32. RECUMBENT FOLDS PRODUCED *as a* RESULT OF FLOW. By WILLIAM JOHNSON SOLLAS, Sc.D., LL.D., F.R.S., F.G.S., Professor of Geology in the University of Oxford. (Read June 13th, 1906.)

OUR views as to the various kinds of deformation which affect the earth's crust received a remarkable extension with the memorable discoveries of Lapworth, Peach, and Horne in the north of Sutherland. These have now culminated in the long series of revelations which we owe to Bertrand, Rothpletz, Schardt, Kilian, Haug, Lugeon, Termier, Suess, and other workers in various regions of the Alps, who seem to have accomplished a veritable revolution in this branch of enquiry.

The long recumbent folds, which are perhaps the most surprising of the new forms of disturbance lately brought to light, can be more readily demonstrated than explained.

If we turn to one of the most complete and consistent accounts of these phenomena, Lugeon's description of the pre-Alps of Chablais, we perceive a series of recumbent folds, so greatly exceeding in horizontal extension their thickness vertically, that they are commonly spoken of as sheets rather than folds: they lie with remarkable flatness one on the other; and as a rule those higher in the series extend farther to the front than those below, a feature referred to as 'déferlement' by the French, or 'leap-frog' as translated by my friend, M. Allorge.

The roots or origin of several of the lower of these folds are visible in the high Alps adjacent, but the roots of the higher folds, which form the pre-Alps, must be sought in the zone of Mont Blanc and the Briançonnais. Thus, some of the uppermost folds may have surmounted the obstacle presented by Mont Blanc on their way to the front in the pre-Alps.

It is no doubt true that overfolds may be traced into normal anticlines, and if long recumbent folds may be regarded as merely exaggerated overfolds, we may admit that their origin is not beyond our powers of comprehension; but, even in this case, their subsequent history presents many difficulties to the imagination.

Many of the features presented by recumbent folds are more suggestive of flowing than bending, and long ago this led me to offer a comparison between some of the features presented by the flow-lines in pitch-glaciers with those made familiar to us by the sections of M. Marcel Bertrand.¹ An account of my first experiments with pitch-glaciers was brought before the Geological Society in 1895²; but, as no detailed description has been published of others made subsequently, I take this opportunity to present the results of one or two of them, which recall in several striking peculiarities

¹ Rep. Brit. Assoc. 1895 (Ipswich) p. 680.

² Quart. Journ. Geol. Soc. vol. li, p. 361

some of the structures brought to light by Prof. Lugeon in the pre-Alps.

In the example that we may consider first (fig. 1, p. 718), the pitch-glacier was built up in the way already described in my previous paper. The three layers, of which the upper surface is indicated by the lines *a, b, c*, were placed in the experimental trough on April 3rd, 1895; it will be seen that they lie wholly behind the obstacle marked *O*. A fourth layer (*d*) was added on April 9th, its anterior termination lying just upon the summit of the obstacle. The experiment was brought to an end on June 12th, and, on cutting the 'poissier' or pitch-glacier longitudinally through the middle, the layers *a, b, c* were found to have assumed the forms shown by the lines *a', b', c'*. The general resemblance between these folded lines and some of the folded sheets in the Alps is sufficiently obvious; the second, marked *c'*, with its 'carapace' of folds is not unlike the Morcles fold behind the Diablerets; and my friend Prof. Lapworth compares the third (*b'*) with the Pilatus and Sentis, and the fourth (*a'*) with the overslide of the Bavarian front.

The roots of the experimental folds lie on the other side of the obstacle *O*, which may be imagined to stand for Mont Blanc. In this respect they recall the views of Prof. Haug, who, to give one instance only, brings the zone of the Aiguilles d'Arve over the summit of Mont Blanc to form the recumbent fold of the Diablerets.

The whole of the four lines exhibit the phenomenon of *déferlement*, and may be compared in this respect with Prof. Lugeon's illustration of the three folds of Morcles, the Diablerets, and Mont Gond.¹ In the case of the pitch-glacier the *déferlement* is clearly a necessary consequence of the conditions of the experiment.

According to our present conceptions, there is one very marked difference which distinguishes the folds exhibited by this pitch-glacier from those of the Alps. In the former, the several folds originate from sheets which were superposed on each other at the commencement of the experiment, and in consequence the lower limb of each fold is adjacent to the similar limb of its neighbours, that is, the folds are 'emboîtés' one in the other. In the mountains, on the other hand, the lower limb of a superior fold reposes on the upper limb of the one immediately beneath it, that is, the folds are superposed, and not fitted one into the other.

In another experiment, however, made between March 24th and June 7th, 1895, even this difference has disappeared, or at least become greatly reduced. In this instance (fig. 2, p. 718), two obstacles *O*₁ and *O*₂ were placed in the path of the pitch: restricting our attention to the second layer, the original position of which is shown by the straight line *a a'*, it will be seen to have formed three folds one behind the other,² all lying on the foreland beyond

¹ 'Les Grandes Nappes de Recouvrement des Alpes du Chablais & de la Suisse' Bull. Soc. Géol. France, ser. 4, vol. i (1901) fig. 3, p. 731.

² Indicated by the thickened lines, the front fold lies above the words '24 March' in fig. 2.

Fig. 1.—Experiment commenced on April 3rd, and concluded on June 12th, 1895.

[aa = Original surface at the commencement of the experiment.]

Fig. 2.—Experiment commenced on March 24th, and concluded on June 7th, 1895.

