TECTONICS

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Author's Preface to the English Edition

THIS ENGLISH TRANSLATION of my book *Traité de Tectonique* (Paris, 1952) has, to some degree, an advantage over the French Edition in that pertinent literature to 1957 could be discussed. However, no change has been made in the original aim or content of the book.

Most of the examples used were chosen either from France or from neighboring western European countries. Since these examples are intended to illustrate general theories rather than to give a systematic description of a certain region, I have not replaced them with examples from the United States or the western hemisphere, nor do I regard them to be of inconvenience to the American reader. I hope, however, that these examples will be of value to geologists in the Western Hemisphere who wish to become more intimately familiar with European geology, and, in particular, with Alpine geology.

The reader is encouraged to search for analogous examples in American geology. This, in my opinion, is the best way in which the information presented can be put to use and applied by the American student of tectonics.

JEAN GOGUEL

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CHAPTER ONE

Introduction

Historical character of geology—Definition of tectonics—Methods to be applied—Plan of the work—Fundamental observations.

AT FIRST GLANCE geology seems to have as its object the study and description of the rocky masses that make up the solid part of the earth. Such practical applications of geology as are employed in mineral exploitation, ground-water exploration, tunnel driving, and the study of artificial construction stability require that both the state and arrangement of rocks be known. In comparison with the activities of man, or in contrast with the freely moving air or surface waters, rocks are the very image of stability and permanence.

Although the descriptive approach is entirely insufficient for promoting an understanding of the nature and disposition of rocks, all becomes clear when a historical point of view is taken and when an attempt is made to reconstruct the genesis of the rocky masses. By considering an initial phase of such historical reconstruction, we can predict their long-term effects. Thus, the comparatively short-term effects of erosion by a brook enable us to comprehend the scooping out of a valley, just as the deposition of a thin film of mud is analogous to the filling in of a sedimentary basin. To make such extrapolations, we need only use our imagination: sea-level variations, the existence of volcanoes in regions where their activity is no longer evident, or the former extension of glaciers much beyond their present size. Comparison of certain areas with other regions furnishes us with another basis for such historical reconstruction.

However, if we wish to extend our reconstruction to explain, for example, the formation of mountains, it is necessary to visualize phenomena that are completely different from anything it is possible to actually observe. Rocks have been stretched and twisted, and hundreds of kilometers have undergone upheavals of an extraordinary amplitude. It is only after having reconstructed these deformations, by analyzing the forms they have given to the rocks, that it has been realized that the changes were not essentially different from certain changes recognized after earthquakes, or from gradual changes in elevation due to uplift or subsidence.

Tectonics is concerned with the examination of these deformations and with the study of the present forms of deformed rock masses. As is characteristic of geology in general, tectonics is principally a historical science, inasmuch as its object is the reconstruction of past phenomena. Only this sort of reconstruction can furnish the key to the interpretation of geologic structures.

For the determination of the present form of rock masses, we have only very fragmentary data concerning parts that are not masked by recent formations; these data concern only the surface produced by erosion at the heart of the deformed mass. However, the indications provided by a historical reconstruction of the deformation are too meager to permit formulation of a hypothesis regarding the disposition of deformed rock masses. Even if we were only concerned with understanding the present disposition of the rocks, a historical reconstruction would be indispensable in order to make the most of our observations. In many instances, precise knowledge concerning the disposition of deformed rocks is of sufficient economic importance to justify a very profound study along these lines.

