ART. XLIII.—*The Geological Structure of the Southwestern New England Region;* by WILLIAM HERBERT HOBBS.

Former Assumption of Deformation largely by Folding.

THE southwestern New England region, by reason of its prominence in the early heated discussions upon the stratigraphic and dynamic problems of geology, has sometimes been designated "The Battlefield of American Geology." Its prominence in this controversy is to be explained chiefly on two grounds—its proximity to the early American colleges and the exceptional intricacy of the problems involved in its study. The first condition is responsible for the large number of geologists who figured in the Taconic Controversy; the second for the wide range of opinions expressed, for where little can be learned by observation much may be assumed, though not without challenge. It is certainly most unfortunate that the solution of the most fundamental problems of the science, in their application to America, should have been sought in a region which probably ranks with any yet known both in the intricacy and in the obscurity of its geological structure.

All work earlier than that of Dana may be to-day passed over as offering nothing of value upon the geological structure of the region. Charles Hitchcock and Ebenezer Emmons in Massachusetts did, indeed, prepare some careful sections across the western mountain ranges, and these sections fail to be of service to-day not from any lack of ability or of thoroughness on the part of the excellent observers, but because any work so limited and carried out upon ideas of rock structure which were current at the time is wholly inadequate. Percival's work in Connecticut was essentially areal mapping, and while his observations of petrographic characters and his correlation of exposures to form rock belts must challenge our admiration, he was yet too wise and too cautious to risk any dogmatic statements regarding the tectonic structure of the region. It is clear, however, that he believed the crystalline rocks to be given their present attitudes as the result of system of flexures.*

Dana by most careful work, chiefly areal, but in part structural also, extending throughout the area from Vermont to Long Island Sound in New England and in much of eastern New York, was able to solve many of the problems which had vexed the early school of geologists, even though he was too

* Percival, Geol. of Connecticut, New Haven, 1842, pp. 289–298.

deeply involved in the controversy to settle them. Walcott, by his discovery of fossils in beds hitherto supposed to be barren of them, was able to review the early questions of stratigraphy and to end forever the Taconic Controversy.

The problem of the areal delimitation of horizons within the New England area and the determination of the geological structure of the region remained, and the early dissensions had at least shown the necessity for a much more thorough survey of the region than any which had been attempted. The work of the U. S. Geological Survey within the region, begun before that of Dana had been completed, was therefore taken up with a plan more comprehensive than any other and on a scale more nearly what was demanded by the conditions of the problem.

In view of the difficulties which have been encountered in the progress of this work and the methods of investigation which experience has shown to be of value, it is well to consider for a moment the fundamental assumption of Dana in his study, and also the dominant idea maintained throughout all the earlier work of the U. S. Geological Survey. Dana in his later papers summarizes the general geological characteristics of the Taconic region and says of the structure:

"The rocks owe their positions to a system of flexures, and the folds are to a large extent overthrust folds."*

It is evident from his sections that it was not Dana's intention to express by the term "overthrust folds" ruptured folds, but folds with inclined axial planes. In his summary he makes no mention of faults, and though a fault is indicated in one or two of the sections, it is evident that faulting hardly figured in his conception of the structure of the region.

Essentially the same opinion was held by Pumpelly, who was in charge of the work of the U. S. Geological Survey during the earlier years, when the Hoosac-Greylock province in northwestern Massachusetts and southern Vermont was surveyed. With him, however, the supposed absence of faulting within the area was clearly expressed as the reason for assuming a deformation wholly by folding. In his report he says:

"It was evident that our first and hardest work would be to find the key to the structure of the region. For this purpose I sought a region where the western edge should present, instead of a straight line, as many bay-like curves as possible, and where the structure of the ridge itself should show folds with pitching axes. I hoped in such a region to eliminate the difficulties introduced by possible faults, as well as the temptation to infer their existence; and also, in the case of pitching folds, to get through

*James D. Dana: On Taconic rocks and stratigraphy, with a geological map of the Taconic region. This Journal (3), xxix, 209, 1885.

radiating cross sections a knowledge of the true order of bedding."*

There have been few geologists more thorough and conscientious than Raphael Pumpelly, and the realization of the danger of inferring faults is perhaps a characteristic of all the best American geologists of the recent past and of the present alike. It ought, however, to be pointed out that the danger of inferring faults where they are absent, is hardly more serious than that of assuming their absence where they are present. The present attitudes of the rock beds must be accounted for either by the one or the other kind of deformation or by the two in conjunction, and these attitudes can in most cases of difficult areal geology be accounted for upon either theory. It is also worth noting that the edge of a ridge which shows many "bay-like curves" is just the kind most likely to be caused by a series of parallel and intersecting faults; and the presence of folds with pitching axes, while offering a possible and perhaps adequate explanation for the alternation of formations in the direction of their strike, does not necessarily reveal the real or the only actual cause.

