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Diagenesis of Triassic evaporites in northern Switzerland

By HANS DRONKERT¹⁾

ABSTRACT

Examination of Triassic cores from the Nagra boreholes Schafisheim, Riniken, Leuggern, Böttstein and Weiach and the NOK well Beznau, reveal a complex sequence of evaporitic authigenic minerals, including dolomite, gypsum, anhydrite, halite, chert and talc, which are interpreted to represent an eogenetic assemblage. Subsequently, during mesogenetic (burial) diagenesis gypsum dehydrated to anhydrite. Later replacement of anhydrite by megaquartz and dolomite is recorded in sulphate-bearing carbonate beds. Concentrations of sphalerite, fluorite and megaquartz are also present throughout the studied sequence. Ultimately, following post-Tertiary uplift, meteoric water ingress into the shallow wells Beznau, Böttstein and Leuggern resulted in telogenetic hydration of the anhydrite, causing fracturing of the host rock and extensive dissolution of the sulphates. Although most original sedimentary structures are still preserved, practically all the primary authigenic minerals have undergone subsequent diagenetic modification since eogenesis.

ZUSAMMENFASSUNG

Mineralogische und textuelle Untersuchungen an den Kernen der evaporitischen Serien des Mittleren Muschelkalks und des Keupers aus den Nagra-Tiefbohrungen Böttstein, Leuggern, Riniken, Schafisheim, und Weiach sowie aus der NOK-Bohrung Beznau lassen erkennen, dass diagenetische Prozesse die primäre mineralogische Zusammensetzung dieser Sedimente stark veränderten. Eine komplexe Abfolge evaporitischer Minerale, hauptsächlich Dolomit, Gips, Anhydrit, Halit, Chert und Talk wird als frühdiagenetische Mineralvergesellschaftung interpretiert. Insbesondere die noch unter dem Einfluss des Ablagerungsmilieus erfolgte Ausscheidung von Gips und knolligem Anhydrit, die Dolomitisierung und Silifizierung von Karbonaten sowie die partielle Lösung von Halit und Sulfaten veränderten diese Gesteinsabfolgen nachhaltig.

Während der folgenden Versenkungsdiagenese wandelte sich bei Temperaturen über 50°C meist aller Gips unter Wasserabgabe zu Anhydrit um. Die Verdrängung von Anhydrit durch Megaquarz und Dolomit und die Freisetzung von im Anhydrit vorhandenen Spurenelementen führte in der Folge zur Ausscheidung schwerlöslicher Mineralphasen wie Fluorit, Sphalerit, Pyrit und Cölestin.

Im Anschluss an die posttektonische Hebung der Region führte der Zufluss von meteorischem Wasser einerseits oberflächennah zur Vergipsung des Anhydrits (z. B. Gipskeuper in Böttstein). Andererseits fand Hydratation der an wasserführende Schichten grenzenden randnahen Partien der Evaporitserien statt (Beznau, Böttstein, Leuggern). In den Bohrungen mit über 500 m Überlagerung des Gipskeupers tritt dieser Effekt nicht auf.

Introduction

A spectacular sequence of Triassic evaporites, only poorly represented at outcrop, is preserved in the Nagra boreholes Schafisheim, Riniken, Böttstein, Leuggern and Weiach and the NOK well Beznau of northern Switzerland (Fig. 1). This paper discusses the

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diagenetic history of these evaporites by means of an integrated sedimentological and petrographical approach. More comprehensive background sedimentological and chemical data is published or will be published in the Nagra reports (MÜLLER et al. 1984; PETERS et al. 1985; MATTER et al. 1987a, b, c; PETERS et al. 1987a, b; BLÄSI et al. 1987; DRONKERT et al. 1987b).

On a European scale the Triassic of northern Switzerland forms the marginal facies between the crystalline massifs (Black Forest-, Vindelician-, and Central Swiss Massif) and the more basal facies towards the north (SCHWARZ 1975; ZIEGLER 1982). The Triassic in northern Switzerland directly covers extensive Hercynian crystalline basement rocks and the less extensive Permo-Carboniferous trough sediments (MÜLLER et al. 1984).

Triassic evaporite sequences are notoriously difficult to interpret (see, for example, ARTHURTON 1980). There is no direct recent analogue to aid their interpretation and they are usually placed in a continental to marginal marine depositional setting based on the data from the over- and underlying clastic and carbonate sediments (HELING 1979; MERKI 1961; SCHWARZ 1975). The peneplaned Triassic continental setting might have

