Folded faults of the Southern Appalachians.

By **Arthur Keith.**

The geological structures of the Appalachian Province are very well defined. Fifteen years ago it was generally supposed that the Appalachian type of structure was well understood and that the structural problems had been at least outlined, if not solved. At that time systematic work in mapping the geological formations was begun by the United States Geological Survey. At first, no structural features were encountered sufficient to modify existing views. In a few years it was seen, however, that some of the broad features of faulting in the Southern Appalachians had not been grasped. Concerning most of these features, it is now possible to make a statement. This is in no sense an argument but merely shows the chief results and their bearings.

The difficulties in the way of a correct solution of some of the complex problems have been very great. These include the rugged character of the region, the heavy forest cover, the deep residual deposits, unconformities of erosion and deposition, close folding and faulting, and metamorphism. The determination of the sequence and age of great areas of the older formations has been forced to wait until these special groups of faults were proven and understood.

Typical structures.

Typical Appalachian structures have many features in common throughout their entire extent. The folds are closely compressed, with dips mainly toward the southeast and are about parallel to the adjacent upthrust strata. These structures are very long, the longest being measured in hundreds of miles; they are also very straight, at times almost geometrically so for thirty or forty miles. The displacement of these faults is such that the older rocks are thrust over upon the younger to varying distances up to two or three miles.

Horizontal overthrusts.

The foregoing features are those which have been understood for many years. A special kind of fault attracted attention after a few years of areal mapping. Its beginnings were seen in that portion of East Tennessee mapped by myself, and its full development in Georgia and northern Alabama, mapped by Dr. C. W. Hayes. These faults are characterized by a great variety of dips, as distinguished from the usual uniformity, and by an equal variety in direction. The dips are noticeably light, and although sometimes slightly toward the northwest, in marked contrast with the type, it was not certain that the fault plane had been folded. Younger rocks were frequently thrust over upon the older, and the inception of the faults in anticlines was often obscure. In those which were studied by myself there was no sufficient evidence to class them separately from the usual faults. An explanation of them offered by Dr. Hayes involved an extensive interval of erosion to account for the attitudes.

Folded overthrusts.

As work progressed eastward from the Appalachian Valley into the mountain section of Tennessee and North Carolina new problems were met among the sedimentary and crystalline rocks; large areas of rocks of unknown age were found, and various hypotheses were presented in connection with them. Still farther work in the mountain section gradually accumulated the evidence of a new type of faults. These showed no trace of anticlinal origin. Most conspicuous of their characteristics was the enormous visible thrust, greatly exceeding the faults previously known. The greatest thrust thus far proven is at least 20 miles and many exceed 10 miles. With further study and further evidence still more of the history of these faults was deciphered. Many planes which were determined to be fault planes were seen to have been deformed again, rock masses, thrust plane, and all. This secondary deformation was of the same kind and magnitude as the usual Appalachian folding. In places it was so extreme that the fault planes were overturned; here and there, also, their planes were broken and displaced, together with the adjacent strata. By such features of folding and faulting subsequent to their formation these fault planes are differentiated from all previously known and compose a new chapter in Appalachian deformation.

Bases of proof.

Statements of the foregoing character, which involve the theory of Appalachian deformation of course require an excellent foundation in fact. It is impracticable to go into details in this connection. It will be sufficient to state that the proof is gathered from observations covering many thousand square miles and considered during many years. In weighing the evidence decisions were arrived at according to a few fundamental ideas. The Appalachian strata were marked by parallel deposition. Even where considerable time elapsed without deposition, divergence of the strata at that horizon is exceedingly rare. Here and there the sequence of strata is broken, and the break constitutes a fault. It may be marked by the juxtaposition of beds which normally are separated, by discordant dips on either side of the plane, or by unconformity on a large scale between the adjoining formations. The fact that the rocks now in contact were separated at first by other layers has to be independently proved, while the unconformity and discordant dips are self evident.

