suggestion that it was formed rapidly have any truth, fossils need not be expected. Thick muddy waters would probably be quite unfitted for life. I do not think there are fish in the muddy Swiss glacial streams.¹ And the artificial clays I have described sometimes show little or no stratification on a small scale. On a large scale the Boulder-clay is stratified. I have seldom gone far without finding traces of this. Often, indeed, it is as clearly stratified as any other clay.

There are doubtless many other difficulties, some of which may be fatal. I offer this paper as an independent contribution to a most controverted, and therefore most attractive, question.

VII.—BRITISH GEOLOGY IN RELATION TO EARTH-FOLDING AND FAULTING.²

By T. MELLARD READE, C.E., F.G.S., F.R.I.B.A.

THE history of every science may be compared to the ascent of lofty and diversified mountains, in which level benches and plateaux alternate with steep and rugged slopes. The first explorers, beginning at the base, toil upwards, hardly knowing which course to take, and having little idea of the country that lies before and above them. But they toil on, gathering information as they go, until, reaching a level resting-place, they can look back and form a more accurate conception of the country they have traversed. Still, they can see but a little way upwards, much less perceive the summit, but ascend they must, gaining an ever-widening view and grander and more just conceptions of the wide world below.

It is thus that the study of geology has progressed. By the combined operation of an army of explorers a vantage-ground has been obtained from which we are enabled to review our position and determine upon the next point of attack.

The history and succession of the rocks have been traced, their position in time and in part, their location in space—but the latter knowledge can never be complete until the whole world has been surveyed, both above and below the waters; now a seemingly impossible task: yet who shall speak for the future?

By the aid of numerous geologists, both great and humble, of all climes and countries, manfully working towards a common end, the order of succession has been outlined, and a fair but very crude knowledge of the earth's history reached. So far as palæontology and stratigraphy can speak, they tell us a good deal, but we cannot realize the meaning of it all without the aid of correct physical conceptions to reveal the processes of the wonderful earth-history which lies buried under our feet.

It is with this object that I ask your indulgence this evening in mentally travelling with me over the British Isles to see what help we can get from known British geology.

¹ In the discussion on this paper it was stated that the Dora Baltea, though thick with glacier mud, contains excellent fish.

² Presidential Address to the Liverpool Geological Society, 1895.

Facts of British Geology.

An examination of a good geological map of England and Wales, such as that known as Greenough's, published by the Geological Society, shows at once that the older rocks from the Cambrian to the Carboniferous constitute the bulk of the more essentially mountain areas.

Thus, North Wales is mainly Cambrian and Silurian; Cumberland and Westmoreland are largely composed of equivalent rocks, surrounded with a fringe of Carboniferous, which, more greatly developed in Northumberland, Durham, Yorkshire, and Derbyshire, forms the mountainous district of the Pennine Chain, the so-called backbone of Northern England. Leaving out of consideration for the moment the pre-Cambrian rocks of Anglesey and Shropshire, it is in the Cambrian and Silurian that the greatest deformations and foldings have taken place. Lying conformably upon the Upper Silurian in Herefordshire and Brecknockshire is the great thickness of Old Red Sandstone, more horizontally developed, but yet in the Beacons of Brecon and the Fans of Carmarthen rising as mountains from two to three thousand feet high. These are overlaid conformably by the South Wales Carboniferous rocks. In the North the Carboniferous Limestone lies unconformably upon the Silurian, the Old Red being practically absent. These Carboniferous rocks are in places considerably folded, the Pennine Chain itself being an anticlinal axis, while the Devonian and Carboniferous in Somerset and Devon are folded often at high inclinations in the Quantocks and the Mendips.

Surrounding these anticlinal areas, and in the depression between them, the Permian Limestone breccias and sandstones and the Triassic sandstones and marls lie unconformably upon the Carboniferous rocks, and much of this country is hilly, but cannot be correctly designated mountainous. The whole of the group of rocks, from the Cambrian to the Trias, occupy, roughly speaking, the western half of England, including Wales, but the eastern half of England is constituted of a succession of younger formations, from the Rhætic to the Pliocene. The Rhætic constitutes the passage from the Trias to the Lias, and, though nowhere developed on an extensive scale, is interesting as showing a conformable succession which is unbroken through the Oolites to the Upper Cretaceous. Between the Cretaceous and Eocene is an unconformable break representing a great time interval separating the Cretaceous and Tertiary, which is further confirmed by the complete change in the fauna and flora. The Eocene, Miocene, and Pliocene are conformable, and with them ends what is called the solid geology of the country, the succeeding deposits being Pleistocene, Glacial, and post-Glacial, consisting mostly of clay, sands and gravels, Boulder-clay and alluvium.

