[American Journal of Science, Vol. 252, June 1954, Pp. 321-344]

American Journal of Science

JUNE 1954

GRAVITATIONAL GLIDING TECTONICS AN ESSAY IN COMPARATIVE STRUCTURAL GEOLOGY

L. U. de SITTER

ABSTRACT. Gravitational gliding tectonics explains certain folded and faulted structures by superficial gliding of relatively large and coherent masses down slopes under the influence of gravity rather than directly by lateral compression, though lateral compression is a possible cause of the slope. Examples of such tectonics have been described from all the continents except perhaps Australia. Study of these examples suggests certain distinctive features by which gravitational gliding tectonics may be recognized; among them are the existence of a suitable slope, the preservation of an unthinned inverted limb, and in certain cases chaotic structure showing little relation to regional trends. The evidence clearly demonstrates, however, the close relation between lateral compression and gravity structures.

INTRODUCTION

Since the birth of the science of structural geology, geologists describing particular phenomena observed in the field have explained certain structures as the result of gliding down an inclined surface. However, the great impetus that the discovery of large thrust masses gave to structural geology, and the resulting prominence that has been given to lateral compression as the origin of these thrusts, has to a large extent caused structures rightly ascribed to gliding to be overlooked or misinterpreted. Modern thought has taken up the concept of gliding again and has applied it with much success to the great nappes of the Helvetian type in Switzerland and to the flysch nappes of both the western and the central Alps.

At the same time, however, another school of thought has developed which emphasizes the fluidity of rocks under high confining pressure, as observed in laboratory experiments, and the obvious uplift that every mountain system has undergone. It attempts to explain all tectonic features by the influence of gravity on elevated parts of the Earth's crust. In this view, the positive and negative vertical movements are caused by hypothetical processes at great depths, and all horizontal movements are due to sliding down hill, even those in the deeper parts of the crust.

Thus there have developed two concepts of gliding, one chiefly concerned with superficial features, the other with deeply buried parts of the Earth's crust. Unfortunately, though they originally sprang from widely different considerations, they have mingled when they met at the surface of the crust, and heated arguments have resulted.

They ought to be kept separated, however, and each judged on its own merits. We are here concerned mostly with observable aspects of structural geology and not with theoretical arguments about their deep-seated cause and origin.

We shall not enter into a historical review of the development of thought on gliding tectonics in the last decades. I want to point out, however, that the idea was hatched in Grenoble by Gignoux and Schneegans (Schneegans, 1938; Gignoux, 1948), in Lausanne by Lugeon and Gagnebin (1941), and in Rome and Florence by Beneo, Merla, Migliorini, and others (Migliorini, 1933, 1936; Merla, 1951), more or less simultaneously, though it had been present in the mind of many geologists before. Haarman, van Bemmelen, and many others used it extensively but from another point of view, more indiscriminately and as an all-comprehensive theory. A survey of the different directions in which such ideas have been tending is provided in: Symposium sur la tectonique d'écoulement par gravité, Geologie en Mijnbouw, 12e Jaarg. 1950, p. 329-365, containing articles by Tercier, Gignoux, Goguel, van Bemmelen, and de Sitter.

PRINCIPLES OF GRAVITATIONAL GLIDING TECTONICS

Gravitational gliding tectonics may be understood as embracing all phenomena where gravity has been the cause of movement of relatively large and coherent superficial portions of the Earth's crust. In this sense it does not include all such movements as landslides or slumping. Starting from a single pebble rolling down a slope and increasing gradually the mass of the dislocated material gliding down, we would be able to establish a continuous scale ending with nappes of the Helvetian type. We will observe, however, that in this scale the smaller masses have a chaotic aspect, as in landslides, and that the larger the mass the more coherent the structure. Also the larger the mass the smaller the dip of the gliding surface need be.

From a more theoretical point of view we can distinguish in superficial gliding tectonics two extremes, with all transitions between. At one end of the series we may place the gliding of a slab of sedimentary rock on a gliding surface formed most frequently by an exceptionally incompetent member of an otherwise competent series. Hardly any disturbance inside the slab need occur; for example, it may simply glide down an appropriate slope, lubricated at its base by shale containing salt or gypsum. At the other end of the series we may place the gliding of a uniformly ill-stratified mass of highly incompetent strata. The basal shearing plane would be much less distinctly developed, and most of the movement would occur within the gliding mass, which therefore would possess a more or less chaotic structure. During its downward course the gliding mass may even pick up and incorporate pieces of its substratum, with the result that it might contain much younger constituents than expected.

All possible transitions between the two extremes can be found. The sedimentary series may possess several incompetent layers, so that the original slab is divided into several slabs moving independently. If these intermediate incompetent layers are relatively thick, the competent layers may be broken up, and distinct secondary folds may develop, separated by internal gliding planes. If the incompetent mass predominates we may find large blocks or folded remnants of the competent layers distributed in an incoherent way throughout the mass. The parautochthonous flysch of the north flanks of the central massifs of the Alps is a good example of this mode of folding and gliding (fig. 1). Some of the masses of the Argille scagliose in the northern foothills of the northern Apennines give a very good idea of the chaotic structure of a large incompetent mass of rocks in which there float fragments of the competent members of the original sequence. This so-called "Argille scagliose" is a comprehensive series, ranging from the Malm at least to the Cretaceous, and is so incompetent that it is able to form glacier-like gliding masses originating from a simple outcrop between younger strata, as I had the occasion to observe in the Turinese foothills.

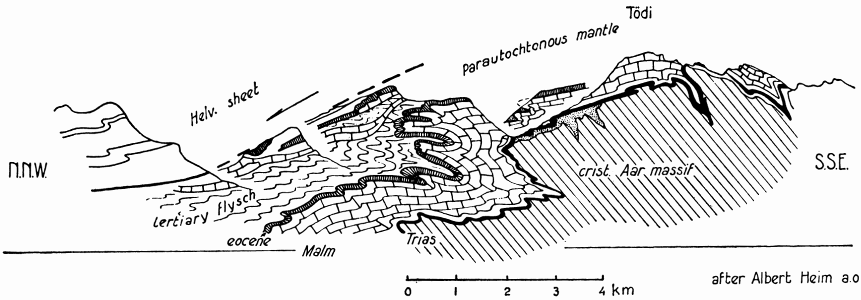

Fig. 1. The cascade folds of the sedimentary mantle of the autochthonous Aar massif, Switzerland, gliding down the northern slope of the massif under the influence of its own weight and that of the overriding Helvetian nappes, also gliding down. After Heim and others.

Many good examples of remnants of synclinal and anticlinal folds of older and competent strata embedded in highly incompetent flysch are described by Schneegans (1938) in his thesis on the Ubaye-Embrunais gliding nappe (fig. 9). The Helvetian nappes, which originally were successive overthrust anticlines, each having its own basal shearing plane at a different stratigraphical level in the series, illustrate nicely the case of a complicated gliding mass divided by incompetent layers into several independent units (fig. 12).

The Liassic slabs on the southern border of the High Atlas, and some of the Cretaceous slabs on the southern border of the Pyrenees are simple undivided masses of competent rocks gliding on a Triassic lubricating plane (fig. 10).

The size of a gliding mass is probably dependent on several factors. If, as in the case of the Helvetian nappes, a pre-existing thrust plane cuts through the whole series from the basal shearing plane upwards to the surface and the back portion is then uplifted and tilted, there will be very little or no resistance at the front. As soon as the slope of the thrust plane is sufficient, gliding will start, and it will accelerate as the tilting continues. If, on the other hand, no previous thrust plane has developed, the resistance at the front will in general prevent the gliding of larger masses. As Goguel (1950) has shown, the larger the mass the smaller the slope of the gliding plane need be. But commonly the gliding will not start even if the minimum slope for a certain mass has been surpassed because there is not sufficient room in front and at the bottom of the slope, where erosion is less active anyhow. Therefore tilting can continue and nothing will happen until finally a gliding plane having sufficient slope to start the gliding can cut through the strata upwards to the surface. At that moment, however, a much smaller mass can detach itself because the slope has considerably increased.

How far erosion at the bottom of the slope plays an active part in preparing the necessary room in front of the gliding mass by cutting through the competent top layers to the basal shearing plane is impossible to determine. Personally I do not think erosion is a very important factor, but direct evidence either way is altogether lacking.

EXAMPLES OF GRAVITATIONAL GLIDING

The following examples of gravitational gliding quoted from the literature will give us the opportunity to discuss its particular character.

Bearpaw Mountains, Montana.—The simplest case of gliding on a tectonic scale I know is that described by Frank Reeves (1924, 1946).

