull" the rim inward as basinal downwarping proceeds. However, if the rim of the basin is regarded as fixed in relation to the subsiding central area, then the formations which are being downwarped have either to stretch or to pull away from the basin rim. Quite possibly both stretching and pulling away from the rim occur together. If, under the postulated conditions, folded strata are subjected to basinal downwarping, the stretching to which

they are subjected will tend to unfold the structures to some extent.

In order to produce significant unfolding, basinal downwarping must be of the fixed-rim type. That is, the uplifts which rim the basin must be in the same place geographically both before and after the subsidence or downwarping of the central area of the basin. Otherwise, major tensional stresses are not likely to be set up and, without tension to stretch the subsiding strata, it is unlikely that unfolding will occur.

Bedding-plane Striations and Slickensides

Before going into the evidence of unfolding which may be provided by bedding-plane striations and slickensides, it is believed that a brief mention of the mechanics of unfolding would be helpful. The actual process of folding and unfolding is carried out by means of such highly localized deformational processes as the compaction of sediments, inter- and intraformational gliding, plastic flowage, etc. This being the case, it is to be expected that some visible evidence of folding and unfolding should be found in the form of striations and slickensides on those surfaces, either in or between strata, along which movement has occurred.

With regard to observable evidence of plastic deformation during folding, Washburne (1940, p. 701) made the following statement:

> "During folding, the creep of strata over each other toward the fold axes probably was finely

> diffused within the beds, for, in most cases, even of strong folding, one does not find striae running down the dip of the recognizable surfaces of beds. Other observations support the idea that slow rock deformation is essentially plastic, and that is consists mainly of gliding along close spaced, parallel planes."

Hence it would appear that, at least in some cases, folding and unfolding may be effected by such finely diffused gliding that the striations and other evidences of movement are too small to be noticed or are actually non-existent due to plasticity of the moving strata.

The writer has heard of slickensided bedding-plane surfaces recovered in cores of wells drilled in flat-lying strata. A search of the literature did not turn up any reference to the subject.

However, an indication of unfolding may be provided by micro-scale lineation or slickensiding. If samples showing bedding-plane surfaces, taken from gently dipping to nearly horizontal strata, are found to have one or more sets of observable lineations, unfolding may have occurred. Careful microscopic examination of fine-grained sedimentary rocks, with samples taken from gently dipping to horizontally disposed beds, should, theoretically at least, show alpha lineation parallel to the direction of gliding and, less likely, beta lineation along the tectonic strike and originally normal to the direction of gliding if the beds have been unfolded. It is worth noting, however, that such fine-scale lineation may be destroyed nearly as quickly as it is formed by later

diffused with [illegible]
of about [illegible]
done dry [illegible]
Other [illegible]
determination [illegible]
[illegible]
parallel [illegible].

Hence [illegible]
folding and [illegible] may be [illegible]
gliding that [illegible]
are too small to be [illegible]
to plasticity of the [illegible].

The [illegible]
surfaces [illegible]
strata. [illegible]
ference to [illegible].

However, as [illegible]
micro-scale [illegible]
bedding-plane surfaces, [illegible] nearly
horizontal [illegible]
observable [illegible]
microscopic examination of [illegible]
with [illegible]
posed [illegible]
tion parallel to the [illegible]
both [illegible]
to the direction [illegible]
It is [illegible]
may be [illegible]

movement of the beds concerned, or at a later date by solution, compaction, cementation, or a new cycle of deformation. Indeed, if the unfolding be accomplished by means of plastic deformation, or rock flowage, it is quite possible that recognizable striae or slickensides would not be formed. It is not likely that the bedding-plane striations produced by the original folding would survive the unfolding, but if found in flat-lying rocks, it would indicate that the strata involved had previously been deformed. If such striations could be shown to form a radial pattern in nearly horizontal strata, the former existence of a dome could be inferred.

This brings up a consideration of the plasticity of stratified rocks and the relationship of plastic deformation to the unfolding process. It is thought that plastic deformation is an important, if not the most important, means by which unfolding is effected.

There is practically no limit to the number of examples which could be cited to demonstrate the plastic behavior of stratified rocks under certain conditions. Because the concept of plasticity has been widely accepted, only one example will be given here. Baker (1928, p. 424) has described competent limestones 3,000 feet thick, occurring in the mountainous country west of Panuco, Mexico that have "behaved like wax." If 3,000 feet of limestone can be described as behaving like wax, the question that arises is this: How can any upward-arched structure manage to exist for any

movements of the rock. [illegible]

composition, [illegible]

If the unfolding [illegible]

tion, or rock flowage, [illegible]

strike or [illegible]

that the [illegible]

folding would [illegible]

lying rocks, [illegible]

previously been [illegible]

to form a [illegible]

former existence [illegible]

This brings up a consideration of [illegible]

stratified rock mass, [illegible]

to the unfolding process. [illegible]

tion is an important, [illegible]

which unfolding is effected.