It is a fundamental principle of geology that an overlying stratum is younger, unless the relation can be proved to be abnormal. The presumption is in favor of the relation as it stands, and the burden of proof rests upon any other theory.

Proof that strata visibly on top of others are actually older instead of younger may be obtained by the discovery of fossils in the beds in question, in which case the strength of the proof goes back to the localities where the relative ages of the fossils were determined, frequently by direct superposition of the strata.

Where fossils cannot be found, proof may also be obtained through the sequence or lack of sequence of the strata. The value of this class of proof varies greatly with the number of formations in the sequence and with their distinctness. A sequence of two or three formations can readily be duplicated at different parts of the geological column. With five or six formations in a definite order the chance of its duplication at another age is very remote. Where beds of unusual and special nature enter into a sequence of five or six membres the chance of duplication may be disregarded. Take, for instance, the great overthrust at the border of the Appalachian Valley in northeastern Tennessee. The beds there involved include a sequence of eight members; the only approach to fossils in these strata is a number of *Scolithus* borings found in one of the quartzites. These markings are a prominent characteristic of the top member of the Cambrian quartzite series in all of the adjoining regions, separated by only a few miles, and occur only in that. A portion of this sequence is composed of a highly specialized group, including granite, basal conglomerate, an amygdaloid flow, and overlying purple quartzites. These beds are all most strongly differentiated. The amygdaloid flow in particular is not known at any horizon or region in the Appalachians except this. This sequence of eight members appears in all its details, both in the overthrust mass and in the Cambrian quartzites three or four miles away. The possibility of their being two identical series of different age is so remote that it can be entirely disregarded. Added to this is the actual unconformity of the formations, both above and below the fault plane. The two lines of proof unite in making a complete demonstration, which is clinched by tracing the plane for a short distance southwest to points where a fault is visible and undeniable.

Similar evidence and similar arguments independently yield the same proof in many localities along this great fault. It should be noted that the proof does not include superposition as an argument, but is arrived at in spite of it, for the Cambrian rocks rest on the Silurian in open synclines of the most unequivocal kind. In fact, the deduction is clear that in faulted regions mere superposition is worthless as a proof of age.

Magnitude.

Having once established the existence of this thrust fault two inferences of great importance are to be made:

First. The fault plane and the adjoining rocks have been deformed since their production.

Second. The amount of thrust is tremendous, far greater than anything previously known in this country. The present distance between the outcrops of the fault plane in a northwest-southeast direction across the strike, is about 12 miles in the fault above cited. With due allowance for the amount of shortening by subsequent folding and for the demands of the local structure, a minimum measure of 20 miles can be given to the displacement along this line. The same great fault farther southwest in Tennessee has displacements of over 15 miles in two places. As the typical Appalachian fault seldom exceeds three miles in throw, the magnitude of these folded thrusts is very evident. Faults with similar features to these, and for similar magnitude, have been discovered in the Rocky Mountains, in Scotland, and in Sweden. In none of these, however, is the element of subsequent folding so extreme. A score of instances can be found in these faults where the fault plane and enclosing strata have been overturned; in fact the subsequent folding and faulting is quite as great as is seen in the typical Appalachian structures.

Age.

It is evident from the foregoing features that these thrust planes were among the earliest stages of the great Appalachian deformation. Whether they were produced at a period entirely separated from the general period of deformation, or whether they merely began it, the evidence at present is not sufficient to decide. Inasmuch as strata of the lower Carboniferous, or Mississippian age, are involved in these thrusts, the earlier limit is thus set.

Original form.

A close study of the unconformities above and below these fault planes shows that the formations above the plane are successively older toward the south and southeast. The angle at which the plane crosses the formations is small and varies considerably. Eliminating the subsequent folding, the reconstructed fault plane is seen to have had a light dip toward the south and southeast, gradually traversing the strata as a shear plane. This is distinct from the usual Appalachian faults, which are for the most part slip planes along the bedding.

Locus and cause.