It is thus seen that the western half of England, together with Wales, possess the mountainous districts *par excellence*, while the eastern half is distinguished by gently undulating or horizontal strata, with sharp folds located in small areas, as in the Isle of Wight, at Purbeck, and the Yorkshire Chalk at Flamborough Head.

That the Lias had formerly extended over a considerable area of the western half is shown by the preservation of outliers in Shropshire, Staffordshire, and Cumberland, and *prima facie* it is probable that the overlying formations have also at one time in geological history been present. To a student of physical geology a glance at the geological map of England is sufficient to show that the outcrop of the Lias extending from the Severn to the Tees is an escarpment of denudation.

It must not be supposed for a moment that Britain represents the normal physiographic condition of the various formations all over the world, and that the mountain areas are always the oldest. Quite the contrary. In the Alps, Himalayas, and Rockies, in the mountains of the Caucasus and Central Turkestan, it is the younger formations that constitute the highest members of the mountain belts, and it is generally conceded that the bulk of the mountain-making in these chains has been geologically a late event.

Of course in great mountain chains we may have, and generally do have, the older rocks, even to the Archean gneisses and schists thrown up and exposed in their axial folds. This, however, as a rule, only shows that the earth movements to which they owe their birth and growth have been extreme and profound, involving the deep-lying sediments, and even their foundation rocks, in the general movement. We thus see that there is no intimate relationship between the *age* of the rocks of which mountain areas are composed and the existence of the mountains themselves.

The Mountain Areas of England and Wales as related to the thickness of the sedimentary and other deposits of which they are composed.

The Lower Cambrian Rocks of South Wales are estimated to have a thickness of from 3500 to 4000 feet, and are supposed to be over 8000 feet in North Wales. The Upper Cambrian, where well developed, attain a thickness of from 5000 to 6000 feet. The Ordovician, or Lower Silurian of the Survey, is estimated at from 12,000 to 25,000 feet; in Shropshire, according to Murchison, 18,000 feet; and between the Menai Straits and the Berwyns 19,000 feet. The Silurian, or Upper Silurian of Murchison and the Survey, may be 14,000 feet in the north-west of England, and from 3000 to 6000 feet in Wales. The total thickness of British Silurians, Lower and Upper, is stated by Murchison to be from 26,000 to 27,000 feet. Thus, from the base of the Cambrian to the top of the Silurian cannot be less than 35,000 feet.

We thus arrive at the grand aggregate thickness of from six to seven miles of rocks constituting the most mountainous parts of England and Wales. These rocks have suffered more intense deformation than any of the overlying formations, and have, as first lucidly explained by Ramsay, suffered enormous denudation since their folding and upheaval.¹

¹ "Denudation of South Wales and the adjacent English Counties": Memoirs of the Geological Survey, vol. i.

The only break in the series of any moment occurs between the Ordovician and Silurian. There can be very little doubt that their areal extension was proportionately as great as their thickness. Between the Carboniferous and the Silurian there is a strong unconformity in the north of England and North Wales, but this is bridged over, as already explained, in Shropshire, Herefordshire, and South Wales, by the Old Red Sandstone, estimated at 10,000 feet. The Silurian shades upwards into the Old Red by well-defined passage beds, to be seen in many sections, while the Old Red graduates into the Carboniferous in no less perfect a manner.

The Carboniferous is an extensively developed formation in Britain. The base of Mountain Limestone varies in thickness from 1000 feet in Monmouthshire to 3000 feet in the Mendips in Somerset, while in Derbyshire it is 1600 feet, in the Vale of Eden 2000 feet, and in Llangollen 1200 feet thick. The Millstone Grit reaches a maximum of 5000 feet, the Coal-measures of South Wales 7000 to 8000 feet, and, according to Logan, reaches 10,000 to 12,000 feet in Monmouthshire, Glamorganshire, and Pembroke. In Lancashire the Coal-measures are 6600 feet, though the upper portions have been denuded.¹

If we add these figures to the Cambrian and Silurian we arrive at a grand total of 55,000 feet, but it is not to be inferred that this occurs in any one place. Ramsay estimates the Silurians, Lower and Upper, the Old Red, and Coal-measures in South Wales at from 20,000 to 33,000 feet (*Mem. of Geol. Survey*, vol. i, p. 316).

