A Depositional Mechanism for the Muschelkalk Salt

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ABSTRACT

The definition of a satisfactory mechanism for the deposition of the Muschelkalk Salt requires explanation of 1) Alternation of vertically striped (Unteres and Oberes) and normally horizontally banded (Unteres Bändersalz) salt; 2) The initial development of normal horizontally banded structure in the now vertically striped salt as indicated by numerous isolated remnants of salt showing primary banded structure in the Unteres Salz; 3) Recrystallization of the Unteres and Oberes Salz without destruction of the primary texture of the Unteres Bändersalz; 4) Recrystallization of the Unteres and Oberes Salz without a reduction of bromine content, the content in the recrystallized salt and the original horizontally banded salt being the same; 5) The development of the vertical stripes which define a crossectional pattern essentially polygonal in shape and without lateral extension; 6) Recrystallization with a minimum of physical disruption as suggested by the middle anhydrite (mittl. Anhydrit-) zone at Stetten; 7) Deposition at temperatures ranging between 20–50°C; 8) Isolated overlapping of the structure of Unteres Salz and Bändersalz. Satisfaction of these requirements appears best met by deposition of Unteres and Oberes Salz as Linien Salz with subsequent destruction of the primary structure during earthquake activity. Lack of destruction of the primary structure in the Unteres Bändersalz is attributed to a reduction in pore space and more complete lithifaction prior to the more rapid deposition of the overlying Oberes Salz.

INTRODUCTION

The Muschelkalk salt, particularly as exposed in Salzwerk Heilbronn and Staatliche Saline Friedrichshall, has undoubtedly excited the imagination of more geologists than has any other salt deposit found anywhere in the world. A continual challenge to evaporite specialists has been an explanation for the development of the unique vertical striping of the Unteres Salz which generally abruptly terminates against an obviously primary overlying Unteres Bänder-(Linien-) Salz (Fig. 1; Table 1). Making even more difficult the discovery of a mechanism capable of totally altering the primary structure is an overlying second cycle of vertically striped (Oberes Salz) salt. Further complicating the picture are the Napf structures, the origin of which most probably should be related to the depositional and metamorphic process accounting for the development of the vertically striped Unteres Salz into which they have penetrated.

PROPOSED MECHANISMS

The necessity for recrystallization of the Unteres and Oberes Salz has generally been accepted. Schachl (1954), as a result of a comprehensive study of the sequence, attributed the development of the vertical striping to recrystallization by synsedimentary solutions. Borchert (Borchert and Muir, 1964) generated solutions for recrystallization through the dehydration of underlying $CaSO_4$. Such a mechanism might be plausible except for the lack of alteration of Unteres Bändersalz immediately above the Unterer Zwischenanhydrit. Kühn (1964) visualized contrasting depositional processes for Oberes and Unteres Salz with Unteres Bändersalz, calling for transportation of clastic salt by turbid waters and deposition without original bedding for the vertically striped units. Richter-Bernburg (1955) called for a uniquely different process for the development of the vertical stripes (Fig. 2) for which he accounted through