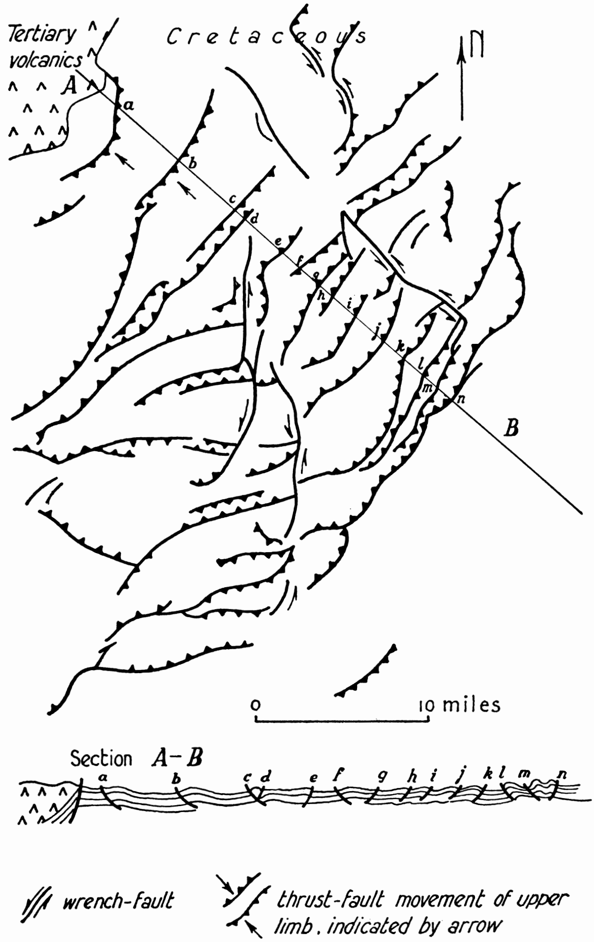

Fig. 2. Gravitational gliding in the Bearpaw Mountains, Montana. After Reeves, 1946.

In the Bearpaw Mountains, Montana, a series of mostly Upper Cretaceous shale and sandstone 4500 feet thick has been domed, and the top of the arched dome has been eroded. In Tertiary time a great mass of extrusive volcanic rocks, 5000 feet in maximum thickness, accumulated on top of the dome. The accumulation of this localized mass caused a plainsward sliding of volcanics and sedimentary strata, probably on one or two particularly incompetent bentonite beds in the lower part of the Upper Cretaceous shale. Still later the central portion of the dome caved in along normal faults. The accompanying map and section (fig. 2) show the thrust fault pattern and the curious arrangement of broad unfolded belts separated by narrow folded and thrust zones.

On the top of the dome there is a large gap in the volcanic cover, evidently because one half of the cover slid northwards and the other southwards, the only actual example of what we may call "tectonic denudation" I know. The slope never had an angle exceeding 3°, and each whole flank glided down this slope producing thrusts and folding in the untilted horizontal strata of the plain.

The thrusts commonly merge laterally into asymmetric folds, the more deeply eroded structures showing thrusting. Probably no thrust plane ever reached the surface. The thrust planes may dip either towards the dome or away from it. Radial tear faults separate different blocs, with different intensity of thrusting; they have a pronounced tendency to cross the structures diagonally. These tear faults therefore illustrate the original stress condition, but subsequently they became limits to different "flows," one advancing farther than its neighbor.

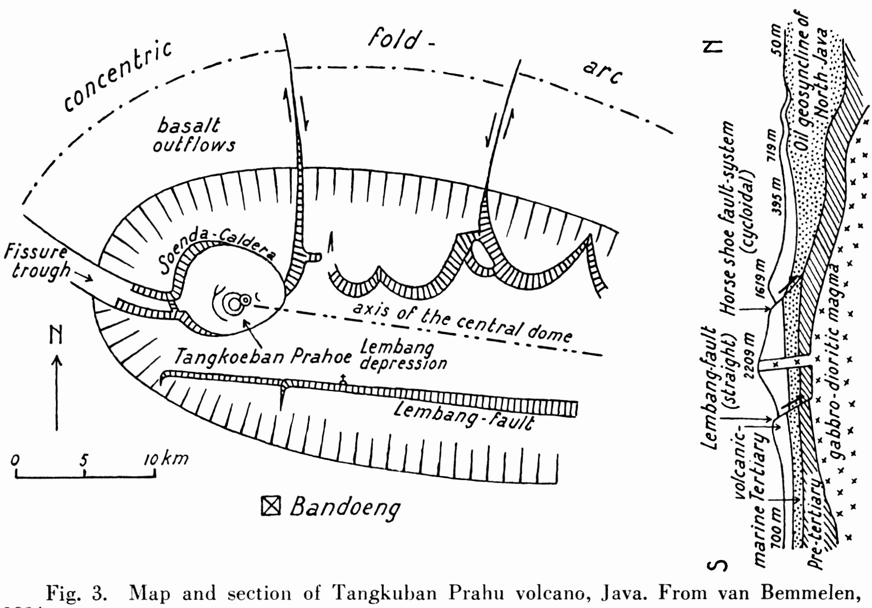

Fig. 3. Map and section of Tangkuban Prahu volcano, Java. From van Bemmelen, 1934.

The mass that slid on the 3° slope had an average thickness of 6250 feet and a total mass of some 55 million tons.

Tangkuban Prahu and Karangkobar volcanoes in Java.—Very similar to the case described by Reeves are two examples of gliding described by van Bemmelen (1934; 1937; 1949, p. 610, 641-644). North of the Bandung basin extends the Quaternary volcanic chain of the Tangkuban Prahu, in which we can distinguish an older and a younger volcanic series. At the foot of the volcanoes the volcanic series lie unconformably on folded Upper Miocene marine sediments. The youngest group of volcanoes, of which Tangkuban Prahu is the most western, lie on the axis of an elongated dome (fig. 3). On the northern flank of the dome a series of arcuate faults were mapped, partly originating in the caldera subsidence of Tangkuban Prahu itself and, judging by their shape, clearly independent of any general tensional faulting. The northern half of the dome is surrounded by the Segalaherang depression and that in turn by a row of hills, the Gunung Tembakan or Damm hills consisting of the older Quaternary volcanic blanket. The flat dips in these foothills, surrounding the Segalaherang depression, are almost exclusively mountainwards (to the south). It seems very probable that the arcuate faults in the volcano mantle and the abnormal dips in the foothills are due to sliding down of portions of the volcanic mantle. We can imagine that similar arcuate faults existed also in the volcanic mantle of the Bearpaw volcano, before erosion obliterated them.

A similar example is cited by van Bemmelen from the Karangkobar volcanic region of central Java. Here the Upper Pliocene uplift reached several thousand meters before the formation of the Pleistocene volcanoes and was accompanied by faulting and tilting of blocks of marine Lower Pliocene. Although some remnants of older volcanic rocks are present, most of the volcanics belong to the Quaternary of the Djembangan Mountain range. In this volcanic mantle arcuate faults have developed, which apparently represent the upper limits of gliding blocks. These Recent faults nowadays form precipitous fault scarps several hundred meters high. In order to check the possibility that these blocks were still moving, the topographical survey triangulated the position of some of the blocks twice, with an interval of 5 years, and noticed a movement of 120 cm, 200 cm, and 200 cm. These displacements are supposed to be much larger than the possible errors of measurements, and should indicate a movement of 24 to 40 cm a year.

Van Bemmelen describes in his work many much larger phenomena, but a careful comparison of his text with the accompanying map and sections allows considerable doubt as to the conclusiveness of the field evidence for ascribing his larger overthrusts to gravitational gliding.

Lobitos oilfield, Peru.—A very uncommon type of gravity gliding is reported from the coastal regions of Peru and Ecuador (Baldry. 1938; Barrington Brown, 1938). The region in question is limited oceanwards by the coastal normal fault, along which movements presumably took place recurrently, and inland by the Amotape metamorphic rocks. The Tertiary rocks deposited in this area measure several tens of thousands of feet of thickness and have been extensively explored for oil in some areas. The strata dip gently oceanwards. According to the authors, slip planes developed in the gently dipping strata every time a sufficient thickness of rocks had been deposited (fig. 4). These slip planes had an original dip of 7° to 10°, and along them are found all kinds of distortion of the beds, often resembling structures due to slumping. Nevertheless the continuous character of the slip planes, and the regular vertical spacing of 2000 to 3000 feet at which they occur make it very improbable that slumping at the time of deposition of the contorted beds is responsible. Along with the brecciated slip zones, sand dikes appear, cutting perpendicularly through the formation.

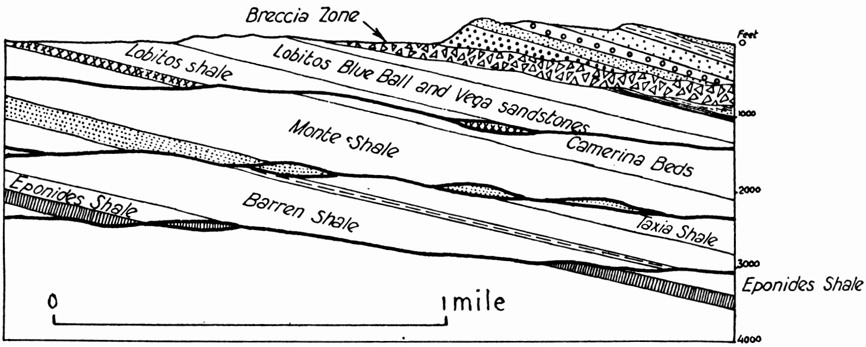

Fig. 4. Schematic section through the Lobitos oilfield, Peru. From Baldry, 1938.

