Reprinted for private circulation from
BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS,
Vol. IX, No. 3, May–June, 1925

BULLETIN

of the

AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

MAY-JUNE 1925

THE UPTHRUST OF THE SALT MASSES OF GERMANY[1]

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ABSTRACT

The Zechstein salt deposits of middle and northern Germany were laid down in a sinking basin in which sinking came to an end during the Jurassic, except in northern Germany, where it persisted into the late Tertiary. The beds deposited in this basin were involved in the Saxon mountain-building movements, which contrast with the older, Variscan movements in being intermediate in character between folding and block faulting. The Saxon movements were periodic and not continuous. That the movements were due to compressive thrust is shown by the fact that the "horsts" were uplifted.

The salt bodies are found in the form of "salt beds," "salt anticlines," and "salt stocks." "Salt anticlines" are normal anticlines both in the form and inner structure of the salt and in the structure of the sedimentary cover. The "salt stocks" are strongly folded, subcircular to elongated masses of salt which are upthrust into faulted rather than folded adjacent formations.

The main theories proposed to explain the upthrust of the salt are three: Lachmann's "atectonic" theory, the "isostatic" theory, and the theory of upthrust by lateral thrust. Lachmann's "atectonic" theory of upthrust of the salt by an inherent autoplastic force is no longer current. The formation of the salt anticlines by the compressive thrust of the Saxon orogenic movements is very generally accepted by German geologists. But as there is every gradation in form between the characteristic salt anticline and characteristic salt stock, as the gradation from one to the other can be followed on the same anticlinal axis, and as with a rare exception the periods of movement in the salt stocks coincide with the periods of the Saxon orogenic movements, it seems reasonable to believe that all have been caused by the same force. The difference in the resulting forms is due rather to the difference in the materials acted upon than to difference in the forces acting. The salt is more plastic and therefore more mobile than the ordinary sedimentary rocks, and is therefore the more easily deformed. Under intensive deformation, it advances far ahead of the other rocks, and thus a salt stock is the extreme form of an anticlinal core. The tectonics of salt upthrust are therefore a phase of the tectonics of mobile materials and are intermediate between the normal tectonics of folding and the tectonics of magmatic intrusion.

D. C. B.

[1] Translated from the German by Donald C. Barton.

THE FORMATION AND SECULAR SINKING OF THE ZECHSTEIN SALT

The folding of the Variscan mountain system which traversed middle Europe in the later Paleozoic was succeeded by depression which prepared a broad basin into which the sea penetrated at the beginning of Zechstein time. The extent of this sea in German territory can be seen from Figure 1. Toward the northwest it stretched

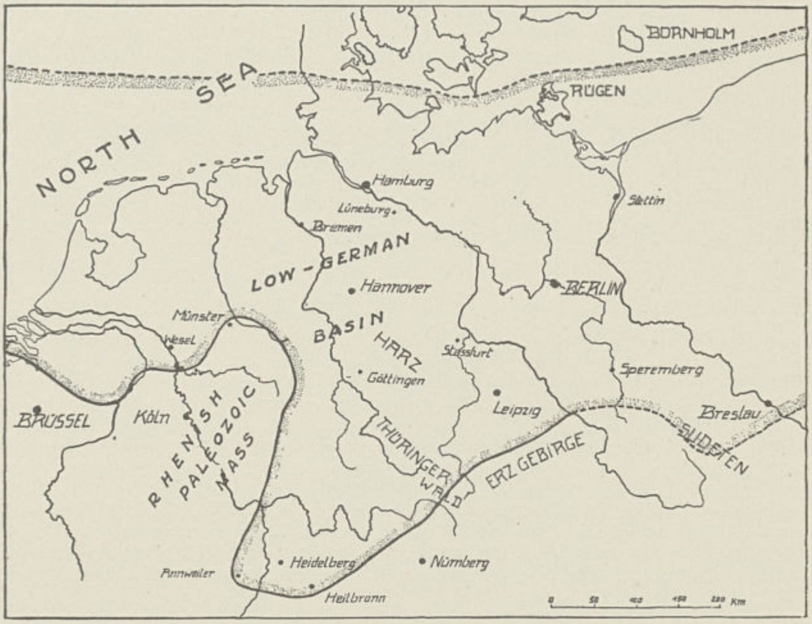

FIG. 1.—Map showing the probable extent of the German Zechstein Sea

to middle England; toward the east it had a broad connection with the Russian late Permian basin. This Zechstein sea has left behind the most widely extended salt deposit that has ever been formed in the course of the earth's history. A valuable feature of this salt deposit is its well-known succession of beds of potash salts, which were deposited principally in the German portion of the great basin, in general in a single series, but in certain areas, in two series.

The Zechstein was followed by the Trias; the great basin, which had become land during the formation of the salt deposits at the end of the Zechstein, broadened into the basin of the Germanic Trias, and within those extended boundaries the sinking movement continued. Buntsandstein, Muschelkalk and Keuper were deposited above the Zechstein salts, which sank correspondingly. Even in the older Jurassic, this sinking process continued generally, but began to be differentiated. In the southern and middle portion of the former Zechstein area, the sinking gradually came to an end; while in the north, in the "North German basin," it continued. There, Dogger and Malm, Cretaceous and Tertiary were deposited in great thickness, although farther south, in the area which formed the "Middle German continent" of that time, these beds are wholly or almost wholly lacking. In the north the salt sank many thousands of meters below the surface; in many portions of the "North German basin," the lower Cretaceous alone has a thickness of over a thousand meters. The great thickness of this sedimentation indicates the "North German basin" especially, as well as the Zechstein-Triassic basin in general, as a geosyncline, if by "geosyncline" we understand broadly a secularly sinking area of sedimentation without regard to the character of the sedimentation which took place in it, without regard to its shape, and without regard to the form of the mountain-building which affected it. By the sinking that has been described and by burial under an ever increasing mass of sediments, the salt reached, in the course of time, warmer and warmer regions. The salt compounds, formed at the temperature of the Zechstein times, in part became no longer stable; varied thermo-metamorphism set in (21, 23)[1] and changed the original composition and structure; thus the paragenesis, sylvinite-kieserite, which as *Hartsalz* is widely extended through the German salt deposits and which can form only above 72° C., can be explained according to Arrhenius' theory (2, 3) as the result of thermo-metamorphism consequent upon the geosynclinal sinking of the Zechstein salt. From the thickness of the overlying sedimentary cover of that time and from the geothermal gradiant, it is possible to calculate at about what time the *Hartsalz* of the various portions of the Germanic basin formed from the original salt compounds. Beneath the present southern Hannover area this must have happened about during Lias times.