The deformations undergone by rocks, the tempests in the solid crust of the globe, deserve an intense study, if only to acquire knowledge of the earth, without regard to practical applications. The geometric analysis of forms evidently constitutes a first phase of this study; these forms are both among the essential data at our disposal, and at the same time one of the results to be obtained. However, a geometric analysis should be supplemented by a study of the chronology. The description of the process of deformation constitutes a problem in kinematics—that is, a problem in analysis of motion. The forces that have deformed the rocks must also be considered, thus bringing dynamics into play. This obliges us to consider the mechanics of deformable solids, thus implying the use of a certain mathematical apparatus. However, we shall leave this out of consideration for the moment, thus avoiding mathematical calculations and limiting ourselves to the point of view of the naturalist. The inquisitive reader eager to investigate more thoroughly the mechanical and mathematical aspects of these questions, or even simply to seek proof of the results cited, is referred to an earlier work of the author.[1]

The successive phases of the analysis that we have just outlined—geometric, kinematic, dynamic—can be applied on different scales. Even the deformation of a small fragment of rock presents problems outside common experience. Moreover, this deformation may strikingly modify the properties of the rock. Then we shall have to show how the deformations undergone by the rock can be analyzed in detail. And finally, we should seek the laws according to which the deformations should be grouped and classified, both in space and in time.

When we attempt to date tectonic deformations in the general history of the earth, insofar as stratigraphy enables us to reconstruct it, it becomes obvious that they are by no means mere chance happenings. Quite the contrary; great paroxysms of tectonic deformation constitute major events in the history of the globe. Except for the evolution of the living world, which seems to have been uninfluenced by tectonic deformations, all other phenomena coordinate themselves around these great crises. The nature and extent of sediments depend upon the corresponding paleogeography—that is, upon the form and extent of the lands and seas that resulted from earlier deformations as well as from contemporaneous deformations. The activity of volcanoes, as well as the deep recrystallizations that have given birth to the plutonic rocks, also appear closely related to tectonic paroxysms. These paroxysms evidently constitute the surface manifestation of a sort of life—an internal pulsation of the globe. The information supplied by tectonics is, then, of primary importance in geophysics. Various methods have been developed within this discipline that provide us with information about the internal structure of the earth. The hypotheses formulated to coordinate these indications should also permit us to explain the deformations observed at the surface. Inversely, geophysical data are essential to an understanding of deformations.

Any author of a treatise on geology is faced with a dilemma: Should he insist, above all, upon methods and general laws, or should he, on the contrary, systematically describe the objects of his study, enumerating the results obtained? When it is a question of stratigraphy, the second alternative seems best. Here we have felt it best to insist upon method, while endeavoring, especially through the choice of illustrations, to base our methods on concrete examples.

However, neither a systematic presentation of results nor an overall description of principal mountain chains will be found here. Since the space available prevents extensive local descriptions, the syntheses we might present would necessarily be somewhat dogmatic. This we preferred to avoid, for even the most classic syntheses may, and should, change. As with many of the laws formulated in geology, the emphasis should be on establishing them, rather than on applying them.

In this investigation of the movements of the earth's crust, the subject matter of tectonics, we shall begin by examining the methods of analysis and then go on to the interpretation of the observations—that is, to the detailed reconstruction of crustal movements. Beginning with Chapter 16, we shall offer a more synthetic point of view and shall attempt to view the tectonic phenomenon as a whole (though there will be no description of the "face of the earth" as shaped by these deformations) and in relation to other phenomena.

In a final chapter, we shall examine what hypotheses may be formulated regarding the internal structure of the globe in order to account for the tectonic observations made at its surface.

Doubtless there would be no better introduction to the study of tectonics than the reading of *Voyages dans les Alpes*[2] by Horace Benedict de Saussure. In this book, we see how an excellent observer, with practically no previous theoretical experience, through his acute observations of natural phenomena, conceived two essential ideas. While contemplating Mont Blanc, from the top of the Grammont (II, p. 341), and later, standing before the Matterhorn (IV, p. 414), he declares that erosion, "by the waters of the snows and rains," scooped out the valleys, leaving behind the mountains as fragments of a formerly unbroken mass. While observing the Vallorsine conglomerates, whose beds are vertical (II, p. 100), or the bend outlined by the beds of Tithonic limestone at the Nant d'Arpenaz Falls, on the right bank of the Arve (IV, p. 414), de Saussure recognized that the layers, today tilted up on edge, or bent, must have been formed horizontally; so there is the proof of the deformation of the rocky mass.