It seems highly probable that gliding has been favored by a decrease of grain pressure as the impermeable shales prevented the escape of water expelled from the surrounding sediments by compaction. Any activity along the border fault, increasing the dip of the strata, could set in motion the gliding of the accumulated mass, and before a new slip plane could be formed a new thick series of sediments had to accumulate in order to establish anew a labile state. The sandstone dikes are formed in general from a normal sandstone, but some contain a mixture of shale and limestone fragments. Some of the breccia beds have a peculiar composition described as "clay pebble bed," which consists of highly polished pebbles of all kinds of rocks in a gritty clay matrix that looks like the deposit of a turbulent flow, combined with slumping.

Collapse structures in Persia.—A very interesting phenomenon in which gravity certainly played a prominent role has been described by Harrison and Falcon (1934, 1936).

In the mountainous part of Iran, bordering the Euphrates-Tigris valley, the structure of the folded strata is extremely well exposed because of the arid climate. The stratigraphic series consists of three thick limestone units, each 1000 to 3000 feet in thickness—the highest being the Asmari limestone, famous for its oil-bearing capacity—separated by marls 1000 to 2000 feet thick and overlain by 10,000 feet of anhydrite-shale and sandstone, called the Fars series. The incompetent marl series between the limestones have given rise, as is normal, to disharmonic folding, but some of the sections show undoubted gliding phenomena.

Harrison distinguishes several types of structures (fig. 5): (a) *slip-sheet* structure, (b) *cascade folds*, where the limestone has crumpled up, as it glided downwards, (c) *flap-structure*, undoubtedly the most curious structural feature of the region, where a limestone wall has bent over gradually until a reversed position has been attained.

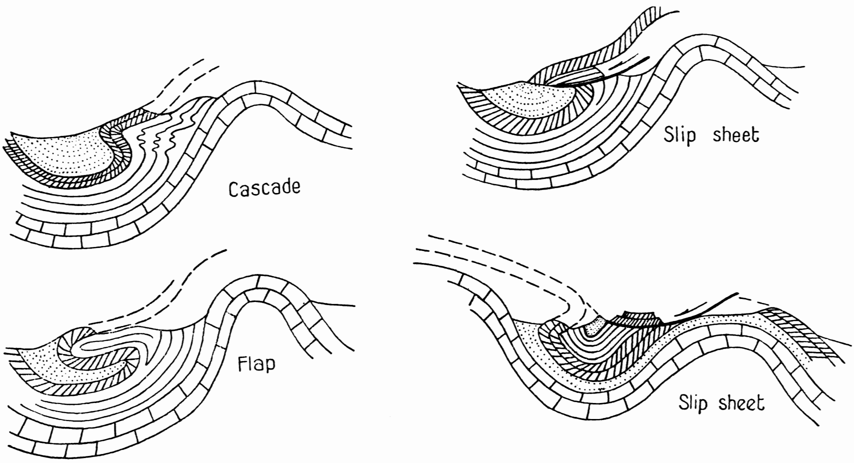

Fig. 5. Examples of collapse structures in Persia. After Harrison.

All these features are explained by Harrison as purely gravitational structures, due to deep erosion in the soft synclinal material of the Fars series and gradual collapse of the vertical limestone flank, which either broke off and glided down the slope in a normal position, or crumpled into cascade folds, or bent over into a recumbent fold.

I am far from convinced that all these structural phenomena ought to be explained by such relatively recent collapse of steep flanks into eroded valleys. The slabs of the normal roofs of the anticline that have glided down in the syncline are doubtless due to gliding only, and some of the cascades probably are also due to these gravitational mechanics, but the most striking "flap" structures can be explained as well by a rather extreme form of disharmonic folding. We know that the folds in the Fars series, the upper incompetent anhydrite, gypsiferous marls, and sandstone overlying the Asmari limestone, are always perfectly independent of the underlying competent limestone in the oil-bearing anticlines of Iran, where no altitude differences are involved. I rather think that most of these structures, which have a distinctly disharmonic character because of the alternation of thick competent and incompetent beds, had already originated in the folding stage and were accentuated later on by gravitational collapse. The overturn is then due mostly to lack of space in the syncline, and it developed because the thick Fars series behaved purely passively and was not a factor in determining the amplitude of the fold at the beginning of folding.

Djebel Friktia, Algeria.—A very instructive example of gliding tectonics has been given by van der Fliert (1953), in describing an anticline and syncline in eastern Algeria. The region consists of two anticlinal ridges composed of Lower and Middle Cretaceous limestones, and between them a synclinal region, filled up with Senonian and Eocene marls and shales. The anticlinal ridges received much thinner Upper Cretaceous sediments than the syncline, thus the sedimentation took place while the basin was sinking much faster than its stable borders. In the whole of eastern Algeria the very plastic Triassic shales and evaporites have acted diapirically, and apparently in the final post-Eocene phases of compression the Triassic was pressed out in the core of the anticline, and the thick Senonian blanket on its flank started gliding down along a slope of 3° to 5°. The top arch of the anticline, loosened from

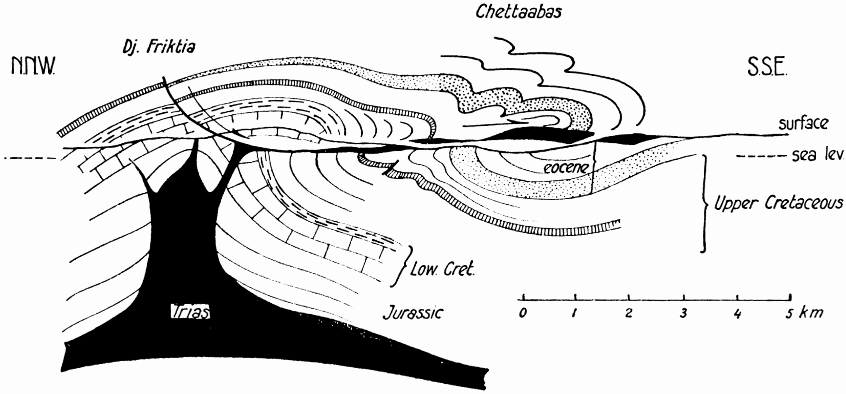

Fig. 6. Cross-section through Djebel Friktia and the Chettaabas syncline in Algeria, showing combination of diapiric and gliding structures. After van der Fliert, 1953.

the flanks by the diapir structure, took part in this gliding action, and the gliding plane became lubricated by Triassic shales. The result (fig. 6) is a rather astounding structure in which Triassic shales cover portions of the Eocene in the syncline while klippen of Upper Cretaceous rocks and locally even wedges of Lower Cretaceous limestone float on them, and the steep south flank of the anticline shows considerable tectonic thickening. It is quite possible that the pressing out of the Triassic from the syncline to the anticline had already started during the accumulation of thick Upper Cretaceous and Eocene sediments in the synclinal basin, before the folding created the truly diapiric structure of the anticline.

Bergamasc and Luganese Alps.—Gliding tectonics can frequently be found on the marginal slopes of the great Tertiary mountain chains. We often find there that the upper surface of the basement is lowered from its lofty position in the axial zone to its deeply buried position in the marginal trough by a series of steps separated by steep zones or faults (de Sitter, 1949). The difference of altitude between two steps commonly gives rise to a gravitational gliding of the sedimentary cover along an appropriate horizon on top of the stationary series of the same age belonging to a lower step. Numerous examples of these structures can be quoted from sections in the southern border of the Alps, of which we reproduce two in figure 7.

In the section east of Lake Lugano we see a whole mass of Triassic and Liassic limestones gliding down a slope and butting against a solid mass of