[1] Numbers in parentheses refer to the bibliography at the end of the paper.

THE SAXON MOUNTAIN-BUILDING OF GERMANY, THE FRAME OF THE TECTONIC DEFORMATION OF THE SALT MASSES

The *downward movement* of the salt was of varying intensity. In the "North German basin" it carried the salt several thousand meters below sea level. In Middle Germany, in those areas which since Dogger times have belonged to the Middle German continent, it was of far less intensity.

The *uplift* of the salt to the levels at which wells and shafts now reach it stands in the closest dependence upon the "Saxon" mountain-building.

Two great mountain systems are to be distinguished in the subsurface structure of Germany. The older, the Variscan, has already been mentioned; it was obliterated at the end of the Paleozoic. The younger is the Saxon, which in form, is widely different from the older. If the older can be said to be true folding ("Alpine type" of mountain-building), the younger can be said to have expressed itself in faulting ("Germanic type" of mountain-building) with subordinate folding. Yet in the "block terrane" of Germany it is possible to recognize an arrangement of structure along certain lines of uplift and depression, just as in folded mountains the strata are elevated along certain lines (anticlinal axes) and depressed along others (synclinal axes). The Saxon mountain-building consequently has as its basis a certain fold plan in which the folds, in contrast to the normal type of folding, are allied in strong degree, already *in statu nascendi*, with faults (compare Fig. 2). They are spoken of in this sense as "fault folds" (Bruchfalten), which in the series of tectonic forms take an intermediate position between true folds and block faults.

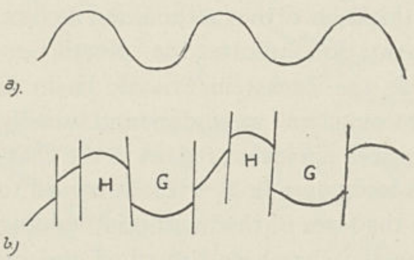

FIG. 2.—Diagrammatic sketch illustrating: (*a*) normal folding, and (*b*) fault-folding.

The conception that lateral pressure had created the Saxon "fault-folding" was strongly contested up to about ten years ago, but at present it seems to have found general acceptance among the

German geologists. The deviation of the forms from the normal forms of folding, especially through the cutting of the folds by a host of faults, may be explained by the increased stability which the subsurface had gained through the Variscan folding and by the magmatic-volcanic processes which took place with that folding and in consequence of it.

A normal fold of folded terrane and a fault-fold of the German block terrane are illustrated in Figure 2. In fault-folding, the horst (*H*) corresponds to the anticline of the normal folding, and the graben (*G*) corresponds to the syncline.

The Saxon mountain-building favored the southeast-northwest (Hercynian) direction. The Rhenish, north-south, direction also is strongly in evidence in a broad zone which lies east of the Rhenish mass of Paleozoic schists, in prolongation of the upper Rhine graben, and which extends far to the north past Hannover and Lüneburg into the area of the lower Elbe. A phenomenon which is of great significance in the explanation of the occurrences of the salt is abundantly recognizable: the intersection of the axes of elevation and depression of Hercynian and of Rhenish directions, respectively, give rise to interference phenomena, as, for example, an especially strong uplift where two zones of uplift cross, or an especially strong depression of the subsurface where two lines of depression cross. That the Saxon orogenesis, like orogenesis in general, took place in individual periods, broken by long periods of relative quiescence in which exclusively movements of epeirogenic character set in, is no longer contested from any side. These periods are recognized by the demonstrable angular unconformities within the sedimentary series of Germany. It thereby becomes recognizable that it is a question of the same periods which elsewhere in the world are evident in the late Mesozoic–Early Cenozoic time. Up to perhaps twenty years ago, it was believed that there were not more than two periods which came in the Miocene, but evidence has now been obtained of other, especially older, mountain-building, of which the earliest, the Cimmerian, took place in three subperiods at the end of the Jurassic. It corresponds to the Pacific revolution in America. Other periods followed in the Cretaceous, and a very important movement took place at the end of the Cretaceous and the beginning of the Tertiary, contemporaneously perhaps with the Laramide Revolution of North America. New orogenic movements set in at the end of the Eocene and Oligocene; several followed even in the late Tertiary; and in fact weak echos are evident in the Quaternary. In the orogenic periods, the beds which had gradually sunk during the preceding time and which had been correspondingly deeply buried under sediments were again moved upward in broad zones in the formation of a fault-fold system. Downward movement, however, soon set in again in many places, and after the fault-folds had been planed off by a denudation, they were covered anew. The renewed movement of depression then continued until another orogenic period brought about yet another movement of uplift. Thus it is possible to recognize in the North-German basin a repeated alternation of long-continued depression broken in certain zones and along certain lines by spontaneous upward movement.

James Hall recognized in North America as much as sixty-five years ago that folding sets in where the sediments are very thick that is, to use Dana's expression, in geosynclines, while the up-arched areas in which there was little or no sedimentation are spared by the folding. This fundamental law of mountain-building is proved true also among the lesser structural features of the Saxon areas. Where sedimentation did not take place after Variscan times or was small in amount, that is, where the sinking of the ground soon came to a stop, we have only weak Saxon mountain-building. Conversely, the folding was most intensive where, after the Variscan folding, the subsurface sank the deepest, and where, correspondingly, the younger sediments were deposited in the greatest thickness. Quite in the sense or in the extension of Hall's thought, in fact, it is possible to recognize in individual basins, as, for example, in the so-called sub-Hercynian basin, increases in the intensity of folding with increase in depth of the basin.