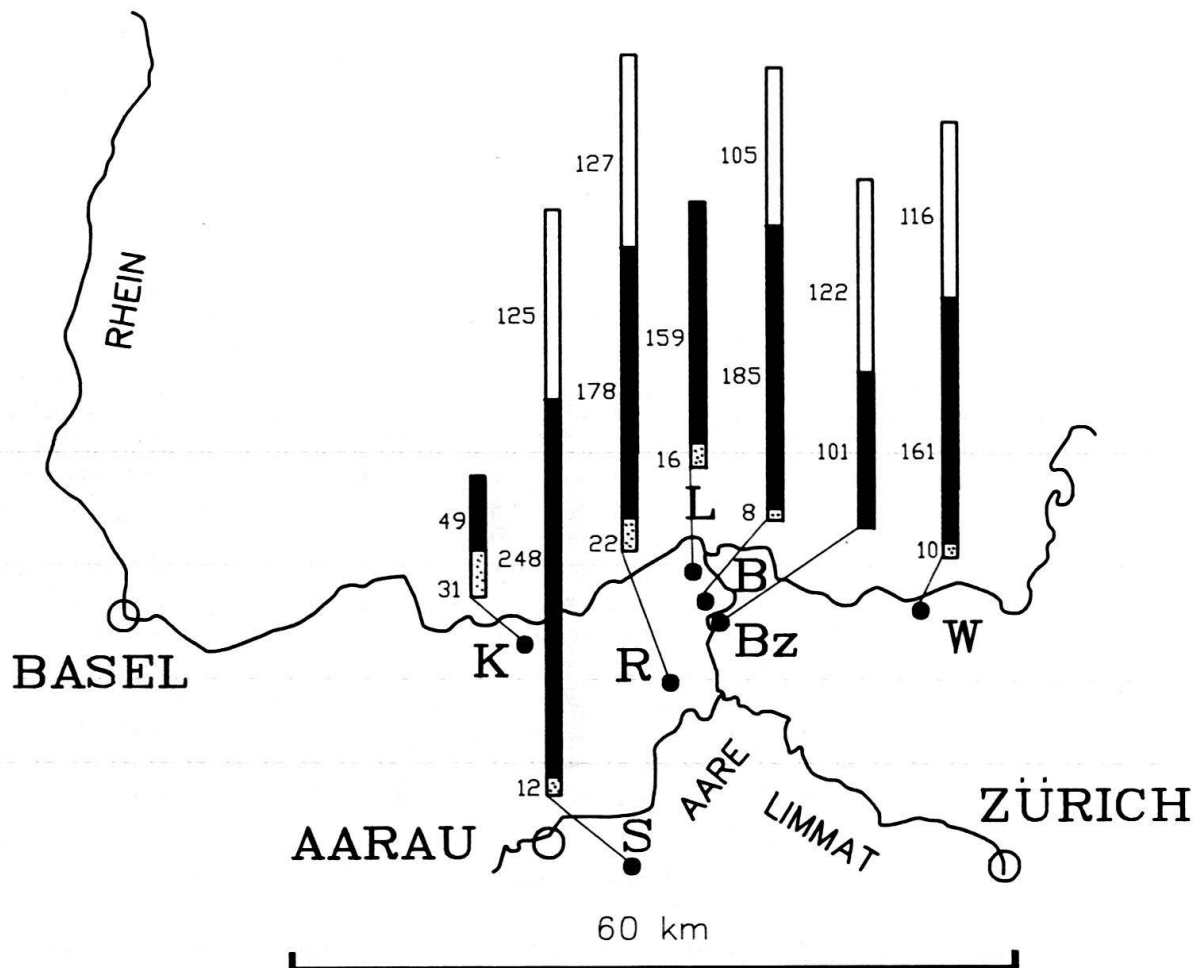


Fig. 1. Location map of Nagra & NOK wells. K = Kaisten, S = Schafisheim, R = Riniken, L = Leuggern, B = Böttstein, Bz = Beznau (NOK), W = Weiach. Columns represent the Triassic from the cores, Buntsandstein is dotted, Muschelkalk is black and Keuper is white. Numbers next to the columns correspond to the thickness of the Triassic subdivisions in meters.

contributed to the development of the typical Triassic evaporite facies, but subsequent mesogenetic and telogenetic diagenetic alteration of the evaporite minerals has played an important role in modifying the evaporite minerals. This paper describes diagenetic textures and minerals observed in these evaporites with the aim to improving the understanding of eogenetic mineral assemblages and textures developed during the Triassic.

Stratigraphy and correlation between wells

The sedimentary sequence in which the northern Swiss evaporites occur belongs to the Triassic. The sequence can be subdivided according to the Germanic Triassic stratigraphic subdivisions of Keuper, Muschelkalk and Buntsandstein (Fig. 1). The Buntsandstein contains no primary evaporites but is locally cemented with sulphate and sporadic sulphate nodules are developed. This study concentrates on the primary evaporites found in the Middle Muschelkalk and the Keuper (BONTE 1951; HAUBER 1960; RICOUR 1960). The Middle Muschelkalk evaporites belong to the Sulfatschichten and the Salzschiechten and contain in addition to sulphates, also halite (HAUBER 1971, 1980). The Keuper evaporites belong to the Gipskeuper and are restricted to anhydrite and gypsum in this area (TRÜMPY 1959).