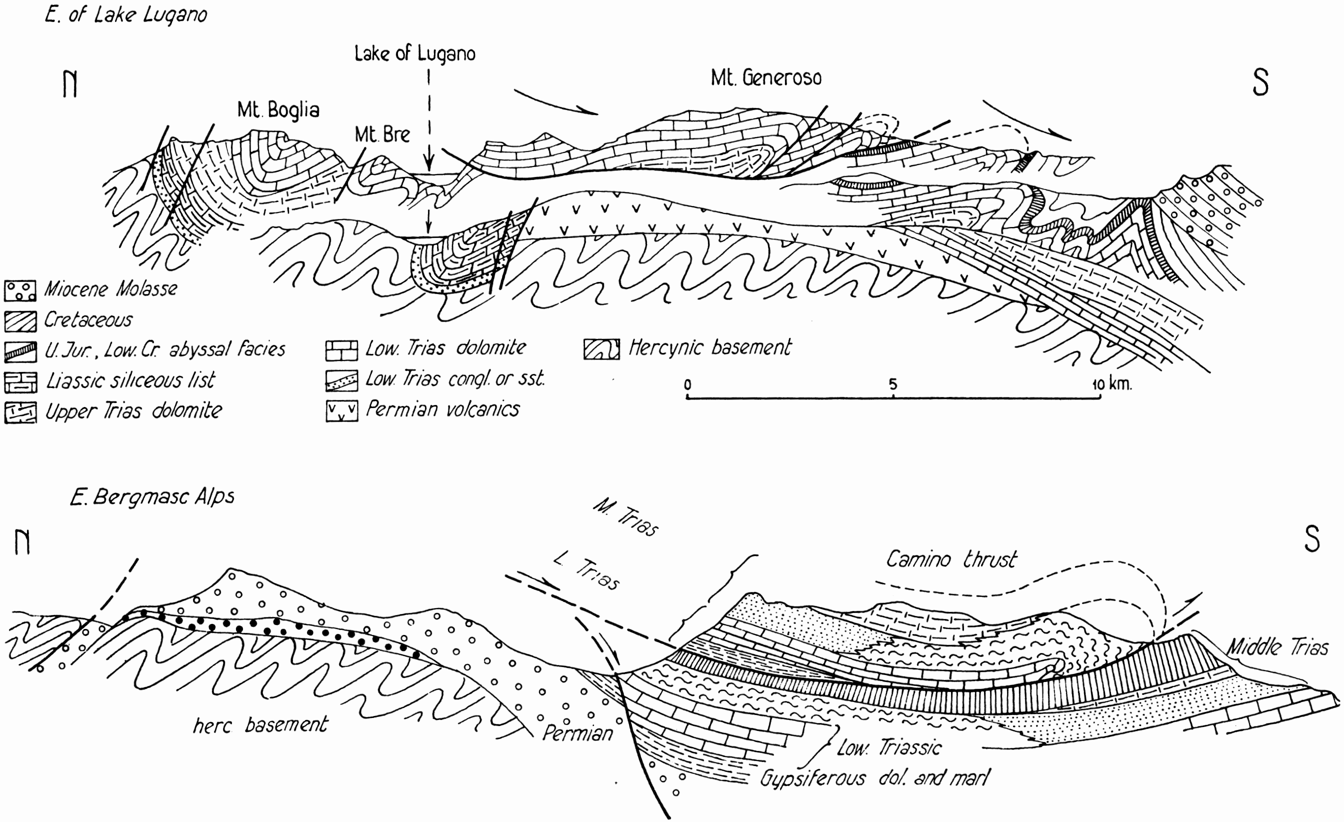

Fig. 7. Two sections showing gliding nappes on the southern slope of the Alps: Mt. Generoso east of Lake Lugano, and Pizzo Camino in the eastern Bergamasc Alps. From de Sitter, 1949.

Miocene Molasse. The cascade folds in front of the gliding mass are typical and illustrate the movement very clearly. The amount of gliding is relatively small, and gliding was probably set in motion by the steep synclinal folding in the Mt. Boglia-Mt. Bre region, which caused a horizontal push in the upper strata.

The Bergamasc section shows how the Triassic limestones, detached along the gypsiferous dolomites of the Lower Triassic, glided down from a higher step onto a lower one in front. In the frontal portion of the Camino thrust we find exposed the transition zone from a calcareous facies of the Middle Triassic to a marl facies. Evidently the motion again originated in a fold cut by a thrust, located on the wedging edge of this limestone; the thrust plane cut through the Lower Triassic limestones to the incompetent gypsiferous layer. Once started, the structure glided down on the lower step. There can be little doubt that the general compression, which caused steep thrusts in the northern and highest region, and the doming of the basement in the central step were contributing factors as well as the vertical upwarping of the successive steps, which originated the height differences and the resulting slopes.

Southern border of the Pyrenees.—The southern border of the Pyrenees offers many similar gliding nappes, mostly of small dimensions. The best known one is doubtless the cascade folds of Mt. Perdu (Mengaud, 1939) (fig. 8). The sedimentary cover of the Paleozoic basement consists here of Senonian and Eocene. In this section we find first of all a subhorizontal thrust

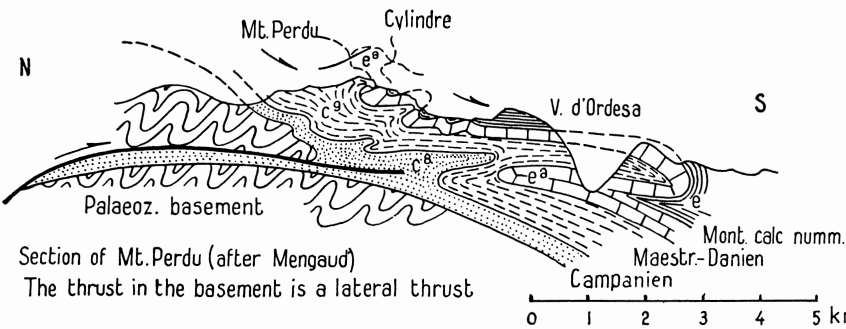

Fig. 8. Combination of thrust and cascade fold on southern slope of Pyrenees. From Mengaud, 1939.

of the basement rock from north to south due to lateral thrust. Below the thrust mass a thin band of Upper Cretaceous has been preserved. The thrusting movement piled up the upper Senonian and Eocene blanket rocks in front of the nose of the basement thrust, and they started to glide down, forming a cascade of folds, the lowermost one being a large recumbent fold exposed in the Ordesa River. The lateral thrust and the gravitational gliding both operated at the same time, the first causing the second.

A recumbent fold with a complete reversed flank, as encountered in this section, can be considered typical for gliding tectonics under circumstances in which a considerable difference in altitude between the two blocks is most important. A reversed flank which has not been drawn out to the extreme or simply replaced by a thrust fault, or a combination of these two phenomena, is impossible in an ordinary overthrust anticline, because the result of lateral thrust is to produce a considerable shortening without accumulating too much mass in a vertical direction, gravity preventing a trebling of the load. When on the other hand the sedimentary rock series is gliding down a slope, the result is to fill up a marginal trough with rock masses from a higher altitude; thus gravity is not opposed to a multiplication of the original thickness of the sedimentary strata—on the contrary, gravity will favor it (fig. 18). Hence when the strata are sufficiently plastic, they may form a cascade of folds in which the larger ones are recumbent folds whose reversed flanks are not attenuated. The recumbent fold of the Grand Morgon (fig. 9), mapped by Schneegans (1938) is a good example of this kind of structure. In that region we find two incompetent layers along which the higher beds have been detached, the Triassic at the bottom of the section and the Callovian-Oxfordian shales in the middle. In the Grand Morgon area both have been active.

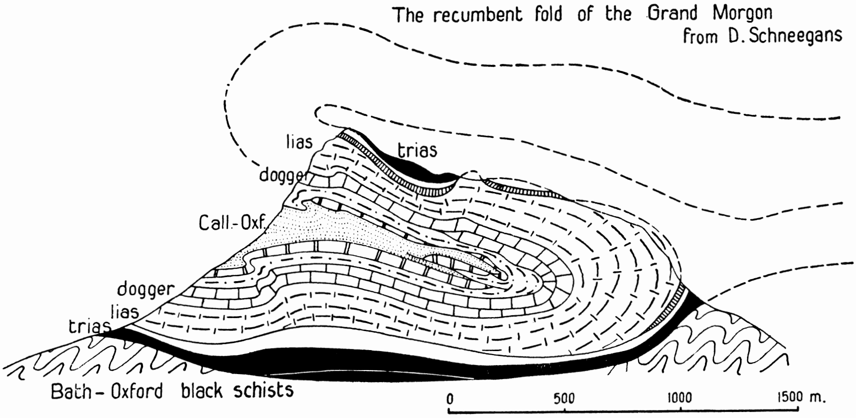

Fig. 9. Inverted middle limb of recumbent syncline due to gliding, preserved in gliding nappe of Ubaye-Embrunais, French Alps. From Schneegans, 1938.

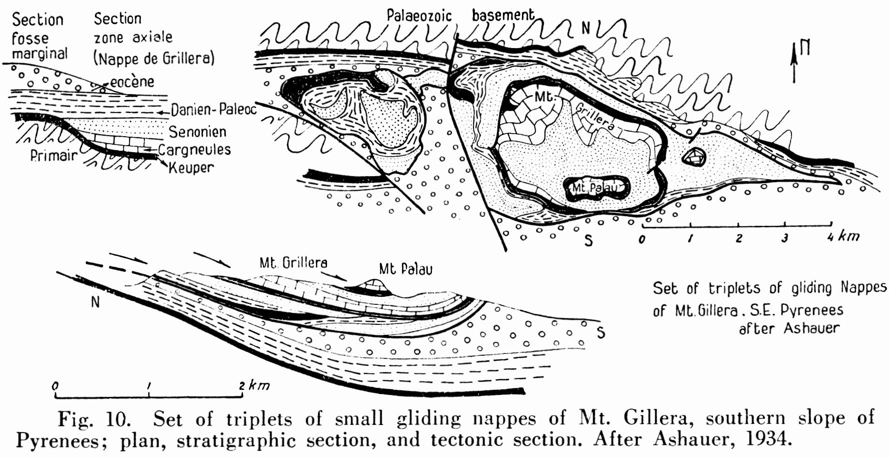

Fig. 10. Set of triplets of small gliding nappes of Mt. Gillera, southern slope of Pyrenees; plan, stratigraphic section, and tectonic section. After Ashauer, 1934.

All along the southern border of the Pyrenees we find gliding structures which have been mapped, however, without a view to gliding tectonics (Jacob and others, 1927; Jacob, 1930; Ashauer, 1934; Misch, 1934; Selzer, 1934), and therefore are sometimes difficult to represent in a section. From Mt. Perdu in the west to the "nappes" of Mt. Grillera in the east, we find these isolated klippen of older formations on the lower Eocene, sometimes doubled, always underlain by a thin slice of Triassic. In Mt. Grillera (fig. 10) we even have three superposed slices, and in the Montsech we find a slice of Paleozoic rocks on the Triassic.