Since the upward movement of the salt masses is most closely connected with the Saxon fault-folding, and especially since tension phenomena are not lacking within the fault-folded zone, it may be asked whether the explanation of the fault-folds by lateral thrust is to be accepted unconditionally.

Edward Suess, as a matter of fact, in *The Face of the Earth,* wished to explain the German "block terrane" by differential downward movement according to the example of horsts and grabens. But subsequently it has become possible to divide the Mesozoic-Cenozoic tectonic processes into individual periods, and by comparison of the successive steps to win a deeper insight into the nature of the processes. Especially it has been shown that in the orogenic periods in which the faults and fault-folds arose, the rock masses affected in no case moved downward but instead moved upward. Beds which before the orogenic movements had lain deep below sea level, after those movements were exposed to sub-aerial denudation as part of the fault-fold system which had arisen in the meantime. Following peneplanation, the area was soon again covered by a new transgression. This problem, which is so important for a comprehensive conception of the Saxon mountain-building, was discussed more in detail by the author in 1911 (32).

In this Saxon folding the terrane which was being changed over into a fault-fold mountain system was moved upward and, in fact, differentially, just as in true folding a differential upward movement takes place, stronger in the anticlines and somewhat weaker in the synclines. The graben in a fault-fold system has not sunk, but has been raised less than the horst, just as, in folded systems, the beds in the syncline have been raised less than those in the anticline. But as yet it has been possible to recognize outside of lateral pressure scarcely any force which could move a block system differentially upward.

THE PRESENT FORMS OF OCCURRENCE OF THE SALT MASSES OF THE GERMAN TERRANE

The outer form and inner structure of the salt masses are intimately related to one another, and in this relationship we recognize everywhere a more intense deformation of the salt than of the adjacent formations and cover. This effect without doubt is the result of the high plasticity of the salt. Even at normal temperature and normal pressure the salt has a relatively high plasticity, which increases extraordinarily with increasing pressure and increasing temperature, as has been shown experimentally by Milch (19) in regard to the temperature and by F. Rinne (20, 21) in regard to pressure.

The following three main types can be distinguished among the various forms of the German salt deposits:

a) Salt beds (*Salztafeln*)

b) Salt anticlines (*Salzsättel*)

c) Salt stocks (*Salzstöcke*)

Salt beds.—The salt beds (see Fig. 3*a*) are horizontally lying or gently inclined platelike masses of salt formations regularly intercalated between the middle Zechstein below and the Bunstandstein above. Within the salt beds the individual strata in general are regularly concordant with one another and with the overlying and underlying formations; yet abundant irregularities and folds are met with which are not present in the overlying and underlying strata. Even overturned folds projecting far out, with salt strata thinning and thickening, are encountered in many places in the salt beds; such phenomena are all the more surprising in view of the great regularity of the bedding of the overlying Buntsandstein. The "salt beds" are present south of the Harz (south Harz area) and west of the Thuringian Forest (Werra area).

Salt anticlines.—The salt anticlines (Fig. 3*b*) are up-archings which have affected the salt and the overlying beds in somewhat the same degree, so that the salt is the core of an anticlinally folded complex of Buntsandstein beds. Although there are many types of special complications (21, Tafel 11), the bedding within the salt mass in general is anticlinal. If the salt core of the anticline has approached the surface and has come in contact with the ground water, a "salt table" (see below) is developed at the top of the salt core as the result of subsurface solution of the salt (Fig. 3*c*). As a result of such solution, the overlying beds sink and in certain areas of middle Hannover, the Tertiary is found preserved in "solution-grabens" above the salt, while off the salt, where the downward movement did not take place, it has been more or less completely removed by denudation.

Salt stocks.—It is in the German salt stock that the American geologist is especially interested, for in the first place the salt stocks are very similar in their general appearance to the salt domes of Texas and Louisiana, and in the second place oil is found in many places on their flank zones, as in Texas and Louisiana (Wietze-

Steinförde, Hänigsen, Oelheim). Their genesis has been the most disputed question of all the German salt occurrences. They show special peculiarities as to: (1) their outer form and especially their