There is [illegible]

which could [illegible]

stratified rocks [illegible]

cept of plasticity [illegible]

will be given here. [illegible]

competent [illegible]

mountainous country [illegible]

like wax." [illegible]

behaving like wax, [illegible]

can any [illegible]

appreciable length of time? Why does it not melt, so to speak, or flow back to its pre-folding form? The answers are not too difficult to perceive. When the compressive forces which folded an area cease, a relaxation effect will set in and the rocks involved have the same potential plasticity. But, to achieve actual plasticity, certain conditions must be met, the principal one being pressure. To produce folding, it is necessary to have active compressive forces--these provide the pressure necessary to make rock plastic, together with such confining pressure as is provided by overburden. On the other hand, to produce unfolding, we must be content with the force of gravity and possibly some loading of the crust to provide pressure and, in many cases, a folded structure must be isolated by erosion or by faulting so that the buttressing effect of neighboring structures do not serve to support it. Furthermore, it is not thought that plasticity is likely to be achieved in surface and near-surface strata, so that in unfolding, the upper beds will act as a rigid shell which must be broken down by faulting and fracturing before the more plastic beds at depth can yield by plastic flowage.

Therefore, it seems logical to expect that evidence of unfolding in the form of lineation and slickensiding may be encountered in surface and near-surface strata if such have not been stripped off by erosion. In those parts of an unfolded structure where plastic deformation accounted for the

appreciable le[illegible] of [illegible]

speak. In Florida [illegible]

not too difficult to [illegible]

which folded [illegible]

and the rocks [illegible]

Thus, to achieve [illegible]

ment, the principal [illegible]

it is necessary to [illegible]

vide the pressure necessary to raise [illegible]

with such [illegible]

On the other hand, to produce [illegible]

with the force of gravity [illegible]

crust to provide [illegible]

structure must be [illegible]

the buttressing effect of [illegible]

to support it. [illegible]

city is likely to be [illegible]

strata, so that [illegible]

rigid shell which [illegible]

turing before the [illegible]

plastic flowage.

Therefore, it seems [illegible]

unfolding in the [illegible]

encountered in [illegible]

not been stripped [illegible]

folded [illegible]

movement, little of this type of evidence is to be expected, at least in recognizable form.

Joint and Fault Patterns

The occurrence of linear joint or fracture systems having an over-all trend indicative of the possibility that they originated as the result of the weakening of the troughs and crests of folded strata by fracturing, but which are now more or less horizontally disposed, could be considered as evidence that unfolding had occurred. In a series of parallel-trending anticlines and synclines, the expected results in this connection would be, after unfolding, a parallel series of fracture or joint systems occurring in essentially flat-lying or gently dipping strata, separated by elongate, unjointed, unfractured zones which mark the former flanks of the anticlines and synclines.

Were unfolding to proceed to its ideal conclusion, that is, to a situation where the strata were without a significant amount of dip, it is to be expected that the erosional agencies would produce a geomorphic expression of the zones weakened by jointing or fracturing, that is, these zones could eventually develop as topographic lows.

A similar case may be made for epi-anticlinal faults. The following quotation from Blackstone (1951, p. 19, ff.) is considered to be pertinent.

> "The detailed maps of the Elk Basin, Grass Creek, Salt Creek, Garland, Big Muddy, Lost Soldier

movement. little of [illegible] [illegible] [illegible] [illegible]
at least in [illegible] [illegible]

Joint and [illegible] [illegible]

The [illegible] [illegible] [illegible] [illegible]
an over-all [illegible] [illegible] of [illegible] [illegible]
originated in the [illegible] [illegible] [illegible] [illegible]
crests of [illegible] [illegible] [illegible] [illegible] [illegible]
or less horizontally [illegible] [illegible] [illegible] [illegible]
[illegible] [illegible] [illegible] [illegible] [illegible]
anticlines and [illegible] [illegible] [illegible] [illegible]
tion would [illegible] [illegible] [illegible] [illegible] [illegible]
or joint systems [illegible] [illegible] [illegible] [illegible]
dipping strata [illegible] [illegible] [illegible] [illegible]
zones which [illegible] [illegible] [illegible] [illegible] and
synclines.

[illegible] [illegible] [illegible] [illegible] [illegible]
ly, to a situation where [illegible] [illegible] [illegible]
seam enough [illegible] [illegible] [illegible] [illegible]
aquatics would [illegible] [illegible] [illegible] [illegible]
weakened by [illegible] of [illegible] [illegible] [illegible]
could eventually [illegible] [illegible] [illegible]

A similar case [illegible] [illegible] [illegible]
The following [illegible] [illegible] [illegible] [illegible]
is considered by its [illegible].

