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PLIOCENE UPLIFT OF TERTIARY MOUNTAIN CHAINS

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ABSTRACT. Modern tectonic theory, strongly influenced by the Alps, attempts to establish a causal connection between tangential compression (as expressed by folds, faults, and nappes) on the one hand and a succeeding mountain uplift on the other. But Pliocene uplifts of virtually equal magnitude have taken place not only in the Alps, which were tremendously compressed from the Cretaceous to the Miocene, but also in the Pyrenees, strongly compressed but mainly without nappes in the Cretaceous and Eocene, the High Atlas, moderately compressed in the Eocene and Miocene, and the Anti-Atlas, not compressed since the Precambrian. Vertical uplifts of this sort are better considered causally connected with contemporary phases of tangential compression than with preceding phases.

GEOLOGICAL thinking on structural questions in Europe has been influenced to a very large extent by the supposed stupendous shortening of the upper part of the earth's crust in the Alps. Many theories as to the cause and mechanism of mountain-building are based on the tectonic features observed in the central and prealpine belts and have been applied, often unconsciously, to other Tertiary fold-systems, thus arriving at a general picture of mountain-building mechanism supposed to be of worldwide application.

One of the most popular conceptions is that which combines the buckling hypothesis of Vening-Meinesz (1934), which explains the negative anomaly generally accompanying Tertiary fold-systems by the downward buckling of the deeper and main part of the earth's crust, with post-tectonic isostatic emergence of the folded belt. It has been realized from the beginning that the cyclic features of the subsidence and emergence and its often very important retardation still need a lot of explaining, but the general sequence of predicted events is in such good harmony with the morphological features of the Alps that objections to this theory of mountain-building have been rejected as minor imperfections of the theory, or have been answered, as for instance by Umbgrove (1949), in applying this way of thought to the Indonesian archipelago, by a somewhat more complex sequence of folding and emergence. However, if this conception has a more than local value, it should conform to the facts equally well when applied to other and similar Tertiary mountain chains.

In Europe and North Africa there are many mountain chains of Tertiary age, which rise nearly as high above their surroundings, both in the topographical and in the geological sense, as the Alps, and which therefore offer the possibility of checking the value of the buckling-isostatic emergence theory. In figure 1 we compare sections through the Alps, the Pyrenees, and the High- and Anti-Atlas.

The most striking difference between the three sections is the intensity of folding. In the center of the Alpine section we find the recumbent nappes of the Pennines, flanked north and south by a zone of crystalline schists with intruding granite masses of Hercynian age. In the Pyrenees anything like the Pennine nappes is missing, but the center of the section is comparable in structure to the Aar-, Gotthardt- and Orobic-masses, only much less metamorphic. In the High Atlas no central zone of crystalline masses appears. However, if we had taken a section farther west through the High Atlas, the Hercynicum would have been exposed in the center, not as individual masses separated by vertical Mesozoic zones as in the Alps and Pyrenees but by simple arching of the Mesozoic blanket. Both in the Alps and in the Pyrenees some gliding tectonics have occurred from the higher levels into the marginal troughs, but on a much larger scale in the Alps with its complicated set of Helvetian nappes in the north and some gliding nappes in the south. In the Pyrenees we find only occasional gliding nappes on a small scale along its southern border, accompanying upthrusting in the Hercynicum as in the Mount Perdu section. In the High Atlas very little of this kind of structure is known; only in the southern region of Skoura some gliding tectonics have been described. On the whole, the original Jurassic basinlike structure of the High Atlas is still preserved in its present state after two Tertiary folding episodes, witnessing to the gentle character of this folding.

On the other hand there are some striking concurrences between the three sections, as, for instance, the longitudinal fault systems on the margins of the folded belts, which are admirably preserved in the northern Pyrenees, southern High Atlas and southern Alps, but probably largely obliterated in the northern Alps by the intense folding and gliding tectonics.