Thrust faults, especially of this type, were due to enormous pressures, transmitted by rocks which were very rigid. The most rigid formations in this region are the great granite masses, which underlie the Cambrian sediments. Down into this granite the faults are seen to pass in northeastern Tennessee, where erosion has best exposed the underlying structures. In a case like this, where one sees a rigid granite mass thrust over upon weak, thin-bedded shales, the conclusion can not be escaped that the granite was the active and moving portion. Relief from pressure comes, not downward and inward, but upward and outward into positions of less strain, and the weak shales could scarcely thrust themselves into the granite or down into regions of greater pressures. The enormous difference in rigidity between the granites and the Cambrian strata, considered in connection with the original eastward dip of the shear plane down into the granite, renders it very clear that the deformation was due to an actual thrust by the granite mass as it moved from southeast to northwest.

On the exotic blocks of the Himálayas.

By **C. L. Griesbach**, C. I. E.

The subject which I have been called upon to discuss is such a large one, that to do it complete justice and to render it perfectly clear to geologists who are not acquainted with the structure of the Indian peninsula, much more ample time would be required than is at my disposal. Those amongst my learned audience who are not already familiar with the salient features of Indian geology I must refer to the publications of the Geological Survey of India. Very few words on the general structure of the Central portion of the Himálayas must therefore suffice. The ranges of hills which are confined between the Kali river (Nepal frontier) on the eastern side, to the valley of the Sutlej on the western side, are known to us in India as the „Central" Himálayas and within this portion several well-defined zones may again be distinguished. Broadly speaking the Himálaya mountains form as it were the outer „rim" of the high plateau of Tibet. This „rim" is pierced by the Indus, the Sutlej and by the Brahmaputra rivers, which escape by way of gigantic transverse gorges into the lower levels of India. The „rim" is, however, intact as far as the so-called Central Himálayas is concerned, as there it forms a well-defined watershed between the Ganges drainage and the Sutlej, and with this portion we are now specially concerned.

This „rim", which also forms the political boundary between India and Tibet, forms a mighty range of an average elevation of 5—6000 meter with many spurs and parallel ridges, crossed by a number of high passes. This line of watershed with its spurs is entirely formed of an immense sequence of sedimentary beds, ranging from the lowest strata of the palaeozoic group into marine deposits of the lower cretaceous system and this seemingly without the slightest break or unconformity. This sequence is however affected by an intense disturbance probably of post-eocene age expressed by complicated folding, and locally by faults. This disturbance affects alike the oldest strata as also the members of the m a r i n e beds of the tertiary (eocene) system, which may be clearly observed. In spite of this the structure of the region is not so difficult to unravel as might be supposed, as, with the exception of patches of snow and large glaciers, the ground is not hidden from view by more than a most primitive vegetation which can not obscure the geological features.

North and northeastwards, the sedimentary belt passes into the Tibetan region; this again is physically well defined. As far as we know a chain of mountains runs parallel to the Indian watershed, exhibiting a geological structure very similar to the latter range, and thus defines the valley of the Sutlej. Vast spreads of horizontally disposed strata of a younger tertiary freshwater formation fill the Sutlej valley and constitute a true high plateau, which is known as the Hundés province of Tibet. The more eastern portion of that area is characterised by enormous outflows of younger eocene volcanic formations probably of the nature of fissure eruptions.

The zone which I have here roughly described forms the true watershed and the rim of the Tibetan high plateau. South and southeast of this sedimentary belt extends a broad zone of mountainous country, arranged into many ramifications of mountain chains within which we distinguish several zones. Most prominent amongst them is the chain of immense snowy peaks, which though not demarcating a waterparting, constitutes the most salient feature of the mountain system; in it are all the great heights of the Central Himálayas with such massifs as that of the Nanda Devi (25660 feet or 7823 meter). This zone of ranges are composed of crystalline rocks within the folds of which narrow strips of the oldest sedimentary deposits are inclosed. With this crystalline zone we are here not more closely concerned and for a more detailed description of it and of the adjoining area I must refer to my earlier reports [1]) and to the description of Prof. Diener [2]).