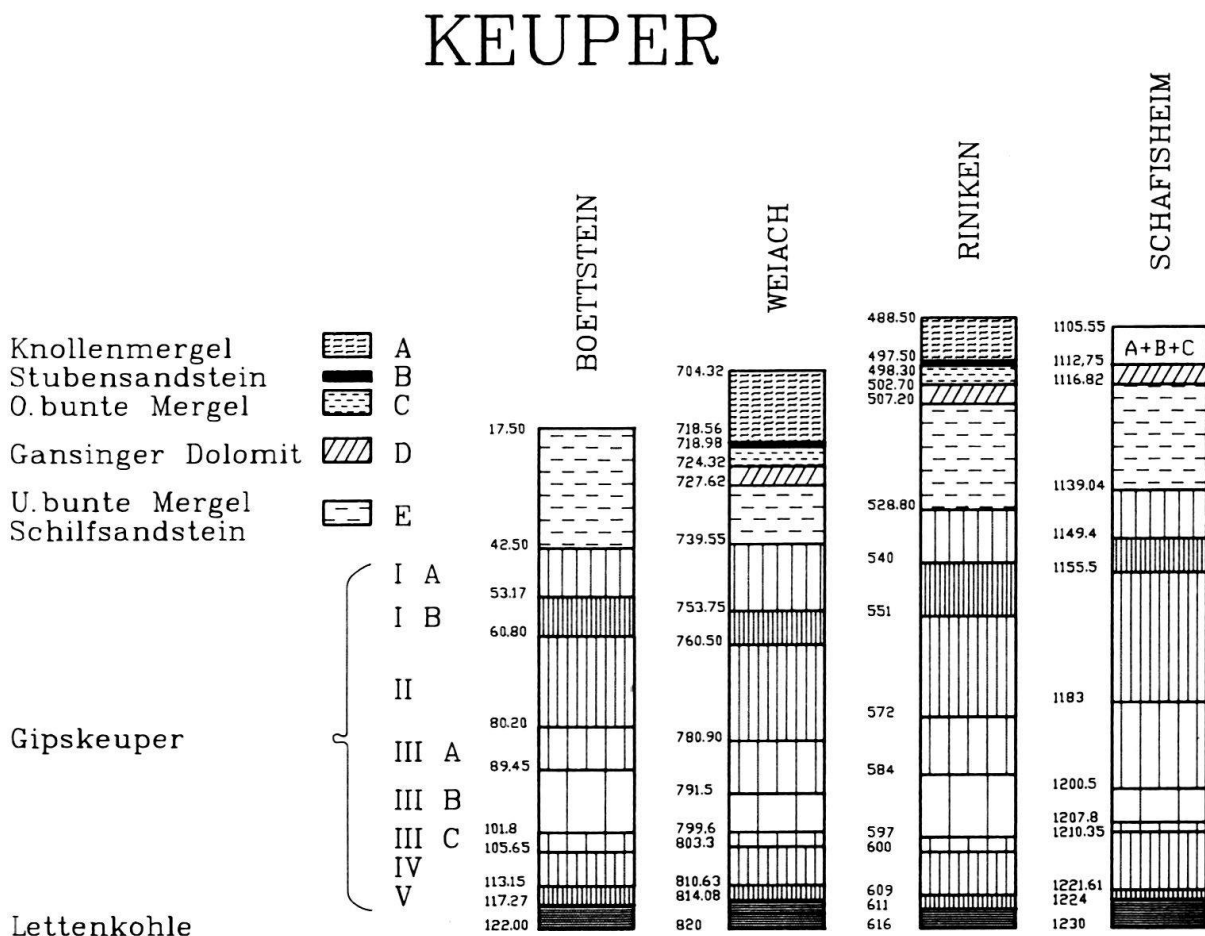


Fig. 2. Keuper profile. The units of the clay and sulfate bearing Gipskeuper are not hatched in sulfate fashion but vertically to facilitate and stress correlation. Depth in meters.

Correlation between the wells is based on core lithology and on well log data. The Keuper sediments are only present in the wells Schafisheim, Riniken, Böttstein and Weiach. In Riniken, however, the Keuper was not cored. The Middle Muschelkalk evaporites are present in cores from Schafisheim, Riniken, Leuggern, Böttstein, Beznau and Weiach. In Schafisheim faults duplicate part of the Muschelkalk and hence the stratigraphic thickness of the evaporites does not represent the true stratigraphic thickness.

Correlation of the various units is discussed in more detail in DRONKERT et al. (1987a), but is remarkably consistent (Fig. 2 & 3). Nonetheless, individual beds, particularly in the Gipskeuper, do vary in lithology and thickness, but this variation is too small to be resolved with the available resistance logs.

There are, however, major differences in the sulphate facies developed between the studied wells. In Schafisheim, Riniken and Weiach, anhydrite is the predominant sulphate, whilst in the shallow wells Böttstein, Beznau and Leuggern most anhydrite down to a depth of respectively 60 m, 140 m, and 210 m and anhydrite adjacent to the more porous zones underlying the Gipskeuper (Lettenkohle) and overlying the Sulfatschichten (Dolomit der Anhydritgruppe and Trochitenkalk) has been hydrated to gypsum.

MIDDLE MUSCHELKALK "ANHYDRITGRUPPE"

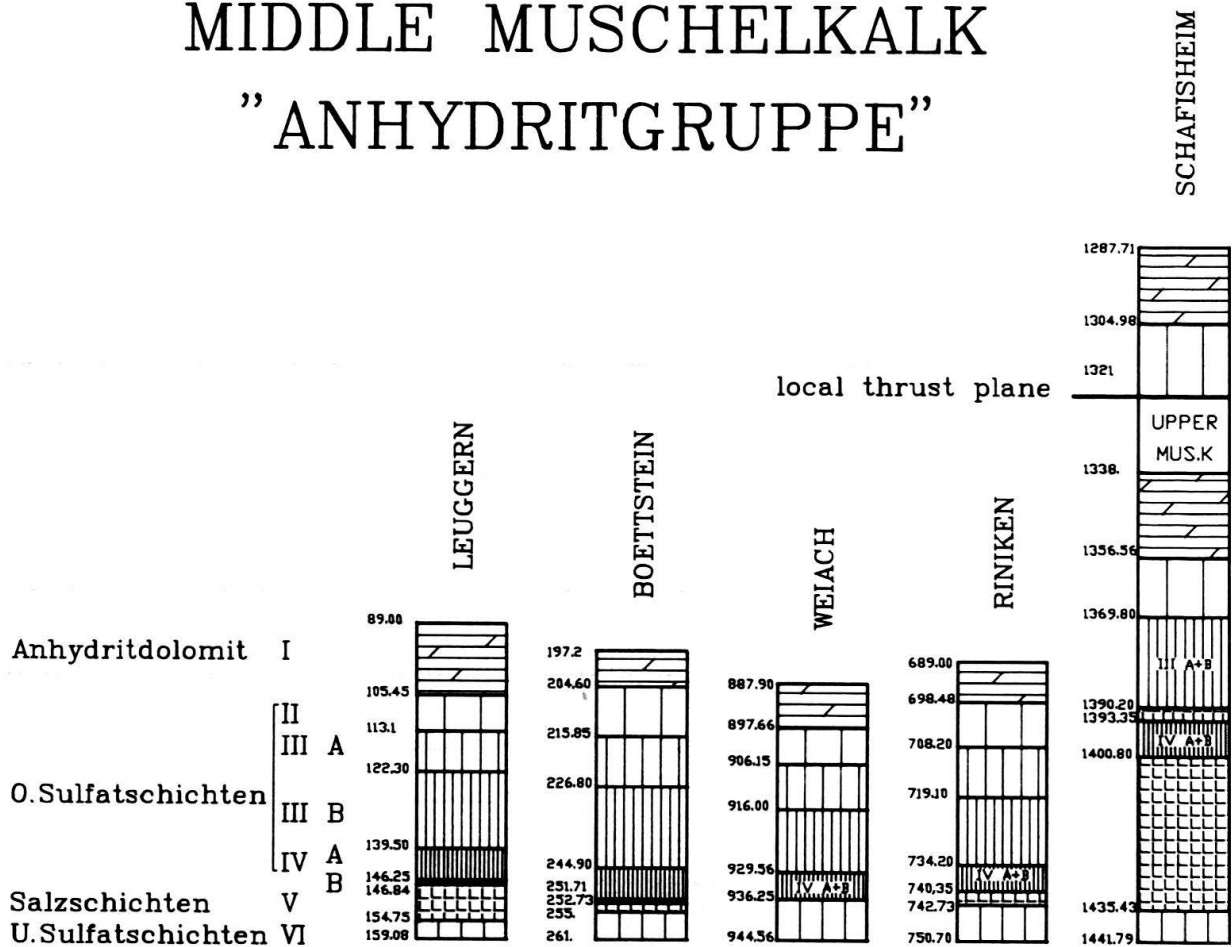


Fig. 3. Middle Muschelkalk profile of the Anhydritgruppe. The units of the clay and sulfate bearing Sulfatschichten are not hatched in sulfate fashion but vertically to facilitate and stress correlation. Depth in meters.

