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FLUID PRESSURE IN THRUST FAULTING, A COROLLARY

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ABSTRACT. Hubbert and Rubey reviewed occurrences of fluid pressure approaching total overburden pressure in sedimentary rocks, particularly clayey sediments, and suggested that such high fluid pressure is capable of greatly reducing internal friction in the rock and thus facilitating the formation of low-angle thrust faults. Although their principal source of water is within the sediments, connate water, and their principal source of pressure is the weight of overlying sediments, they mention metasomatic and magmatic fluids and the processes that produce these fluids as possible additional sources. Intrusive or remobilized granitic rock is here considered as a source of the water under high pressure because this source has the advantage that it may arrive any time after the stratigraphic seal has been made. Hence thrusting need not occur immediately after a climax of sedimentation. Several possible examples are discussed, and one or two appear reasonable.

INTRODUCTION

Comprehension of all the possibilities inherent in the role of fluid pressure in thrust faulting as analyzed by Hubbert and Rubey (1959) will take a long time. as it always takes a long time to adjust one's thinking to a basic step forward. This paper considers a possible corollary to their theory.

Their mechanism requires two simple conditions: a highly impermeable layer and a fluid under abnormal pressure (pressure approaching overburden pressure) below the highly impermeable layer. They indicate that both these conditions are achieved by rapid deposition of a thick sequence of sediments including clay. which becomes shale during burial. The clay as originally deposited contains considerable water, and, as the weight of overburden increases, the entrapped connate water is put under higher and higher pressure. Finally only a small push, or a small slope, or both, is required to move the thick sequence of rocks which is virtually floating on its own connate water.

Obviously an important factor is the quality of the seal that forms in the clay or shale. No matter how small the permeability in the relatively impermeable layer that effectively seals the connate water beneath the thick sequence, some leakage does occur. In other words, some increment of the finite amount of trapped water is lost for each increment of time of delay after the buildup of the pressure, that is, after deposition. Hence, if fluid support is to be available to "float" the rocks, the thrust movement must occur soon (geologically) after the deposition of the final weight of the thick sediments. If the delay is sufficient, the seal of shale becomes very good, but there is no fluid left to seal off. The condition that thrust faulting occur soon after—in fact during—a climax of deposition seems to obtain in the Wyoming thrust belt (Rubey and Hubbert, 1959, p. 191. and fig. 8). This condition is vividly portrayed in the beer can experiment, figure 32 of the first paper (Hubbert and Rubey, 1959. p. 161). In order for the beer can to float on the pressure of expanding air inside it, the seal against the glass plate is made with a water film, and the pressure is built up as the previously cooled can warms during the demonstration. Once the beer can and its contained air arrive at the temperature of the room, the pressure inside the beer can is not maintained, for some leakage around the can naturally occurs.

The other experimental demonstration of the possibilities of fluid pressure (Hubbert and Rubey, 1959, fig. 30) does not have this artifact built in. The supporting water can be supplied any time the demonstrator has a glass of it handy. This appears to be a significant point. Translating it to geological terms, once shale or any other kind of seal is made, if water at sufficient pressure can be introduced below, the general mechanism that Hubbert and Rubey describe will obtain, and large thrusts are possible.

SUGGESTED COROLLARY

Ingerson (1950, p. 813-814) has tabulated estimates of the amount of water in a granite pluton.[1] Field evidence, such as miarolitic structure and primary hydrous minerals, and experimental evidence (Tuttle and Bowen, 1958, p. 46-48, figs. 19 and 21, p. 89) indicate that at least a few percent of a pluton at the time of its intrusion is water. Little note has been made of the possible geologic significance of this water after it leaves the pluton (except by economic geologists for deposits like the lead mines in Missouri), though the total amount expelled from a pluton (and from the immediately adjacent rocks as they are metamorphosed) may be huge. Schwartz (1959, p. 162) comments on hydrothermal water as follows:

> "Hydrothermal alteration is extremely varied and the kind of host rock obviously has a large influence on the result. It is evident, however, that abundant changes in mineralogy, and often in chemical composition, can be made only by relatively large amounts of solutions. The argument that it is unreasonable to assume the large quantities of solutions necessary to form large ore bodies is not valid because altered rocks are proof that enormous amounts of solutions moved through the rocks quite aside from the ore minerals deposited".