To return to the discussion of the geological structure of the sedimentary belt which constitutes the great divide between the Sutlej and Ganges systems, I have already mentioned that it consists of an unbroken sequence of strata from the lowest member of the palaeozoic group up to the cretaceous system.

It is probable that the cretaceous beds are overlaid conformably by marine eocene strata, which may be seen in a fragmentary section north of the Niti pass. Portions of such lower tertiary sections may also be seen in obscure positions in the deeply eroded V-shaped gorges which the tributaries of the Sutlej river have scooped through

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[1]) Records, G. S. I. Vol. XIII. Pt. 2. 1880. Memoirs, G. S. I. XXIII. 1891.

[2]) Denkschr. d. Akad. d. Wissensch. 1895. Bd. LXII, pp. 533—608.

the horizontal upper tertiary deposits of Hundés. In this belt of the Central Himálayas we have not met with any intrusions of volcanic rocks and it is not until we get actually into the waterparting itself that we come across isolated dykes of igneous rocks and further northwards (region of the Balchdhura passes and Manasarowar lakes) into areas of widespread flows of such rocks. The latter have been described many years ago by General Sir Richard Strachey, K. C. B., to whom we owe the first description of the geological features of this portion of the Himálayas.

It was in 1879 when examining the Tibetan area just north of the passes that I had come across masses of limestone, more or less in isolated and obscure positions which at the time puzzled me not a little. They were found generally at the base of several of the deep V-shaped valleys of Hundés north of the Ma-Rhi-La already mentioned above, and were with few exceptions highly altered, even converted into a kind of marble. They are closely connected, and in places partly inclosed in igneous rocks and they are locally also greatly obscured by the younger tertiary deposits of Hundés.

A few of them however have yielded in less altered portions a few *nummulites* which proved their eocene age, and their occurrence together with volcanic rocks reminded me of Dr. Stoliczka's discovery of similar eocene limestone associated with volcanic rocks in the Rupshu area in the northwest Himálayas. The find of *nummulites* and their position close to the cretaceous Gieumal formation led me to believe then that I had to do with fragmentary sections of possibly upper cretaceous and eocene beds both much influenced and altered by intrusive volcanic rocks. In reality they were isolated masses of rock, true exotic blocks of the same nature, and belonging to the same set of phenomena, as the later discovered blocks which form the subject of this paper.

It was not until 1892 when visitig the ground northeast of the Kungribingri passes in company with Dr. Carl Diener and Mr. Middlemiss, that we met with less altered specimens of limestone more or less structurally involved with igneous rocks.

It may be said that our more exact knowledge of exotic blocks within the Himálayas dated from that time, when our party discovered and closely examined the fine crag of Chitichun, or as Dr. Krafft afterwards preferred to call it, „Chirchun“; this crag is 17.740 ft. in height (5408 meter).

It is a mass of limestone, which rests apparently on much crushed strata of Spiti shales (upper jurassic), and might have been taken to be younger than the latter, had the limestone not yielded a fine series of fossils which demonstrated that the strata ranged from permian into the lower trias and could therefore not overlay the jurassic Spiti shales in a natural manner. It was also found that the crag was connected with an outburst of basic igneous rocks, which could be observed in situ not far west of the crag; moreover the igneous rock traversed the limestone block right across in form of a dyke. Several other blocks similar in nature, were found in the same neighbourhood, and it was thought with regard to them that an arrangement into well defined zones could be discerned. I described the crags later on in the Records of the Geological Survey of India[1]) and Dr. Diener[2]) did the same in 1898.