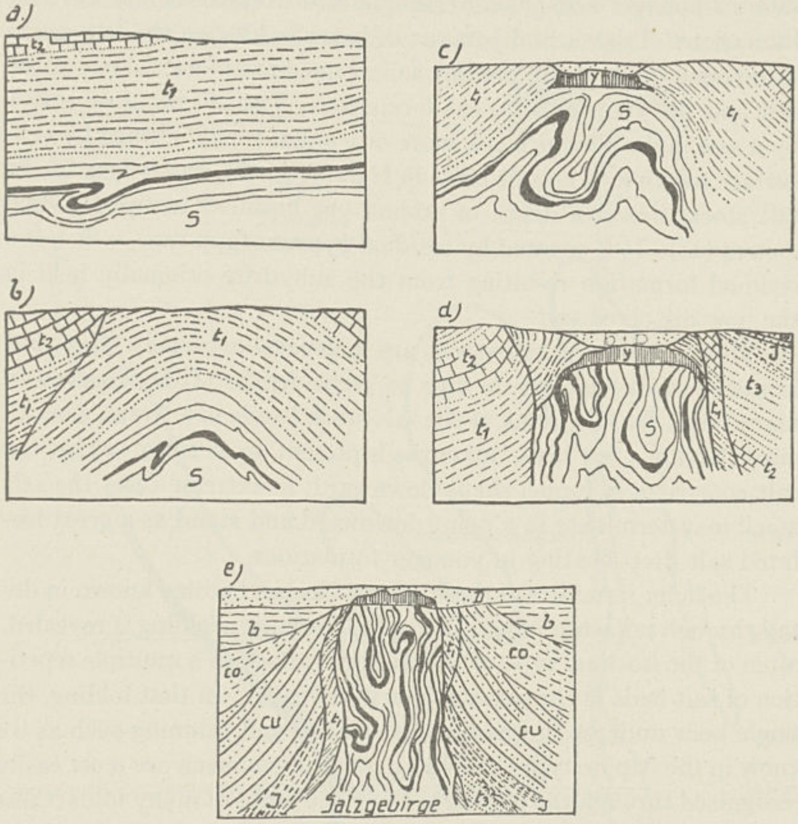

FIG. 3.—Tectonic forms of the occurrence of the German salt deposits: (*a*) "salt bed," south of the Harz; (*b*) salt anticline, South Hannover; (*c*) salt anticlines with "salt table," Hildesheim; (*d*) transition between salt anticline and salt stock, Benthe; (*e*) salt stock, North Hannover. Stratigraphic legend: *D*, Diluvium; *b*, Tertiary; *CO*, Upper Cretaceous; *J*, Jurassic; t_3, Upper Triassic (Keuper); t_2, Middle Triassic (Muschelkalk); t_1 Lower Triassic (Buntsandstein); *Y*, Residual gypsum cap; *S*, Salt formations with potash beds in heavy black lines; *CU*, Lower Cretaceous

position with reference to the adjacent formations, and (2) their inner structure.

The salt stocks are salt masses of circular, elliptical, elongated, or quite irregular plan, rising from great depths where in general they still have their roots. They no longer stand in the normal relation to their original cover, the Buntsandstein, but usually have penetrated into far younger beds, as for example into Cretaceous and Tertiary formations. Triassic and Jurassic beds are lacking on the salt stocks in extreme cases or are present as intermediate blocks between the salt and the younger adjacent formations. The salt is cut off above by a salt table (6) which is a more or less flat plane, formed by subsurface solution. The salt table in Hannover, the classic land of the salt stock, lies at a depth of around one hundred to two hundred meters (29). It is covered by residual gypsum (gyp cap), which is a residual formation resulting from the anhydrite originally held in the now dissolved salt.

The flanks of the salt stocks are in general extremely steep, but in many cases have gentle dips to great depths. It is observed in many cases that the flank of the salt stock bends in a "swan's neck" curve, and in a few cases this curve is present on all sides, so that the salt constricts in funnel shape downward; in extreme cases the salt stock may terminate in a point downward and stand as a great isolated salt drop floating in younger formations.

The inner structure of these salt stocks has become known in detail through potash-mining. In general, intensive folding is revealed, often of the isoclinal type, which expresses itself in a multiple repetition of salt beds in the same profile (see Fig. 4). In that folding, the single beds undergo mechanical thickening and thinning such as we know in the Alpine types of folding; such phenomena are most easily recognized through the potash beds; in the limbs of many folds, these show supernormal thicknesses, although in other places they have thinned until they are unworkable. Thus in the Riedel shaft (north Hannover), a series of salt beds which normally possess a thickness of sixty meters is only two meters thick in places, yet each individual bed is discernible though proportionately thinned (28). In rock salt which shows "yearly rings" (*Jahresringe*) with a greater or lesser content of anhydrite, Seidl (25, 26) has differentiated "compression salt" (*Stausalz*) and "tension salt" (*Zerrsalz*). In the compression salt, the yearly rings have separated from one another, while on the contrary in the tension salt they have approached one another, since the salt has been very greatly squeezed. The salt formations of the Zechstein in fact comprise beds of varying plasticity; carnallite is less plastic than the rock salt (21), and least plastic of all is the anhydrite, which occurs in thin beds as well as in the "main" anhydrite, with a thickness of forty to fifty meters. The "main" anhydrite,

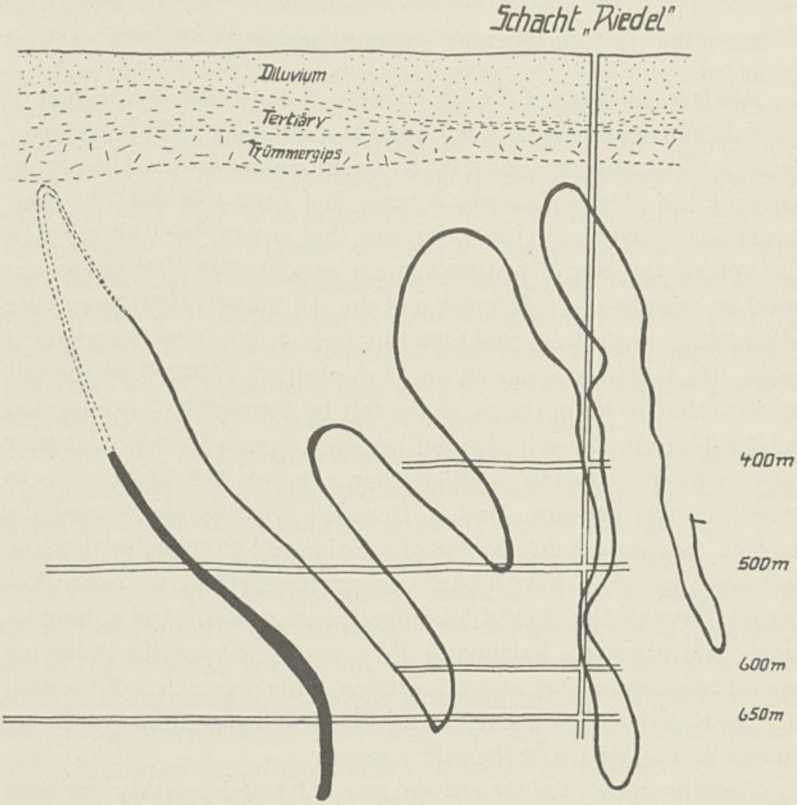

FIG. 4.—Section through the Riedel shaft (North Hannover), showing the folding of a single stratum in the potash salt beds.