This assumption of the absence of faulting throughout the New England area has been fundamental and far-reaching in the work of the Survey, as is shown by the fact that in the area of 200 square miles mapped with great detail and described in the report cited, but a single fault is indicated, and this a strike fault, presumably an overthrust. As the work has been extended to the south the same tendency to resist the temptation to locate faults has been manifest, and from his own experience the writer can testify that in twelve seasons of independent field work, or until the Pomperaug Valley area of Newark rocks was examined, not a single normal fault was entered upon his maps. It is believed that the tendency has been hardly less marked in the work of other members of the division, and it might almost be added, for the most careful work upon the crystalline schists throughout the country. Indeed it would hardly be too much to say that structural studies of the crystalline areas of the United States, with the single exception of the Great Basin region, have been carried out upon the assumption that rock deformation takes place by one process only, namely, by crustal folding and the thrusts incident to folding. Even in the classical area of the Great Basin the attempt has recently been made, though unsuccessfully, to explain the structure by a system of folds alone. This marked trend in American geological work may be in no small measure due to the classical geological studies of the

* Pumpelly, Wolff, and Dale; Geology of the Green Mountains in Massachusetts. U. S. Geol. Survey, Mon. xxiii, 7, 1894.

Rogers brothers, who by their explanation of Appalachian structure on the basis of folding alone, not only established a new type which bears that name, but developed methods which have been left as a legacy to their successors.

In Europe, on the other hand, the principles so long ago worked out by Kjerulf, Sedgwick, De La Bèche, John Phillips, and especially by Daubrée* have been utilized to such an extent that the recognition of systems of faults as important elements of crustal deformation may be truly said to be the most marked line of cleavage which separates European structural studies from American. It has been especially the work of Suess to correlate these scattered studies and to show that the lineaments of the continents are lines of normal faulting, between which great orographic blocks have been depressed by different amounts. His monumental work upon The Face of the Earth† has been the greatest interpretative work upon structural geology of the past quarter century, and marks an epoch in the history of the science. In the Principles of North American pre-Cambrian Geology, the most comprehensive American treatment of rock deformation, Van Hise devotes 75 pages to a consideration of deformation by folding, whereas 10 pages suffice for a treatment of jointing and faulting inclusive of thrust faults which are connected with folds. There is no doubt that the proportion of space thus devoted to joint and fault structure is far beyond what its consideration by American geologists would warrant.

Inadequacy of Hypothesis of Folding.

As respects the study of the southwestern New England area, it is, I believe, time to admit that the basal assumption of a deformation by folding alone, which has now been given a trial by the Survey during a period of nearly twenty years, has proven entirely inadequate. Where belts of limestone are present to serve as guides in the areal and structural work, the order of superposition of formations, and in a very general way the geological structure, have been made out with a reasonable degree of certainty. In the broad belt of schists and gneisses which lie to the eastward of the limestone, on the other hand, it has thus far been found impracticable to discover any structure regarding the presence or absence of which any two of the workers can agree. This is true in spite of the fact that the geologists in the field have acquired by long experience a familiarity with the varied petrographical types of the province and with the apparent structures developed in

* Daubrée, Géologie experimentale, pp. 304–306, Paris, 1879.
† Antlitz der Erde, two vols., Prag and Leipsic, 1885.

them, and are, moreover, by reason of the most cordial personal relations desirous of securing perfect harmony of view. From examination of himself, no less than of others, the writer is inclined to believe that confidence in any structure worked out in the region upon a doctrine of deformation by folding alone is more largely based upon psychological than upon geological conditions; and this for the reason that a feeling of confidence inspired by observation at one locality has too often been quickly and most effectually dispelled by the next succeeding observation at an adjacent exposure. In the study of the structure within the gneiss belts there are two main tendencies which in varying proportions will be found to characterize the work of different geologists. One tendency is to group together within a single formation a considerable number of variant types of gneiss because no apparently satisfactory basis for their separation is at hand; and as the work progresses it is found that all the types of one formation can be duplicated in the others. The other tendency is to make an elaborate differentiation of units on a petrographical basis, with the result that extreme difficulty is met with in accounting for the present attitudes of the rocks, and large drafts must be made upon the imagination. At different points between the two horns of the dilemma different workers will very naturally be ranged.

The Newark Areas in their Relation to the Crystalline Belts.

