

Geology. — “*The structure of the Sierra Nevada*”¹⁾. By Prof. H. A. BROUWER.

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According, to one of the recent publications on the structure of the Sierra Nevada²⁾, the Alpine mountain-building has but caused the great geanticline of the existent mountains, without forming any important foldings. Explorations in the central part of the Sierra de los Filabres^{3, 4)}, the eastern prolongations of the Sierra Nevada have shown the existence of large overthrusts in this part of the betic ranges, proving a movement in a northern direction. Our explorations were continued in the western part of the Sierra Nevada and resulted in determining large overthrusts also in this region, and therefore in concluding to a similarity in structure in a large part of the betic mountains with the Alps. Just as in the Sierra de los Filabres, we can distinguish in the Sierra Nevada a central part, consisting of crystalline schists, from a border zone, where triassic sediments predominate. Fossils were not found here, but the limestones are like those of the Sierra de Gador, the Sierra de los Filabres and the Alpujarras, where *Myophoria*, *Monotis*, *Avicula*, *Mytilus* and *Megalodon* have been found. BARROIS and OFFRET⁵⁾ have distinguished pre-Cambrian, Cambrian and Triassic in the Sierra Nevada and the Alpujarras. Later explorers^{6, 7)} consider a part of the Cambrian sediments to be Triassic, while ranging the pre-Cambrian sediments as pre-Triassic, without a definite determination of their age. They presume an important unconformity between Triassic and pre-Triassic sediments, but we did not find any unconformity in the Sierra Nevada and take the unconformable succession, observed locally and rarely in adjacent regions, to be a tectonic unconformity. Also the relict structure of the Sierra de los Filabres formerly

1) Some additions to the original paper have been made after a recent visit to the region.

2) J. CARANDELL. La morfología de la Sierra Nevada, ensayo de su interpretación tectónica. Madrid 1921.

3) H. A. BROUWER and C. P. A. ZEYLMANS VAN EMMICHOVEN. The tectonics of the central part of the Sierra de los Filabres. (South Spain). These Proceedings 28, 55.

4) C. P. A. ZEYLMANS VAN EMMICHOVEN. Geologische Onderzoekingen in de Sierra de los Filabres. Proefschrift. Delft. 1925.

5) CH. BARROIS et A. OFFRET. Mémoire sur la constitution géologique du sud de l'Andalousie de la Sierra Tejada à la Sierra Nevada. Mission d'Andalousie. Mém. Acad. des Sciences. Tome XXX, N^o. 2, 1889.

6) C. P. A. ZEYLMANS VAN EMMICHOVEN. loc. cit.

7) W. A. HETZEL. Bijdrage tot de geologie van de Sierra Alhamilla. Proefschrift. 's-Gravenhage 1923.

described by us ¹⁾ may have been caused by deposition in a basin of sedimentation with a hercynic direction. In any case, the structure shows a strong resemblance to the penninic regions of the Alps, where slight hercynic elevations were existent and denuded before the Triassic, but where the Triassic transgression is but rarely found and is slightly unconformable on the older sediments. It is nearly always a parallel-transgression.

We therefore believe that there is no reason to suppose an important stratigraphic break and the absence of the late-Palaeozoic. While exploring in the Sierra Nevada we found a zone between the Triassic and the crystalline schists, characterized by micaceous marbles, slates, quartzites, lime-bearing sandstones and marls, muscovitegneisses with felspar-eyes, turmaline- and garnet-bearing gneisses, amphibolites and micaschists, which often contain garnet. Also serpentine is sometimes found in this zone. This zone often shows a very complicated structure, which will be dealt with hereafter; some sediments bear a resemblance to Triassic in metamorphic state, others might very well be of Permian age, while crystalline schists, which are found nearer to the central parts of the Sierra could belong likewise — anyway partly — to the late-Palaeozoic. Some authors suppose the occurrence of "Bündner Schiefer" (schistes lustrés) in the Sierra Nevada. The lack of lime in the crystalline schists of the central part of the mountain is in our opinion against this supposition, at least if this name is used for metamorphic mesozoic sediments. But in the above-mentioned zone, between the Triassic border-zone and the crystalline schists of the central part of the mountain range, marbles with alternating beds of schist, which are very similar to the mesozoic "Bündner Schiefer" are sometimes found. An exact stratigraphy of the crystalline schists cannot be made without future explorations and for the present we will distinguish subsequently from the border to the central parts of the Sierra Nevada the following zones:

1. *Triassic* (limestones and dolomites, silky slates, sandstones and quartzites, gypsum, rauchwackes) and older rocks.