[$b\ b'$ = Layer in its original position on March 24th, now seen overfolded immediately above $a\ b$.]

the obstacle O_1 , while still farther on are a few scattered fragments, which may be compared with 'klippen.' In this instance, the several lobes of a complex fold would appear to have been sheared away from each other, passing through a series of stages such as are suggested by the folds in fig. 1.

If a flow has taken place in the Alpine regions at all comparable with that of these experiments, it is obvious that particular beds may have been very far from continuous at the conclusion of the movement. Thus, if we regard the layer just referred to as representing a limestone-series in the Alps, we might expect, on leaving the region of the 'klippen,' to enter another of recumbent folds; ascending the mountain-core O_1 , we should find on its 'stoss'-side patches of the series, showing obvious signs of excessive pressure; and then we should have to traverse the wide interval between the two crystalline masses O_1 and O_2 before we again encountered insignificant remnants of the original sheet. The absence of the limestone-series between these several points might not, therefore, be the result of denudation, but the natural consequence of mountain-movement. If so, the removal of the stupendous masses of sediment by subaërial agencies, to which the Alps bear such striking witness, is brought closer to our powers of comprehension, since the material thus removed may have been the softer, more mobile argillaceous rock already deprived of its stiffening of comparatively-rigid strata.

Since, in the first experiment, it is only the first four layers that have assumed a complex folded character, and since these were the only layers which were compelled to make a somewhat abrupt ascent on passing over the obstacle O , it would appear probable that the folding stands in some relation to this fact. Such a suggestion is confirmed by reference to the illustration given in my previous paper,¹ where the layers marked 1 and 2, which commenced their existence wholly behind the barrier, have only taken the first step towards surmounting it, by forming comparatively-simple folds. It is in this region then, immediately behind an obstacle, that the production of folds originates, and the reason is clear: the anterior extremity of the layer is in contact, either with the floor of the experimental trough, or with the back of the obstacle, and in these regions the flow of the pitch is greatly retarded or even arrested by adhesion or excessive friction. The layer is held fast at this extremity, and as an upward and forward movement of the pitch takes place immediately behind, the layer is bulged upwards and forwards in the form of a fold. Slight inequalities of friction between the coloured layers of pitch and those to which pigment has not been added, may bring about the formation of secondary folds. In making these comparisons between flowing pitch and mountain-movements, I am anxious not to push the analogy too far; but observation has already so greatly outpaced explanation, that even remote resemblances may possess some value.

¹ Quart. Journ. Geol. Soc. vol. li (1895) fig. 3, p. 364.

DISCUSSION.

The PRESIDENT remarked that it was a source of gratification to the geologists of this country to learn that the types of mountain-structure which were first worked out in detail in the North-West of Scotland had been found so widely distributed over the globe, and that the conclusions regarding them had been so fully accepted by geologists in other lands. Whether or not the extremes to which these conclusions had been pushed by some of the more enthusiastic spirits who had taken them up would ultimately be justified, time must show. In such papers as the present, there always seemed to the speaker to be two distinct, but closely-related aspects of interest. On the one hand, the questions of physical structure possess an absorbing fascination: every year the answers to them are becoming clearer, and our conceptions of the manner in which the crust of the earth has been shaped into its present condition are growing more definite. On the other hand, the solution of these physical problems brings ever into more vivid prominence the stupendous extent to which the surface of our globe has been affected by denudation, and the prodigious length of time during which this slow process of sculpture must have been at work. Even if such gigantic displacements as some observers maintain to have occurred, were eventually found to be somewhat exaggerated, there can be no doubt that the types of mountain-structure which have been proved to exist, while they furnish fresh demonstration of the potency of denudation, supply valuable evidence as to the high antiquity of our globe.

Mr. A. P. YOUNG suggested, in relation to the Author's theory requiring the presence of massive obstacles, that it might be profitable to discuss the hypothesis framed by geodesists to explain the results of pendulum-observations, which require a defect of mass under high mountains.

M. M. ALLORGE pointed out the close correspondence between the structure of the northern side of the Western Alps and the results of the Author's suggestive experiments. In the central part of the Alps there are two series of elliptical granitic masses, the major axis of which indicates the trend of pre-Permian (Hercynian) folds: the Belledonne zone, and the Pelvoux-Mont-Blanc zone. When the Tertiary overfoldings took place, in consequence of pressures coming chiefly from the south-east, these pre-existing Hercynian horsts were able to play a part similar to that played by the two obstacles of the Author's experiment. They have very likely strengthened the tendency of the folds to form secondary undulations, and to leap one over the other. He considered that the Author's results afforded an experimental verification of the law established by Prof. Lugeon, namely, that the internal folds first produced are the shortest. The most external are the longest, and overlap those which precede them. The difficulties sometimes encountered in attempting to correlate the front of the sheets with their roots are due to the fact that their present separation is not only caused by recent erosion, but some-

times by tectonic disjunctions. He thought that this experiment also gave a good illustration of the structure *en chapelet* of the Alpine geologists; that was, the tendency of the beds of limestone to parcel out into a series of broken segments separated each from the other, recalling on a large scale the dislocated belemnites figured by Prof. Albert Heim in his '*Mechanism of Mountain-building*.'

It seemed scarcely necessary to add that plastic movements of such magnitude are only possible at a great depth, and have taken place under a thick covering of Tertiary strata; and perhaps even beneath the *background* (*rückland* of Prof. Suess) of the Dinarides thrust over the Alpine zone. These external layers have since been swept away by erosion.

The Author thanked the Fellows for their considerate attention; he was of opinion that some of the folds described by Prof. Lugeon had passed over Mont Blanc.