It is of these enormously developed rocks that the typical mountain areas of England and Wales are composed. The question may well suggest itself to us whether there is not here a relation of cause and effect. We have seen that with the exception of the break between the Ordovician and Silurian there has been continuous deposit of sediment from the beginning of the Cambrian to the end of the Silurian, and still further, that in the Old Red Sandstone districts this sedimentation appears to have gone on almost uninterruptedly to the close of the Carboniferous. It is certainly a striking fact that a portion of the earth loaded with sediment to the vertical extent of some five to ten miles should be the very spot where the earth's crust has been elevated not less than four miles, according to Ramsay, and where even now the basal wrecks of these former gigantic elevations should reach 3000 feet above the sea-level. Consider for a moment what five miles of consolidated sediment means. It is equal to a load of 2000 tons per square foot on the normal crust of the earth.

This loading doubtless squeezed and shifted laterally some of the deeply lying and more mobile matter underlying the normal crust, until a balance of stability was attained. Then, by a process of expansion, the effect of a necessary rise of temperature of the old crust and overlying deposits, the conditions were reversed: the

¹ The authorities for these statements are principally Murchison and Ramsay, together with other authorities quoted by H. B. Woodward in the "Geology of England and Wales."

lengthening beds, unable to expand, laterally folded upon themselves, and the whole mass of sediment, by cubical expansion, increased in volume to the extent shown, by the rise of the mountain mass above the sea-level. But we are not to limit this action to the immediate mountain area, for the flanking area, probably largely constituted of more horizontal beds, now covered by newer deposits by successive lateral expansions, added to the folding and heaping up of the mountain masses.

Areas occupied by the Rocks newer than the Carboniferous.

If this relation between extensive and massive sedimentation and mountain-making stood alone it might justly be considered as merely accidental. I have, however, elsewhere shown that such relations may be traced in every known great mountain range; that formations here thinly developed and horizontal are in the Alps and Pyrenees, to go no further afield, extensive, thickly developed, and thrown into immense mountain masses.

In Britain the Permian and Trias, which lie unconformably upon the Carboniferous, reach a thickness of some 6000 feet, but the variation of thickness is very considerable from the overlapping of these formations on the mountain slopes. They are, however, as a rule, more affected by folding and faulting than the succeeding formations, and constitute some considerable hills and escarpments.

The Jurassic and Cretaceous occupy the largest part of the eastern half of England, and may be put down at perhaps 5000 feet, and the Tertiary at say 1500 feet; the total thickness of the British rocks from the Permian to the Tertiary inclusive, working out to about 12,500 feet. It is, however, very questionable whether such an aggregate thickness occurs in any one locality; while in the case of the older rocks, from the base of the Permian down to the base of the Cambrian they are developed in great thickness in direct superposition.

Characteristics of the Folding of the Eastern and Western Areas of England and Wales contrasted.

The rocks already described as occupying the eastern half and south of England are characterized by long low folds breaking into sharp anticlinals and synclinals at a few points only, such as in the Chalk at Flamborough Head and in the Tertiaries of the Isle of Wight, the eroded edges of these long folds forming the characteristic escarpments stretching across the country in a south-westerly and north-easterly direction. Sharply contrasted with these long undulations are the strata forming the mountain nuclei of Wales and Cumberland, where we find the rocks sharply bent and compressed, the remnants of the primitive folds forming by denudation the mountain scenery as now beheld by us. Intermediately we find areas of the Carboniferous and Old Red having a horizontal development, such as is to be seen in the Carboniferous of the neighbourhood of Whernside and Ingleborough, and can be well studied near to Dent, where the much contorted Silurians are in

juxtaposition to the less disturbed Carboniferous, the latter being let down by an enormous fault of unascertained throw. Again, in Herefordshire and South Wales we see a considerable extent of horizontal Old Red, which, as it approaches the Silurian mountain folds, becomes itself conformably inclined.

Not less interesting and instructive are the dome-like structures, such as the celebrated dissected Silurian dome of Woolhope, which rises in successive rings through the Old Red, which it carries on its flanks. May Hill is another similar structure, not so perfectly formed and also bisected by faulting against the Trias.

The physical constitution of Herefordshire and Brecknockshire is largely a horizontal plane of Old Red Sandstone, which, where it approaches the folded Silurian areas at the margins or round the enclosed domes, takes on the folds of the older rocks on which it lies.

Silurian and Old Red of the South-east of Scotland.