Tuttle and Bowen (1958, p. 89) state: "Evidence has been presented to show that residual solutions developed during the crystallization of hydrous granitic magmas may exhibit a continuous gradation from hydrous silicate liquid to hydrothermal solution." These quotations indicate that many plutons expel large amounts of water as they become immobile. Tuttle and Bowen (1958, p. 126) observe that "granitization by low-temperature hydrothermal metasomatism can now assume the minor role long proposed for this process", and it may be that loss of water immobilizes the granite body rather than crystallization of magma driving out the volatile constituents.

One aspect of this water is difficult to evaluate, namely, the pressure at which it escapes from the pluton. For the purposes of this paper, I am assuming that the water pressure, or, to be more general, the fluid pressure, approaches the effective overburden pressure at depths greater than a few thousand feet. A number of lines of evidence lend plausibility to this assumption. Buddington (1959, p. 679) reports that "many epizonal stocks have at least local miarolitic facies"; these openings must have been maintained by vapor at rock pressure. Albite porphyroblasts and pegmatites surrounding plutons, copper sulfide, and quartz veins, particularly those with free euhedral

[1] For the purposes of this paper, Buddington's definitions (1959, p. 675) are used: "Granite . . . will include the family of granitoids such as quartz diorite or tonalite and trondhjemite, granodiorite, quartz monzonite or adamellite, and granite or leucogranite and alaskite. The term pluton will be used here in a very general sense for any body of intrusive igneous (or 'pseudo-igneous' by metasomatism or recrystallization) rock of any size or shape."

crystals, and hydrothermal alteration associated with brecciation all suggest that vapors or solutions are commonly at total rock pressure. Schwartz (1959, p. 178) points out that, "Permeability is necessary for a high degree of hydrothermal alteration and in many districts intense fracturing and brecciation is conspicuous . . . . the intensity of shattering seems to be directly proportional to the alteration and unaltered rocks seem to lack the intense shattering."

Turner and Verhoogen (1951, p. 317) discuss the possible increase of vapor pressure with cooling of a magma. They note (p. 323) : "If the walls [of the magma chamber] were mechanically weak, the volume of the system [magma-vapor] might vary as crystallization proceeds, but the pressure presumably would then be constant and equal to the weight of the overlying column." These various observations lead me to believe that the pressure of volatile constituents in plutons has, at least in many cases, equaled total overburden pressure, particularly in the later stages of emplacement. Remobilized granites can have this property as easily as first-generation plutons.

The time of emplacement of a pluton is not necessarily related to accelerated deposition. For example, slow deposition during a long time could provide a thoroughly compacted, very impermeable layer of shale. The rise of a pluton at any later time under this pile of sediments could provide the necessary water at sufficient pressure, and the conditions of high fluid pressure under a stratigraphic seal would exist.

POSSIBLE EXAMPLES

If the suggested mechanism is to operate, the thrusting or gliding must coincide with generation or remobilization of the granite both in space and in time. In other words, the area of the thrust plate cannot be much greater than the area of the pluton, and the granite must be younger than all the sediments of the thrust plate but no younger than the movement of that plate.