I expressed the opinion that the crags were not of the nature of the Klippen of the Karpathians, for which a totally different origin is claimed by the Austrian geologists, but owed their existence rather to structural causes, being fragments of the older series of rocks brought to the surface through extensive crushing and thrust-faults. The faults itself could not be distinguished on the surface: as is generally the case in disturbances within a complex of soft shales, such as the Spiti shales, the actual line of dislocation must have been obliterated on the surface itself, and could only be inferred by the presence of igneous rocks, which had reached the surface along the resultant fissure. That was my opinion in 1892 and in some modification, that explanation I believe to be still applicable to this locality, which as we hare learned subsequently, forms the southernmost example of these blocks. Rather than call it an example of „Klippen", which we thought it to be when first examining the locality, I preferred to define it as an „exotic block", which actually it is in relation to the rock-system on which the crag rested.

As later researches have demonstrated, these blocks are veritable foreign substances in the surrounding rocks and in that sense the term exotic block has remained in Indian geological nomenclature.

It was not until 1900 that further opportunities for a study of these interesting localities occurred. Drs. T. L Walker and A. von Krafft, both officers of the Geological Departement were deputed to the borderland between India and Tibet; Dr. Walker to Chitichun, and Dr. von Krafft to the Balchdhura pass. The first owing to sickness was unable to stay more than a few days, but the second spent a considerable time in the neighbourbord of the Balchdhura pass and in the region known as Laptal, which places I had only cursorily

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[1]) Records. XXVI. Pt. 1.

[2]) Memoirs. XXVIII. Pt. 1.

examined in 1879, and scarcely touched in 1892 when visiting the country in company with Dr. Diener and Middlemiss.

The result of Dr. von Krafft's work is embodied in a fairly detailed report in Memoirs of the G. S. I. Vol. XXXII. Pt. 3, and in it the author reviews some of the theories wlich have been advanced from time to time by various observers on the so called Klippen phenomena of Europe, and he comes to the conclusion that the blocks of the Balchdhura, of which be describes a large number in great detail, have nothing in common with the Karpathian or Swiss Klippen, but are fragments torn from sedimentary rocks in situ and have been ejected along with the igneous mass, through the fissures by way of which the latter were forced to the surface.

Whilst it cannot be denied that this theory meets the case of the numerous blocks, which were found to be entirely enveloped in the igneous flows, it appears probable to me that enormous dislocations must be supposed as having taken place, to enable fissures to form, through which great masses of volcanic lava could be erupted to cause widespread flows in that region, and in such a case it is certain that much of the older sedimentary rocks must have been brought to the surface, not only as part of the sections, but also in crushed masses, and detached blocks torn off from situations in situ, a phenomenon common to all disturbed areas. The outcrops of dislocations which have later undergone weathering and denudation, must of course have been shorn of all crushed and loose fragmentary masses, but where dislocations are accompanied by the ejection of vast igneous flows, the fragmentary sedimentary rocks, the result of crushing and dislocation of the strata, must surely hare been swept up and carried along with the flows. This does not disprove the possibility that many of the blocks have actually been torn off from the strata below by the action of the volcanic outbursts itself.

But I do not think that it is necessary to assume that the blocks have come originally from a situation very far from their present resting place.

Much of the fragmentary evidence which we possess of the geological structure of Hundés is in favour of the theory that the Sutlej valley marks a long dislocation which runs parallel to the general trend of the Himálayan ranges, for we know that the watershed between the Sutlej and Indus resembles structurally the ranges which form the outer rim of Hundés and with it the watershed between the Ganges and Sutlej, and is in fact a repetition of the same section.

To explain such a feature it is plainly obvious that we have to assume parallel dislocations, which with or without an overthrust, are able to originate such a structure, and I advance the supposition that it is along these very dislocations and systems of faults that the eruptive flows found an outlet to the surface; and whilst I agree with Dr. von Krafft that the eruptive masses may have torn off rocks from in situ, I also contend that they also must have swept up masses that had already been torn off the main mass by the crushing and dislocating action. The latter was part of the gigantic structural agencies which led to the latest stage of the Himálayan upheaval which falls into the period after the deposition of the upper cretaceous system and occurred prior to the deposition of the younger tertiaries, and in fact, fits into the period during which the great flows of Dekkan trap took place in India generally.