[illegible] [illegible] [illegible] [illegible]
[illegible] [illegible] [illegible] [illegible]

and other anticlines present a pattern of fracture of obviously common origin. Similar fault patterns are recognized in California and elsewhere.

"The structural studies of the Elk Basin anticline, originally known as Silvertip, will suffice as an example of the evolution of structural thinking on this particular problem...Estabrook, (1923) published the first of many maps clearly defining the transverse fault pattern common to this and many other Rocky Mountain anticlines. Irwin (1926) proposed the name of "epi-anticlinal" faults for such systems in the following statement: Normal faults, which occur characteristically in parallel and radial systems on domes and anticlines in the Cretaceous strata of the Rocky Mountain region, are normal accompaniments of the uplifts. They are confined to the uplifts and formed at the same time as the uplifts. For such features the name "epi-anticlinal" faults is suggested.

"The choice of words had been suggested by Wallace Pratt (1922) in a discussion of a paper by Gardner (1922).

"Irwin considered the relationship between folding and faulting to be genetic, and therefore local. His conclusions on the origin of the faults were stated thusly: Just why the apparent normal habit of epi-anticlinal fault systems should be transverse to the anticlinal axis is a fundamental question and one for which this writer has no explanation. In some cases the arrangement of the faults is more or less radial, with the crest of the uplift as a center. Such an arrangement, and reasons therefore, would have been easier to conceive as the normal. The problem is apparently one of pure mechanics. The reason for the occurrence of epi-anticlinal faults is, at least in part, apparent. It has been noted by Willis that gravity faults of normal displacement frequently occur in consequence of the unequal subsidence of the shale, resulting from any disturbance of equilibrium. Now, certainly domes and anticlines are the loci of maximum disturbance during their growth, and where the strata involved are composed of great thicknesses of shale, alternating with relatively thin competent members, the conditions are ideal for a shaking-down process which results in gravity faulting.

"...Bartram, (1929), published a discussion of the structure of the fold [the Elk Basin anticline]

and a detailed map prepared by H. T. Morley. Bartram believed that the folding and faulting were contemporaneous, and that the faulting was caused by torsion and settling on the upwarped dome.

"A student of the writer, G. P. Salisbury, (1948), made an intensive study of the subsurface structure of the Elk Basin fold by means of electric logs of over 135 wells. Several observations on the behavior of strata at depth resulted from the analysis. Salisbury's general observations show that similar folding becomes more dominant as dip increases in any given formation. The degree of similar folding seems to increase with depth, and consequently with the increase of overburden. Both folding and faulting are genetically related in that they represent modes of relief of strains imposed by identical stresses.

"Salisbury also points out that the transverse faults die out with depth and the majority of the faults are restricted to the section above the Muddy sandstone. The faults are the result of continued deformation, causing movement to localize on the fracture pattern initiated at the inception of deformation, in this case the inception of the fold. The fault movement is absorbed at depth by slippage within the plastic strata of such units as the Morrison formation."

Several points in the above quotation are applicable to the unfolding concept, notably the ideas that epi-anticlinal faulting is the result of a shaking-down process or is caused by torsion and settling. Taken together with the typical pattern which is developed by this type of faulting (Fig. 4), the possibility that unfolding is involved should not be overlooked.

It is not implied in any case that unfolding will be a complete or sole means of markedly changing the attitudes of the beds in folded structures. On the contrary, it is felt that the normal association would be unfolding accompanied

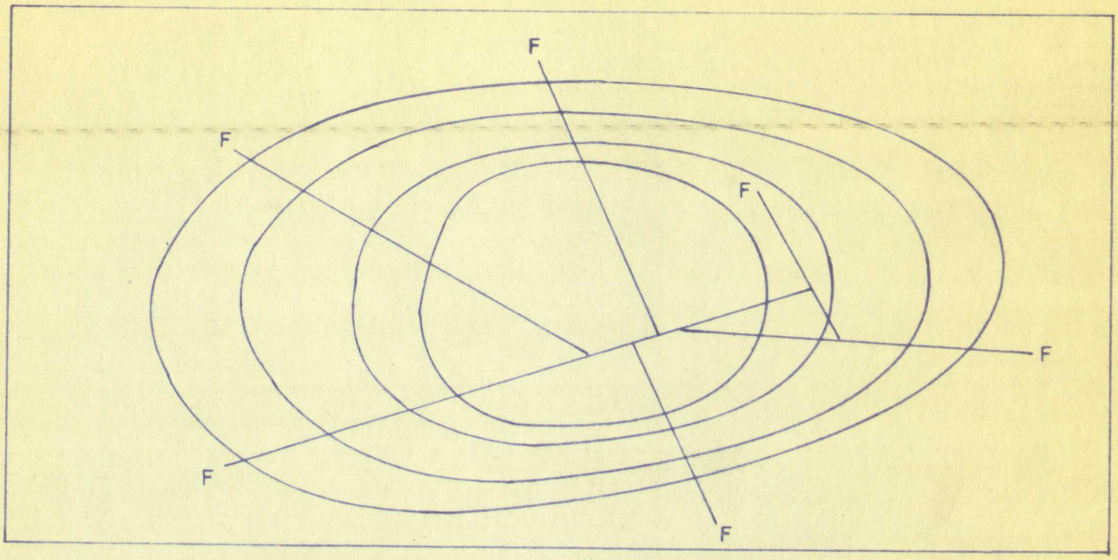

Figure 4. Diagram showing typical pattern made by epi-anticlinal faults occurring in a dome or anticline.