(*Hauptanhydrit*) and in part also the "gray salt clay" (*Grauer salzton*) that accompanies it, show quite a different reaction to the tectonic forces from the rock salt and potash salt. The "main" anhydrite in most cases does not take part in the intensive folding, and does not deform plasticly like the salt, but in many cases is shattered. There arises therefore the form which has been designated by Seidl (25, 26) in correspondence with Mrazec as "diapir" folds, in which the more mobile salt wells up through the gaps in the "main" anhydrite.

Although the salt shows the typical phenomena of folded formations, the surrounding younger beds, everything considered, are displaced more after the type of block faulting.

THEORIES OF EXPLANATION OF THE UPTHRUST OF THE SALT

Atectonic upthrust of the salt masses.—The theory of upthrust of the salt independently of the normal tectonic forces has been advocated in Germany especially by R. Lachmann (12–18). The peculiarity of the phenomena which have just been described in their larger phases led him to the conception that any explanation through the normal theories of tectonics is not possible and that in the upward movement and deformation of the salt masses, therefore, quite other forces must have acted than those which deformed the adjacent rocks. He therefore spoke of an "autoplastic" upthrust of the salt masses, that is, an upthrust of the salt by forces which are located substantially in the salt. He had an idea especially of a molecular movement of dissolved material from zones of strong pressure to zones of lesser pressure, that is, from the great depths toward the surface. Through such processes of solution and recrystallization, the salt was supposed to have broken through the earth's crust as an ulcer breaks through the skin of an animal; hence Lachmann's designation, "salt eczeme." Lachmann did a very great service in having aroused discussion over many questions of the occurrence of the salt, but his theory lacked a satisfactory physical explanation for the assumed autoplasticity of the salt masses.

Isostatic upthrust of the salt masses.—Although isostasy has been awarded in Europe, and especially in Germany, only a secondary significance as the cause of the present structural relations of sedimentary beds, it has enjoyed more common acceptance as the cause of salt upthrust. E. Harbort (8–10) especially recognized the motive force for at least a part of the salt upthrust in the loading of the salt masses that already were present in a strongly plastic condition at great depth, and that therefore were already capable of being upthrust. According to Harbort, who did not misunderstand the position of the salt masses in the cores of the anticlines in the province of Saxony, in the sub-Hercynian basin, in southern Hannover, etc., the upward movement and the folding of the salt in the older Saxon periods was a folding phenomenon which affected the salt masses more strongly than the less mobile adjacent formations; but according to him, the latest upward movements at least are to be explained through the loading of the deeply buried salt by the younger sedimentary masses and the subsequent passage of the salt upward along fractures after the manner of a magma. Prominent students of salt domes such as Beyschlag (4), Seidl (26), and to a certain extent also Rinne (23–24) share Harbort's conception. Lachmann also approaches very near to it in leaning toward Arrhenius' (2, 3) ideas. Interested in the salt dome problems by Lachmann, who hoped to get from him a physical explanation of the atectonic upthrust of the salt, Arrhenius attributed the upward movement of the salt mass to its lesser specific gravity, compared with that of the normal rocks. He seems to have assumed that the salt stocks in general are surrounded by wet soft clay or even by ground water.

Upthrust of the salt masses through folding.—The chief exponent of the conception that in the upward movement of the salt the same forces have been active as in the adjacent formations, that is, in last analysis, lateral compression acting in the earth's depths, is the author (27, 29–31). In this theory, the cause of the peculiarities of the tectonic forms of the salt masses lies exclusively in the peculiarities of the materials in question. It is not that different forces have acted in the salt and in the adjacent formations, but rather that the same forces have worked differently, and they have worked differently because of the different character of the materials.

THE INTERPRETATION OF THE SALT UPTHRUST IN THE FRAME OF THE SAXON STRUCTURE AS A WHOLE

Everything considered, the theory of atectonic change of form of the salt formations can be regarded as overthrown. In opposition to one another there remain therefore to be evaluated the theories of isostatic upthrust and upthrust through folding.

The continuity of the forms of occurrence of the German salt deposits.

—Unquestionably one main error has repeatedly been made in the investigations and discussions of the German salt bodies, that is, that to account satisfactorily for a single object or a single type will solve a problem which in the last analysis must find its explanation in the consideration of the totality of the phenomena. Scientific controversy in Germany turned in the main around the salt stocks ("salt pillars," "salt eczemes"), although there is a certain agreement to the effect that the salt *anticlines* were the result of the lateral pressure that had affected the other rocks of the German terrane. But one may not regard the salt stocks apart from the other occurrences of the salt, especially the salt anticlines. The salt stocks are connected with the salt anticlines: (1) as types of phenomena; (2) in space.

The connection as types of phenomena consists of a complete series of intermediate forms between the typical salt anticline and the typical salt stock, not only in regard to position in reference to the adjacent formations, but also as to the yet more complicated inner structure (see Fig. 3). Certainly an anticline as we find it at Salzderhelden, in south Hannover, where the salt shows no great special complications in its inner structure and where it is regularly covered and mantled by the older Triassic as the core of an anticline, is immensely different from a typical salt stock of the Lüneburg type, where a huge pillar of salt sticks up in the middle of Cretaceous and Tertiary beds, even lacking, in some cases, the intermediate beds of Triassic and Jurassic, and where there prevails a folded structure which is comparable to the Alpine types of folding. But between these two there stand other forms, anticlines in which the salt core has experienced a somewhat intensified upward movement so that perhaps it is mantled in some parts by Buntsandstein but in other parts by much younger beds, in which, however, the anticlinal character is visible both in the inner structure as well as in the anticlinal structure of the adjacent formations. Such intermediate forms are met, for example, east and west of the city of Hannover. The series of the forms of the salt bodies can be begun with the flat salt beds, which can be thought of as derived from salt anticlines by the decrease of the dip of the wings, such a series, from the salt bed through the salt anticline to the salt stock, is represented in Figure 3.