All those gravitational gliding structures reflect two circumstances, to wit, the presence of an extremely incompetent layer at the base of the Mesozoic mantle—the argillaceous Keuper—and very pronounced post-folding uplift along a narrow zone causing a rather steep slope, locally accompanied by thrusting as in Mt. Perdu.

Helvetian nappes of the Alps.—The Helvetian nappes are without doubt the largest coherent gliding masses which have been described as such. In order to understand their mechanism I should like to recall the series of overthrusts exposed in the Charleroi coal basin of the Ardennes, of which Kaisin (1936) has given a section (fig. 11).

In this section one sees two major anticlines, both of which show an overthrust towards the north. Their shape is classical for this type of thrusted folds. The thrust planes are more steeply inclined at the front and flatten out towards the rear. The thrust planes probably do not disappear downward at the same level, that of fold 2 is supposed to stay above the Viseen limestone, those of folds 1 and 3 to cut through this competent layer and join the basal shearing plane below it, like the flat thrusts which may be observed in the northern part of the section (4 and 5).

Obviously gravity has not played a prominent role in these structures as all the thrusting has been upwards. But we may imagine that subsequent to this folding the rear could have been lifted up to a certain degree, tilting the thrust planes to a horizontal position and even further to a northward slope. If such vertical movement had been accompanied by a further slight contraction, the same thrusts would have been reactivated, and in all probability one sheared-off thrust mass after the other would have glided downwards along the slope of their pre-existing thrust planes. Three nappes would result, piled one on the other in the marginal trough farther north which would have originated during the uplift of the central part of the folded basin. As our imagined uplift started somewhere to the rear of the thrust masses it is evident that the southernmost thrust anticline would have started gliding first and successively the other ones would have followed suit as the uplift moved forward. The frontal ones might thus have carried the rear ones forward on their backs.

If we turn now to the Helvetian nappes (Oberholzer, 1933; de Sitter, 1939) and first consider their respective position in the still undisturbed position before folding, we find that each of the three principal units, the Upper, Middle, and Lower Helvetian nappes is characterized by its own stratigraphical sequence (fig. 12). The Upper nappes show a Cretaceous sequence with a

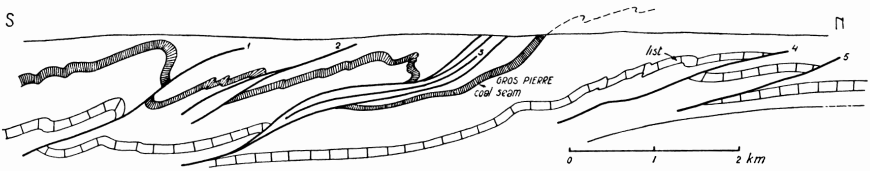

Fig. 11. Section through Charleroi coal basin, Belgium, showing a series of overthrusts against the high-standing Brabant massif to the north. After Kaisin, 1936.

thick competent limestone wedging out towards its front, the Middle nappes are characterized by a Liassic limestone also wedging out in the same direction, and finally the Lower nappes consist primarily of Permo-Triassic and are located on wedges of Malm limestone and Verrucano (Permian). The rear of the thrust planes are located respectively in the incompetent Valenginian, Upper Triassic, and basal Permian, the fronts are located on the wedges of competent strata. Each thrust plane forced the next one in front of it down, with the result that in the rear all thrust planes converged on the same basal shearing plane below the Permian and above the crystalline basement. Whereever a rearward thrust plane cuts obliquely downwards to the same shearing plane as that of the next thrust plane in front, it first forces the frontal one down to another, lower gliding plane which, however, soon became inactive because it had been cut off from its own rear.

This phenomenon is particularly well demonstrated by the Cumberland overthrust in the southern Appalachians (fig. 13); there the Pine Mountain overthrust first follows the Devonian and Mississippian shale but is forced down below the Maynardville limestone by the Wallen valley fault (Miller and Fuller, 1947).

Strong compression narrowed the Helvetian basin between the Aar and Gotthard massifs, and the thrust anticlines were piled one above the other against the south flank of the Aar massif. Subsequent uplift in the rear started them gliding down the northern slope of the Aar massif, accompanied by more chaotic gliding and shearing of the sedimentary cover of this massif (fig. 1).

We are obviously not able to trace the events in detail but can only point out some general features of the mechanism, in which gliding down is probably continuously or rhythmically accompanied by compression.

Where the trough into which the nappes came tumbling down was particularly deep, the frontal noses were partly overturned, as in the section along the Axen road on the Lake of Luzern (fig. 14). Where thick masses of conglomerates had accumulated already in the Molasse trough, the frontal lobes were arrested sooner than where the syntectonic sediment was less coarse and less massive.

It is impossible to evaluate the amount of erosion that preceded the gliding mechanism, but I do not think that erosion ever was an important factor because the nappes themselves were never carried away by denundation while at the top of the slope nor was the autochthonous cover on the northern flank of the Aar massif, and the trough was a place of sedimentation and not of denundation.

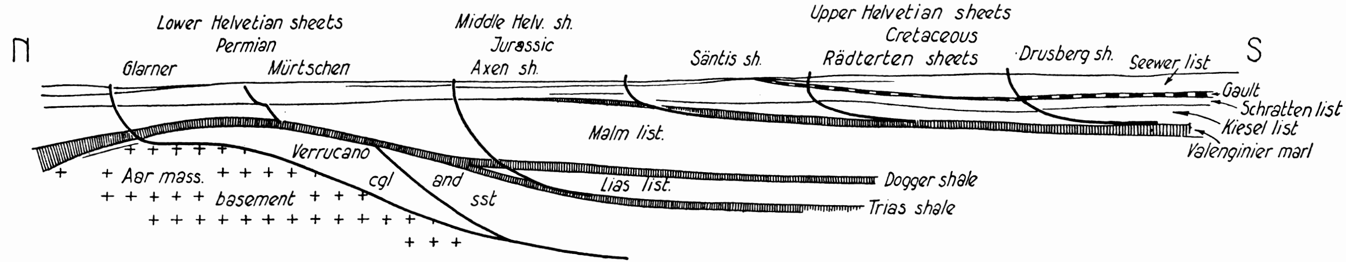

Fig. 12. Reconstruction of the original sedimentary basin of Helvetian nappes between the Aar and Gotthard massifs. Incompetent layers (Valenginian marl, Dogger shale, Triassic shale and evaporites) alternate with competent layers (Cretaceous limestone, Malm limestone, Liassic limestone, Permian conglomerate and sandstone). Thinning out of competent layers against basement ridge of Aar massif has caused splitting up of mass by low-angle thrust planes into future Upper, Middle, and Lower Helvetian thrust sheets, which later, after uplift of the Gotthard massif, glided down the northern slope of the Aar massif. After de Sitter, 1939.

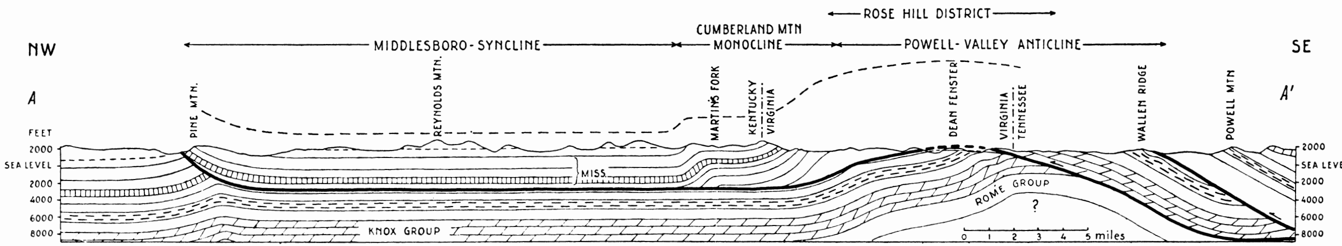

Fig. 13. Cumberland thrust, Virginia, Kentucky, and Tennessee. The Wallen Valley fault forced down the Pine Mountain overthrust from the Devonian shale to below the Maynardville limestone. From Miller and Fuller, 1947.

Montagne Noire.—An instructive case for which gliding tectonics has been proposed is represented by the southern Paleozoic zone of the Montagne Noire, of which the general geology is described by Gèze (1949) and the gliding tectonics by Trümpy and de Sitter (Gèze, de Sitter, and Trümpy, 1952). The Paleozoic block of the Montagne Noire in southern France is the southwestern prolongation of the Massif Central and is separated only by the small gap of the Corbières from the massif de Mouthoumet, which is considered a part of the Pyrenees.

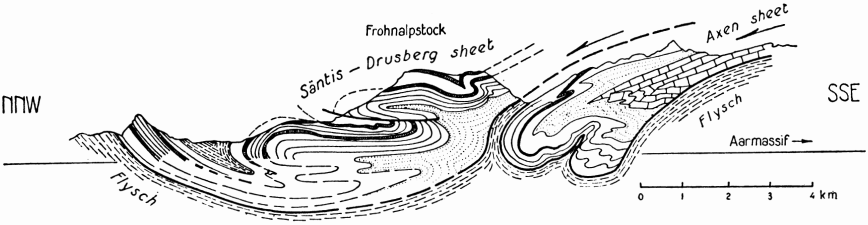

Fig. 14. The piling up of the Upper and Middle Helvetian sheets in the marginal trough of the Alps, north of the Aar massif. After Buxtorf and Arbenz, in A. Heim, 1921 (profile 4, table 19, p. 31).