The occurrence of such a pattern, which is typically more or less radial from the crest of the structure, in flat or nearly flat beds could indicate the presence of a former dome or anticline.

by faulting when the availability for movement is greater than can be taken up by the bending of the strata alone, or when conditions of confining pressures, or plasticity of the beds, do not permit sufficient unfolding by bending alone to complete the movement required to achieve structural stability.

As an example, it is unlikely that an anticline, having a 30° dip on each limb would ever completely unfold to a plane surface. Structural stability would probably be achieved when the anticline had unfolded to the point where the dips were very gentle.

Finally, with regard to the evidence which may be afforded by joint and fracture patterns, it may be said that this type of evidence is thought to be the most likely kind to be found in field studies of areas which are, at present, relatively undeformed. It is the kind of evidence which would pass unnoticed in a local study and probably in a regional study, if the possibility of unfolding had not occurred to those people doing the geology.

Migrating or "Wave" Folds

The following excerpt from W. M. Davis', "The Coral Reef Problem", (1928, p. 471), strongly indicates the probability of, and the evidence for, unfolding by undulations in the earth's crust:

"The evidence for Darwin's theory, [foundation subsidence and reef upgrowth], given by some of the elevated atolls of eastern Fiji is believed to be beyond refutation. The region has evidently long been unstable; it has clearly suffered diverse movements of upheaval and subsidence; and reef formation has been closely associated with the movements of subsidence. Moreover, the evidence there given, [in a preceding section of the book], for Darwin's theory was not obtained merely by searching for such evidence; it was obtained by working out the geological history of the region, in which the formation of coral reefs was seen to be simply one of a number of events, all of which had to be arranged in a reasonable order. When that order was found, it appeared that reefs had been formed wherever and whenever subsidence took place, essentially as Darwin had supposed; but it was also found that subsidence alternating with upheaval had been determined by the westward migration of a broad and low anticline, of which he knew nothing whatever."

Davis, (1928, p. 447 ff.), continued:

"...the breadth of the anticline, measured from the trough of the preceding to the trough of the following syncline, may be some 60 or 80 miles; its height was probably only a few thousand feet. ...to be sure, the anticline and its preceding and following synclines should not be conceived of as rigidly defined forms during their westward migration and the several island belts should not be conceived as precisely parallel to each other. On the other hand, the marvel is that the anticline is so persistently an anticline and that the several belts (of atolls, islands, i.e.) which it defines are so nearly parallel.

"...It should be recalled in this connection that Brouwer and other observers have given good reasons for believing in the occurrence of migrating anticlines in the East Indies. The central Alps have recently been affected by a broad, northward-moving anticline, _not recognizable in the deformation of the rocks_, (italics by the present writer), but in the changes of altitude that its surface has experienced. ...When a sea-floor anticline migrates, it will not only cause the islands that it passes to rise and sink but will also cause them to tilt forward as it approaches and backward as it passes by. Such tilting has been well certified in the East Indies."

The relevance of the above quoted material is thought to be applicable to the subject at hand. If one accepts Davis' postulated anticline, it is logical to assume that there are others of a similar nature and that such features may indeed have a worldwide distribution as indicated by the instances cited by Davis in such widely separated geographic locations as the East Indies and the central Alps of Europe. Nor is it likely that the migration of such an anticline is restricted to what Davis refers to as recent time. It seems probable that such migration is either a more or less continuous phenomenon, or perhaps more likely, an intermittent or cyclic type of movement, possibly associated with the periodicity of orogenesis.

The recognition of an anticline (here considered as being of near-geanticlinal proportions) which has migrated to its present position is a difficult feat. A possible indication of such a condition would be the presence of an anomalous stratigraphic sequence as indicated in Figure 5. If the structure had remained fixed at the location shown in Figure 5B while sedimentation was in progress, then shaded strata should either wedge-out or at least thin over the crest of the anticline.

Another criterion for recognition of the former presence of a wave fold would be a series of intertonguing deposits which would be progressively younger in the direction of migration of the fold. (Fig. 6).