In the summer of 1899 the writer, in surveying for folio publication the areas for 30″ quadrangles, mapped with much detail the circumscribed area of Newark rocks lying within the basin of the Pomperaug River in Connecticut. These formations of the Newark system present markedly contrasted petrographical types, are practically unaffected by flexuring or metamorphism, but exhibit in the most beautiful manner the results of a deformation by jointing and normal faulting. After long attempts to decipher the obscure and illegible characters in the structure of the surrounding gneiss belt, the transition to the clearness and simplicity of the record preserved within the Newark basin was like the passage from darkness to light. The study of the Newark area showed that it was deformed by a complex system of parallel and intersecting faults all near the vertical, and that the system of joints which preceded and conditioned the system of faults was with little doubt the result of compressive stresses which affected the southwestern New England province as a whole. The principles underlying such a deformation by fracture as a result of compressive stress have been given a somewhat full exposi-

tion by Becker* and were extended and applied to the area in the writer's report upon it.† The greatest value of the investigation of this Newark area, as it relates to the structural problems involved in the study of the crystalline belt, has been to show that no adequate explanation can be offered for the present attitudes of the rocks within that belt which fails to take account of a deformation by normal faulting as well as by folding, for it would be absurd to suppose that the faults characteristic of the Newark areas are not extended beyond their margin. Indeed, the evidence that they pass far beyond these margins into the crystallines has been shown by their direction of the courses of streams.‡ A somewhat careful review of the studies made of the other Newark areas§ of the Piedmont plateau has shown that while systems of parallel joints and faults had not been generally recognized as such, with not an exception numerous intersecting faults of the normal type had in each area been observed, and all recent observers have further expressed the view that many other faults remained concealed. The obvious lesson from these considerations is that the deformation of the intervening areas of crystalline schists—and these areas are not large in proportion to the Newark basins—must be not only by folding and probably also by faulting in pre-Newark time, but there must have been superimposed upon the earlier structures the system of jointing and faulting of post-Newark time. It is probable that the throws along the faults of this system outside the Newark basins will in general not be as great as those within the basins, for the reason that the latter are depressed areas within the crystalline terrane, but it will hardly admit of doubt that they have been important enough to produce a mosaic of orographic blocks in which different beds will be placed in juxtaposition along essentially vertical walls at the present surface. Another result of the study of the Newark areas has been to confirm the views of some writers that displacements are seldom concentrated upon a single plane of faulting but are usually distributed over a number of parallel planes lying in a zone more or less extended. Such distributive faulting renders more difficult the observation of individual fault planes, and even when these are discovered it is apt to leave an erroneous impression of their relative importance.

* George F. Becker, Finite homogeneous strain, flow and rupture of rocks; Bull. Geol. Soc. Am., iv, 50, 1893.

† The Newark system of the Pomperaug valley, Connecticut, Twenty-first Annual Report of the Director of the U. S. Geological Survey, Part III, pp. 1–160.

‡ The river system of Connecticut; Jour. Geol., ix, pp. 469–484 (1901).

§ On the former extent of the Newark system; Bull. Geol. Soc. Am., xiii, pp. 139–148, 1902.

Methods of Investigation.

Convinced, then, of the presence of a system of faults within the crystalline belt, the writer's next problem was to determine, if possible, its relation to the system of joints, the direction of its component series of parallel faults, and the part which it has played in the deformation of the area. The difficulties in the way of reading at once the composite structure of folding and faulting in rocks so nearly of one petrographical type as are the gneisses of the region, seemed, in the absence of established methods, to be insuperable, and attention was therefore first directed to those parts of the area in which limestone occurred. In the search for evidence of the system of faults within these areas the most hopeful factor was that rectilinear surface elements are characteristic of joint and fault structures, which are in contrast with the curves characteristic of folding. To this was added the knowledge derived from study of the Newark areas that the post-Newark system of faults, at least, had not been affected by subsequent folding.

It may be stated that based upon this and other known peculiarities of faults, methods more or less decisive have been developed which have led to the determination of elements in the fault system of the region. These methods have been elsewhere described* and can be but briefly referred to here.

Some of the indications of faults are:

1. Beds formed at different times in juxtaposition along a plane transverse to their bedding.
2. Offsetting of formations in outcrop.
3. Offsetting of outcrops as definite topographic features.
4. Dikes.
5. Abrupt changes of strike and dip not indicated in the folds.
6. Fault breccias.
7. Slickensides.
8. Abrupt disappearance of outcrops along a markedly rectilinear boundary.
9. Occurrence of scarps in the more resistant rocks.
10. Fault gorges.
11. Arrangement of surface springs in rectilinear directions.

It was further realized that it would probably be difficult to locate more than a small proportion of the individual faults occurring within the district, and effort was therefore made as early as possible to learn the distinguishing characteristics—especially the bearings of the individual fault series—of the

*The Mapping of the Crystalline Schists, I, Methods; II, Basal Assumptions. Jour. Geol., x, pp. 780–792, 858–890, 1902.

fault system. Additional observations of value for determining the system of faults as a whole are:

1. The arrangement of rectilinear formation boundaries in a network of parallel series.
2. The arrangement of individual faults in intersecting parallel series.
3. Determination of the joint system and its relation to the fault system.
4. Zigzag topographic relief composed of straight elements in parallel series.
5. The drainage system a network of intersecting parallel series.