Those are the two essential notions upon which the study of tectonics is based, proven with a care no longer to be found in later authors, who consider them evident. Terrestrial surface relief has been carved out by the erosion of a formerly unbroken mass. In certain regions, especially in most mountains, this mass is formed of rocks that have undergone deformation. We are going to seek to analyze this deformation.

Notes and References

1. Goguel, J., *Introduction à l'étude mécanique des déformations de l'Écorce Terrestre*, Mém. Carte géol. France, 2nd ed., Paris, 1948.

2. Neuchâtel, 4 vols., 1779–1796.

CHAPTER TWO

Morphology and Tectonics

Role of morphology in the study of the form of rock masses—Successive cycles of erosion or of deposition—Eustatic movements—Deformation of erosional or alluvial surfaces—Morphological role of recent faults—Movements verified through earthquakes—Other present movements.

THERE IS NO *a priori* difference between the present epoch and the geologic periods of the past; consequently, tectonic movements may now be studied at least in certain regions. If these movements are too slow to be directly perceptible, they may possibly be recognized by comparing the forms of the terranes with those that would have resulted through the simple action of erosion.

However, it must be recognized that many geographers have acquired the habit of analyzing relief forms, assuming more or less implicitly, that they result from the action of erosion upon an immobile rocky mass. According to all evidence, this is an approximation, sound only in regions unaffected by recent movements. In order to explain the formation of terraces, for instance, we must assume movement of the entire continent relative to sea level, or the reverse (eustatic movement).

However, in certain zones, the morphology can only be explained by postulating a deformation at a more or less recent epoch. The more ancient the erosion from which the erosion forms result, the more they manifest the trace of such movements.

Before examining the manner in which morphology indicates either wholly vertical movements or true folding, we should indicate the role it plays, even where the tectonic movements to be studied are older than the shaping of relief by erosion.

For the geologist who proposes simply to determine the form of the various rock masses, morphology is an indispensable complement to the direct observation of outcrop lithology. For a statement of the laws of erosion and of the resultant relations between land forms and the nature of rocks, we refer to specialized treatises.[1] A geologist with a good command of these laws can verify his working hypothesis about rock distribution by examining the terranes, and can sometimes be put on the trail of a geologic peculiarity by an apparently inexplicable morphologic feature.

The study of morphology begins with the topographic map, but no matter how detailed and precise it may be, the topographic map alone would obviously not suffice. Morphologic studies should be made during the observation of outcrops. In mountains, where the view is very extensive, morphologic analysis can often be conducted quite rapidly if the observation points are varied so as to avoid errors due to perspective.

Direct observation may be supplemented by the study of stereoscopic photographs, taken either on the ground (from the ends of a relatively long base) or from the air. It is often suggested that the length of the base on the ground should be one tenth of the distance to the nearest feature. Stereoscopic observation then gives unexaggerated relief, corresponding to a model that would be in our scale. If n and f are the distances to the nearest and farthest points, a base up to $nf/10(f - n)$ may be chosen, with the risk of producing an exaggerated relief, which is always the case with air photos.

Except when the nature of an outcrop is discernible on the photographs (either directly or through the nature of the vegetation), we should keep in mind that the photographs reveal only morphologic data, which is altogether insufficient for a tectonic interpretation. The ease with which air photographs can be used tempts us to make premature interpretations that are insufficiently supported or insufficiently verified by the direct study of outcrops. A number of errors have resulted from this vicious method of work, and it may be that the list is still open.

Whether an understanding of morphology results from direct examination, from map study, or from observation of stereoscopic photographs, it is known that hard rocks are characterized by steeper slopes than less resistant rocks. This "hardness" is something entirely relative; it characterizes the relative resistance to erosion of rocks within a particular climate and does not correspond directly to any physical qualities of the rocks.