But we are more interested at present with the younger

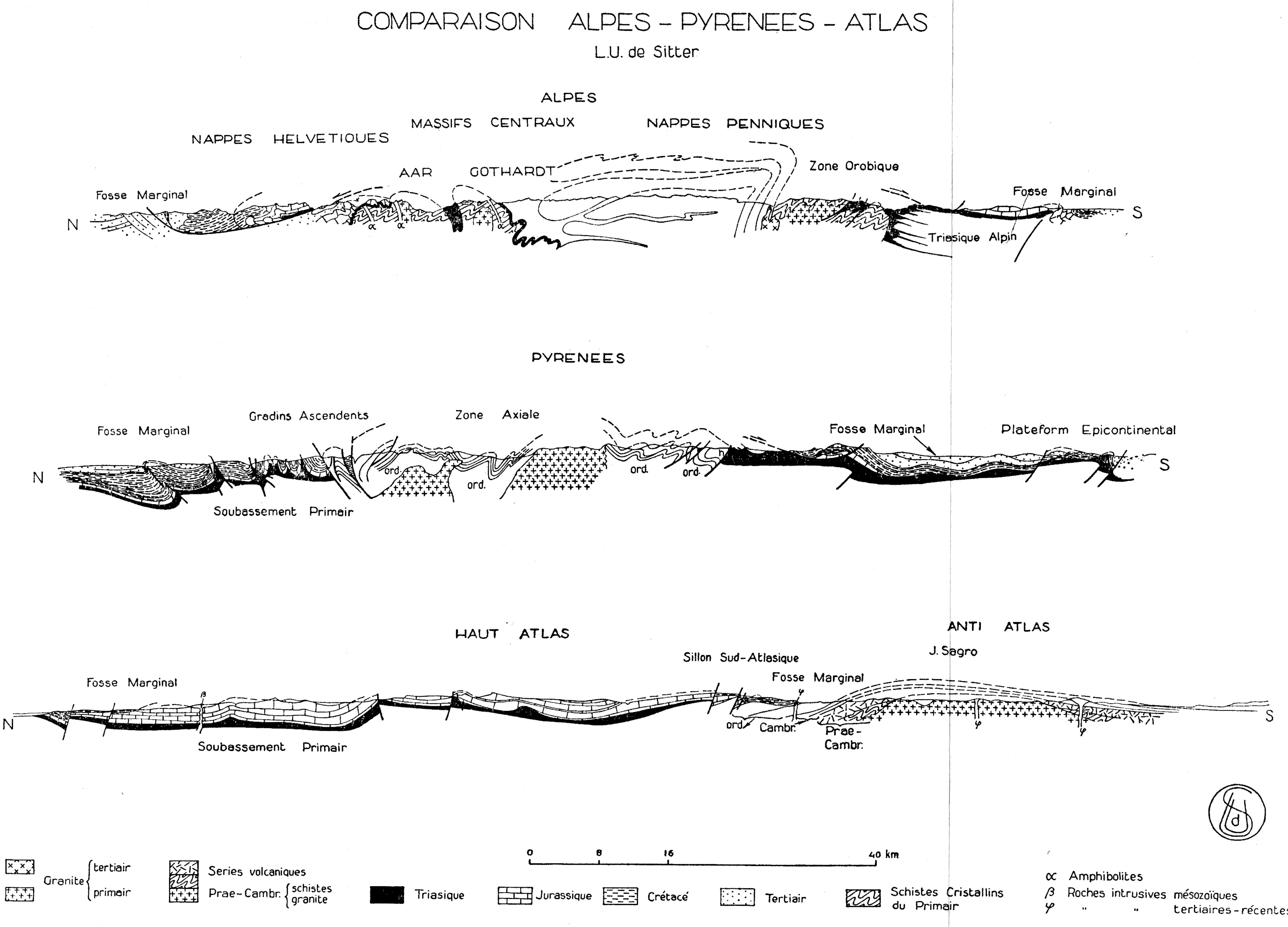

Fig. 1. Structure sections across the Alps, the Pyrenees, and the High- and Anti-Atlas.