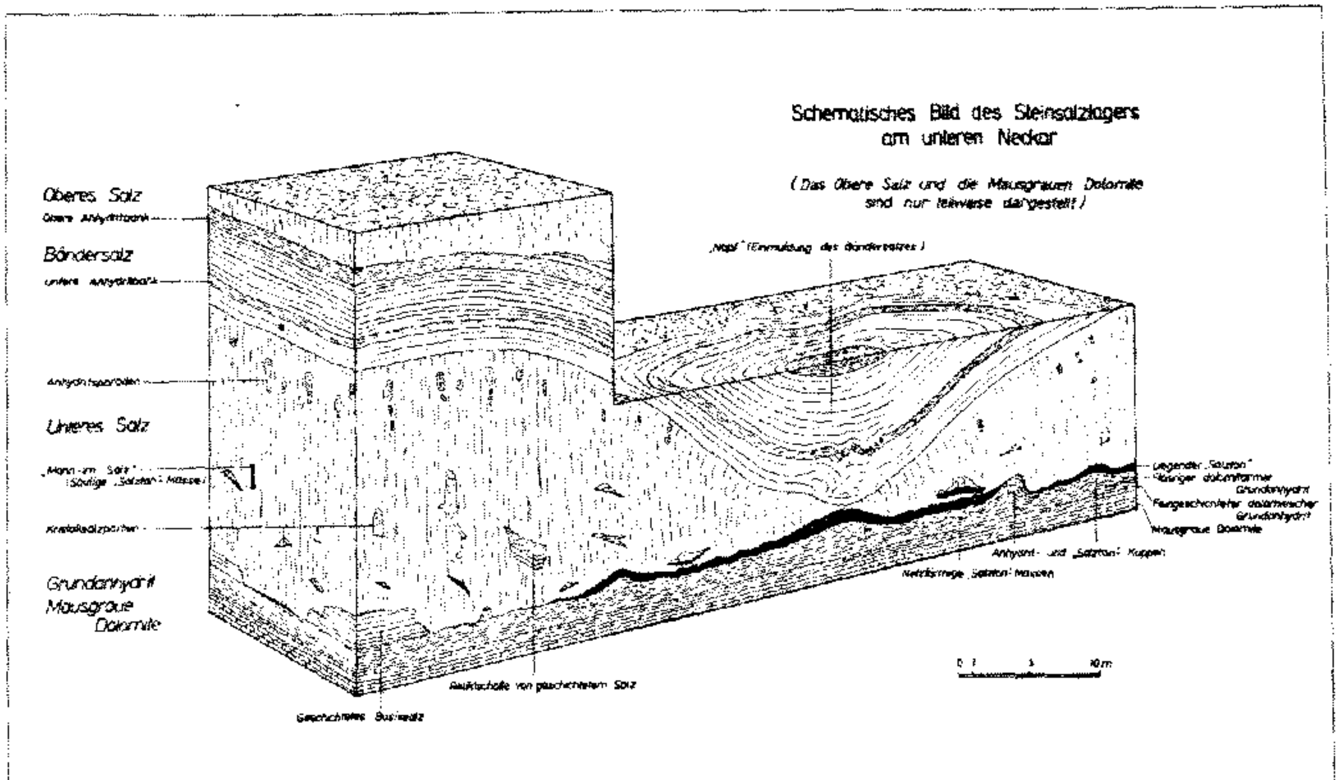

Figure 1. Schematic diagram of the halite sequence in the Middle Muschelkalk in the Lower Neckar District (Schachl, 1954).

TABLE 1

Muschelkalk Salt Section, Heilbronn (Schachl, 1954)

Thickness in Meters		Description
A. 20	Na3	Oberes Salz, grobkristallin und vertikalgestreift Na3w—heller bzw. weißer Halit Na3d—dunkler bzw. tonreicher Halit
	Na3s	Schollen von geschichtetem, ± mittelkristallinem (Linien-) Salz im Na3 eingelagert
B. 6–10	Na2c	Unteres Bänder-(Linien-)Salz, feinkristalliner Halit mit deutlichen tonigunhydritischen Linien, meist nur in Relikten erhalten (oberer Teil)
	A2b	Oberer Zwischenanhydrit, feingeschichteter, toniger Anhydrit
	Na2b	Unteres Bänder-(Linien-)Salz, feinkristalliner Halit mit tonig-anhydritischen Linien und Bänkchen (mittlerer Teil)
		Unterer Zwischenanhydrit, feingeschichteter, toniger Anhydrit
	Na2a	Unteres Bänder-(Linien-)Salz, feinkristalliner Halit mit tonig-anhydritischen Linien und kleinen Bankchen (Löser), (unterer Teil)
C. 12–20	Na1	Unteres Salz, grobkristalliner und vertikalgestreifter Halit mit großen Anhydritsporaden, vor allem im Hangendteil und großen Salztonfetzen ("Mann im Salz"), vor allem im Liegendteil Na1w—heller bzw. weißer Halit, z.T. gelblich, oft nur mittelkörnig Na1d—dunkler bzw. ton- und anhydritreicher Halit, grobkristallin
	Na1#	Kristallsalz (Klarsalz), in Linsen, Spalten und Nestern innerhalb des Na1, klar durchsichtig, z.T. mit Laugen- und Gaseinschlüssen
	Na1s	Schollen von geschichtetem, ± mittelkristallinem Bänder-(Linien-)Salz im Na1 eingelagert
	Na1a	Basissalz, ± mittelkristalliner Halit mit deutlichen tonig-anhydritischen Linien und Bandern, nur in Relikten erhalten
D. 1–3	A1	Grundanhydrit (T1 Salzton, nur lokal vorhanden)
	Ca1	Liegendes: Orbicularisschichten und Unterer Muschelkalk (Mausgraue Dolomite 2–3 m)

*Spezielle Einzelwerte aus den rund 250 Analysen konnen auf Anfrage gern mitgeteilt werden.

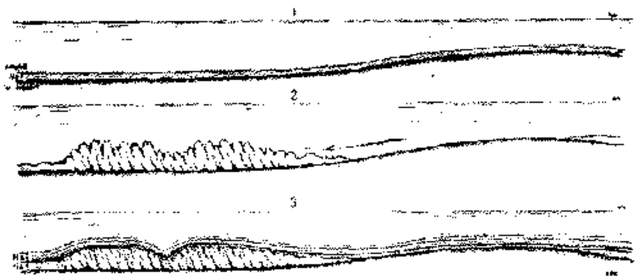

Figure 2. Development of vertical banding in Unteres Salz through subaqueous slumping. (1) Deposition of Unteres Salz, (2) subaqueous slumping, and (3) deposition of overlying Bändersalz (Richter-Bernburg, 1955).

subaqueous gliding and the generation of isoclinal folds with the primary bedding reflected in the fold limbs. None of these or other mechanisms proposed explain all of the observed features and characteristics.