Certain rocks are readily interpreted in terms of morphology: such, for example, are the limestones, whose solution by infiltrating waters produces the easy to recognize karst forms; gypsum is often riddled with funnel-shaped holes. In general, the depressions characteristic of soluble rocks may be sought on the air photo or on the ground. Besides the resistance to the erosion agents, permeability is shown in the topographic forms by the density of the hydrographic network, which is sometimes very characteristic.

But the use of morphologic analysis to distinguish rock types (often an unconscious process) involves grave risks of error. We must be able to distinguish successive related cycles of erosion, whose limits are marked (even in a homogeneous terrain) by changes in slope, from traces of hard horizontal

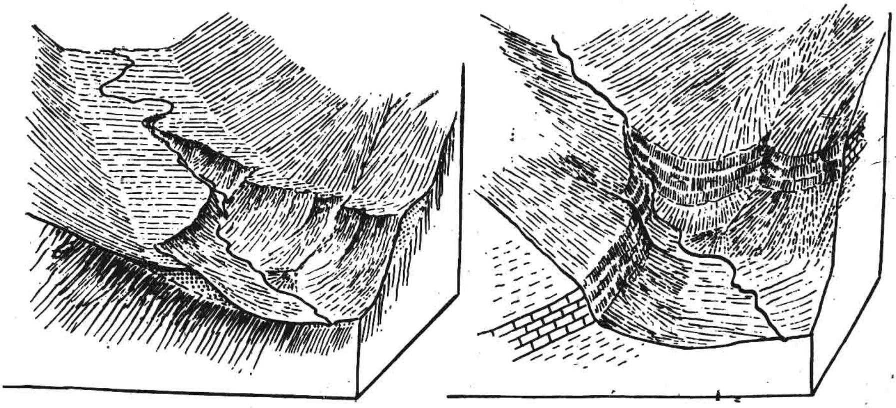

FIGURE 1. *Right, change of slope and discontinuity of longitudinal profile, determined by the presence of a hard bed. This situation should not be confused with that shown on the left, the nesting of an erosion cycle into a cycle of alluvial deposition.*

beds; this applies both to valley cross profile and longitudinal profiles (Fig. 1).

There is also a danger of committing serious errors in interpreting recent depositional forms (moraines, talus piles, and so on) as erosional forms on bed rock. The best way to avoid such errors is to study the depositional forms themselves, try to understand their genesis and distribution, and plot their boundaries as exactly as possible. At the same time, in this manner, the zones in which there is little hope of observing outcrops are defined.

To sum up, superficial morphologic analysis may involve grave errors, but even a thorough analysis merely furnishes suggestions that should be verified by the direct study of outcrops. It is mainly a way of making a sort of rough draft of the work and of determining the zones within which our observation should be focused.

There is, however, one case in which morphologic study furnishes results that might escape direct observation; we refer to mass landslips. Especially

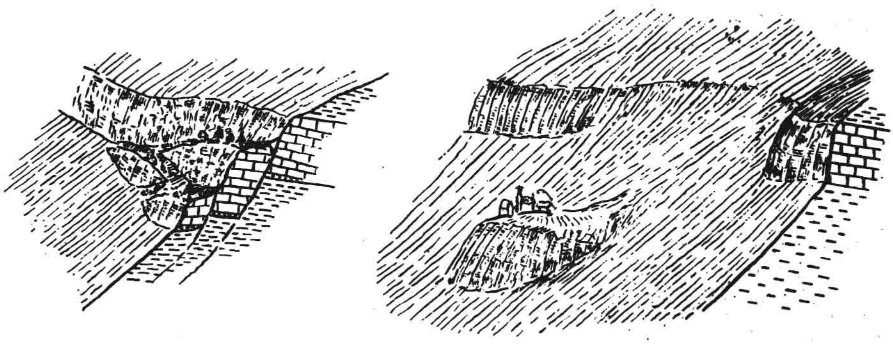

FIGURE 2. *Relationships that may develop on a slope by the slipping of calcareous masses resting on a clayey formation (see also Fig. 52).*