For various reasons it is difficult to establish these conditions. One reason is that plutons are even more difficult to date paleontologically than are thrust faults, for the obvious reason that plutons destroy fossils. On the other hand, sedimentary thrust faults are not so easily dated by radiometric means as are plutons. Worse, where sediments and plutons of about the same paleontologic age have been assigned radiometric ages, the results are not by any means in perfect agreement, as Faul (1960, p. 639-640, 642) has shown. Finally, even where agreement appears satisfactory within accepted limits of error, and the interpretation of the data appears final, a few years and a few experiments later, the results can be reinterpreted drastically (Holmes, 1960, p. 183; Rodgers, 1952, *compared with* Hurley and others, 1959). Yet, for a causal relationship to exist between pluton and thrusting, the granitic body must be generated or remobilized at the time of thrusting.

Following the lead of Rubey (Rubey and Hubbert, 1959, p. 186), I would like to apply the source of abnormal fluid pressure here discussed to the thrust fault with which I am most acquainted (Platt, 1960). Field evidence around the present position of the Taconic allochthon (Zen, 1959) indicates that Taconic thrusting occurred late in the Middle Ordovician, rather than at the end of that period, as earlier interpretations had indicated (Ruedemann, 1930, p. 132-133). Radiometric ages that agree are difficult to find, but this can be blamed on the Devonian igneous activity in New Hampshire and eastern Vermont (for example, Billings, 1960, fig. 12), which would mask Ordovician effects. We can, with Rodgers (1952), look some tens of miles along strike away from Vermont, where perhaps the effect of the Devonian igneous activity is not a complicating factor. The radiometric dates which seemed to agree with the field evidence for an Ordovician Taconic orogeny are, however, now considered much later on the paleontologic time scale. (Note, in this regard, certain new dates recorded on pages 29 and 69 of U. S. Geol. Survey Prof. Paper 400A.) Cady (1960, p. 561) notes that rocks similar to the Highlandcroft plutonic series may have been intruded "at about the time of the Taconic disturbance", but such rocks may not contain the water I want to "float" a big thrust plate. Kay (1942, p. 1605, 1609) considers that "a belt of uplift, Vermontia", formed in middle Trenton time, although no plutonic activity is implied. He infers that the Taconic allochthon was thrust at the end of the Ordovician by analogy with thrusts in southeastern Quebec (p. 1619).

Some more suggestive examples of the possible role of fluid pressure can be found. De Sitter (1960, p. 195) summarizes his picture of cross folding in the Pyrenees as follows:

> "From our Pyrenean work we concluded that there is a distinct zone separating a suprastructure from an infrastructure, the suprastructure being characterized by vertical cleavage, the infrastructure by horizontal schistosity and crystal growth lineation. The surface or zone separating the two structural units is determined in the first place by the metamorphic front but may be influenced by the lithology of the strata. Where the metamorphism rose very high, to the top of the Cambro-Ordovician, the incompetent black shale horizon of the Silurian became the separating horizon(i.e. Bosost area in the Valle de Aran). But when it stopped lower down in the little differentiated rock sequence of the upper 1000 m. of the Cambro-Ordovician, then the separating zone is independent of the lithology and is strongly discordant to the stratigraphy."

On the following page he notes, "It would not be surprising if the classical succeeding tectonic phases of an orogenic period did reflect deeply buried events of metamorphic origin." It seems possible to interpret the surface or zone separating suprastructure from infrastructure as the separation of excessive fluid pressure below from normal pore pressure above; the metamorphic front would be rising fluids under high pressure and this would be a metamorphic event. Unfortunately there is no clear evidence that the metamorphic event was synchronous with deformation.

One of the most difficult problems faced by those who suggest gravity gliding of large masses has been the slope down which the nappes or thrust sheets slide. It has sometimes been claimed that large massifs rose very high in order to provide the slope that appeared necessary on mechanical grounds. Longwell (1945, p. 428) emphasizes this difficulty, and cross sections with vertical exaggeration may attest to our difficulty in accounting for the inferred sliding on slopes of low dip. Only Alpine geologists seem entirely free of this difficulty. If the role of fluid pressure in "floating" the gliding mass is accepted, then any thrust plate that apparently originated on a rising massif is a logical place to look for examples of the mechanism here discussed. The massif need not, after all, have risen so very high, if its expelled water can be called on to facilitate movement of the sliding mass.