Lithofacies

Four main lithofacies associations can be recognized in the studied cores from the Gipskeuper and the Anhydritegruppe:

1. a sulphate facies,
2. a carbonate facies,
3. a clay facies,
4. and a chloride facies.

Additionally, coarse siliciclastics, chert and phosphate lithologies are interbedded with the main lithofacies. More detailed descriptions are given in DRONKERT et al. (1987a).

Sulphate lithofacies association

The sulphate facies association comprises seven main sulphate lithofacies with related subfacies. Where possible use has been made of the nomenclature defined by HOLLIDAY (1970), MAIKLEM et al. (1969), ORTI (1977) and DRONKERT (1985).

1. *nodular sulphate*. Anhydrite or gypsum nodules, red, rose, white, grey or blue coloured. Three subfacies can be distinguished: chickenwire anhydrite (Pl. 1A), grey ragged nodular sulphcretcs (Pl. 1B) and whitish isolated nodules in carbonates or sulpharenites,
2. *selenitic sulphate*: pseudomorphs of selenitic gypsum crystals as crystal stringers or massive beds (Pl. 1C & 1D),
3. *arenitic sulphate*: clastic gypsum grains now anhydrite (Pl. 1E),
4. *crystal accumulates*: anhydrite lath crystals that have accumulated horizontally on the bedding plane (Pl. 2F),
5. *dissolution accumulates*: after halite (concentration in bands of less soluble minerals as anhydrite, carbonates and siliciclastics during dissolution of halite incorporating these minerals),
6. *sulphate rudites*: collapse breccia and intraformational conglomerates,
7. *sulphate veins*: anhydritized early gypsum veins (KENDALL 1975, Pl. 1F), and late fibrous gypsum (Pl. 1A, 1E & 1H).

Carbonate lithofacies association

Four main lithofacies associations are recognized each with subfacies:

1. *homogeneous carbonate mud facies*: micrites and dolomicrites,
2. *laminated carbonate mud*: even laminated or irregular, wavy to domed micrites and dolomicrites, sometimes with birds-eye laminae (partly stromatolitic (GEBELEIN & HOFFMAN 1968, 1973)),
3. *carbonate arenites*: oosparites, oopackstones, pelsparites and pelmicrites with carbonate, quartz or anhydrite cements, and pseudo arenites of dolomite rhombs that have recrystallized from calcite or sulphate precursor grains,
4. *carbonate rudites*: coarse shell debris, bone beds, collapse breccia (dissolution of carbonate or sulphate) and intraformational conglomerates created through erosion of carbonate beds (Pl. 1G).

Clay lithofacies association

The clay facies association consists of three main lithofacies:

1. *carbonate-poor black clays* often rich in organic matter, associated with sulpharenite and selenite facies,
2. *carbonate-rich dark to light brownish green clays*, often associated with sulphcretes,
3. *carbonate-containing red to brownish green clays*, associated with nodular sulphates (Pl. 1F).

Other lithologies

In addition to the main lithofacies, several minor lithologies are variously interbedded with the lithofacies associations:

1. chert bands or layers replacing sulphate nodules (Pl. 1H),
2. chert replacing carbonate beds (replace ooids, micrites, stromatolites),
3. siliciclastic sand- and siltstones with quartz, plagioclase, K-feldspar and quartz overgrowth mostly in carbonate matrix or cemented by sulphate or carbonate,
4. phosphatic bone beds, containing common fish teeth and scales together with rare bone fragments all set in a coarse carbonate matrix,
5. sphalerite crystal stringers in carbonate and sulphate beds,
6. pyrite concentrations in carbonate or sulphate beds,
7. fluorite in carbonate and former sulphate beds (Pl. 3B, 3E & 3F).

Sedimentary structures

Detailed sedimentological study of the cores reveals abundant primary and secondary sedimentary structures. These will not be discussed in detail in this paper but are published elsewhere (DRONKERT et al. 1987 a & b in prep.). Erosional surfaces, dissolution surfaces (Pl. 1G) and primary crystal precipitates provide evidence for the presence of original depositional surfaces and surface relief. Deposits of pools and ponds, larger lagoons, gullies and salt flats can be recognized. Cross-bedding, oscillation (wave) ripples and graded bedding are indicative for subaqueous traction currents. Convolute bedding, load casts, ball- and pillow-structures together with oversteepened cross-bedding suggest considerable mechanical sediment instability contemporary with deposition.

Desiccation is indicated by the presence of mudcracks, particle shrinkage, dish and teepee structures (Pl. 1E), and intraformational conglomerates (Pl. 1G), whilst the local development of burrows and roots reflects the less hostile initiation of evaporite deposition in the Middle Muschelkalk.

These sedimentary structures indicate deposition in a complex, low lying, salt flat environment that can be compared with modern environments such as the North African inland sabkhas (Gipskeuper, see BOURCART & RICOUR 1952; DUSSART 1962; BUSSON & PERTHUISOT 1977) and the coastal sabkhas of the Persian Gulf (Sulfatschichten, see PURSER 1973). However, a variety of structures that do not have recent analogues are here considered as diagenetic features. Extreme caution is required to avoid confusing diagenetic fabrics that mimic many of the original sedimentary structures.

Microfacies

Observation of the evaporites under the polarizing microscope was carried out on the carbonate-, sulphate- and quartz-microfacies groups.