in places where calcareous beds rest upon a marly series, we very frequently find that a large mass (perhaps several hundred meters across) has slipped progressively down slope (Fig. 2). The outcrops within the affected area may not appear to be lowered, and the dip may be only slightly changed. Very often, morphologic analysis will put us on the right track and prevent an erroneoous interpretation of the outcrop pattern as being due to deep-seated displacement.

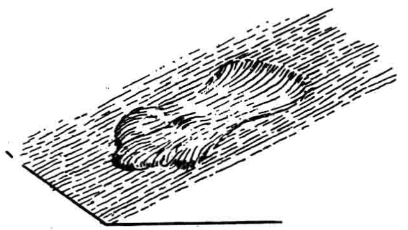

FIGURE 3

Elementary slip on a slope in clayey strata.

Forms more or less approximating a slip will be observed to have a bulge at the base and a small depression toward the top (Fig. 3). Similarly, the surface undulations on a marly slope reveal the presence of slips that may involve rocks below outcrop level. Real landslips, whose masses were notably displaced, are recognized through topographic forms, but their interpretation is confirmed in a decisive manner through examination of the slipped mass.

Morphology enables us to identify the cycles of erosion and alluvial deposition in a given region, the most recent of which are represented by alluvial terraces. The succession of these cycles records the changes in erosion processes, the causes of which must be analyzed: a change in elevation above sea level, for example, may either be the result of local upwarping, regional uplift, or even of variation in local base level (due to a landslip or to a cut off meander). Finally, the variations in climate may completely modify the conditions under which erosion takes place, both through variations in stream discharge and in modifications of the vegetal cover.

It is important to be able to recognize the succession of alluvial cycles due to such causes, in order to avoid making incorrect interpretations regarding continental deformation or sea-level variations. Figure 4 shows an example of terraces that were formed after a landslip barred the valley, causing a change in local base level.

The importance of climatic factors in the formation of terraces has been vigorously supported by certain recent geographic research findings.[2] The profile toward which a water course tends, which represents only a temporary equilibrium, depends both upon the flow (especially the flow at flood) and the proportion of solids carried by running waters; the destruction of vegetal covering enormously increases erosion and completely modifies the runoff.

At the eastern foot of the Andes, near Mendoza, for example, at the edge of the plains, there is a whole system of terraces not found in the plains themselves. It is impossible to assume that they record variation in sea level, since

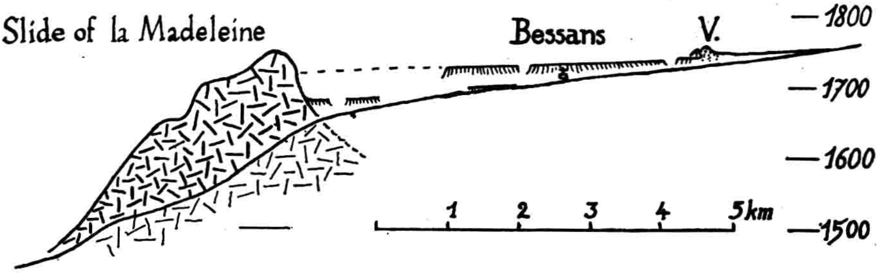

FIGURE 4. *An example of strictly local terraces in a section of the Arc River, upstream from Lansbourg (Savoie). The landslip of la Madeleine has barred the valley and caused the deposition of alluvial fill, which formed the Bessans terraces. The river has excavated a gorge through the slip and increased the slope of its profile. The frontal moraine of the Villaron (at V) rests upon the terrace, indicating the maximum extension of the glacier after the slip, which occurred after the warm period.*

this would imply recent erosion of earlier alluvium over a width of 1500 km. Nor is it necessary to assume an uplift of the chain corresponding to each of the terraces or erosion levels. Alluvial cones were probably formed during a period of heavy deposition and were subsequently cut through when the torrents began to erode more than they deposited. This example is rendered very striking by the considerable distance that separates the sea from the mountains in this part of the Argentine. Such changes in the behavior of torrents may have played a similar part in other countries.