movements of the mountain chains than with their tectogenic history. Let us consider first the Pyrenees, which look down on the Aquitanian plain and basin as the Alps look down on the Bavarian plain. The Pyrenees rise to an altitude locally well above 3000 m., somewhat lower than the Alps, a difference due to their much narrower structure. As in the Alps the Mesozoic cover has been removed from the central zone, hence their elevation is perhaps of the same order. Admirably preserved post-tectonic erosional levelling surfaces witness to the original low altitude of the folded chain and to later elevation (Faucher, 1934; Birot, 1937; Goron, 1941). In figure 2, for instance, the plateau at about 900 m. altitude, deeply dissected by younger rivers, represents the end of a Tertiary denudation period of probable late Miocene age, which truncates vertical Paleozoic and Cretaceous strata. In figure 3, a similar pause in the upheaval of the Pyrenees is represented by the Esplas plateau. Both examples are taken from the north-Pyrenean zone in which large Paleozoic domes with their Mesozoic mantles are separated from one another and from the axial

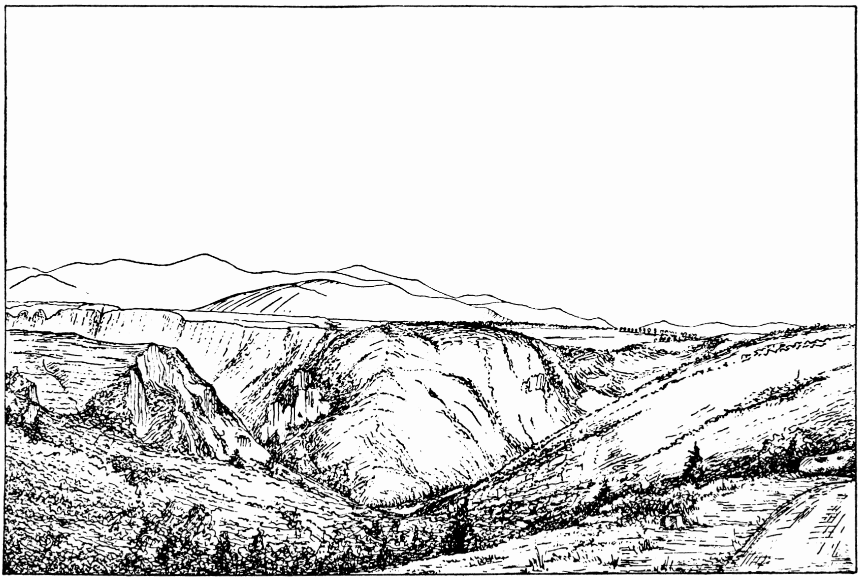

Fig. 2. Pyrenees. The Pays de Sault aplanation surface, Pliocene?, altitude $\pm$ 900 m., with the Rebenty canyon, looking towards the south. The peneplain truncates Mesozoic and Paleozoic vertical strata exposed in the canyon.

zone by vertical, narrow, and strongly compressed Mesozoic belts. The Tertiary aplanation surfaces continue, however, in the axial zone, where for instance the "plate-forme d'Aston," at an altitude of 1800 to 1900 m., south of the longitudinal east-west Ariège valley between Tarascon and Ax-les-Thermes along such a Mesozoic vertical belt, rises slowly towards the central divide. On its broad back it carries mountain peaks, remodeled by Quaternary glaciers, which, however, do not rise more than 600 or 700 m. above its level. The Aston surface also has a Miocene age; it is still discernible at the other side of the Ariège valley and therefore is post-tectonic.