The Montagne Noire consists of a central massif of gneiss and granite surrounded on all sides by Paleozoic sediments ranging from Lower Cambrian to Lower Carboniferous (fig. 15). To the north and southeast the Cambrian and Ordovician, with occasionally some Silurian, is thrust in an imbricated structure against the ancient massif, but to the south of the central massif we

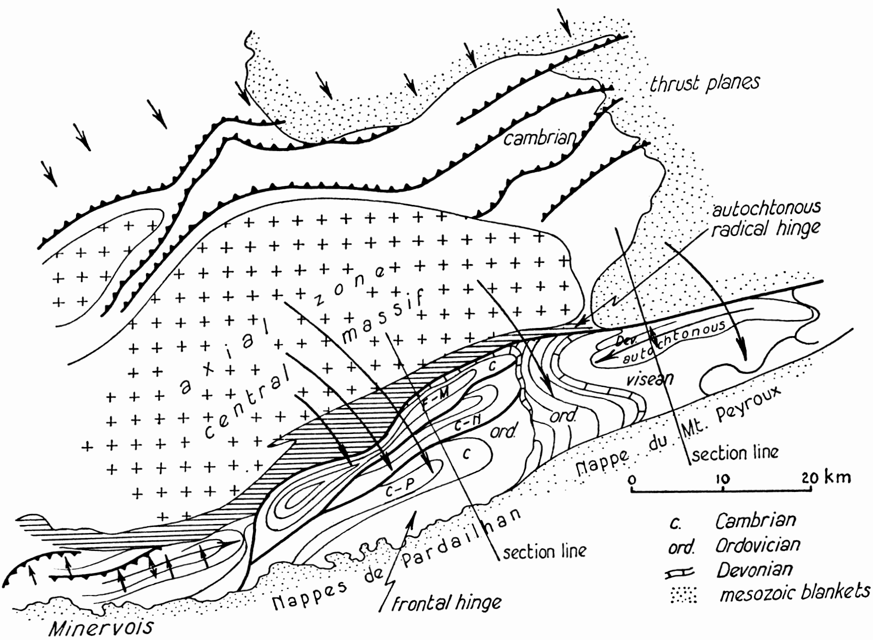

Fig. 15. Tectonic sketch map of Montagne Noire, southern France. Modified after Gèze to show interpretation of de Sitter and Trümpy.

find a series of folds which are all, except in the west, characterized by the curious fact that the whole sequence is reversed. In the core of synclines we find the Lower Cambrian and the flanks contain Ordovician and further to the east the Devonian covers the Visean schists. The whole zone is some 20 km wide and thrice as long.

The stratigraphic sequence consists of two competent zones, viz. the Devonian limestones and dolomites, and the Lower and Middle Cambrian limestones and sandstones, separated, covered, and underlain by incompetent zones of great thickness, viz: the Visean shales above, the Ordovician slates and schists in between, and the Lower Cambrian and Precambrian schists below. All formations are well dated by a classical fauna.

Whatever the course of events has been, it is obvious that in order to overturn completely a thick series of sediments a considerable trough must have been formed south of the central mass before and during the folding process, which was subsequently filled by the overturned folds, of which we now see only the reversed flank.

As explained below, the development of a reversed flank is already strong evidence for gravity tectonics, and since we see exposed here the inclined gliding surface, I have little doubt that the reversed synclines and anticlines of the southern border of the Montagne Noire are indeed due to a southward gliding of the sedimentary blanket down the south flank of the central massif. To be sure, Gèze originally thought and still thinks that the folds have a southern origin; his view and the alternative here presented are contrasted in a joint paper by Gèze, de Sitter, and Trümpy (1952).

The southern border consists of three units. The western one, the Minervois, consists of normal steeply folded anticlines pressed against the buttress of the central massif; the central one, the Pardailhan nappe, is formed by three longitudinal reversed Cambrian synclines floating in a mass of Ordovician schists, and the eastern one has an autochthonous anticlinal core of Devonian, the Montredon anticline, covered by an arch of Visean shales overlain by Devonian and Ordovician, together called the Mt. Peyroux nappe. There is a strong westward plunge so that the Pardailhan nappe covers the Mt. Peyroux nappe, the two being separated by a narrow squeezed-out band of Devonian limestone in Ordovician schists.

Evidently the two nappes, which are formed of totally different series of sediments, represent two portions of the same blanket, sheared off in turn from the crest of the central massif. The upper part of the blanket, consisting of Visean and Devonian with a basal shearing plane in the incompetent Ordovician, forms the Mt. Peyroux nappe, and it is covered by the Cambrian core of what was originally the same blanket, now forming the Pardailhan nappe. Most probably the shearing-off started as a series of thrust faults on top of the still submerged central mass, identical with the structures still preserved north and east of the central mass. The basal shearing plane of the upper nappe cut obliquely through the Devonian with the result that the frontal lobe of the lower nappe still retained a broad wedge of this limestone on top, which now still forms the base of the Pardailhan nappe.

The three Cambrian synclines of the Pardailhan nappe were originally three fronts of thrust-faulted anticlines which slid down one after the other, the originally southernmost one first, being nearest to the edge of the central mass. The frontal nose of the last one is still preserved, and the innermost contact of the whole nappe against the central mass shows all the characteristics of a squeezed-out, stretched, and broken middle limb.

The disharmony between the Devonian-Visean cover and the Cambrian core is emphasized by the fact that the former is now found as one undivided inverted sheet whereas the latter is formed by three separate synclinal folds. It seems probable that this disharmony had already originated in the early

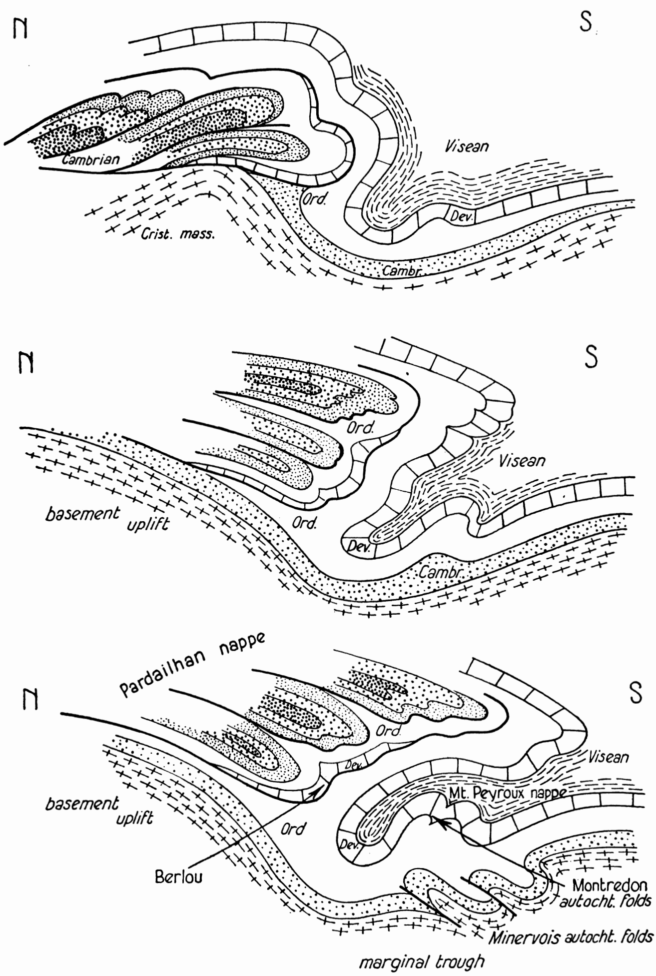

Fig. 16. Development of Montagne Noire gliding nappes according to de Sitter and Trümpy. The three superposed units, Pardailhan nappe, Mt. Peyroux nappe, and autochthonous Minervois folds, are in reality nowhere present in one section. Hence this section represents a combination of sections along the two lines indicated on figure 15.

phase of folding and thrusting, the Cambrian beds in three separate thrust anticlines penetrating into the Ordovician slates and schists whereas the Devonian limestone with Visean shales on top sheared off in a single large blanket along the top of the Ordovician (fig. 16). This kind of structure was called an intercutaneous thrust by Fallot (1949).

When the whole structure started gliding down along the newly formed south-facing slope, a large slab of Devonian limestones came into a vertical position, measuring from top to bottom the total height difference between trough and horst. It rested with its back against a Visean syncline and was pushed down and outwards by the advancing Cambrian structures embedded in the Ordovician schists. In this way the mechanism of the nappes can be imagined without having to postulate an unrolling of the Devonian limestone, the width of the Mt. Peyroux being about equal to the total subsidence of the marginal trough.

The whole structure resembles very much the plunging fronts of the Axen and Säntis-Drusberg nappes on the Luzern Lake (fig. 14).