2. *Mixed zone* (micaceous marbles, slates and quartzites, lime-bearing sandstones and marls, muscovite-bearing gneisses with felspar-eyes, turmaline- and garnet-bearing gneisses, amphibolites and micaschists, often bearing garnet). Pre-Mesozoic and older-Mesozoic.

3. *Crystalline schists* (partly garnetiferous micaschists, locally amphibolites and serpentine).

The rocks of the mixed zone resemble in many respects to part of the rocks of the "zone des schistes lustrés" in the Alps. Without entering further into the stratigraphic relation — the judgment of which cannot be final, because it should be derived from the petrographic characteristics of metamorphic sediments without fossils —, we consider now the tectonic relation between the three zones, which was studied by us at various

¹⁾ H. A. BROUWER and C. P. A. ZEYLMANS VAN EMMICHOVEN. loc. cit.

places. In another paper ¹⁾ we gave a more extensive description of our results, confining them here to some general conclusions about the structure of this part of the betic ranges.

Structure of the "mixed zone".

In this zone complicated folding can be traced, especially in the mica-bearing marbles. In the Cerro del Cardal near La Calahorra, S. of Guadix, the folds are dipping in a N. direction, while at the base of the micaceous marbles an overthrust-breccia is found at different places. The quartzites of the mixed zone are locally stowed to great thicknesses, while further to the N. there are but small isolated lenses of quartzites in the blue slates, on which the micaceous marbles could easily slide forward. To the E. of Niguelas, at the western border of the Sierra, the mixed zone is equally disturbed by folding and overthrusting, special layers can often be followed for a short distance only and are thinning out as well in the direction of the strike as in that of the dip. We found similar relations at other places along the N. and S. border of the Sierra, and the mixed zone gives the impression of being a series of sediments characterized by strong lamination and overthrusting between the crystalline schists of the central part of the Sierra and the Triassic.

Crystalline schists in the border-zone and in the Alpujarras.

The sometimes garnetiferous crystalline schists in the central Sierra Nevada are not confined to this central part. We found them to the S.E. of Granada near the village Monachil, as well N. as S. of the Rio Monachil. They rest with varying strike and dip upon the strongly disturbed Triassic limestones in the vicinity of the Tertiary of the basin of Granada. Also in the more central parts of the Triassic border-zone sediments of the same kind have been found further to the E. near the path, which leads to the Picacho de Veleta, W.N.W. of the Cortijo de Membris ²⁾.

To the S. and S.W. of Lanjaron, near the border of Sierra Nevada and Alpujarras we found in the crystalline schists isolated blocks of crystalline limestones, which are limited by tectonic contacts, while the Triassic limestones, which form a large syncline S. of Lanjaron are covered by phyllitic rocks and, sometimes garnetiferous, micaschists. These garnetiferous micaschists have also been found between Ugijar and Mairena in a region where Triassic sediments prevail. In the Alpujarras, farther south, several large windows („Fenster") of Triassic limestones and slates, covered by garnetiferous micaschists have been found (e.g. window of Albulol, window of the Cerrón etc.).

The above mentioned examples may be sufficient proof, that the

¹⁾ H. A. BROUWER. Zur Geologie der Sierra Nevada. Geol. Rundschau. April 1926.

²⁾ It has been found since, that they have an extensive development resting upon and also dipping below the Triassic limestones and slates to the east of the basin of Granada.

connection between the Triassic border-zone and the central crystalline schists cannot be simply considered to be an older nucleus of which the later sediments in the most upheaved parts have been removed by erosion. The crystalline schists have been found far to the south of the central part and were pushed to the north of it by very important horizontal movements.

Repeated occurrence of the rocks of the mixed zone.

At both sides of the Rio Monachil in the N.W. part of the Sierra Nevada, about 1 K.M. up river from the mixed zone between the Triassic and the crystalline schists, another series of strata is found, which is characterized by the existence of micaceous marbles, turmalinegneiss, amphibolites, serpentines etc. Marly limestones with intrusive dioritic to amphibolitic rocks were also locally found E. of Niguelas, in the western part of the Sierra, about 1 K.M. to the E. of the mixed zone in the Barranco del Torrente. Likewise at different other places in the central part of the Sierra serpentine and amphibolites were found.