By the end of the Miocene the Pyrenees represented there-

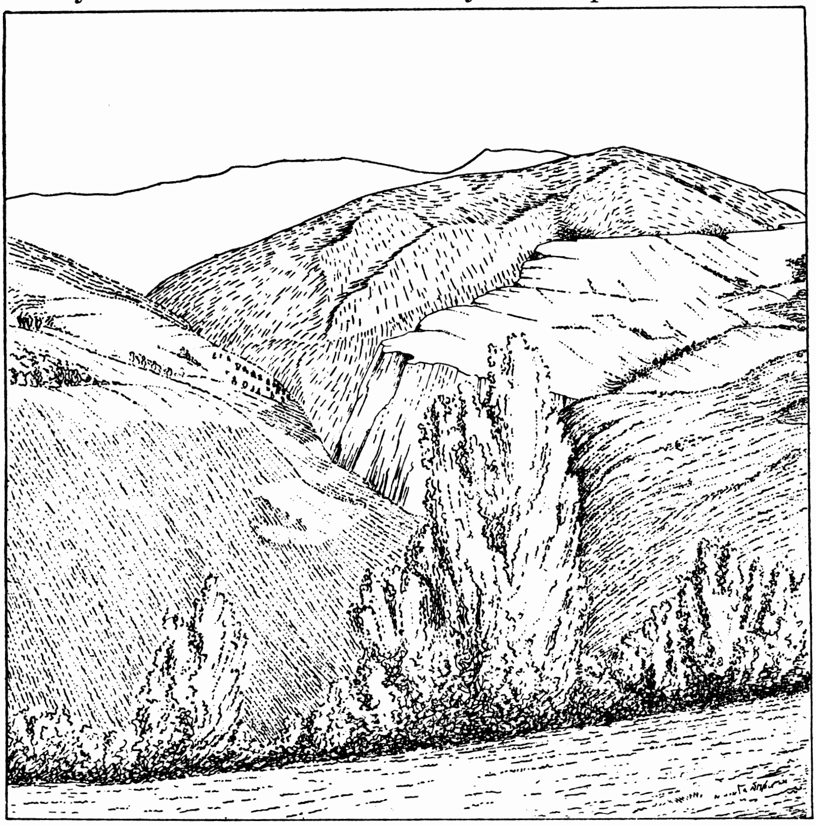

Fig. 3. Pyrenees. The pre-Aquitanian (?) aplanation surface, altitude ± 800 m., preserved in the Massif d'Arize near Esplas and Montagnon; in the background the top ridge of the Massif d'Arize. The steep canyon is the higher Arize valley, all in Paleozoic rocks.

fore a gently undulating, very mature landscape, almost a peneplain with low hills, which in the center did not rise above 1000 m. altitude. Since then, and before the Quaternary glaciations, the upheaval elevated the center at least 2000 m., tilting the Miocene aplanation surfaces, which now slope gently towards the north. This history is in all respects comparable to that of the Alps.

The great difference from the Alpine chain lies, however, in the pre-upheaval tectonic history. The Tertiary folding of the Pyrenees was finished by the end of the Eocene, whereas, in the Alps, Miocene and Pliocene phases are important. Not only is the age of the folding quite different, but also the character of the folding. In the Pyrenees we find nothing of the kind of large thrust sheets, neither of the Penninic type nor of the Helvetian type. (In the southern marginal zones we find a series of gravitational gliding structures, the largest being the cascade folds of Mount Perdu.) In the center there has been a strong compression of longitudinal blocks, large "plis de fonds" between which the Mesozoic mantle in the synclines has been strongly compressed and often metamorphosed, and in the foothills we find long superficial structures of moderately folded Mesozoic and older Tertiary strata. The total meridional shortening is therefore only a fraction of that of the Alps. There is hardly any evidence of recrystallization in the Paleozoic strata down to the Ordovician, there are no nappes, and the whole tectonic development ended in the Eocene, but the large Pliocene epeirogenetic movement which elevated the present mountain chain is of the same age and the same magnitude as that of the Alps.

Let us now turn our attention to the southern border of the Tethys geosyncline, to the great mountain system of the Atlas.