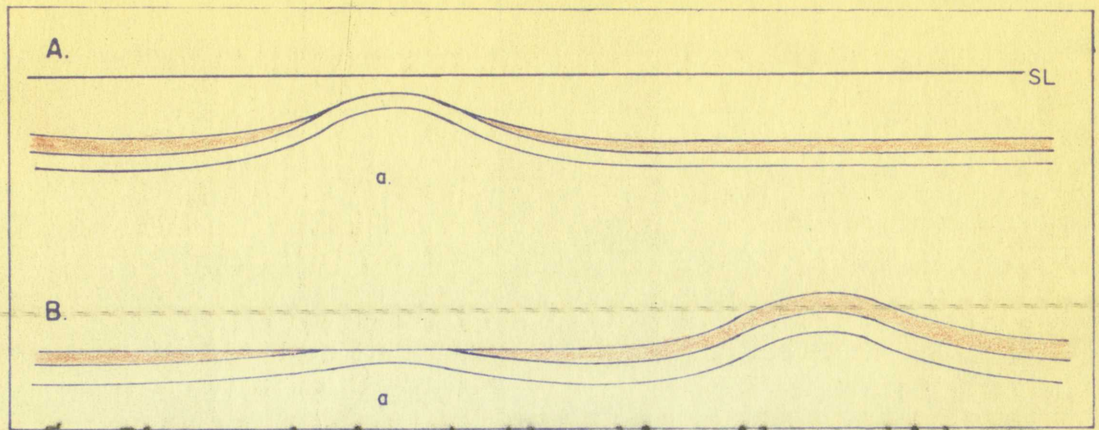

Figure 5. Diagram showing stratigraphic evidence which may indicate the former presence of a "wave" fold.

A. Migrating anticline in depositional environment. Sediments are deposited at the base of the fold, wedging out against the flanks with little or no deposition on the crest as shown by the shaded stratum.

B. Migrated anticline now exposed on land. Fine-grained material forms a continuous stratum of even thickness over the fold with no thinning over the crest or wedging out on the flanks. The former position of the crest of the fold is marked by the pinch-out of the shaded stratum in both directions.

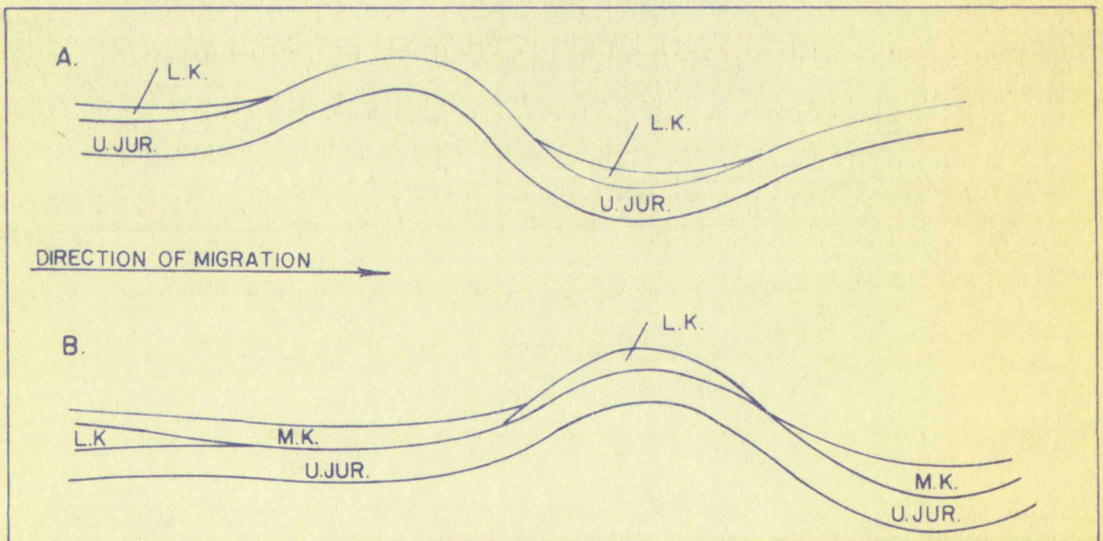

Figure 6. Diagram showing intertonguing and the possibility of deposits decreasing in age in the direction of migration.

A. Migrating fold in early Cretaceous time, with sedimentation in the trough and against the flank of the anticline.

B. By middle Cretaceous time, the fold has migrated to the position shown. Middle Cretaceous deposits are laid down with intertonguing as indicated.

If it be assumed that sedimentation takes place only in the synclinal trough, it can be seen that each succeeding deposit in the direction of migration will be younger than the deposits in the opposite direction.

General Evidence

An example of basining action on a local scale is to be found in Ulrich's work entitled, "The Revision of the Paleozoic Systems." Under the heading of minor and local tilting, by which he meant local differential vertical movements of the lithosphere, Ulrich (1911, p. 411) stated, "These differential movements indicate actual elevation of one area, while another nearby was sinking, and a reversal of movement in succeeding time. The condition is recognized by the alternate absence and presence of sediments on opposite sides of the tilting platform." Abundant stratigraphic evidence is presented by Ulrich to justify the view that this recurrent, and geologically frequent, undulation was widespread, both in space and in time.