It will be instructive now to turn our attention to the rocks of a similar age to be seen dissected in the splendid line of cliffs from Berwick-on-Tweed to the far north of St. Abbs Head and Siccar Point. Here the Silurian (Lower Silurian) are intensely folded, and instead of the conformable succession from the Silurian, through the Old Red and Carboniferous which we have just seen obtains in Herefordshire and South Wales we see the Upper Old Red Sandstone conglomerate resting upon the edges of the Lower Silurian in the strongest unconformity. Well may the justly celebrated Hutton have exhibited this phenomenon, as seen at Siccar Point, as one of the best illustrations of the views he developed in the "Theory of the Earth."

So perfectly are the two formations cemented together that it is possible to get hand specimens of the unconformity. It would appear that while the sediments of South Wales were being laid down in quiet waters from the beginning of the Upper Silurian to the close of the Carboniferous, the succession of events was several times broken in Scotland, as shown, not only by the strong unconformity already spoken of between the Upper Old Red and the Lower Silurian, which I have myself seen, but by the unconformity Sir Archibald Geikie shows exists between the Lower Old Red and the Lower Silurian,¹ and even between the Upper and Lower Old Red²; and he further states "that the great earth movements which plicated the Highlands and Southern Uplands were probably simultaneous, and took place chiefly during the long series of ages represented by Upper Silurian deposits."³ As the Upper Silurian in Lanarkshire passes gradually into the overlying Old Red Sandstone,⁴ it is probable that the break between the Upper and Lower Silurian we have seen exists in England and Wales also extends to Scotland. The succession of events in the latter country are indeed more

¹ "The Geology of Eastern Berwickshire": Memoirs of Geological Survey, p. 20.
² "Scenery and Geology of Scotland," second edition, p. 122, also p. 138.

³ *Ibid.* p. 329.

⁴ *Ibid.* p. 299.

⁵ *Ibid.* p. 327.

complex and difficult to trace than in South Britain, but it is sufficient for the present purpose simply to mention them as all pointing towards the immense range of geological time represented by the conformable Upper Silurian Old Red Sandstone and Carboniferous of South-west Britain.

Thickness and Extent of Rock Formations a measure of their plication.

The preceding sketch is little more than the barest outline of geological events recorded in the rocks of our own island, yet attentively studied the following facts stand out prominently:—The sedimentary rocks which were deposited in the greatest volume are those also that subsequently became most plicated. Though they were the earliest laid down they even now constitute the distinctly mountain masses of Britain, and possess actually the highest peaks and the highest average elevation. When it is considered that these mountains have been exposed to the destroying agencies of denudation for an enormous period of geological time, and still stand pre-eminent above those built out of younger formations, we may perhaps picture to ourselves in some slight degree the extent of the original mass. Not only are the Cambrian and Silurian formations here of enormous thickness, but they are of surprising and unknown extent, and they are found whenever denudation has proceeded far enough to bare them to the eye.

Again, the Carboniferous, taken together with the Devonian and Old Red Sandstone, occupying the second place in the mountain structure of the British Isles, consist of great masses of sediment, not indeed rivalling the Silurian in volume, but of great extent and thickness, though much denuded. Some portions are considerably folded, and most are greatly faulted, but as a whole do not show anything like the signs of lateral compression which are seen in the Cambrian and Silurian.

The Permian and Triassic rocks come next in time and, curiously enough, in importance as regards thickness, and the country they occupy, if not mountainous, possesses a more faulted structure than any of the following formations, and is of a more hilly character.

When we ascend to the Lias, Oolites, and Cretaceous, then the beds become more continuous, horizontal, and less faulted. Folds, and sharp ones, are to be met with, but these, as a rule, are local, the lateral pressure to which they were subjected having been less, and concentrated at fewer points. The same peculiarities apply to the Tertiary rocks, perhaps in a stronger degree.

Relation of Orographic Structures to the mass of the sediment composing them.

I trust that I have now said sufficient to show that there is in the British Isles an intimate connection between the depth, extent, and mass of the several great deposits marking the progress of geologically recorded events, and the structures into which they have been severally raised.

The mountain-building and the foldings and the faultings are,

roughly speaking, found to be proportionate to the original mass of the deposits out of which they have been fashioned by earth forces. If these facts stood alone they might be considered nothing more than curious coincidences. If, however, we cast our eyes abroad to the great continents we find that similar principles hold good, and that the mountain massives are related the world over to the thickness and volume of the deposits out of which they have been fashioned. Thus, the Alps, the mountains of the Caucasus, the Himalayas, are Tertiary structures; the Appalachians and Urals, Carboniferous; and these mountain chains are constructed of enormous thicknesses and volumes of sedimentary rocks.