The High Atlas again reaches well above 3000 m. in its highest peaks. The Tertiary folding is of Eocene and Miocene age, the upheaval much younger.

In the Atlas we find again, as in the Pyrenees, folded longitudinal blocks, but with much less compression. On the south side of the western High Atlas the Cretaceous, directly overlying the Triassic cover of the Paleozoic, rises gently and continuously, broken only by an occasional fault, towards the center, where only strongly compressed Paleozoic is exposed. The same is true of the northern flank of the mountain chain, where long and almost horizontal Lower Eocene escarpments lie on top of the foothills, formed by Cretaceous on Triassic strata, unconformably overlying the folded Paleozoic.

Farther east the Jurassic cover is either moderately folded in sharp anticlines and broad synclines of the surface type (fig. 4) or unfolded and gently sloping southwards, on a southern block (fig. 5).

A Pliocene upheaval is very evident and has given rise to intensified erosion in the Quaternary (Choubert, 1949). To a large extent, the inner valleys of the eastern High Atlas still have their Pliocene geography with very large synclinal valleys (fig. 4), although many of the "cluses" leading through the Lower Liassic cores of anticlines probably have a Quaternary origin due to the tilting of the whole block. In the southern slope deep ravines have been cut since the Pliocene upheaval (fig. 5).

Still farther south the edge of the Sahara block has been slightly folded in the Anti-Atlas Mountain chain. Precambrian

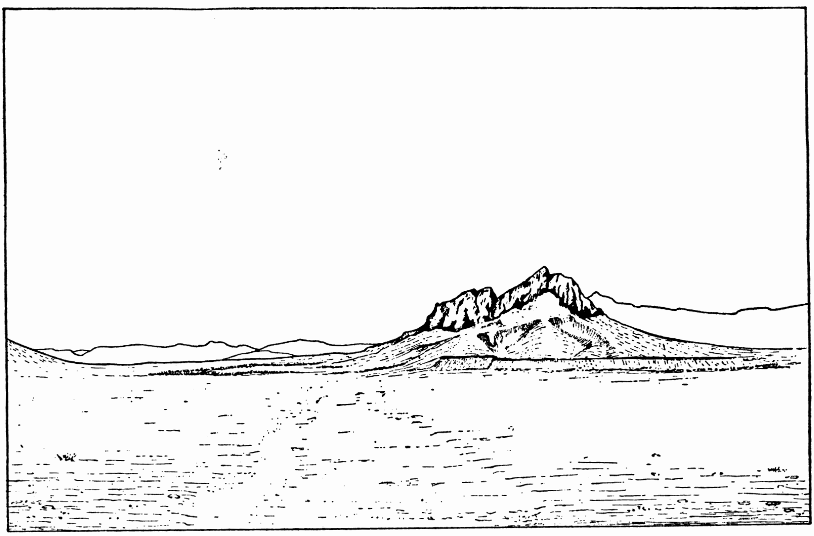

Fig. 4. High Atlas of Morocco. The plunging anticline of Bau Hamid with a hard Lower-Liassic limestone core and softer marly limestones of Upper Lias in the flanks. The river Ziz curves round the nose of the anticline. To left and right the broad synclinal plains are cut in soft Dogger marls. Pliocene landscape of the center of the High Atlas.

rocks crop out in the core of the large dome of the Jebel Saghro, disconformably covered by the Lower Cambrian which shows dips not exceeding 30° and generally much less than that. The center of the dome is occupied by a Pliocene plateau modeled in granite and schists of the Middle Precambrian on which occurred phonolitic extrusions in the Pliocene. This central plain lies at about 1900 m. altitude and is dissected only on its borders where young river systems have cut deep gullies in granite and late Precambrian volcanics. There the same Pliocene phonolites are found now only on the tops of mountains at the same altitude of about 1900 m., sometimes preserving at their base Pliocene lake deposits (fig. 6). The history of this Anti-Atlas chain can therefore be reconstructed as a levelling of the very gentle Hercynian folding, in Mesozoic and Tertiary times, followed by lake deposits and phonolite flows in the Lower Pliocene on Precambrian and Cambrian rocks, then upheaval of at least 1000 m. in the Pliocene and renewed erosion since then.