It is no less a fact that the terrace steps downstream in a fluvial valley (especially when they correspond to raised beaches) indicate variations in sea level. The negative phases are difficult to date exactly, but may be indicated by the flooding of topographical forms, such as meander valleys.

It is customary to contrast orogenic movements, revealed by true deformation, with epeirogenic movements, which imply a vertical displacement of an entire land mass. The latter should, in turn, be distinguished from eustatic movements, resulting from changes in sea level.

Among the causes of eustatic movements in the Quaternary Period, the most important is certainly the accumulation of ice in the great glacial ice caps, which greatly decreased the volume of water in the oceans. Estimates of the corresponding fall of sea level vary greatly. Shepard[3] has proposed a figure of 1800 m, but this figure seems far too high and does not even suffice to explain the formation of submarine canyons by subaerial erosion, since some of them are as deep as 4000 m. Other estimates vary between 40 and 300 m. Moreover, owing to the changes produced in the terrestrial gravitational field as a result of mass displacements, the depressed oceans were not everywhere at a uniform distance below the present level, even in the absence of deformation.[4]

Glaciation is not the only possible cause of eustatic movements; in principle, the tectonic deformation of a marine zone may very well produce a global variation in sea level. This phenomenon may have played an important role during interglacial periods, but it is impossible to prove that the same applies to the Quaternary.

Having made an allowance for eustatic movements, the role of epeirogenic movements seems singularly restricted. The only movements that can be established with any certainty are those of isostatic adjustment, such as that undergone by Scandinavia since the disappearance of the Quaternary glacier (Chap. 16). This movement is revealed by the arrangement of raised beaches, which increase in elevation from south to north along the shores of the Baltic and are characterized by different shells (*Yoldia, Ancylus, Littorina, Lymnaea, Mya*).

Except for such passive isostatic readjustments, it is very difficult to discriminate between epeirogenic and orogenic movements. It must be admitted that the amplitude of the former may vary gradually from one location to another. On the other hand, the first consequence of a slight orogenic movement (or of an orogenic movement of short duration) should be a local change in elevation.

The variations of altitude of a given marine level, whether marked by raised beaches or by the terraces of lateral valleys, should then be interpreted as evidence of a deformation of the earth's crust. But when applying this principle, we must be sure that we are tracing the same bed. Too often, unfortunately, beds (observed bits of which it was hoped would fit into the picture) have been identified solely on the basis of their elevations. Errors of identification can be very serious in alluvial terraces. In raised beaches, paleontologic evidence may make identification possible if the beaches are old enough (Pleistocene and Pliocene). In the Baltic, important variations in the salinity have brought about a series of striking changes in the Recent fauna; thus the paleontologic record is particularly useful for such identification.

We might be tempted to introduce as evidence the variations of altitude of alluvial terraces, which, at the time of their deposition, followed the profile of a water course. But it is very difficult to discern what the former gradient of the water course was. Depending on the nature of the material transported, the discharge, and the flood regime, the equilibrium profile could vary greatly. Thus we cannot postulate that deformation followed deposition of the terrace alluvium, unless the terrace elevation increases downstream, or at least remains constant for a considerable distance. According to Rigo,[5] such would be the case for the Meuse above Mézieres; that is, at the point where the Meuse penetrates the Ardenne Massif.