The tectonic significance of these repeated occurrences can for the present not be exactly determined.

The tectonics of the late-Tertiary.

S. of the Sierra Nevada the village Ugijar is situated in a Tertiary basin, which consists, according to BARROIS and OFFRET, of miocene lake-deposits. This Tertiary is folded in anticlines and synclines, in the N. part the Triassic is uncovered between the younger sediments and in a syncline between Ugijar and Mairena, along the N. border of the basin, dip and strike are strongly varying, the northern limb shows a very steep dip of the strata, locally these are overfolded at the contact with the Triassic.

The Tertiary is also folded along the W. border of the Sierra. In the vicinity of Monachil, at the N.W. border, the strata dip away from the Triassic border-zone. We likewise located steep dips S. of the Rio Monachil. Dips of 50° — 60° and even vertical or overfolded position of the strata were observed at the contact with the Triassic in Tertiary sandstones and conglomerates.

Summary.

All these results give ample proof, that the structure of the Sierra Nevada, as well as that of the eastern continuation has — as has been supposed already by several authors ¹⁾ — a strong similarity with the structure of

¹⁾ P. TERMIER. Les problèmes de la géologie tectonique de la Méditerranée occidentale. Rev. gén. des Sc. t. 22. 1911. L. GENTIL. Sur l'origine des nappes de recouvrement de l'Andalousie. Comptes Rendus Acad. des Sciences. T. 167. 1918, p. 238. E. ARGAND. Des Alpes et de l'Afrique. Bull. Soc. Vaudoise des Sc. Nat. Vol. 55, 1924, p. 233. E. ARGAND. La tectonique de l'Asie. C. R. Congr. Géol. Int. XIII session. 1922. R. STAUB. Der Bau der Alpen. Beitr. zur geol. Karte der Schweiz. N. F., 52 Lief. p. 250. 1924.

the Alps, of which the betic ranges may be considered to be a direct continuation.

Because of the lack of a clear unconformity between Triassic and prae-Triassic sediments the Sierra Nevada bears a resemblance to the penninic or axial zone of the Alps. In the N. as well as in the S. part of the Sierra the Triassic border zone and the mixed zone have a very complicated structure, principally denoting large overthrusts in a N. direction, which direction of movement is also indicated in the crystalline schists of the central part. Crystalline schists, similar to those of the Alpujarras, being existent till near the outer border of the northern Triassic border-zone, these movements must be very intensive.

One of the windows in the Alpujarras (window of Albulon) proves already a slip of one of the overthrusts in these mountains of at least 7 kilometers. The roots of the overthrust sheets in the Triassic rocks and crystalline schists of the northern border-zone of the Sierra Nevada have to be looked for to the south of the Sierra in the Alpujarras, where similar rocks are found. Where the highest parts of these overthrust sheets, which can be compared with the lower "East-Alpine overthrust sheets" of the Alps have been eroded away, the crystalline schists of the central part of the Sierra Nevada are uncovered and form the highest peaks of the mountain range. Between these lower "East-Alpine overthrust sheets" and the crystalline schists of the central part the mixed zone is found, which is characterized by a higher crystallinity of its rocks, if compared with the crystalline schists of the central part, upon which they rest, while the rocks resemble in many respects those of the "zone des schistes lustrés" of the Alps. Although different in many respects, the structure remembers that of the Hohe Tauern in the Eastern Alps, where a penninic window, surrounded by the "East-Alpine overthrust sheets" is uncovered by erosion ¹⁾.

That the movements have continued after the formation of these structures is proved by the great uplift of the present mountain range and by the sometimes very steep dips and overfolded position of the late-Tertiary deposits, which have not been eroded away in the marginal parts of the mountain range only.

¹⁾ Proofs of the existence of higher overthrust sheets, of which the roots have to be looked for to the south of the Alpujarras (Mediterranean) have been found this summer. In the region between Nivar and Diezma to the north-east of Granada the overthrust sheets with the Triassic in Alpine development dip below the sediments of the sub-betic chains, where the Triassic is found in the more continental development with reddish sandstones, shales and conglomerates.