Northern Apennines.—The most grandiose example of gliding tectonics that has ever been imagined is that of the northern Apennines. The geology is extremely difficult to unravel because of the lack of distinctive formations with distinctive fossils, but the effort of three Italian geologists, Trevisan from Pisa, Merla and Migliorini from Florence (Trevisan, 1950; Merla, 1951), have finally resulted in a comprehensible general picture, in which gliding tectonics and vertical movements play a dominant role. Long before these geologists formulated their point of view it was known (Steinmann, 1907) that great portions of both the calcareous core of the northern Apennines, the Apuane Alps, and its extensive northern flank, the northern Apennines s. str., were overthrusted in an abnormal position. The lubricating formation is the Argille scagliose, or scaly shale, a chaotic shale-marl formation characterized by chunks of greenstones (ophiolites), red radiolarites, jaspers (diaspiri), and limestones. The cover consists of a series of beautifully graded sandstones, the Macigno, and a marl-sandstone sequence, which floats in large masses on the Argille scagliose. As the Macigno-Argille scagliose sequence occurs both west and east of the Apuane Alps, whereas this core itself is free of any ophiolitic intrusion, it has been suggested both by the older school of lateral thrusting and by the modern school of gliding tectonics that the origin of the Argille scagliose sedimentary basin must be sought in the Tyrrhenean Sea between Corsica and Elba. The major objection to a lateral thrust mass of 200 km width is its extreme thinness and its general incompetent character which by no stretch of imagination can be thought able to transmit the stress needed to transport the whole as one coherent mass. The new point of view therefore supposes that the original deep sea basin in which the Argille scagliose accumulated was situated between the islands of Elba and Corsica, and that the shale was pressed out by an east-west lateral thrust, flowing over its borderland far to the east. Afterwards a first zone of upwarping on the eastern border of the original basin, now covered by a thick mass of the Argille scagliose that had been pressed out, made it slide down farther towards the east. This mechanism of upheaval of longitudinal anticlinal ridges was repeated five

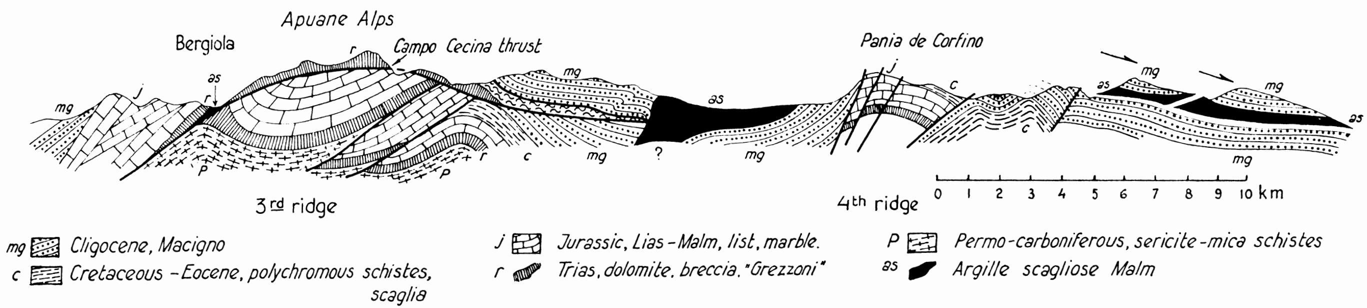

Fig. 17. Section through Apuane Alps and Northern Apennines, showing 3rd ridge—Apuane Alps in the core of the Apennines—and 4th ridge of quite different structure. After Merla, 1951.

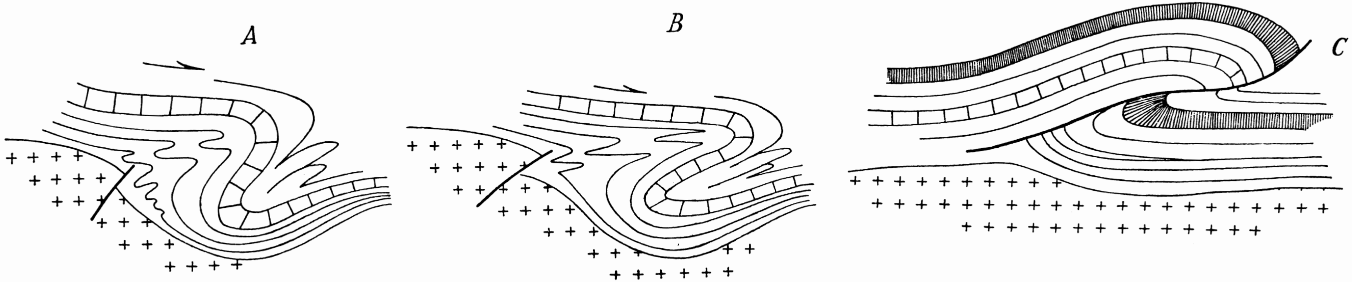

Fig. 18. Contrast between structures produced by gravitational gliding (A, B) and by lateral thrust (C). A middle limb is preserved unthinned in gliding but is absent in thrusting.

times, each successive ridge being situated farther to the east. Each time the plastic mass of Argille scagliose glided down the eastern flank of the new ridge and was thus displaced further eastwards. During its repeated movements, its original content of clay, ophiolites, and radiolarites became diluted with strange elements of much younger date, of which the more coherent portions moved as great slabs and the softer formations like shales and marls simply became mixed up with the original shale content. In this way the relative decrease of the ophiolite content of the Argille scagliose in an eastern direction finds a ready explanation.

Several objections against this rather sweeping theory of gliding can be made. First of all, if one abandons the theory of lateral thrust over 200 km and accepts gliding to explain the superposition of the Argille scagliose on younger strata, it sems illogical still to postulate such enormous transportation. Second, the whole mechanism of the 200 km transportation would break down if one of the ridges rose before its turn, thus stopping all further eastward transport. Third, the ridges are very different in tectonical style. The first ridge on Western Elba is a Miocene granite intrusion, the second ridge is represented by the insufficiently exposed synclinal structure of Spezia containing Triassic and Liassic, the third ridge is the large arch of the Apuane Alps in which a thrust sheet of non-metamorphic limestones of considerable size overlies highly metamorphic marbles of the same age (Lower Mesozoic) (fig. 17), the fourth and fifth ridges consist of more or less simply compressed domes in Oligocene strata, locally with Liassic cores, much broken by steep thrusts of the kind called "composite wedges" by Migliorini (1948). Personally I think that the Italian investigators have underrated to some extent the intrusive capacity of such an incompetent formation as the Argille scagliose under lateral compression, producing simple diapiric action. Much of the abnormal position of this formation must certainly be due to gliding down appropriate slopes, but much may be due also to lateral compression, squeezing out, and diapiric intrusions. This implies of course that originally more than one deep sea basin with ophiolite intrusions existed, most probably both east and west of the central core, the Apuane Alps, the latter being free from these ophiolitic intrusions. The intensive mixing of younger and older strata, the gliding down of great slabs, the inverted position of some of these slabs and their frontal noses (which can be ascertained most convincingly by the graded facies of the Macigno sandstones) are facts which very strongly suggest gliding as the origin of many of the structures; on the other hand, the steep thrusts bounding the ridges suggest strong lateral compression through the whole width of the northern Apennines. The combination of the two structural theories evidently leads to the conception that the gliding followed the compression and is due to the upheaval of the longitudinal ridges.

CHARACTERISTICS OF GLIDING STRUCTURES

The main question that arises from our survey of gliding structures is: How can one distinguish between a lateral low-angle thrust and a gliding nappe? As always in geology the answer cannot be conclusive. There is no structural feature that can be decisive in either direction, but the evidence must necessarily be of a circumstantial nature. To my mind the most important evidence consists of:

1. An appropriate slope must be recognizable in the field to account for any gliding. One may of course reason, in case such a slope is absent, that the original slope has been destroyed since the gliding by the sinking of its highest portion, and if such oscillation can be proved by independent evidence, the reasoning may be sound, but in general it can hardly be accepted. For instance, a gravitational gliding of the Jura Mountains towards the north against its present slope seems highly improbable. Marginal troughs of orogenic belts seem to be the most favorable recipients of gliding nappes.

2. A downward plunge of the basal thrust plane at the rear of the thrust sheet can be regarded as conclusive evidence of its thrust nature. The upward curve one would expect in a gliding nappe will seldom be conserved except in small-scale gliding like that of the volcanic mantles described in the foregoing pages. As many gliding structures originated as thrust sheets, a downward curve may be present at the rear even in the case of gliding, but then it can no longer be directly connected with the frontal lobes.

3. An inverted position of a large mass, in particular when it is not laminated or squeezed or otherwise tectonically reduced in thickness, is strong evidence of the gliding nature of the transport mechanism (fig. 18). A real thrust sheet has no inverted flank; it is the result of maximum lateral shortening with a minimum of piling up of strata, a compromise between the lateral stress and gravity. Whereas gravity prevents the development of an inverted flank in the case of the thrust sheet, it favors its formation in the case of a gliding nappe because in the latter case the ultimate aim of gliding is the filling up of a pre-existing trough. See figures 1, 5, 6, 7, 8, 9, 14 and 16 as compared with figures 11, 12, 13.