Expansion and Contraction the cause of Folding and Faultings.

We may well ask ourselves why this relation between volume of sediment and greatness of disturbance should be so constant, and any theory of mountain genesis must necessarily explain these associated facts. The once favourite hypothesis which accounts for them by a shrinkage of the nucleus of the earth and the closing in of the non-shrinking crust upon it, and consequent folding by tangential pressure, fails to explain the constancy of the connection of great thicknesses of sedimentary rocks with the evolution of mountain ranges.

Neither does the principle of isostasy so insisted upon by American geologists explain the compression, folding, and building up of great masses of sediment into mountain ranges. On the principle of isostasy, it must be obvious to anyone possessing even a rudimentary acquaintance with mechanics that the sinking of the bed of the seas on which great deposits are accumulating, and to some extent a rise of surrounding land, may be explained, but not the lateral compression and elevation of the sediments themselves into mountain ranges.

Where, then, are we to look for the agency constantly associated with the deposit of great volumes of sediment which is capable of eventually upheaving them from below the sea-level, and by lateral compression and folding throwing them into mountain chains?

Again, when after the lapse of lengthened periods of geological time, denudation has cut away and removed into the sea large masses of elevated land, what agency is it that causes it to shrink and become traversed by great lines of faulting?

It appears to me now, even more vividly than it has done in the past, that the only agency with which we are acquainted constantly associated with sedimentation and denudation, and capable of these enormous dynamical effects, is change of temperature: that expansion by increase of heat is the cause of the folding, compression, and upheaval of rocks, while loss of heat and consequent shrinkage is the cause of the earth fractures known as normal faults. This principle I explained fully in 1886 in my "Origin of Mountain Ranges"; since then the theory has been subjected to much criticism, ranging from a questioning of fundamental principles down to a minor examination of small details.

The fundamental position has, I maintain, not been shaken, either by mathematical physics or geological facts. The more the theory is tested by the light of practical geology the more remarkable is the explanation it affords of the associated phenomena of sedimentation and mountain-building; denudation and faulting. Furthermore, no other theory yet brought forward attempts to offer an explanation of more than one set of these phenomena, namely, those of compression. Normal faulting cannot be accounted for by compression, yet the rival theory of tangential pressure on the crust through the shrinkage of the earth's nucleus provides for compression only. Contraction, by which I have shown that normal faults are produced, is not part of the machinery of any other theory than the one associated with my name.

I ask geologists to bring to the consideration of these great problems clearness of vision, for, usually, a single aspect only is examined, the rest being left in an impenetrable haze.

I trust I have now brought sufficient evidence before you to show that a broad examination of the formations of these islands, and their associated physical phenomena, throws a good deal of light on the problems of mountain-building, and that their remarkable relations are well worth more detailed examination than I have been able to give them in this address.

NOTICES OF MEMOIRS.

I.—NOTES ON SOME TARNs NEAR SNOWDON. By W. W. WATTS,
M.A., F.G.S.¹

DURING a recent visit to North Wales, the writer has taken the opportunity of examining a few of the tarns in the immediate vicinity of Snowdon, including the two small lakes in Cwm Glas, Glaslyn, and Llyn Llydaw.

In the hollow of Cwm Glas there are two tiny tarns named Ffynnon Frech and Ffynnon Felen; both lakes drain over a barrier of rock, but in a rainy season the upper one appears to find a second outlet over the long, low col to the east, so that in this state it has the two outlets depicted on the six-inch map. The upper lake appears to be a portion of a bending valley dammed at both ends by scree and stream-débris, and thus compelled to find an escape over the rocky side. The lower lake is confined in a rock-basin, as rock occurs at its actual outlet and at every point where any former outlet might have been possible. The lake is, however, so shallow that its occurrence in a basin of rock is perhaps of little consequence.

The neighbouring hollow of Cwm Dyli, as is well known, contains three lakes, the highest being Glaslyn, the next Llyn Llydaw, and the lowest Llyn Teyrn. Glaslyn is bounded on all sides by live rock, except at and near its outlet. This exit is over moraine, which, however, is evidently not very deep, for rock makes its appearance just below, and in such a way as to almost compel belief

¹ Read before Section C of the British Association at Ipswich, September, 1895.