The best known example of tectonically deformed alluvium is the low terrace of the Rhine, north of Mulhouse. This terrace slopes progressively downward, from an elevation 10 m above the present alluvium to stream level at a point 90 km downstream. Were this peculiarity isolated, it might be interpreted as due other than to tectonic deformation, but Jung[6] has shown the existence of surface upwarpings on the order of 2 m, which are directly above salt plugs that were located by geophysical prospecting. We would certainly have hesitated to interpret such slight surface irregularities as the result of tectonic deformation, if analogous deformations of much greater amplitude, which affected the base of the alluvium, had not been previously identified. The formation of this level, which began in the early Quaternary, was evidently much earlier than that of the low terrace, although the deformation was cumulative and extended over a much longer time. The sinking of the low terrace to the level of the present alluvial surface was accompanied by a sinking of the bottom of the alluvium, which drops to 44 m below sea level at Vieux Brisach but rises again to an elevation of 57 m above sea level downstream at Karlsruhe.[7] Above the Hettenschlag salt plug, the uplift of the base of the alluvium, relative to the surrounding regions, reaches 150 m in places.

By studying the base of the alluvium, known here through numerous borings, we avoid the causes of error introduced by erosion in the study of alluvial terraces. By itself, the comparison with a surface of the early Quaternary permits us to say that the very slight deformations of a relatively recent surface, such as that of the low terrace, are of tectonic origin. In Alsace, these tectonic deformations result from the superposition of two phenomena: the continued subsidence of the Rhenish trench, which represents the last action of a very ancient movement; and the local uplift of the salt plugs.

We shall have occasion to come back to the action of the salt plugs (Chaps. 10 and 13), whose upheaval may develop without the intervention of external forces. In the Gulf Coast region of Texas, there are numerous examples of upwarping of the alluvial plain (called "mounds"), which conceal salt plugs whose movements have continued until a quite recent epoch.

In certain regions, which are, in general, seismically active, tectonic movements can be inferred from faults, which may break the surface of the soil, interrupt the course of a stream, thus forming a lake, and so on. Fault scarps are rapidly altered by erosion, but the topographic forms resulting from very recent faulting are nevertheless characteristic. They have been abundantly described in California and in New Zealand,[8] but they are found in other active seismic regions (Japan, Assam, and elsewhere). Fractures of this type, changes in the level of Recent moraines, and bounding lakes have recently been described in the south of the Aar Massif (Grisons, Switzerland).[9]

Except within regions where faulting may be observed, there is evidently a better chance to prove tectonic deformation of an erosion surface the older the surface is. In Basse Provence, for instance, certain erosion surfaces are covered in places by Miocene sediments, which elsewhere are very clearly tilted. However, it is quite unusual to observe a definitely tilted erosion surface, inasmuch as a tilted surface is easily attacked by erosion, and as soon