The central massif of the Montagne Noire, according to de Sitter's interpretation (1954, p. 337; see also Gèze, de Sitter, and Trümpy, 1953) rose and shed the Nappes de Pardailhan and the Nappe du Mt. Peyroux, or at least there was subsidence of the trough into which the nappes glided, which amounts to the same thing. De Sitter observes that these thrust sheets have soles of shale, but he does not indicate that magmatism or remobilization was associated with thrusting. De Sitter's other examples of gliding nappes also appear suggestive, for areas now exposed as granite seem to be at the original site of deposition of the sedimentary nappes.

As my personal experience of the examples above, the Pyrenees and the Montagne Noire, is nil, it is highly presumptuous to suggest their mode of origin without more specific supporting evidence. Jäger and Faul (1959, p. 1556) have supplied specific evidence from the southern Alps of exactly the sort for which I sought in vain in the previous examples. They observe that "The results from Val Verzasca leave little doubt that the Penninic nappes were thrust and the micas completely recrystallized 18 m. y. ago, thus confirming the views of Wenk (1948) and Niggli (Cadisch, 1953, p. 77) based on petrography and field relations". This age of 18 m. y. falls in the middle of the Miocene according to the best available figures (Holmes, 1960, p. 202). Hence the conclusion that the granitic material in the Pennine nappes was remobilized in conjunction with movement of the Prealps is reasonable, for Heim (1919, p. 53, fig. 6, p. 65) indicates that the Molasse at the beginning of the Vindobonien, Middle Miocene, contains a great increase of polygenetic pebbles, apparently from the southeast. Heim (1919, p. 53) and Collett (1927, p. 118) conclude that the polygenous pebbles come from the Prealps and Austrides but not from the autochthonous massifs or the Helvetian nappes.

In this example from the Alps, a radiometric date for recrystallization and movement of the Pennine granitic nappes appears to be concordant with a paleontologic date for thrusting of the Prealps over the Helvetian nappes, covering the latter (fig. 1). This accounts for the increase in the polygenetic pebble content of the Molasse and the lack of pebbles from the Helvetian nappes at this particular time. The Prealps obviously moved again, along with the Niesen thrust sheet, later, for they cover younger Molasse along the Vierwaldstättersee below the Rigihochfluh (Heim, 1921, Tafel XIX).

Having indicated the time relationship between recrystallization (and movement) of Pennine nappes and the movement of some part of the sedimentary cover, it remains to show the possibility that fluid pressure played a part. Collet (1927, p. 158-159) notes that the Niesen Flysch now lies under the Prealps (fig. 1). The Niesen Flysch, therefore, may have been the stratigraphic seal below the Prealps when these were moved onto the Helvetian nappes in the Miocene, and, in fact, the basal beds of the Niesen nappe do show some metamorphism (Trümpy, 1960, p. 897).

That fluid pressure was important is inferred from the presence of tourmaline in the remaining Schistes lustrés of the Pennine zone (Collet, 1927, p. 157). Turner and Verhoogen (1951, p. 332) consider tourmaline an indicator of the "pneumatolitic stage" in pegmatite formation, particularly where gas was evolved as a result of the second-boiling-point phenomenon (p. 331).