4. In general, a chaotic or even a geometrically obscure structure may be an indication of gliding because each portion of the gliding nappe may move independently of the other, each being under the same gravitational stress as the other. On the other hand, in a thrust sheet the stress must necessarily be conveyed from one end of the sheet to the other by a coherent and competent mass, and any failure would result in the standstill of the portion beyond the failure. Therefore isolated slabs, often anticlinal or synclinal in shape, of competent rocks in an incompetent matrix are valuable indications for later gliding following on former lateral-thrust folding.

5. In the smaller-scale gliding structures the lateral extension of the structure is ordinarily small and has no connection with its surrounding, whereas in lateral-thrust structures the opposite is true. This is so because the gliding may be due to the hazards of erosion in the lower reaches of the slope or to other irregularities, whereas the thrust structures can only move when a large portion of the crust is in a stressed condition.

From the general outlook on gravitational gliding tectonics we have now gained, there is one fact that emerges clearly, to wit, the close relation between gliding tectonics on a larger scale and lateral compression. In all instances which we quoted, the southern Pyrenees and the southern Alps, the Montagne Noire, the Appenines, and the Helvetian nappes, we found that the structures started as thrust sheets, that the upheaval that caused the slope was probably due to compression, and that the gliding tectonics are only an accompanying feature. The cascade fold of the Mt. Perdu is the direct result of a deeper-seated thrust revealed in the same section. The original thrusts on top of the central massif of the Montagne Noire are still preserved on its eastward-plunging nose, and the nappes of the southern Alps override thrust structures abutting against the very thrust faults which limit the upthrusted block from which the nappes glided down. The roots of the Helvetian nappes compressed between the Aar and Gotthard massifs are as real as the piling up of their frontal noses in the marginal trough, and finally the ridges between the troughs filled with Argille scagliose and Macigno slabs are surely compressional features.

Hence there can be no doubt that the lateral compression is primary, the gliding secondary. This evidence suggests strongly that the vertical movements which give rise to the slope are also due to lateral stress. This close relation between gravitational gliding and tangential compression explains also why there is no clear-cut limit between the two phenomena. In all the larger structures which we described it is very much a question of taste how much one believes should be accounted for by thrusting and how much by gliding. We find this transition not only between thrusting and gliding but also between slumping and gliding. The slip planes in the non-folded sediments of the Peru oilfield show many characteristics of slumping, and their origin is due to the same kind of circumstances as slumping, viz. a soft formation saturated with water. The difference is not only a question of size and state of consolidation but also of origin of the slope. In slumping no earth movements of structural character are supposed to have created the slope, whereas the blocks in the marginal trough of the Andes in Peru are believed to have been tilted by movements along longitudinal faults.

In the case of gliding in a volcanic mantle there is no longer even any real difference in origin from slumping, for both are due to accumulation of sedimentary materials; their distinguishing feature is only that in one case the process took place under water and in the other not.

Gravity is certainly not a force that plays a role in tectonics only occasionally; it is always present and always influences any structural shape, whether we think of folds, faults, or gliding.

The extent to which the conception of gliding tectonics changes our views on the structural characteristics of mountain chains is rather important in one aspect. Formerly any klippe meant to us that large-scale horizontal thrusting had occurred and therefore that the particular mountain chain had been submitted to important lateral compression. Such a conclusion is no longer warranted. The supposition that the Helvetian nappes and the Klippe nappes have gained their present position by gliding certainly means a considerable reduction of the formerly supposed total lateral shortening of the cross-section of the Alps. The same is true for the Argille scagliose gliding nappes of the Appennines and for many other less well-known structures. A klippe is no longer a proof of strong compression.

REFERENCES

Ashauer, H., 1934, Die östliche Endigung der Pyrenäen: Gesell. Wiss. Göttingen, Math.-phys. Kl., Abh., F. 3, Heft 10, p. 5-115.
Baldry, R. A., 1938, Slip planes and breccia zones in the Tertiary rocks of Peru: Geol. Soc. London Quart. Jour., v. 94, p. 347-358.
Barrington Brown, Ch., 1938, On a theory of gravitational sliding applied to the Tertiary of Ancon, Ecuador: Geol. Soc. London Quart. Jour., v. 94, p. 359-370.
de Sitter, L. U., 1939, The principle of concentric folding and the dependence of tectonical structure on original sedimentary structure: K. Akad. Wetensch. Amsterdam Verh., v. 42, p. 412-430.
———, 1949, Le style Nord-Pyrénéen dans les Alpes Bergamasques: Soc. géol. France Bull., sér. 5, tome 19, p. 617-621.
Fallot, P., 1949, Les chevauchements intercutanés de Roya: Annales Hébert et Haug, tome 7, p. 161-169.
Gèze, B., 1949, Etude géologique de la Montagne Noire et des Cévennes méridionales: Soc. géol. France Mém. 62, tome 29.
Gèze, B., de Sitter, L. U., and Trümpy, R., 1952, Sur le sens du déversement des nappes de la Montagne Noire: Soc. géol. France Bull., sér. 6, tome 2, p. 491-533.
Gignoux, M., 1948, La tectonique d'écoulement par gravité et la structure des Alpes: Soc. géol. France Bull., sér. 5, tome 18, p. 739-761.
Goguel, J., 1950, L'influence de l'échelle dans les phénomènes d'écoulement: Geol. en Mijnbouw, 12e Jaarg., p. 346-351.
Harrison, J. V., and Falcon, N. L., 1934, Collapse structures: Geol. Mag., v. 71, p. 529-539.
———, ———, 1936, Gravity collapse structures and mountain ranges as exemplified in southwestern Iran: Geol. Soc. London Quart. Jour., v. 92, p. 91-102.
Heim, A., 1921, Geologie der Schweiz, Band II: Leipzig.
Jacob, Ch., 1930, Zone axiale, versant sud et versant nord des Pyrénées: Soc. géol. France Bull., Livre jub., p. 389.
Jacob, Ch., Fallot, P., Astre, G., Ciry, R., 1927: Observations tectoniques sur le versant méridional des Pyrénées centrales et orientales: 14e Cong. géol. internat. Compte rendu, v. 2, p. 235.
Kaisin, F., 1936, Le problème tectonique de l'Ardenne: Louvain Univ., Inst. géol., Mém., tome 11.
Lugeon, M., and Gagnebin, E., 1941, Observations et vues nouvelles sur la géologie des Préalpes romandes: Univ. Lausanne, Lab. géol. Bull. 72.
Mengaud, L., 1939: Etudes géologiques dans la région de Gavarnie et du Mont Perdu: Service Carte géol. France Bull. 199, p. 197-223.
Merla, G., 1951, Geologia dell'Appennino settentrionale: Soc. geol. italiana Boll., v. 70, p. 95-382.
Migliorini, C. I., 1933, Considerazioni su di particolare effetto dell'orogenesi: Soc. geol. italiana Boll., v. 52, p. 293-304.
———, 1936, Alcune questioni geologiche casentinesi: Firenze.
———, 1948, I cunei composti nell'orogenesi: Soc. geol. italiana Boll., v. 67, p. 31-142.
Miller, R. L., and Fuller, J. O., 1947, Geologic and structure maps of the Rose Hill oil field, Lee County, Virginia: U. S. Geol. Survey Oil and Gas Inv. Prelim. Map. 76.
Misch, P., 1934, Der Bau der mittleren Südpyrenäen: Gesell. Wiss. Gottingen, Math.-phys. Kl., Abh., F. 3, Heft 12.
Oberholzer, J., 1933, Geologie der Glarneralpen: Beitr. geol. Karte Schweiz, neue Folge, Lief. 28.
Reeves, Frank, 1924, Geology and possible oil and gas resources of the faulted area south of the Bearpaw Mountains, Montana: U. S. Geol. Survey Bull. 751-C, p. 71-114.
———, 1946, Origin and mechanics of thrust faults adjacent to the Bearpaw Mountains, Montana: Geol. Soc. America Bull., v. 57, p. 1033-1047.
Schneegans, D., 1938, La géologie des nappes de l'Ubaye-Embrunais entre la Durance et l'Ubaye: Mém., Carte géol. de France.
Selzer, G., 1934, Geologie der südpyrenäischen Sierren in Oberaragonien: Neues Jahrb., Beilage-Band 71, Abt. B, p. 370-406.
Steinmann, G., 1907, Alpen und Appennin: Deutsche geol. Gesell. Monatsber. 8/9.
Trevisan, L., 1950, L'Elba orientale e la sua tettonica di scivolamento per gravita: Padua Univ., Inst. geol. Mem., v. 16, p. 1-40.
van Bemmelen, R. W., 1934, Ein Beispiel für Sekundärtektogenese auf Java: Geol. Rundschau, Band 25, p. 175-194.
———, 1937, Examples of gravitational tectogenesis from central Java: Die Ingenieur in Nederl.-Indie, Jahrg. 4, p. 55-65.
———, 1949, The geology of Indonesia, vol. IA: The Hague, Govt. Printing Office.
van der Fliert, J. R., 1953, Tectonique d'écoulement et Trias diapir au Chettaaba, S. W. de Constatine (Algerie): 19e Cong. géol. internat. (1952) Compte rendu, sec. 3, Fasc. 3, p. 63-80.

LEIDEN UNIVERSITY
HOLLAND