TO BE EXPLAINED

In developing a depositional and metamorphic mechanism for Muschelkalk salt genesis one must explain the following:

1. At Heilbronn where the sequence shows the maximum complexity in development, both the Unteres and Oberes Salz are underlain by anhydrite, potentially providing a source of solution for recrystallization through dehydration of the sulfate. However, the lower portion of the Unteres Bändersalz includes a sulfate layer (Unterer Zwischenanhydrit) which gives no indication of dehydration and consequent alteration of the overlying salt which retains its original structure and texture (Fig. 1, Table 1).
2. The contact between the Unteres Salz and the Unteres Bändersalz, although generally sharp (Fig. 3), may be gradational in the sense that the vertical striping characteristic of the Unteres Salz overlaps the lowermost layers of the Bändersalz or may be marked by a lens or band of anhydrite (Fig. 4).
3. A number of isolated irregular masses of typical primary (Linien Salz) structure are contained in the Unteres Salz, in every instance with the original banding still horizontal (Figs. 5a, 6a).
4. Bromine content of the salt in the pods of unaltered primary salt surrounded by Unteres Salz is essentially identical with that in the adjacent Unteres Salz, this supporting the recrystallization by synsedimentary solutions hypothesis proposed by Schachl (Figs. 5b, 6b).[1]
5. The vertical striping is not an expression of a linear trend. Continuation of the stripes into the mine roof presents a crude polygonal or cellular pattern (Fig. 7).
6. The structure of Anhydritsporaden, displaying bedding often horizontally banded in the center and dipping inward at the margins, strongly suggests a development of cavities into which sediment could be added following or

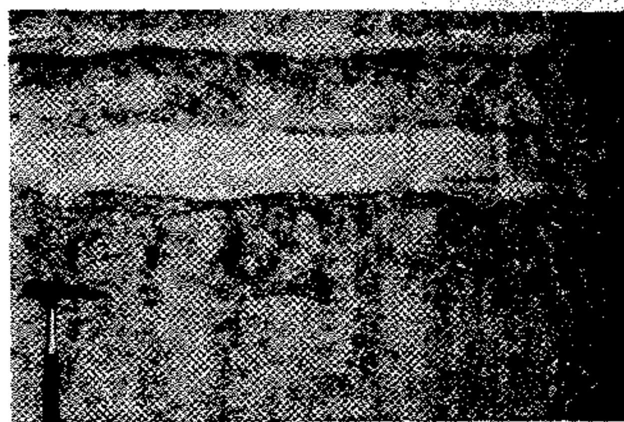

Figure 3. Sharp, relatively smooth contact between Unteres Salz and Unteres Bändersalz, Heilbronn.

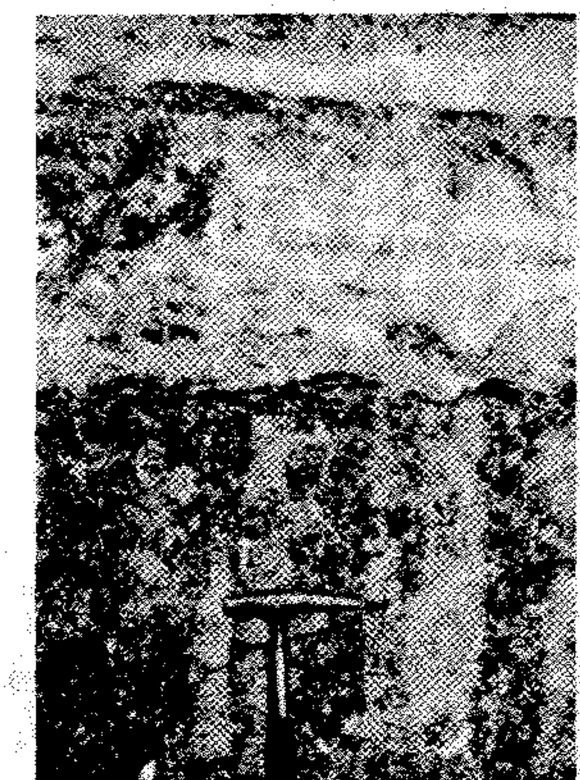

Figure 4. Irregular contact marked by local concentrations of anhydrite between Unteres Salz and Unteres Bändersalz. Heilbronn.