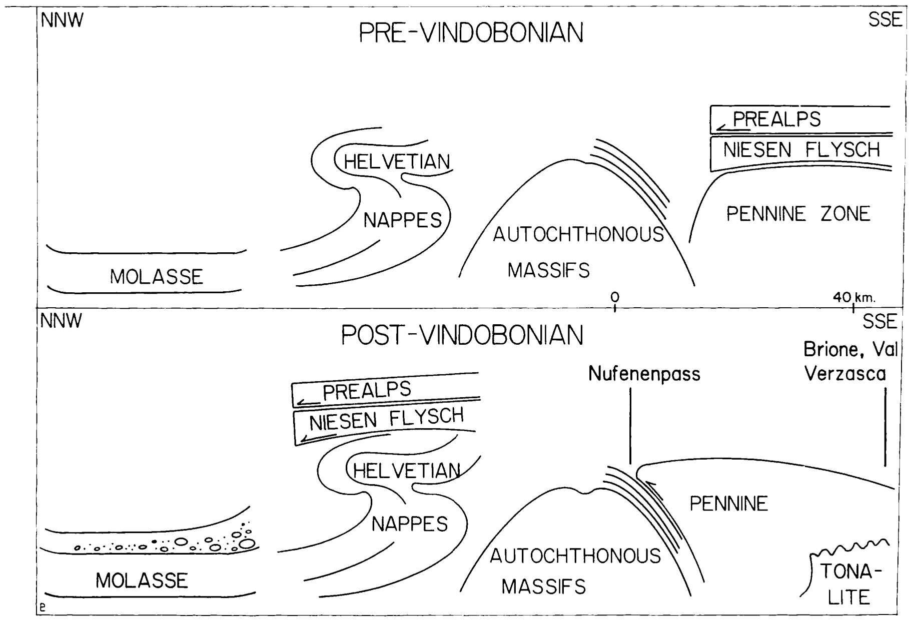

Fig. 1. Diagramatic cross section of the Alps showing the suggested movement of the Prealps with the Niesen Flysch in the middle Miocene. Brione is the location of an 18 m.y. radiometric date by Jäger and Faul (1959). Nufenenpass is the location of Eichenberger's tourmaline schist.

Eichenberger (1924, p. 474-475) suggests that the metamorphism of the Nufenen sediments, which are autochthonous on the Gotthard massif, was caused by the Pennine nappes. He goes on to say that the abundant tourmaline in the Nufenen sediments has perhaps a magmatic origin. The recrystallization and remobilization of the Pennine nappes is the magmatic origin, and Collet's difficulty with Eichenberger's suggestion, namely that tourmaline cannot be produced by dynamometamorphism (Collet, 1927, p. 51), no longer exists.

De Sitter (compare de Sitter, 1956, p. 478, fig. 302 with Heim, 1922, Tafel XXVII or XXXV) considers the tonalite beneath the southern end of the Pennine zone to be syntectonic with Alpine orogeny. The point of this discussion is to suggest that the movement of the thrust plate of the Prealps upon the rocks now forming the Helvetian nappes was synchronous with and caused by recrystallization of the cores of Pennine nappes, which recrystallization might have been produced by the tonalite. Hence rather than refer to the tonalite as syntectonic, I would prefer to call the tectonics, the shallow thrusting or gliding, syn-granitic.

Van Bemmelen (1960, p. 114) has noted the belief of Franz Karl (1959) that "the granodioritic rocks of the Tauern window were injected synorogenically in the cores of the Pennides, but at a rather high crustal level". Here again, I suggest that the orogeny is synchronous with and partly caused by the granodiorite. It seems suitable to remark that although van Bemmelen's results are somewhat similar to those given here, his mechanism is quite different and far deeper than the mechanism discussed here.

CONCLUSION

The literature has supplied at least one case where fluid pressure derived from an igneous or "pseudo-igneous" (Buddington. 1959, p. 675) source might have facilitated movement of a large thrust plate. According to this mechanism, the time of movement is independent of time or rate of deposition of the sediments to be moved.

In suggesting a variant of a theory of orogeny, I am aware of and concur with de Sitter. who points out (1956, p. 483) "the extremely flimsy grounds on which such theories are built". Scheidegger. after arriving at the same verdict, concludes (1958, p. 220), "It would therefore be much more satisfactory if it could be assumed that only the crust proper (as defined by the Mohorovicic discontinuity) is involved in 'basic' (or: primary) orogenesis". Perhaps abnormal fluid pressure as set forth by Hubbert and Rubey, will serve.

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