1. The carbonate microfacies group consists of micrite, dolomicrite, pelsparite, pelmicrite, oosparite, oopackstones, birds-eye-micrites, radial (spherulithic) calcites, dolomite rhombs, coarse dolomite crystals replacing anhydrite, dolomite pore-lining cements, calcite fracture-fills (nomenclature based on DUNHAM 1962; FOLK 1962).
2. The sulphate microfacies group consists of anhydrite and gypsum microfacies (nomenclature based on MAIKLEM (1969) and DRONKERT (1985):

Anhydrite microfacies:

- a. *blocky anhydrite* (slow growth, replacement of anhydrite and gypsum, Pl. 2A, C, E),
- b. *aphanitic anhydrite* (microcrystalline anhydrite, Pl. 2B),
- c. *felted anhydrite* (small lath of randomly oriented anhydrite, Pl. 2C),
- d. *fibrous anhydrite* (replacement of fibrous gypsum or later anhydrite outgrowth, Pl. 2B),
- e. *lath-type anhydrite* (later outgrowth of anhydrite nodules, Pl. 2D),
- f. *anhydrite lath accumulates* in dolomicrite/clay matrix (Pl. 2F),

Gypsum microfacies:

- a. *alabastrine gypsum* (fine crystalline gypsum, undulose wavy extinction, vague crystal boundaries, equidimensional to elongate anhedronal crystals (Pl. 2G),
- b. *fibrous satin spar veins* (fibrous crystallites perpendicular orientation of the long fibres to the attachment surface, elongate sharp to vague crystal contacts, s-distortion due to differential movement of fracture walls (Pl. 2G & 2H),
- c. *lenticular gypsum*, typical in-sediment type of gypsum (only recorded as voids, anhydrite, carbonate, or fluorite replacements),
- d. *selenitic gypsum*, typical subaqueous type of gypsum (only recorded as anhydrite and carbonate replacements, Pl. 2C & 2E),
- e. *gypsarenites*, only observed as dirty blocky anhydrite, as felted anhydrite or as coarse crystalline carbonates with variable grains and matrices.

3. The quartz microfacies group consists of various types of chert, quartz and chalcedony:

- a. *chert replacement* of micrite,
- b. *chert fill* of birds-eyes/fenestrae,
- c. *chert replacement* of ooids,
- d. *mega-quartz cement* in carbonate grainstones,
- e. *mega-quartz cements* as quartz overgrowth,
- f. *mega-quartz replacement* of anhydrite (GRIMM 1962),
- g. *chalcedony replacement* of dolomite,
- h. *quartz-arenite and quartz-wacke* in rare sand and siltstones.

Additionally, various other authigenic minerals occur as replacements, including fluorite, sphalerite, pyrite, phosphate and halite.

Early diagenesis

Sulphate and carbonate sediments are very susceptible to early diagenetic changes (KINSMAN 1969, 1974; SHEARMAN 1966, 1978). In the studied Triassic evaporites, textural and mineralogical observations indicate that many of the present fabrics and authigenic assemblages can be attributed to eogenetic modifications that are related to the Triassic environment. No primary gypsum has been preserved, but sedimentary structures and diagenetic fabrics indicate its original presence as lenses and selenite crystals. The petrographic studies documented here are interpreted to indicate that the main products of eogenesis were anhydrite/gypsum nodule formation, dolomitization of micrites, silicification of selected carbonates, sulphate and halite dissolution, reduction of sulphate by bacteria and the consequent formation of pyrite, and precipitation of early carbonate cements (cement A, meniscus cements, cement B). Additionally, X-ray diffraction studies (MATTER et al. 1987a, b, c (in press) & PETERS et al. 1985, 1987a, b (in press)) indicate the presence of authigenic talc and corrensite in clayrich evaporite horizons and oolite beds.

This authigenic mineral assemblage is typical of that reported from modern evaporite environments (see for sulphate nodules HOLLIDAY 1970; DRONKERT 1977; WEST et al. 1979, for dolomitization DEFFEYES et al. 1964; MURRAY & LUCIA 1967, for chemical alterations in sabkha sediments BUSH 1970, 1973 and for bacterial reduction of sulphates BERNER 1985; BIRNBAUM & WIREMAN 1984).

Burial diagenesis

In the deep wells anhydrite dominates the sulphate mineralogy whereas in the shallow wells gypsum is common and dominant in the top and bottom parts of the evaporitic sequence. This remarkable difference is easily explained when one looks at the temperature and pressure ranges of the stability fields of both minerals.

Gypsum is not stable at temperatures above 50–60°C under 1 atmosphere pressure (see compilation of work on gypsum-anhydrite transition point temperatures in DRONKERT 1985) and it will therefore dehydrate to anhydrite. This transition takes place after a few hundred meters of burial in an open system when lattice water is expelled during compaction due to lithostatic pressure.

Nonetheless, in a closed system gypsum occupies less volume than anhydrite plus the equivalent quantity of lattice water and therefore gypsum is more stable than anhydrite at high pressures. Nevertheless, the temperature effect is stronger than the pressure effect and therefore, given a normal geothermal gradient of 30°C/km, will convert gypsum to anhydrite at depths below 1000 m (MARSAL, 1952). However, the system was not completely closed as the investigations on the Muschelkalk aquifers confirm (BLÄSI et al. 1987). When the lattice water of the gypsum can escape the gypsum-anhydrite transition will take place as soon as the lithostatic pressure is greater than the hydrostatic pressure. Because the depositional brine was saturated in halite at times, infiltration and persistence of this brine in the pore space will create a high salinity pore brine that will lower the dehydration temperature for gypsum to about 20–40°C at 1 atmosphere pressure. Also the geothermal gradient was a little higher, about 45°C/km (KEMPTER in this issue). Therefore, the transition from gypsum to anhydrite took place at a depth of considerably less than 1000 m, probably between 200 and 600 m. This burial depth was reached in

northern Switzerland during the Upper Jurassic to Lower Cretaceous (LAUBSCHER 1980) and under the ambient conditions at these depth, the most important mesogenetic reactions in the Triassic evaporites were initiated. These changes involved the complete transition from gypsum to anhydrite (see contrasting opinion of BAUMANN & STUCKY 1984), followed by replacement of the anhydrite. Anhydrite was subsequently replaced by mega-quartz, dolomite and fluorite (SHEARMAN & FULLER 1969). Despite the "exotic" nature of the present mesogenetic authigenetic mineral assemblage, comprising fluorite, sphalerite, pyrite and celestite, all the ions required for these cements/replacements can be derived from the original eogenetic sulphates and halite (RENFRO 1974; EUGSTER 1985). Most mesogenetic reactions are inferred, therefore, to have operated in an essentially closed system with redistribution and concentration of the described ionic species taking place. Late mesogenetic dolomite, occurring as large rhombic replacements, was probably precipitated from Mg-rich brines. The origin of late mega-quartz is problematical but probably originates from the remobilization of eogenetic opaline chert. In addition to the complex cementation and replacement fabrics outlined above, some secondary porosity was also created through the dissolution of carbonates and sulphates during mesogenesis.