1. Bromine analyses by Kühn for Schachl (1954) were interpreted by Borchert (Borchert and Muir, 1964) as indicative of recrystallization by water released during dehydration of primarily gypsum because of an existing bromine content below that of normally first deposited halite. However, Muller (1964) proposed that the water from which Muschelkalk sulfates were deposited was altered in composition by influx of water from adjacent land surfaces. If such is also true for the overlying salt the potential exists for deviation from the percentage of bromine usually found in halite of primary deposition. Analyses referenced in this investigation are of 1) salt defined as primary on the basis of the preservation of depositional banding (not bromine content) and 2) salt in close proximity to primary salt defined as recrystallized on the basis of the development of vertical striping

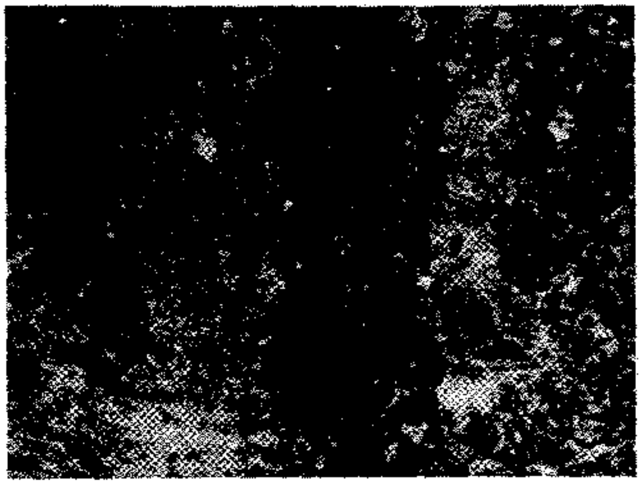

Figure 5a. Linien Salz in Unteres Salz, Heilbronn, Abbaustrecke NW1, 38.

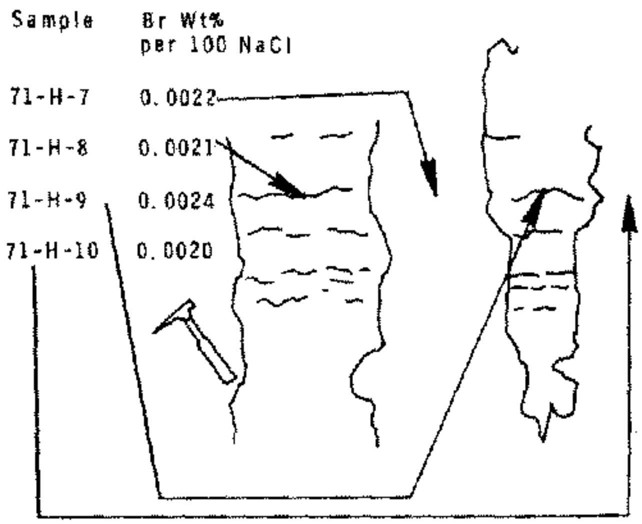

Figure 5b. Bromine analyses of Linien Salz and adjacent Unteres Salz.

simultaneously with the recrystallization of the Unteres Salz (Fig. 8).

7. Because of the position of the intervening Unteres Bändersalz, simultaneous post depositional recrystallization of Unteres and Oberes Salts is not feasible.
8. Disruption of the primary structure in Unteres Salz has not been of such a nature so as to destroy the continuity of a 2 centimeter thick anhydrite band as observed in the mine at Stetten bei Hagerlock. The band, although cross fractured into short segments, retains lateral continuity throughout the area of exposure (Figs. 9, 10).

To satisfy such requirements calls for an intermittent energy source acting during deposition or shortly following deposition of not only the Unteres Salz but the Oberes Salz, in the latter case without disturbance of the underlying Unteres Bändersalz.

Figure 6a. Linien Salz in Unteres Salz, Heilbronn, Abbaustrecke NW1, 33.

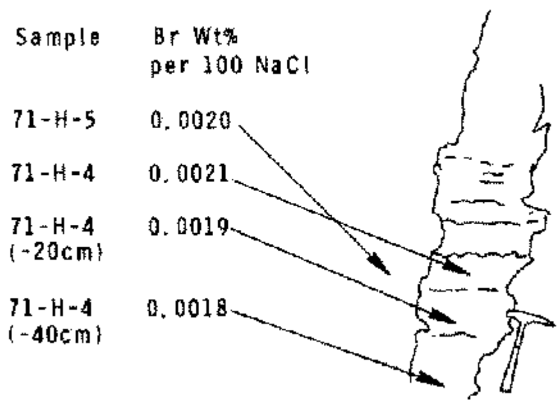

Figure 6b. Bromine analysis of Linien Salz and adjacent Unteres Salz.