Thus the application of detailed stratigraphic analysis is of great importance in detecting unfolding, for if in a presently undeformed area it is found that beds are alternately present and absent on opposite sides of a line (actually the hinge line for the local differential vertical movements discussed by Ulrich) it may be that the source area or anticline, and the depositional area or syncline may have been unfolded to produce the existing relatively flat-lying strata. While it is obvious that regional tilt, first in one direction and subsequently in the opposite direction, could produce the same result without either folding or unfolding, it is possible that unfolding produced by a "wave" fold could lead to the same results.

The presence of lenticular strata of considerable areal extent could result from the flattening or unfolding of a series of similar folds. A like effect is to be expected from the unfolding of supratenuous folds.

PRACTICAL IMPLICATIONS OF UNFOLDING

General Statement

Generally speaking, assuming the validity of the unfolding concept, the failure to recognize the fact of its having occurred could lead to serious errors in the deciphering of the geologic history of a region and thereby to serious errors in the practical application of geologic thought to such practical affairs as the search for petroleum. Complete episodes of deformation, particularly if of a local nature, could be overlooked or misinterpreted. An example might be the existence of very gently folded strata exposed in a canyon. If the possibility of unfolding had not occurred to the observer, the area would probably be written off as one characterized by little or no tectonic activity whereas if the observed gently folded strata were the remnants of a previously more strongly folded area, the inferred tectonic history would be quite different.

Application of the Concept to Petroleum Geology

From an economic point of view, probably the redistribution or dissemination of oil and gas accumulations would

be the most important results of unfolding. For example, the fluid trapped by an anticlinal structure which is subjected to unfolding might take one of the following courses:

(1) The fluid could be dispersed laterally along such paths of least resistance as bedding planes, zones of relatively greater permeability or porosity, or along planes of slippage modified by subsequent solution activity.

(2) The oil could escape upward through fracture zones into overlying reservoir rocks or be disseminated through the overlying strata. The assumption in both cases is that the fold under consideration had constituted an anticlinal trap in which oil or gas had accumulated. If the anticlinal structure were modified or destroyed by being unfolded, there would no longer be a trap to hold the accumulated fluids which would then be free to continue migrating.

(3) The oil could escape to the surface and become a "La Brea" tar pit or an asphalt lake such as occurs on the island of Trinidad.

(4) The oil could just as well be forced downward during the process of unfolding of the containing structure and be either reaccumulated in suitable reservoir rocks beneath the former folded structure (in schist or granite, for instance) or be dispersed downward. The unfolding of an arched structure would tend to develop tensional stress in the lower strata of the fold with a consequent reduction of pressure which could cause the fluids originally trapped by

the fold to migrate downward. Such movement would be facilitated by development of tension cracks or fractures.

(5) The oil could stay in place, held in its reservoir by peripheral cementation which occurred while the oil occupied the crestal portion of an anticline. In such a case, the resulting oil pool, after unfolding, might be classified as a porosity trap.

(6) In the case of migrating anticlines, the fluid could stay with the anticline, or be left behind, depending upon the relative rate of movement of the fluid as compared to that of the migrating anticline.

(7) A combination of two or more of the preceding possibilities.

It has long been known that, in general, folds are more numerous and have steeper dips at depth than near the surface of the earth. Among the reasons given to explain this increase in intensity of folding with depth are progressive uplift during deposition, more periods of folding in the deeper formations and the type of folding involved. Bucher (1933, p. 391) pointed out with reference to the classic experiments of Willis (1893, p. 217-282) that the downward increase in intensity of folding is not due to the folding which occurs during the period of deformation, but rather to the struggle for space in the more plastic beds below, which cannot escape by the simple device of fracturing as do the beds near the surface. To state the same proposition in

different terms, let it be assumed that the original folding is of the same intensity from surface to basement. At the moment compressions stops, relaxation and the tendency to flatten-out will begin. Those strata at and near the surface will be afforded space for lateral expansion by such results of erosion as canyon cutting which interrupts the continuity of a given stratum and hence destroys the mutually supporting effect that exists between the synclinal and anticlinal parts of the given stratum. The folded strata at depth are not afforded such space for lateral expansion and therefore retain their original intensity of folding. The end product might then be very gently folded strata at the surface, with a constant increase in intensity with depth. As the erosion cycle continues, the deeper folds are progressively exposed at the surface where the partial process of unfolding discussed immediately above may become operative.