If these natural relationships had been kept more sharply in view, much misdirected effort in working out the tectonics of the salt deposits would have been avoided

With regard to their connection in space: the three main types of salt occurrences are somewhat separated in their geographical relations; the flat salt beds are found in general in those areas where the downward movement came to an end in the early Jurassic and in which therefore the salt sank only a relatively small distance. These areas have experienced only slight post-Variscan deformation in connection with the relatively slight post-Variscan sedimentation.

The salt stocks are confined to the areas of stronger post-Variscan sinking and sedimentation, that is, especially the North German basin.

The salt anticlines are found in their characteristic form in the transition areas, therefore in the areas of medium sinking and sedimentation.

Certain zones of uplift can be traced from the peripheral areas far into the North German basin (35); *and with the advance into the latter, along one and the same line of uplift, the form of the anticline goes over more and more into the form of the salt stock.*

The time relations of the upthrust of the salt.—Of decisive importance for the significance of a salt upthrust are its time relations compared with the time relations of the other Saxon tectonics. In both cases time relations are ascertained through the help of angular unconformities, and it is to be said that in general the same series transgress over and around the salt formation which transgress discordantly elsewhere in the Saxon area. From those relations as well as from the massive sedimentation in the intervals between the periods of deformation of the salt formations, it follows that the salt beds participated in the above-described upward and downward movement of the Saxon fault-folding in the alternation of orogenic and epirogenic processes, and that they participated in a far stronger degree in the upward movement than the non-saline formations; the author illustrated this in a diagram published some time ago which showed only four periods of orogenic upward movement, but newer investigations now indicate that the number of the periods is much greater. To the transient character and periodicity of the folding and of the upward movement of the salt masses, an exception is to be taken farther on, but if this exception is disregarded, it follows (27) *that the salt has been folded and has been moved upward in the same orogenic periods which are recognizable elsewhere as the periods of folding in the German terrane.*

The salt stock as the extreme form of an anticlinal core.—The position of the salt in the core of an anticline is very clear in the case of a salt anticline; the clarity, however, decreases with the transition to the salt stocks, and in individual extreme cases of salt stocks, the anticlinal position is perhaps no longer recognizable; but, as we have seen, salt stocks are tied together by transition of form and transition in space with salt anticlines, so that both must be explained in the same way. They fall, moreover, into the same periods of formation, if again we neglect the exception previously mentioned. The salt stocks, in last analysis, are the extreme form of anticlinal cores, in which the anticline is modified to unrecognizability; they are anticlinal cores that have advanced far ahead of the anticlinal wings and in the process have undergone an extensive change of form.

The rounded horizontal plan of many of the salt stocks does not contradict the conception of the salt as an anticlinal core; comparable forms, the so-called (structural) domes, are known also in Saxon structures of non-saline formations, and in fact they occur in many cases as the result of the summation of effects at the intersection of two axes of uplifts (see above). Thus it can be recognized that in many places in north Hannover the salt stocks lie at the intersection of the lines of uplift of Hercynian and Rhenish direction (29). In general, as in the Saxon tectonics, a substantial rôle is played by interference phenomena in determining the distribution and form of the salt bodies.

It appears therefore from (1) the recognizability of the occurrence of the salt as anticlinal cores or as derived from such through intermediate forms and through gradation in space, and (2) the contemporaneity of the upthrust of the salt with the periods of the Saxon folding, that it is not pertinent to call on other forces for the folding and uplift of the salt than those which folded and uplifted the non-saline beds of the German terrane.

The thesis is untenable and as yet has never been seriously advocated that in salt anticlines the lateral formations have come into their present position through folding, while the salt has come into its present position in the anticlinal cores and has been deformed in general by other forces. If the salt anticlines have arisen under the same compression which, acting upon the earth crust, led to the Saxon folding, the same theory of origin should be valid also for the salt stocks, which are traceable from the salt anticlines in all degrees of transition. That the upward movement was far stronger and the inner deformation far more intensive than in the non-saline beds is explained by the extraordinary capacity of the material for deformation. By "inharmonious" folding the author understands the quantitatively and qualitatively unlike reaction of different rock masses of the same section to mountain-building forces. Thus schists fold much more intensively than the overlying quartzites and in many cases force themselves injectively into the gaps in the quartzite masses. The salt tectonics are nothing other than an extreme form of inharmonious folding (31). In Figure 5, in case (*a*) it is assumed that the beds from *a* to *l*, including beds *c* and *f*, have reacted harmoniously to the folding force, and thus a normal anticline arose, cut by a few faults. In contrast to this, in case (*b*), bed *c* is assumed to be highly mobile (salt) and bed *f* is assumed as more strongly mobile. When bed *c* is strongly compressed it advances far ahead of the overlying beds and bed *f* is disturbed in an increased degree next to the salt.

By the advocates of the theory of the autoplastic upthrust of the salt, it is assumed that the formations underlying the salt (middle Zechstein) are not involved in the upward movement and folding which affected the salt. Borings and exposures in shafts show the opposite; but that the more stable underlying formations are far less affected than the much-disturbed salt is quite in accordance with the picture of inharmonious folding.

THE SALT UPTHRUST AS AN INTERMEDIATE FORM BETWEEN NORMAL TECTONICS AND VULCANISM

Harbort, Rinne, and others have compared the upthrust of the salt with eruptive processes, since they assumed the cause of the upthrust to be the weight of the overlying sediment; but under the explanation of the upthrust of the salt through lateral compression, the comparison with the upwelling of magmas still stands, so that in this sense the salt upthrust is "injective folding" (31). Salt tectonics therefore fill a gap in "normal tectonics," that is, between the tec-