A POTENTIAL MECHANISM

Earthquake activity may be capable of satisfying the requirements outlined. As a primary objection to such a mechanism one might point to the amassed evidence of quiescence in central Europe during Middle Triassic time, a period of deposition in shallow epicontinental seas, not a period of tectonic activity. However, evidence of earthquakes in the geologic record is sparce and has only recently been brought to light. An assumption of quiescence in the absence of information suggesting activity does not preclude examination of the geologic evidence and the revelation of the occurrence of such an evident. For example, studies of sedimentary rocks in Oklahoma indicate earthquake activity in Late Pennsylvanian time (Rasco, 1975), a pressure on the grains following the application of stress, tion of the United States.

Liquifaction has been observed in numerous sand bodies during and following earthquake activity. Liquifaction and its effects have not been observed or described in salt deposits, sediment which in physical properties contrasts strongly

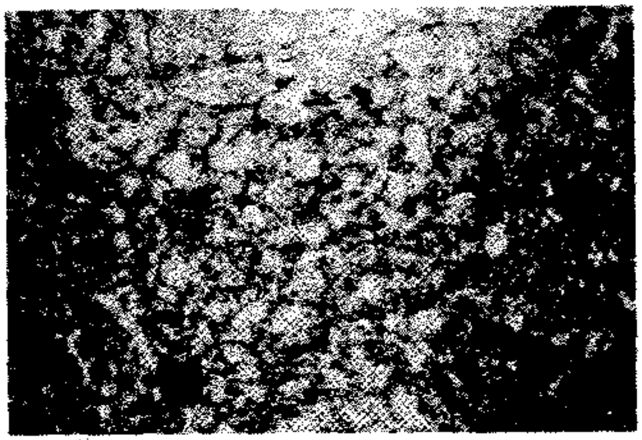

Figure 7. Polygonal pattern in roof, Heilbronn.

Figure 8. Typical Anhydritsporaden internal structure. Bedding in center is horizontal, progressively increasing in dip toward margin of structure. Specimen is approximately 12 centimeters high and only a part of the structure. Heilbronn.

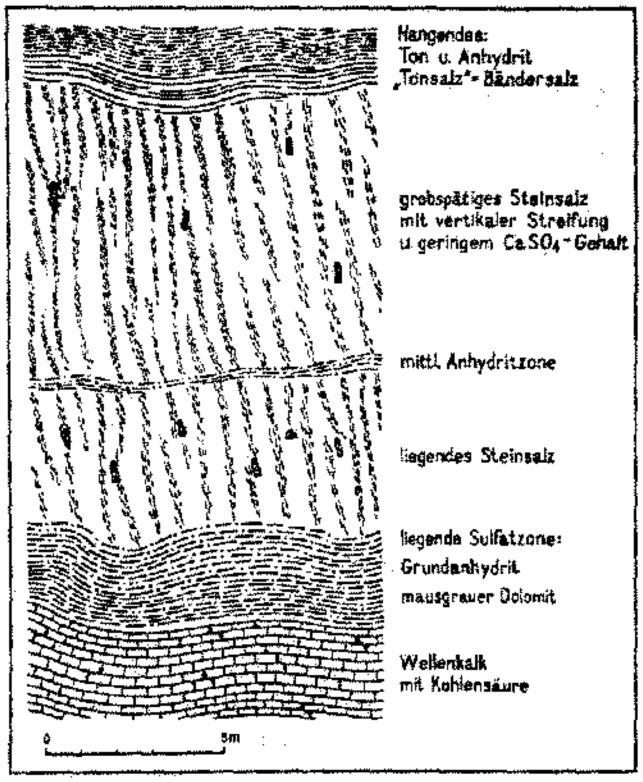

Figure 9. Schematic diagram showing salt sequence at Stetten bei Haigerloch (Schulz, 1967).

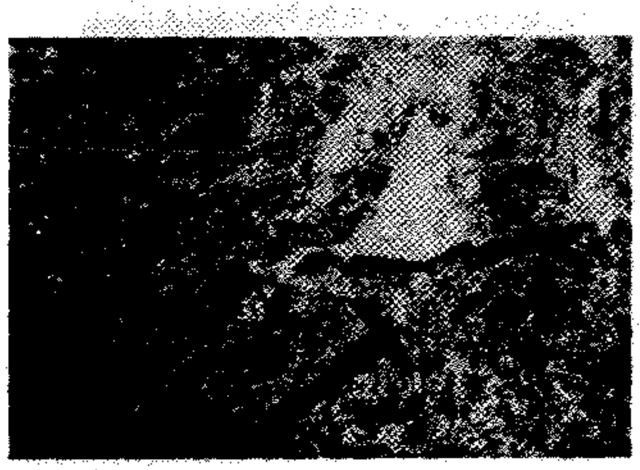

Figure 10. Mittl. Anhydritzone, Stetten by Haigerloch.

with the sand deposits in which liquifaction is generally observed.