The question which then arises is whether present structural conditions of only a few degrees of dip are adequate to explain the migration and accumulation of oil in commercial quantities, assuming that there is no gas or water pressure to drive the oil in a particular direction. It is here suggested that migration and accumulation may be accomplished at a time relatively soon after the period of deformation and that at that time the intensity of folding was much greater than that which now exists and that in the intervening time the folded structures have gradually

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flattened out or unfolded. If such is actually the case, it is conceivable that many of the oil fields or pools which have been classified as porosity-trap accumulations were simple structural traps in which the anticline or dome has unfolded to the extent that it is no longer discernible as such.

The following description of plains-type folding (Powers, 1928, p. 208) is illustrative of the vertical variation in intensity of folding and also to some extent of the time-intensity relationship.

> "Gentle folds, mostly of small size, characterize the Plains type of folding typical of the Mid-Continent region. Some of them form long lines of folding, others are irregularly scattered and do not lend themselves to any pattern. Their areal extent increases and the amount of structural closure decreases upward. Many of them show very gentle or even no reflection at the surface. ...Structural relief of these folds may be 50 feet at the surface and 300 feet in the Ordovician at a depth of 3,500 to 4,500 feet. Irregularly distributed folds are small, usually less than one mile in diameter. They are shown as gentle noses at the surface but have structural closure of 100 to 400 feet in the Ordovician."

Powers subscribed to the theory that the origin of the folding was a matter of recurrent folding at several periods, with a common locus of movement for each succeeding period. The increasing intensity of the folds with depth is referred to the fact that the older beds have been folded more often than the younger ones.

An explanation of the plains-type folding is suggested in Figure 7. The diagram is modified from one by Clark

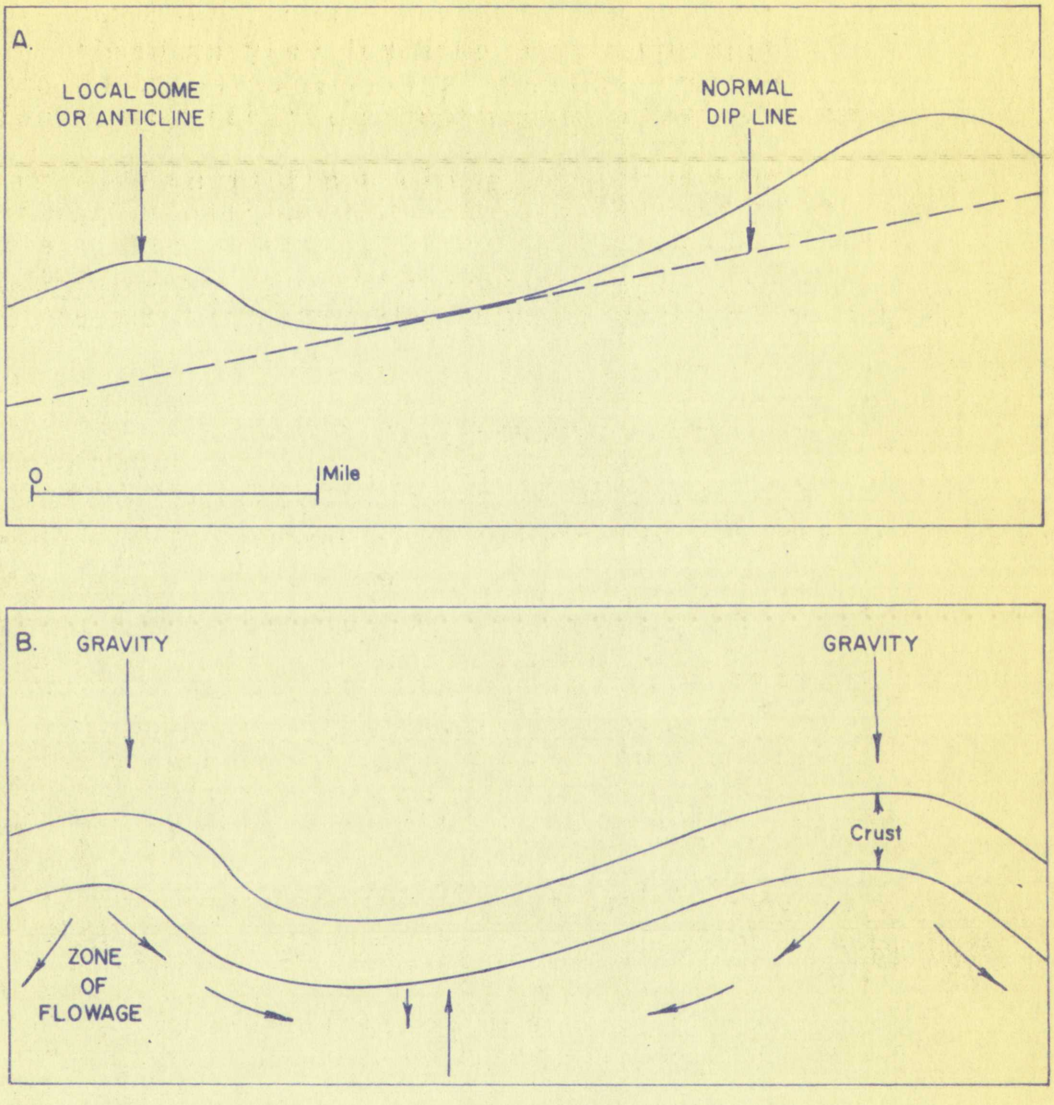

Figure 7. Diagram showing postulated origin of Great Plains type structure.