Our review has shown that a Pliocene upheaval of 1000 to

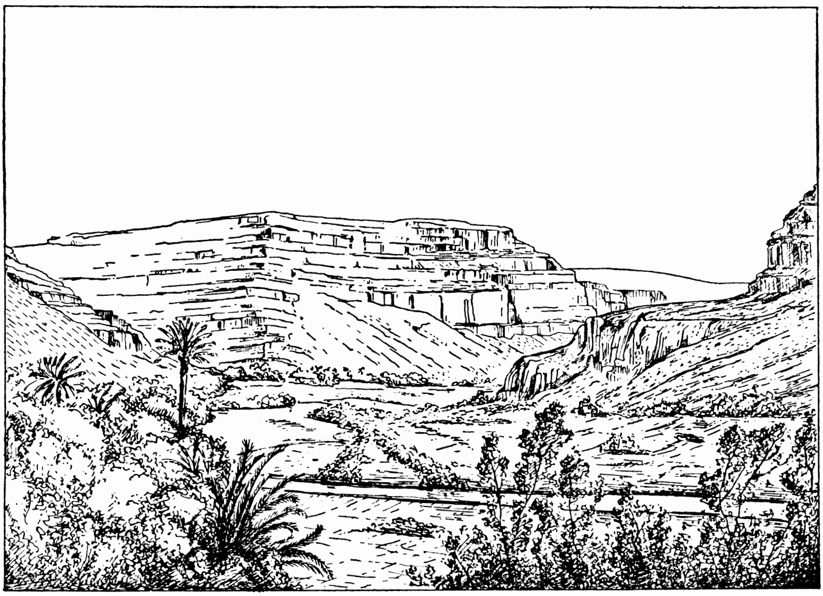

Fig. 5. High Atlas of Morocco. The canyon of the lower Ziz between Kerrando and Ksar es Soukh in unfolded Upper Lias. Post-Pliocene erosion.

2000 m. occurred as well in the Alps, the Pyrenees, the High Atlas and the Anti-Atlas. The tectonic history of these mighty mountain chains is, however, widely different: extreme compression in the Alps in successive stages since the Cretaceous and including the Miocene, strong compression in the Pyrenees in the Cretaceous and Eocene, moderate compression in the Eocene and Miocene in the High Atlas, and no compression in the Anti-Atlas.

Whereas in the Alps the isostatic upheaval of a mountain root is an adequate explanation of the Pliocene emergence, it is less so in the Pyrenees where the time interval is much greater and the evidence of a root much smaller; in the High Atlas a buckling down of the deeper crust is hardly conceivable, and it is certainly absent in the Anti-Atlas. The Pliocene upheaval is of the same order in all four mountain chains.

Hence there is no evidence to support the theory that younger Tertiary upheaval is a consequence of the older Tertiary compression; on the contrary the two phenomena seem to be wholly independent when seen from this point of view. Epeirogenic and tectogenic movements may have a common cause but the one need not be the consequence of the other.