Influence of meteoric water

In wells where the Triassic evaporites occur at only shallow depths, hydration of the anhydrite is pervasive and complete down to depth of 60 m in Böttstein, 140 m in Beznau and 210 m in Leuggern. Anhydrite relics remain only where preserved in megaquartz crystals and as nuclei of the largest sulphate nodules. The hydration of anhydrite to gypsum results in a volume increase of 64%, that will create an excess volume of gypsum if all original anhydrite is replaced by the same volume of gypsum. The resulting gypsum precipitated destroyed the original anhydrite fabric with the formation of alabaster (Plate 2G). The excess gypsum is precipitated as fibrous satin spar gypsum veins that are mostly orientated parallel to bedding (see SHEARMAN 1982; SHEARMAN et al. 1972; also Pl. 2H). At greater depth the hydration diminishes and affects the nodule margins while the nodule core survives as anhydrite (Pl. 1A). On Plate 1A the effect of hydraulic fracturing and the subsequent generation of extension veinlets is remarkably clear. This extensive gypsification is considered to be related to the initial ingress of meteoric waters in response to telogenetic uplift.

Meteoric water is highly undersaturated with respect to gypsum or anhydrite and will readily dissolve these calcium sulphates. The fact that not all sulphate has been dissolved completely is due to slow dissolution kinetics and the rapid saturation of the groundwater in the porous watercontaining limestone sequences that border the Muschelkalk evaporites (BLÄSI et. al. 1987). Calcite is probably the latest authigenic cement to have precipitated, occurring in open veins and may be a result of meteoric water ingress.

The deep wells do not appear to have undergone telogenetic modifications, that have affected the sulphate minerals.

Conclusion

Diagenetic modifications have played a fundamental role in producing the textural fabric and mineralogical composition of the Keuper and Muschelkalk evaporites from

the boreholes of northern Switzerland. Eogenetic alteration during the Triassic resulted in formation of typical nodular evaporite sequences well known from modern playa lakes and coastal sabkhas. During mesogenesis, when the sediments reached a burial depth between 0.5–1 km at the end of the Jurassic, dehydration of gypsum to anhydrite altered the mineralogy but preserved the original sedimentary structures. The highest secondary porosity and the most intense silicification is recorded from sediments of the transition zone between the brine-pool and the subaerial floodplain environment. The mesogenetic mega-quartz is most abundant in these sediments due to remobilization of eogenetic opaline quartz. In the clayey brine pool and salt flat environment silicification is of minor importance. Concentration of additional authigenic minerals such as siderite, fluorite and celestite also took place during mesogenesis.

Meteoric water ingress during the Pleistocene telogenesis was only important in the shallow wells and has not affected the deep wells. Telogenetic modification is particularly destructive to the original sedimentary structures and textures as it reduces sediment cohesion.

Petrographic studies indicate that, despite the variety of eogenetic, mesogenetic and telogenetic modifications to these sediments, there is little evidence for gross mass transfer of solutes through the system. Most diagenetic modifications reflect redistribution of ions in response towards stability with the existing ambient temperature/pressure regime. In those wells which have not been affected by meteoric water ingress many of the evaporitic fabrics have been remarkably well preserved despite the gypsum to anhydrite dehydration.

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REFERENCES

- ARTHURTON, R. S. (1980): Rhythmic sedimentary sequences in the Triassic Keuper Marl (Mercia Mudstone Group) of Cheshire, northwest England. – *Geol. J. (Liverpool)* 15, 43–58.
- BAUMANN, W., & STUCKY, K. (1984): Geologische Untersuchungen an Evaporiten der Mittleren Trias in der Nordschweiz am Beispiel des Bergwerks Felsenau. – *Eclogae geol. Helv.* 77/3, 511–540.
- BERNER, R. A. (1985): Sulphate reduction, organic matter decomposition and pyrite formation. – *Phil. Trans. r. Soc. Lond. A.* 315, 25–38.
- BIRNBAUM, S. J., & WIREMAN, J. W. (1984): Bacterial sulfate reduction and pH: Implications for early diagenesis. – *Chem. Geol.* 43, 143–149.
- BLÄSI, H.-R., DRONKERT, H., MATTER, A., & RAMSEYER, K. (1987): Diagenese des Muschelkalk- und des Buntsandsteinaquifers in den Nagra Tiefbohrungen. – Pilot Studie Nagra Technischer Bericht *NTB 87-02* (in press).
- BONTE, A. (1951): Contribution a la stratigraphie du Keuper du Jura. – *Bull. Soc. géol. France, Ser. 6/1*, 319–331.
- BOURCART, J., & RICOUR, J. (1952): Une hypothèse sur les conditions de sédimentation des niveaux salifères du Trias. – *C. R. Somm. Soc. géol. France*, 37–39.