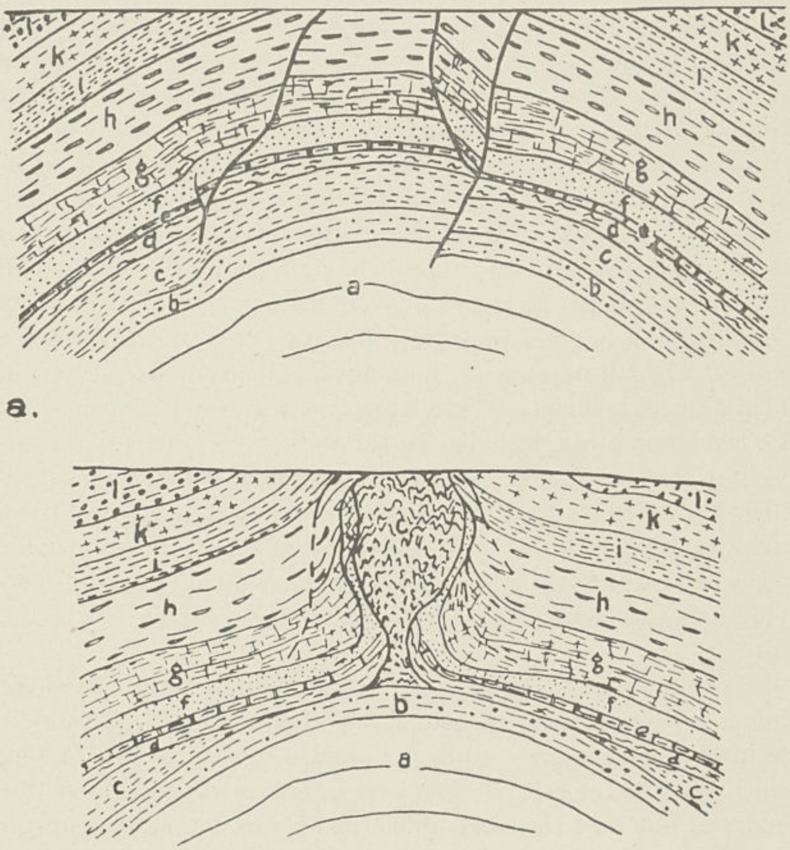

Fig. 5.—Diagrammatic sketch showing the relation of the form of folding to the mobility of the rocks.

tonics of rocks of normal mobility and the tectonics of vulcanism, if we except from the latter the explosion phenomena developed by gas pressure, that is, if we take vulcanism especially in the sense of the deep-seated vulcanism (34). In recent times in Germany, Hans

Cloos, starting from the micro-structure of the plutonic rocks, has advocated tectonic thrust as the cause of the rise of magma and its penetration into the beds of the earth's crust in the form of laccoliths; he has spoken of vulcanism as "the tectonics of highly mobile materials." Vulcanism, of course, is differentiated from the orogenesis of normal rocks in that it is not only tied up with the orogenic periods of the past, but in that it also occurs outside of those periods in times which in the structure of the normal rocks are characterized as exclusively epeirogenic. Not only the strong forces which are at work in orogenesis but also even the far weaker ones which call forth epeirogenesis, therefore, are capable of setting magma into movement on account of its high mobility. Salt in this regard is intermediate between the normal rock and the magma. If it was said previously that the folding and upward movement of the salt were confined to the well-known orogenic periods of Mesozoic and Cenozoic tectonics, the salt appears also exceptionally to have been highly disturbed once outside of these periods. Gripp (7) thinks he recognizes such an exception in one region in which the salt formations feeding the salt rock sank very deep and therefore were especially mobile. With that exception, the law of the time relations of orogenesis, that is, that orogenesis is confined to very definite periods of the earth's history which possess more or less world-wide significance, is valid for normal tectonics. Its validity for vulcanism, on the contrary, if we accept vulcanism as tectonic in Cloos' sense, is incomplete for although orogenic times are in general periods of increased vulcanism, yet vulcanism can take place outside those periods. For salt formations, also, the law of the time relation of orogenesis holds only with restrictions. As was expressed by Rinne, magma and salt, as mobile materials, as masses with very high capacity for deformation, react to tectonic forces far earlier than the rigid rocks (24).

The salt structure and even its extreme form, the salt stock, become understandable as structures of uncommonly mobile masses. The highly peculiar phenomena shown by the salt structures are sufficiently explained thereby and need not mislead us into postulating for their formation forces other than those which have given the non-saline beds their tectonic forms.

F. Rinne, the Leipzig scholar to whom we are indebted not only for long years of investigation into the geology of German salt deposits, but also for his researches, holds the periodicity of the processes, of deformation, in the sense of the law of the time relation of orogenesis, as valid for the non-saline rock and considers it natural that plastic masses intercalated in those rocks should participate in temporary processes of folding and should hasten ahead of the adjacent formations. At the same time, according to him, the salt stocks can be brought into upward movement by the weight of the overlying beds. The fact of the covering of the salt by transgressive series, and in fact by the same series that appear transgressively quite generally in the Saxon terrane, finds an explanation in the fact that such series barred the way to the uprising of the salt in shattered territory, as the result of the weight of the overlying beds. But as the deformation in the adjacent formations, which are cut off equally by the transgressive series, is older than the transgression, the much more pertinent assumption is that the salt had experienced upward movement before the transgression, together with the adjacent formations; that is, that the transgression series was laid down on the salt, and not conversely that the salt was gradually pushed up to the transgressive series. Rinne asserts especially that mountain-building, salt upthrust, and magma intrusion lead back to a single fundamental motive force, gravity. But does not the unity of this motive force remain protected if salt upthrust and intrusion of magma are brought into connection with the phenomena of folding? for this also in the last analysis finds its cause in gravity. The salt upthrust in this sense, is not an immediate but an indirect effect of gravity, for the tectonic forces active in the earth's crust arise first of all from gravity, and these forces cause the salt to move upward.

In Arrhenius' hypothesis, the upthrust of the salt as a result of its lesser specific gravity depends on the direct effect of the gravitative field. But in this case the comparison with magmatic upthrust fails; the uprising masses of magma in many cases are heavier than those through which they are being forced. If we wish to speak of magma upthrust as tectonic here, it is surely only the increased mobility which is the cause of the increased movement. There is a contradiction in the fact that on one side the upthrust of the salt is compared with the upthrust of magma, and on the other side the upthrust is to be explained through the lesser specific gravity of the salt.