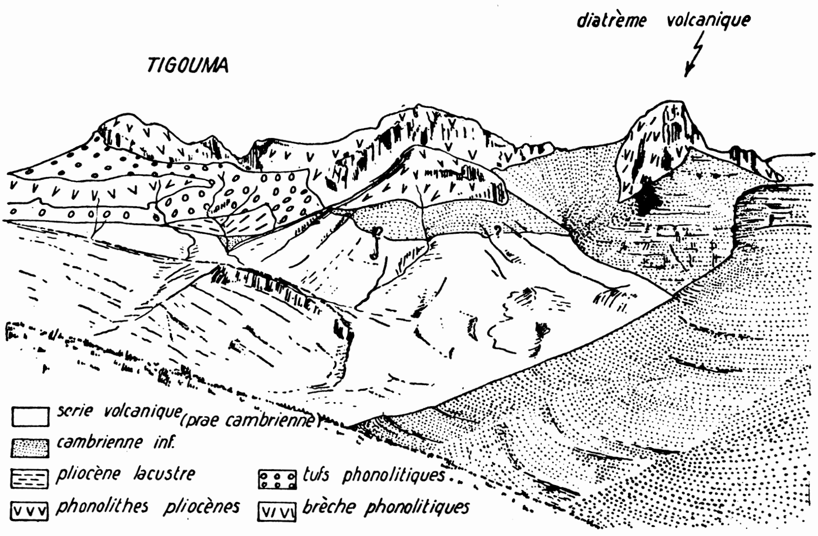

Fig. 6. Anti-Atlas of Morocco. Pliocene phonolites on top of the Tigouma in the Jebel Saghro, Anti-Atlas, disconformably overlying Precambrian volcanics and Lower Cambrian sandstones. Altitude ± 1900 m.

Both Escher (1948) and Fourmarier (1950) use the term "tectogenetic" as opposed to "orogenetic," the former indicating "true" tectonic structures, folds and faults, the latter indicating the upheaval of the already folded belt, the truly mountain-building movement in the orographic meaning of the word. The causal connection between tectogenesis and orogenesis is, however, often obscure, and the time interval between the two occurrences has to be taken carefully into account.

In this respect we may recall a similar situation where two separate movements have been ascribed to one cause, but where again the time interval makes us hesitate to accept the theory. According to the fascinating theory of H. Cloos (1929, 1932), the upper Rhine rift valley and its northern continuation in the Cologne embayment is due to the arching of the Rhenish shield, the arching causing tension in the upper part of the crust and hence the formation of the normal faults and the subsidence of the central block. Again we are concerned with a theory combining two structural phenomena, the arching of the shield and the subsidence of the rift valley, and again the theory is contradicted by the time the events occurred. In this case the subsidence ought to be contemporaneous with the arching, but this is certainly not the case; a considerable time interval separates the two events. In the Cologne embayment, for instance, we know that the central portion of the arch was already elevated in Cretaceous time and the rift occurred only in the Miocene. In the upper Rhine valley the subsidence started earlier, in the Oligocene, probably in connection with the strong Oligocene folding phase of the Alps.

Anyhow the tangential movements and vertical movements during a mountain-building period are often very complex, and the two phenomena can seldom be separated logically as individual phenomena, each having its own cause and mechanism, except in the cases we have described, where a later upheaval occurred after a considerable time interval. Without doubt there are in the Alps many instances of direct vertical movements which occurred intermittently between the folding phases. In the southern Alps, for instance, the general structure consists of a series of broad steps, separated by vertical zones or faults, leading up to the Orobic crystalline zone (de Sitter, 1949, 1950). The structure of the Triassic strata of a lower step shows that they have been compressed against the vertical wall leading to the next higher step, and on the other hand the same strata have glided down along appropriate weak strata from a higher step onto a lower step. Hence some of the compression took place after the upheaval of the steps and some of the folding occurred after this vertical displacement.

The uplifted Pliocene surface has perhaps received undue emphasis, because it is the latest and best preserved from ravages by Pleistocene glaciation. Any tectogenic belt is characterized by alternations of strong compressions and positive and negative vertical movements.

When we perceive that the large amplitude Pliocene movements of High- and Anti-Atlas coincide exactly in time with an extreme paroxysm of the Rif Mountain chain, and the Oligocene sinking of the Upper Rhine rift with one in the Alps, I prefer to see these coincidences as a causal connection, instead of accepting a purely hypothetical theory that does not establish such time agreement. This does not imply that I would reject altogether the theory of buckling and isostatic adjustment for the Alps or the Indonesian archipelago—on the contrary—but the supposed causal connection between the two different structural events does not have general application.

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