The process of liquifaction in sand has been studied in the laboratory and criteria for the buildup of pore water pressure have been defined. Under ideal conditions liquifaction occurs in loose sands which, when subjected to a shearing stress tend to decrease in volume with a resulting increase in pore water pressure (Fig. 11) (Gilbert, 1976). During earthquake activity cyclic shear stresses are induced by ground motions and, if there is a residual pore water pressure on the grains following the application of stress, upward flow of water will occur, the time at which such occurs depending on overburden pressure. The basic conditions necessary for liquifaction are: 1) deposits of loose unconsolidated soil or sand, 2) saturation or near saturation and 3) a triggering mechanism.

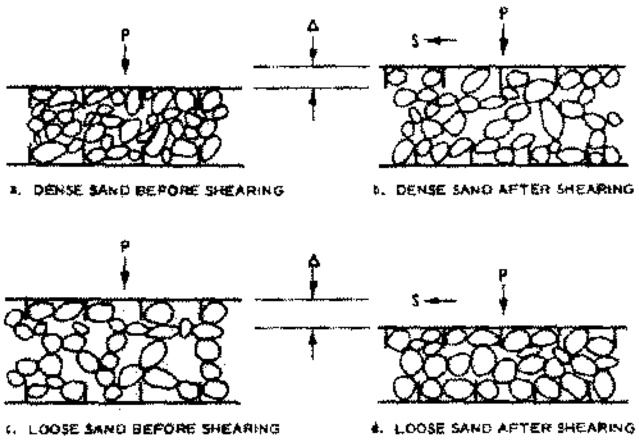

Figure 11. Comparative results of shearing in dense and loose sand (Gilbert, 1976).

A SCENARIO FOR DEPOSITION

It is proposed that the saturated, only partly lithified Unteres Salz with a primary (Linien) structure like that of the overlying Unteres Bändersalz acted in a manner similar to that of a saturated, loosely packed sand and, with the application of a cyclically applied shear stress as is generated during earthquake activity, responded in the manner of a sand during liquifaction. Having been disturbed with destruction of the crystal network and the ejection of a large volume of water lithifaction and recrystallization progressed rapidly. The overlying Unteres Bändersalz was subsequently deposited, in some areas directly on the underlying Unteres Salz (which in some areas lacked total disruption of the uppermost bands) and in other areas on an eroded surface above which is found a thin band of water insolubles of either 1) primary precipitation or 2) clastic accumulation through solution of the uppermost portion of the Unteres Salz. The inclusion of two anhydrite bands, one within and one at the top of the Unteres Bändersalz suggests relatively slow deposition of this intermediate sequence because of the necessity of reconcentration of the brine following dilution as suggested by the sulfate bands. Such time may be sufficient for consolidation of the Unteres Bändersalz. With renewed and rapid salt deposition, a sequence once more accumulated in such a physical state that liquifaction this time occurred only in Oberes Salz, the earlier deposited units having reached a state of near total consolidation.

The physical state of the salt sequence during or immediately after deposition can be predicted only through examination of modern analogues. At Zuni Salt Lake, New Mexico, a salt crust up to 20 centimeters thick immediately after termination of a single season of precipitation is consolidated although fragile and contains a high percentage of interstitial water. In the north arm of the Great Salt Lake, Utah, salt in a 1.5 meter core (maximum thickness in the lake) had undergone lithifaction to such a degree to achieve some strength but not to the state of removal of all pore water (J.H. Goodwin, personal communication). The degree to which 12–20 meters of salt would be consolidated is difficult to project. Because of the angularity of the grains and the ease of cleavage and crushing anticipated, volume reduction appears to be feasible, particularly with the application of cyclic stress as realized during earthquake activity. Impedence of drainage and buildup of pore pressure might be aided by the confining pressure of the overlying brine from which the salt had been precipitated. During vibration, primary structure expressed merely as thin laminae would surely be destroyed, and only isolated masses in which recrystallization had progressed to a greater degree would survive. Recrystallization as a consequence of disruption of structure and cohesion would be effected by the synsedimentary waters and early upward escape of brine may be responsible for the definition of the vertical cell pattern defined by concentrations of insolubles. The lack of development of the vertical striping in the Unteres Bändersalz should be interpreted as the result of achievement of a degree of consolidation and the expulsion of pore water before the onset of earthquake activity responsible for the development of the Oberes Salz structure. The deposition of anhydrite layers (Unterer and Oberer Zwischenanhydrit) within and at the top of the Unteres Bändersalz indicate brine addition and time lapses for the achievement of the degree of saturation required for renewed deposition of halite, time during which lithifaction might take place.