A. Typical present structure in the Great Plains area. After Clark, 1932, p. 47.

B. Postulated original structure. The force of gravity will tend to induce subcrustal flowage away from the crestal parts of the folds with the net result being an upward force whose locus is beneath the syncline. This will tend to raise the syncline at the same time as the anticlines are gradually unfolding.

(1932, p. 47-48), who has the following to say regarding plains-type folding:

> "The first outstanding characteristic of the Plains-type fold is that the net result of the folding is always a local uplift, without any corresponding depression. That is, there are virtually no true synclines, in the sense of downwarped fold, but only anticlines and domes raised above the normal monocline. ...It will be noted, (relative to the diagram), that no part of the profile of the key bed extends below the normal dip line projected across it."

It should be noted that in the diagrammatic representation of the present structure, which according to Clark is structure contoured on a shallow bed, no synclinal structure, in the sense described in the preceding paragraph, has been developed. In terms of the concept here presented, it is possible to develop a hypothesis which accounts for the existing field conditions, namely that synclines did develop during the original period of deformation but have since been modified by the settling of the anticlines with the consequent subsurface displacement acting to exert an upward pressure on the synclines.

Generally speaking, it may be said that the unfolding concept provides an explanation for the accumulation of oil in those types of traps in which there is little or no structure present today. The presence of oil in porosity and stratigraphic type traps in which structural closure is negligible or absent has been accounted for on the basis of differential porosities and wedging-out of reservoir strata.

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What is not demonstrated is what caused the concentration of the oil in the first place. That is, how did the oil manage to arrive in the lenses or porous zones if little or no structure was available to facilitate migration? If lack of peripheral permeability or porosity can constitute a trap, it also poses a difficult hurdle for any explanation of how the oil got in the trap in the first place.

In the light of the unfolding concept, it can be seen that lenticular concentrations and those confined by porosity-type traps may well occur when such areas are anticlinal or domal in nature. While in such a structural situation, circulating ground water could effectively destroy the porosity of all but the oil-carrying areas by means of cementation. Subsequently, the structural pattern could be altered by the means and in the manner heretofore discussed, leaving little or no indication of the structural aspect of the strata involved at the time of oil accumulation.

If the attempt here made, to demonstrate the probability that unfolding is and has been a common and widespread form of deformation, has achieved some measure of success, it is evident that the subject is worthy of a more extensive and expert study. It is believed that the implications of unfolding noted herein could be of considerable geologic significance. The failure to consider the possibility that unfolding may have occurred could lead to errors in the interpretation of the geologic history of an area.

Unfolding could therefore become a matter of practical importance as well as being of theoretical or academic interest.

CONCLUSIONS

Following are the conclusions arrived at by the writer; the reader is invited to draw his own.

1. Two of the most important factors that enter into the unfolding process are subcrustal flowage and the force of gravity.

2. The depth of folding is a point critical to the development of the unfolding hypothesis. Unfortunately, little has been definitely established relative to this question. It is concluded that in areas of large-scale folding, in which the individual folds are of considerable size, that a large part of the total thickness of the "rigid" crust, if not all of it, is involved.

3. It is thought that gently to moderately folded structures are the most likely to be affected by unfolding.

4. Unfolding is not likely to proceed to its ideal conclusion, which would be completely flat strata. Therefore, it is thought that, for practical purposes, unfolding will always be partial.

5. The branch of the geologic sciences most directly concerned with folded structures is petroleum geology. It

Unfolding could [illegible] importance [illegible] interest.

CONCLUSIONS

Following are the conclusions [illegible] the reader is invited to draw [illegible].

1. Two of the most important factors [illegible] the unfolding process are [illegible] of gravity.

2. The depth of [illegible] development of [illegible] little has been definitely [illegible] question. It is [illegible] folding, in which [illegible] size, that a large part of [illegible] crust, if not all of it, [illegible].

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4. Unfolding [illegible] normal [illegible], which [illegible] fore, it is [illegible] will always be parallel [illegible].

5. The [illegible] concerned with [illegible].

follows that the concept of unfolding would be most useful in that field.

6. The unfolding hypotheses here presented may well be applicable to the solution of some of the problems that arise in detailed stratigraphic studies.

7. A correct interpretation of the geologic history of deformed areas that may have been unfolded to a greater or lesser extent must take the unfolding concept into account if it be granted that the concept is valid.

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