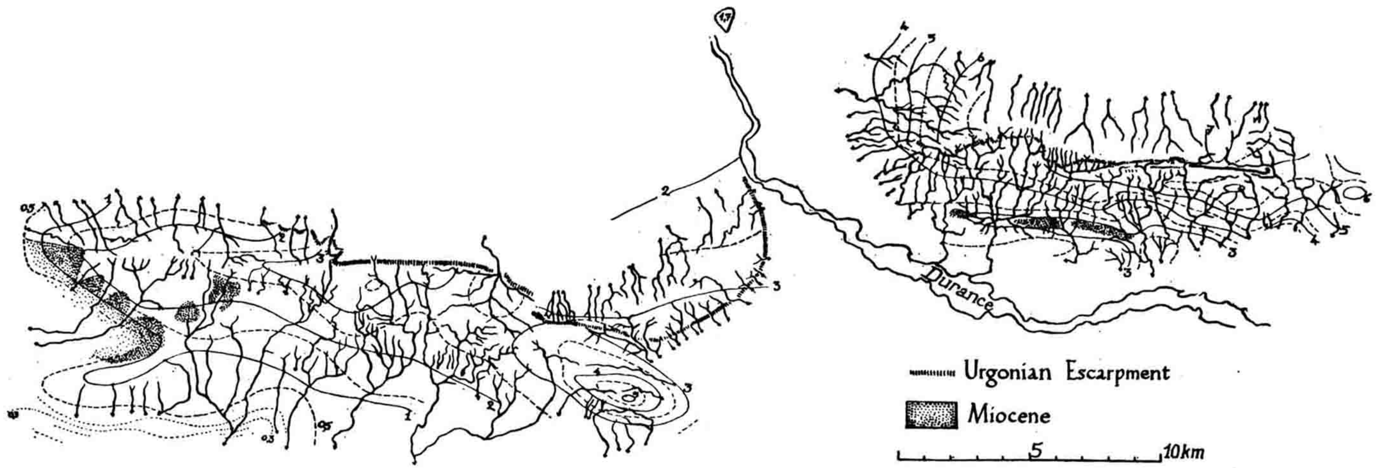

FIGURE 5. *Example of reconstruction, by morphology, of the present character of an old erosion surface. Map of the Alpilles and the Luberon (Bouches-du-Rhône and Vaucluse). The contour lines indicate the elevation in hectometers of the culminating points, the corresponding surface being deeply cut by many channels. Some Miocene remnants are to be found on this surface. (Reduced from a map drawn to a scale of 1:20,000.)*

as the protecting sediments are removed, it is soon reduced to shreds. But regular variations in the elevation of surface remnants may indicate that they formerly belonged to the same surface. In the Alpilles, and in the Luberon, we can confirm such an interpretation and can show that the present hydrographic network is everywhere orthogonal to the contours of the reconstructed surface. (See Fig. 5.) Obviously the bits of surface that remain horizontal cannot be correlated by their heights, since their vertical displacements must vary.

However, many geographers have distinguished between successive cycles of erosion on the basis of a comparison of the altitudes of old erosion surfaces. In the absence of positive arguments one way or the other, the choice between the two methods of interpretation is largely subjective. One method assumes the absence of deformation and the succession of erosion cycles whereas the other attempts to follow the deformations of an erosion surface. A quite striking example of the analysis of the movements by reconstruction of old, deformed erosion surfaces is found in the Besançon region, French Jura.[10]

In the absence of originally horizontal erosion surfaces, the analysis of a more complex relief may at times enable us to identify the trace of deformation. The very form of Lake Kioga in Central Africa shows that it is the product of warping, which affected a system of valleys and reversed the slope of the stream, thus producing a lake that discharges toward the Nile through what was originally one of its affluent branches.

In a remarkable study of the relief of Belgium,[11] Stevens has deliberately chosen the second method. His conclusions, however, are not accepted by all geographers. In the absence of well preserved erosion surfaces, he has made special use of the courses of streams and the altitudes of certain points, which do not seem to be in accordance with the nature of the rocks of which they are constituted, in order to reconstruct recent movements that would have modified the course of streams or caused captures. Such an approach may have to be fruitful, but in order to remove the uncertainties that exist, *it must be carried out in an extremely rigorous manner.*

As is shown by J. Bourcart,[12] the Dinarides folding actually continues throughout the more external chains, which make up the line of the Dalmatian Islands. Archeological investigations have proved that the site of Durazzo has, since ancient times, undergone warping, which has been found to correspond to the characteristics of the folds. The strings of islands separated from the coast by straits were, in general, probably formed as a result of this accentuation of folding. Through a study of the Tertiary sediments in Albania, Bourcart has shown that folding continued during sedimentation. Thus, Bourcart's stratigraphic arguments with respect to Dalmatia tend to confirm the morphologic indications, which are based, in part, upon the existence of archeological remains. In general, it is quite difficult to demonstrate, through simple morphologic considerations, recent tectonic movements, that is, movements that occur after erosion or contemporaneous with erosion.