PROBLEMS

It is recognized that the proposed mechanism of Unteres and Oberes Salz formation is not without weaknesses. Whether or not poorly or unconsolidated salt behaves as does a loosely packed sand when subjected to such cyclic stress is yet to be determined. The degree to which the Unteres Salz was consolidated prior to the deposition of the overlying Unteres Bändersalz or the Oberes Salz prior to the deposition of the overlying clay carbonates or sulfates is unknown. The depth of water in the basin at the time of the earthquake activity, the motion of water in the basin and the degree to which the water level changed or the basin dessicated cannot be determined. That a change in composition of basin water might occur as the result of a violent disturbance of the basin is suggested by the sharp change in bromine content noted at the contact between Unteres and Unters Bändersalz (Kühn, 1964) (Figs. 12, 13). The degree of saturation of the basin brine when thoroughly mixed during the period of turbulence and the extent to which previously deposited salt was removed is also unknown. However, in the absence of a more conventional mechanism of layer-selective, primary structure destruction and metamorphism, such an unconventional mechanism at least merits evaluation.

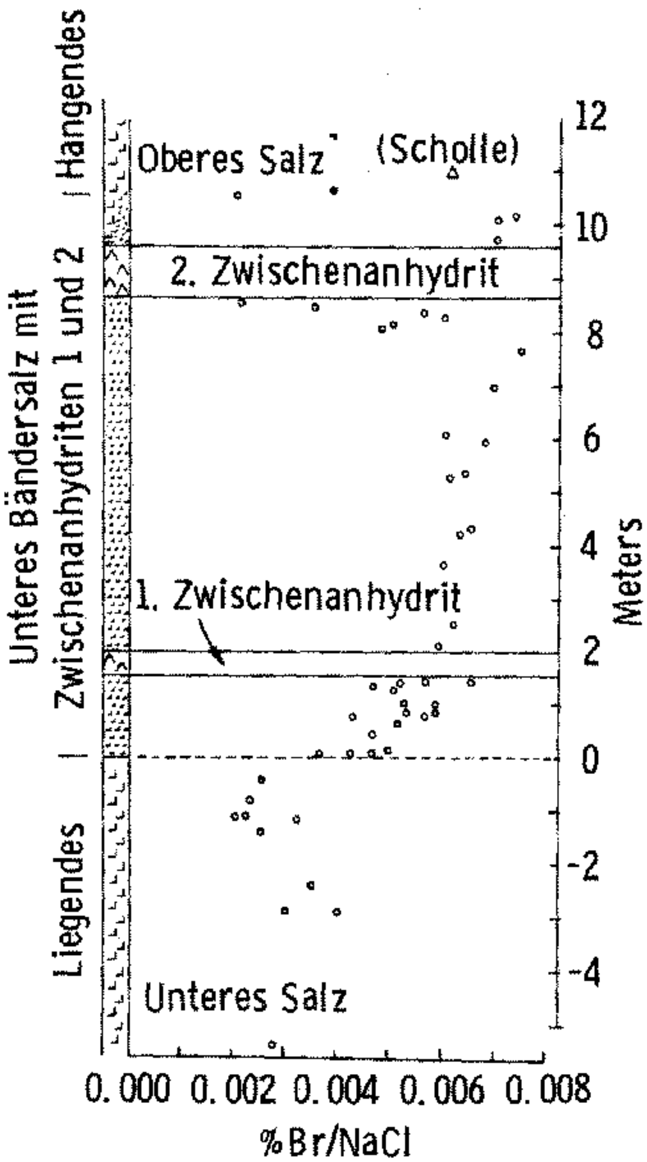

Figure 12. Bromine profile through Unteres Salz and Unteres Bändersalz at Kochendorf (Kühn, 1964).

SOLUTIONS

Considering the number of unknown parameters of deposition and alteration, the merit of any mechanism can be determined only on the basis of the degree to which it accounts for the existing salt sequence. Specifically:

1. An earthquake mechanism explains the contrast of Oberes and Unteres Salz with Unteres Bändersalz without the need for explaining the lack of recrystallization in Unteres Bändersalz immediately above the Unterer Zwishenanhydrit.
2. It permits the development of all observed contacts between the Unteres Salz and Unteres Bändersalz: 1) overlap due to lack of total destruction of the bedding in the uppermost part of the Unteres Salz, 2) a sharp contact due to erosion (solution) of the uppermost portion of the Unteres Salz or 3) the concentration of insolubles along the contact prior to deposition of Unteres Bändersalz.
3. It provides for preservation of some masses of primary salt in the Unteres Salz.
4. It uses synsedimentary water for recrystallization, eliminating a need for contrast in bromine content between Unteres Salz and the enclosed remnants of Linien Salz.
5. It provides a mechanism for development of channels along which water insolubles can enter the Unteres Salz following primary bedding destruction.