CONCLUSION

If the formation of the German salt anticlines is attributed to the same compressive thrust which has affected the beds above and below the salt formation, then, if one does not wish to separate things which quite evidently and naturally belong together, orogenic thrust must be recognized as the cause of the upthrust and of the inner change of form of the salt stocks as well. That the salt stocks project as folded formations into the middle of block-faulted masses of adjacent beds and of the cover, that the salt has therefore been more intensively deformed than the adjacent beds, and that, coincidently with its heightened inner deformation, it has advanced in the general deformation far ahead of the non-saline adjacent formations, is explained sufficiently by its higher mobility. This is merely a special case of general experience that the form to which orogenesis leads is principally a function of the mobility of the material in question (33). In this sense, the salt stocks illustrate the extreme case of inharmonious folding.

Thus the author conceives the upthrust of the salt less as the ejection of an especially *light* material than as that of an especially *mobile* material. In this sense, there is agreement with the upthrust of magma, which in so many cases is heavier than the beds which it penetrates.

Against the explanation of the upthrust of the salt isostatically through the weight of the overlying cover, there is the connection of the movement of the salt with the periods of Saxon orogenesis. The fact that quite exceptionally salt bodies appear once to have been moved upward outside of these periods may be explained by the fact that the salt, as a rock of very highly increased capacity for deformation, reacts to lesser tectonic forces that could effect no deformation in the normal rocks. Thus the movement of the salt fills a gap between the tectonics of deformation of normal periods, and the upward movement of magma which occurs so often outside such periods.

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DISCUSSION

D. C. Barton: Stille's views have been severely questioned recently by Franz Schuh[1] in the three papers in *Kali*. The following is a digest of a rather detailed review by Brinkmeier of the papers.[2]

Schuh discusses the two fundamental theories of mountain-building, contraction, and isostasy, and, accepting the latter, is enabled to regard compression and tension as co-ordinate, while advocates of the contraction theory have to regard tension and uplift as subordinate to compression. In a critical discussion

[1] "Beitrag zur Tektonik unserer Salzstöcke," *Kali*, Heft 1; "Die saxonische Gebirgsbildung," I, II, *Kali*, Heft 8; "Salztektonik," *Kali*, Heft 17, 18.

[2] *Zeitschrift für angewandte Geophysik*, I (1923), Heft 3, pp. 86–89.

of Stille's views of the later Mesozoic (Saxon) mountain-building in Germany, he attempts to show that at the beginning of the folding in the Cimmerian period," a tectonic frame (*Rahmen*) in Stille's sense was not present, and, rejecting Stille's "injective folding," advocates the view that the Cimmerian and early Senonian folding belongs in two completely different dynamic periods; i.e., that the first indicates a period of tangential tension, and that the second indicates a period of tangential compression in a southwest-northeast direction; that is, in contrast to Stille's belief in "fault-folding" repeated in every tectonic period, he regards the separation of the faulting from the folding as necessary and possible.

The essence of the author's views, in regard to salt dome tectonics, is that the salt stocks correspond genetically to the graben of normal tectonics; that the areas of depression (*Senkungsfeld*) on either side of the salt stock correspond to horsts which remained standing, and between which the graben sank, and that salt stocks, as well as grabens, go back in their origin to tension faults. On the ground of these assertions, for which no real evidence is brought forward, the views of Stille in regard to the special connection of horsts, normal anticlines, and anticlinal swells (*Breitsättel*) on the one side, and shallow synclines (*Breitmulde*), synclines, and grabens on the other, are regarded as erroneous. Stille's explanation of the formation of these various structures from the character of the deep-lying Variscan basement is rejected as resting on mechanically impossible conceptions, while the effect of the massive cover is recognized only in Harbort's and Seidl's sense. The conception of the Cimmerian period as a period of tangential tension is combined in the explanation of the upward movement of the salt forces.

After contrasting the opposing views of Lachmann, Stille, and Harbort, Schuh accepts Harbort's conceptions, as expressed by Seidl in his "Notes on the Theory of Genesis of the Permian Salt Deposits in Middle Germany": i.e., that the upward flowage of the salt masses is brought about originally by tectonic causes, and takes place along zones of dislocation, and that the concomitant squeezing out of the salt under the flat-lying blocks on either side results in a sinking of the center of each block and a tilting up of its edges. On the assumptions (1) that the salt formation is overlain by a massive cover several kilometers thick; (2) that after a period of faulting following tangential tension there follows a longer period of relative tectonic quiet, and then a period of tangential compression in a northeasterly direction; and (3) that the cover yields easily, but does not fracture, he attempts to show experimentally that such special features arise as gentle archings between the fracture zones, movement of the plastic material (salt) to the fracture zones, rupturing of the less plastic beds, piercing and upward bending of the edges of the cover.

The type of the form of the salt stock, according to Schuh, depends on the varying types of combination of fracture systems, i.e., he predicates "intersection of fractures" in contrast to Stille's "intersection of axes" and "axial nodes."

The tangential compression in the later periods, he believes, causes a decrease in the width of the salt stock and forces it up, and causes the formation of an anticline in the prolongation of the salt stock, if the fracture through which the salt has risen is perpendicular to the direction of thrust. If, however, the fracture runs parallel to the direction of thrust, this late tangential compression causes the broadening and cross-folding of the salt stock and the formation of a broad arch.

On the basis of the published data, he discusses the tectonics of many of the German salt domes, and, according to the reviewer, rather tries to bend the published descriptions of the structure to his previously conceived theories in a way that would probably not be acceptable to most of the respective authors. Although known in a few cases, the tectonics of the basement underlying the salt deposit remains unconsidered by Schuh.

Brinkmeier's verdict regarding the paper is that Schuh fails to prove his point, and instead of presenting definite evidence, reiterates mere assertions. He believes, however, that even if it is not possible to agree with the author's arguments, yet that they may present suggestive points of view for future work.