- BUSH, P. (1970): Chloride-rich brines from sabkha sediments and their possible role in ore formation. – *Trans. Instn. Min. Metall.*, *B79*, no. 765, B137–144.
- BUSH, P. (1973): Some aspects of the diagenetic history of the sabkha in Abu Dhabi, Persian Gulf. In: *The Persian Gulf*. Ed. B. H. PURSER. – Springer Verlag (p. 395–407).
- BUSSON, G., & PERTHUISOT, J. P. (1977): Intérêt de la sebkha El Mélah (Sud Tunisie) pour l'interprétation des séries évaporitiques anciennes. – *Sediment. Geol.* *19*, 139–164.
- CODY, R. D. (1976): Growth and early diagenetic changes in artificial gypsum crystals grown within benthonic muds and gels. – *Bull. geol. Soc. Amer.* *87/8*, 1163–1168.
- DEFFEYES, K. S., LUCIA, F. J., & WEYL, P. K. (1964): Dolomitization: Observations on the Island of Bonaire, Netherlands Antilles. – *Science*, *143*, 678–679.
- DRONKERT, H. (1977): A preliminary note on a Recent sabkha deposit in SE Spain. – *Inst. Invest. Geol. Dip. Prov. Barcelona* *32*, 153–166.
- DRONKERT, H. (1985): Evaporite models and the sedimentology of Messinian and Recent evaporites. – Thesis Univ. Amsterdam, GUA papers, ser. 1, 24.
- DRONKERT, H., BLÄSI, H.-R., & MATTER, A. (1987a): Sedimentology and petrology of Triassic evaporites from Northern Swiss boreholes. – in prep.
- (1987b): Investigation of the Triassic evaporites in the Nagra cores. – Nagra report, in prep.
- DUNHAM, R. J. (1962): Classification of carbonate rocks according to depositional texture. – *Mem. amer. Assoc. Petroleum Geol.* *1*, 108–121.
- DUSSART, B. (1962): Dépôts salifères anciens et géologie de l'Actuel. – *Rev. Géogr. phys. Géol. dyn.* (2), *5*, fasc. 1, 55–59.
- EUGSTER, H. P. (1985): Oil shales, evaporites and ore deposits. – *Geochim. cosmochim. Acta* *49*, 619–635.
- FOLK, R. L. (1962): Spectral subdivision of limestone types. – *Mem. Amer. Assoc. Petroleum Geol.* *1*, 62–84.
- GEBELEIN, C. D., & HOFFMAN, P. (1968): Intertidal stromatolites and associated facies from Cape Sable, Florida. – *Spec. Pap. geol. Soc. Amer.* *121*, 109.
- (1973): Algal origin of dolomite laminations in stromatolitic limestone. – *J. sediment. Petrol.* *43*, 603–613.
- GRIMM, W. D. (1962): Idiomorphe Quarze als Leitmineralien für salinäre Fazies. – *Erdöl u. Kohle, Erdgas Petrochemie* *15*, 880–887.
- HAUBER, L. (1960): Geologie des Tafel- und Faltenjura zwischen Reigoldswil und Eptingen. – *Beitr. geol. Karte Schweiz (N. F.)*, *112*.
- (1971): Zur Geologie des Salzfeldes Schweizerhalle – Zinggibrunn (Kt. Baselland). – *Eclogae geol. Helv.* *64/1*, 163–183.
- (1980): Geology of the salt field Rheinfelden-Riburg, Switzerland. – In: *5th Symposium on Salt*. North. Ohio geol. Soc., Proc. *1*, 83–90.
- HELING, D. (1979): Zur Faziesanalyse des Schilfsandsteins. – *Jber. Mitt. oberrh. geol. Ver.*, (N. F.) *61*, 153–156.
- HOFMANN, B. (1979): Blei-, Zink-, Kupfer- und Arsenvererzungen im Wellengebirge (Unterer Muschelkalk, Trias) am südlichen und östlichen Schwarzwald. – *Mitt. natf. Ges. Schaffhausen* *31* (1978–1980), 1–40.
- HOLLIDAY, D. W. (1970): The petrology of secondary gypsum rocks: a review. – *J. sediment. Petrol.* *40*, 734–744.
- KENDALL, A. C. (1975): Anhydrite replacements of gypsum (satin-spar) veins in the Mississippian caprocks of southeastern Saskatchewan. – *Canad. J. Earth Sci.* *12/7*, 1190–1195.
- KINSMAN, D. J. J. (1969): Modes of formation, sedimentary associations and diagnostic features of shallow water and supratidal evaporites. – *Bull. amer. Assoc. Petroleum Geol.* *53*, 830–840.
- (1974): Calciumsulphate minerals of evaporite deposits: their primary mineralogy. – in: *4th Symposium on Salt*. Ed.: A. H. COOGAN. North. Ohio Geol. Soc. *1*, 343–348.
- LAUBSCHER, H. (1980): Die Entwicklung des Faltenjuras – Daten und Vorstellungen. – *N. Jb. Geol. Paläont., Abh.* *160/3*, 289–320.
- MAIKLEM, W. R., BEBOUT, D. G., & GLAISTER, R. P. (1969): Classification of anhydrite – A practical approach. – *Bull. Canad. Petroleum Geol.* *17/2*, 194–233.
- MARSAL, D. (1952): Der Einfluss des Druckes auf das System CaSO₄-H₂O. – *Heidelb. Beitr. Mineral. Petrogr.* *3*, 289–296.
- MATTER, A., PETERS, Tj., BLÄSI, H.-R., MEYER, J., & ISCHI, H. (1987a): Sondierbohrung Weiach – Geologie. – Nagra Technischer Bericht NTB 86–01 Nagra, Baden, in press.
- MATTER, A., PETERS, Tj., ISENSCHMID, Chr., BLÄSI, H.-R., & ZIEGLER, H.-J. (1987b): Sondierbohrung Riniken – Geologie. – Nagra Technischer Bericht NTB 86–02 Nagra, Baden, in press.
- MATTER, A., PETERS, Tj., BLÄSI, H.-R., SCHENKER, F., & WEISS, H.-P. (1987c): Sondierbohrung Schafisheim – Geologie. – Nagra Technischer Bericht NTB 86–03 Nagra, Baden, in prep.