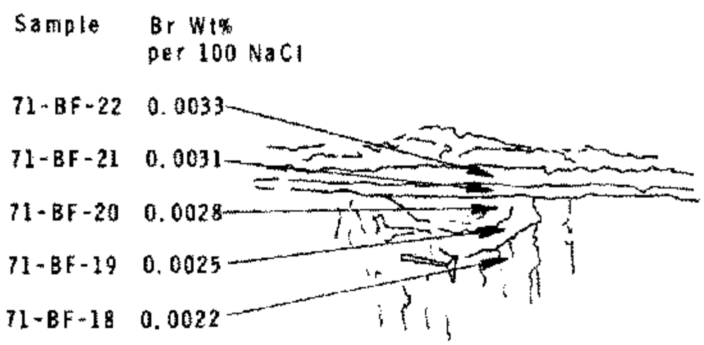

Figure 13. Contact (with bromine analyses above and below) between Unteres Salz and Unteres Bändersalz, Kochendorf, Wetterstrecke A, 10W.

6. It permits the retention of continuity in the anhydrite band through the Unteres Salz at Stetten.
7. Potentially it presents an opportunity for the development of vortices in basin waters which might scoop out the depressions in the Unteres Salz in which the Napf structures have developed as proposed by Schachl (Kühn, personal communication).

Improbable this explanation may be, but it does offer an alternative to the impossible!

DISCUSSION

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Comment. Der vorgelegte Beitrag beinhaltet eine recht unkonventionelle Deutung eines Phänomens, das zu deuten bis anhin noch nicht befriedigend gelungen ist. Wir begrüssen deshalb jeden Versuch einer Erklärung, auch wenn die Ideen noch nicht durch abgesicherte Fakten untermauert sind. Hier aber stellen sich u. a. zwei Fragen, auf die unseres Erachtens unbedingt eingegangen werden sollte:

1) Der vorgeschlagene Mechanismus setzt eine Art thixotropes Verhalten des Salzes im Zeitpunkt des Erdbebens voraus. Eine solche Eigenschaft ist bis anhin noch nicht bekannt und sollte deshalb unbedingt experimentell untermauert werden.

2) Die Erdbeben müßten praktisch während der Bildung des Salzlagers stattgefunden haben, bevor es zu einer stärkeren Überlagerung gekommen ist. Auch wären spätere Rekristallisationen praktisch auszuschließen. Nun stehen wir aber unter dem Eindruck, daß das vertikal ausgerichtete, hexagonale Muster ein schon verfestigtes Salzlager überprägt hat, Bändersalz-Schollen mit scharfen Umrissen darin enthalten sind. Es ist deshalb sehr wesentlich, die zeitlichen Relationen mit in die Betrachtung einzubeziehen.

Answer. Although the proposed mechanism may have been somewhat of a shock to those familiar with the Muschelkalk, it was the feeling of the senior author that a complete reevaluation of all of the geologic data without the consideration of mechanisms previously proposed was in order. It is true that the proposed mechanism has not been demonstrated experimentally (and we agree that it should be attempted), but our proposal does not stand alone in this respect. We realize that what is presented is open to criticism, if for no other reason than because of its radical departure from those offered previously, and if proven to be grossly in error, will have at least inspired an interest in the development of a mechanism which (like ours) is compatible with all of the geologic evidence now available.

REFERENCES

Borchert, Herman and Muir, R.O. 1964. Salt Deposits, the Origin Metamorphism and Deformation of Evaporites. New York, D. van Nostrand, 204–210.

Gilbert, P.A. 1976. Case Histories of Liquifaction Failures. U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, 5–8.

Kühn, Robert. 1964. Salzmineralien (Geochemie) bezüglich der Salzlagerstätten von Wurttemberg/Hohenzollern und Südbaden. Hannover, Kaliforschungs-Institut e. V., 16 pp.

Müller, Gerhard. 1964. Ein Beitrag zur Geochemie des Strontiums in Ca-Sulfat-Gesteinen. Unpublished doctoral dissertation, Univ. Saarbrücken.

Rasco, Bailey, Jr. 1975. Tectonic Origin of Preconsolidation Deformation in Upper Pennsylvanian Rocks Near Bartlesville, Oklahoma. Am. Assoc. Petrol. Geol. Bull. 59: 1626–1638.

Richter-Bernburg, G. 1955. Über salinare Sedimentation. Deutsche geol. Gesell. Zeitschr., 105 (1953): 593–645.

Schachl, Erich. 1954. Das Muschelkalk in Südwestdeutschland. Neues Jahrb. Geologie u. Paläontologie Abh., 89: 309–394.

Schulz, Günter. 1967. Die Geschichte des Salzwerks Stetten bei Haigerloch. Landeskundlichen Forschungsstelle des Landeskommunalverbandes der Hohenzollerischen Lande, 7: 70 pp.