With abundant outcrops a fault system may be disclosed upon the areal map by the generally rectilinear or zigzag boundaries of formations. If not, some indication may be afforded by the prevalence of straight lines and sharp bends in the topography, particularly if the lines fall into intersecting parallel series. Such a relief may not be apparent without careful examination of the map, for the reason that the particular combination of directions is not known, and it may yet be quite striking when once discovered. Again, the drainage lines may compose a network which in direction conforms both to that of the topographic lines and that of the formation boundaries. The prominent joints observed at the individual exposures, as was long since shown by Daubrée, will, if of the same origin as the fault planes, conform in direction to the directions of these planes.

Application of Methods.

In applying the above principles to the structural study of the crystalline belt in southwestern New England, advantage has been taken of two important considerations.

1. *The areas of most intricate areal development of the formations are key areas for determination of the manner of deformation.*—In geological mapping it is almost an unwritten law that geological sequences must be established in areas where formations appear in their larger masses at the surface, it being generally assumed that structural relationships are in such cases the simpler. Those areas, on the other hand, which exhibit a considerable number of formations brought closely together in small masses at the surface are apt to be looked upon with suspicion as areas of local and so-called "minor" faulting, or as containing intercalated beds of unusual types due to purely local conditions of sedimentation. Whichever of these views be assumed, the areas are likely to receive but

small attention: first, because the problem of their structure is difficult to solve and perhaps is not regarded as affecting the larger questions of the region; and, second, because if once solved the scale of the map would not allow of its representation. Such areas are therefore more frequently represented upon the map in the color of the formation which is believed to compose their greater part.

However unsuited these intricate areas may be supposed to be for establishing the order of succession of geological formations, they are, nevertheless, it is believed, in many cases the keys, and in some cases the only ones, to unlock the secret of the manner of deformation which has affected the region as a whole. Complicated though these problems may be, they often require only patience and industry for their solution, whereas the larger masses by their very simplicity of areal distribution allow of several hypotheses, any one of which would explain them.

Four areas of exceptionally intricate areal relations and widely separated in the region were selected for study. They are the area of sharp ridges near Lee, Massachusetts; Evergreen Hill in Stockbridge, Massachusetts; the Sheffield-Salisbury area; and the Greater New York area. Between the two last mentioned is located the Pomperaug valley area, which, from its detailed mapping, may be counted as a fifth. The Greater New York area has been discussed in papers before the New York Academy of Sciences* and the Geological Society of America.†

After working out so far as possible the local conditions of deformation within the circumscribed areas above mentioned, the larger surrounding areas have been studied not only with respect to the kind of rock and the inclination of its plane of lamination at each locality (as usually done), but the broad distribution of outcroppings, the direction of outcrop margins, the lineaments of the landscape as revealed in topographic relief and drainage lines, and the directions of joints and faults, have all been considered in their relation to the structure disclosed within the smaller areas.

2. *Fault structures are best preserved by the more resistant rock masses.*—Revelations of fault structure through the topographic relief are most likely to be made in areas where the more resistant rock masses are at the surface. The perfection of fault structures preserved in the Newark areas is in no small measure accounted for by the presence there of the dense resistant basalt masses. So resistant a type is not found within

* See review of this paper in Science, xvi, pp. 905-906, 1902.

† Read at Washington December, 1902. See review in Science, xvii, 298 (1903).

the crystalline belt, but some approach to it is afforded by a zone of silicified limestone or dolomite lying between Sheffield, Massachusetts, and Falls Village, Connecticut. This zone of silicification has been supposed to be accounted for by fracture and infiltration along a fault and has already been designated the Housatonic fault.*

Conclusions.

As a result of the studies of these areas it may be stated that, based upon the peculiarities of faults and of fault systems as outlined above, an abundance of evidence has been discovered to show that the area of soutwestern New England has been deformed by a system of joints and faults of post-Newark age superimposed upon older structures which appear to be largely due to folding. The system of faults conforms in direction with the system of joints and is in fact occasioned by a displacement which has occurred along the joint planes. The evidence of this can only be presented with the aid of detailed maps of the several areas accompanied by full descriptions and illustrations. The present paper can therefore be considered only as a preliminary notice of a larger work to appear in a professional paper of the United States Geological Survey. The relative importance of the fold structure and the superimposed fault structure it is difficult to estimate quantitatively. It appears, as expected, that both have played their part, but the result of the investigation has been to show that, so far as the areal distribution of formations and the directions and positions of their mutual boundaries are concerned, the rôle of the system of folds has been altogether subordinate to that of the system of Post-Newark faults.

Madison, Wisconsin.

* Jour. Geol., i, pp. 793–798 (1893).