- MERKI, P. (1961): Der obere Muschelkalk im östlichen Schweizer Jura. – *Eclogae geol. Helv.* 54/1, 137–220.
- MÜLLER, W. H., HUBER, M., ISLER, A., & KLEBOTH, P. (1984): Erläuterungen zur geologischen Karte der zentralen Nordschweiz, 1:100 000. – Nagra Technischer Bericht NTB 84–25, 234p.
- MURRAY, R. C., & LUCIA, F. J. (1967): Cause and control of dolomite distribution by rock selectivity. – *Bull. geol. Soc. Amer.* 78, 21–36.
- ORTI-CABO, F. (1977): Aproximacion estudio petrografico de las microestructuras de las rocas de yeso secundario y a su origen. – *Inst. Invest. Geol., Univ. Barcelona* 32, 87–152.
- PETERS, Tj., MATTER, A., BLÄSI, H.-R., & GAUTSCHI, A. (1987a): Sondierbohrung Böttstein – Geologie. – Nagra Technischer Bericht NTB 85–02 Nagra, Baden, in press.
- PETERS, Tj., MATTER, A., ISENSCHMID, Chr., BLÄSI, H.-R., MEYER, J., & ZIEGLER, H.-J. (1987b): Sondierbohrung Kaisten – Geologie. – Nagra Technischer Bericht NTB 86–04 Nagra, Baden, in press.
- PETERS, Tj., MATTER, A., ISENSCHMID, Chr., BLÄSI, H.-R., MEYER, J., & MEYER, Chr. (1987c): Sondierbohrung Leuggern – Geologie. – Nagra Technischer Bericht NTB 86–05 Nagra, Baden, in press.
- PURSER, B. H. (1973): *The Persian Gulf*. – (Editor) Springer, New York.
- RENFRO, A. R. (1974): Genesis of evaporite-associated stratiform metalliferous deposits – a sabkha process. – *Econ. Geol.* 69, 33–45.
- RICOUR, J. (1960): La g n se des niveaux salif res; cas du Trias fran ais. – *Rev. G ogr. phys. G ol. dyn.* 3, fasc. 3, 139–148.
- SCHWARZ, H. U. (1975): Sedimentary structures and facies analysis of shallow marine carbonates (Lower Muschelkalk, Middle Triassic, Southwestern Germany). – *Contr. Sedimentology* 3.
- SHEARMAN, D. J. (1966): Origin of marine evaporites by diagenesis. – *Trans. Instn. Min. Metall. Sect. B.*, 75, 208–215.
- (1978): Evaporites of coastal sabkhas. – In DEAN, W. E. & SCHREIBER, B. C.: *Marine evaporites*. – S. E. P. M. Short Course notes no.4, 6–42.
- (1982): Changes accompanying exhumation of gypsum/anhydrite rocks. – 11th Int. Congr. Sed. IAS, McMaster Univ. Hamilton, Ont. Canada, p. 9.
- SHEARMAN, D. J., & FULLER, J. G. C. M. (1969): Anhydrite diagenesis, calcitization and organic lamination, Winnipegosis Formation, Middle Devonian, Saskatchewan. – *Bull. canad. Petroleum Geol.* 17, 496–525.
- SHEARMAN, D. J., MOSSOP, G. D., DUNSMORE, H., & MARTIN, M. (1972): Origin of gypsum veins by hydrolic fracture. – *Trans. Instn. Min. Metall. (sect. B: appl. earth sci)* 76, 179.
- TR MPY, R. (1959): Hypothesen  ber die Ausbildung von Trias, Lias und Dogger im Untergrund des schweizerischen Molassebeckens. – *Eclogae geol. Helv.* 52/2, 435–448.
- WEST, I. M., ALI, Y. A., & HILMY, M. E. (1979): Primary gypsum nodules in a modern Sabkha on the Mediterranean coast of Egypt. – *Geology* 7, 354–358.
- ZIEGLER, P. A. (1982): *Geological atlas of Western and Central Europe*. – Shell Int. Petr. Maatschappij, Elsevier, Amsterdam/New York.

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Triassic evaporite lithofacies. Core photographs of the Nagra wells. Depth figures in meters.



53.48
Anhydrite nodules with
gypsum rim and expansion
veins,
Gipskeuper I B



68.30
Sulphcrete of ragged sulphate
nodules of irregular
size.
Gipskeuper II



99.06
Clastic gypsum beds
and selenite crystals
Gipskeuper III B



910.53
Anhydrite marker bed
containing selenite
ghosts and chevron clay
bands. Muschelkalk
Sulfatschichten III A



101.92
Anhydritized porphyro-
blasts in arenite and
satin spar gypsum vein.
Gipskeuper III C



76.40
Early gypsum veins now
anhydritized in
brownish green clay.
Gipskeuper II



234.74
Erosional surface with
well rounded dissolution
crust overlain by intra-
formational conglomerate.
Muschelkalk
Sulfatschichten III B



94.95
Banded silicified sulph-
crete, chalcedony
replacement and young
satin spar veins.
Gipskeuper III B

Plate 2

Microscope photographs of thin sections of Triassic evaporites from Nagra core material. Scale bar in micrometers.

- A Blocky anhydrite as part of a reddish anhydrite nodule. Gipskeuper I B, Böttstein 55.95, x polars
- B Anhydrite nodules with an aphanitic anhydrite core and a fibrous anhydrite rim. Carbonate rich clay partings separate the nodules. Muschelkalk Dolomit der Anhydritgruppe, Riniken 696.83, x polars
- C Felted anhydrite matrix in which blocky anhydrite has replaced a selenitic gypsum crystal. Gipskeuper III B, Böttstein 98.95, x polars
- D Anhydrite nodules with later blocky lath type anhydrite outgrowth in carbonate rich clay parting. Gipskeuper I B, Böttstein 55.35, x polars
- E Blocky anhydrite replacing selenitic gypsum crystal. The selenite crystals were covered by a carbonate/clay mud drape. Gipskeuper III B, Böttstein 98.95, x polars
- F Anhydrite lath crystal cumulate within a carbonate rich clay matrix. Lath's have a sub horizontal orientation, partly due to compaction, but mainly caused by settling out of a saline brine. Gipskeuper III B, Böttstein 98.95, = polars
- G Gypsified anhydrite (top), carbonate/anhydrite mush (bottom) and gypsum vein (middle). Gipskeuper I A, Böttstein 47.85, x polars
- H Gypsum veins and chert. Muschelkalk Sulfatschichten II, Böttstein 212.75, x polars

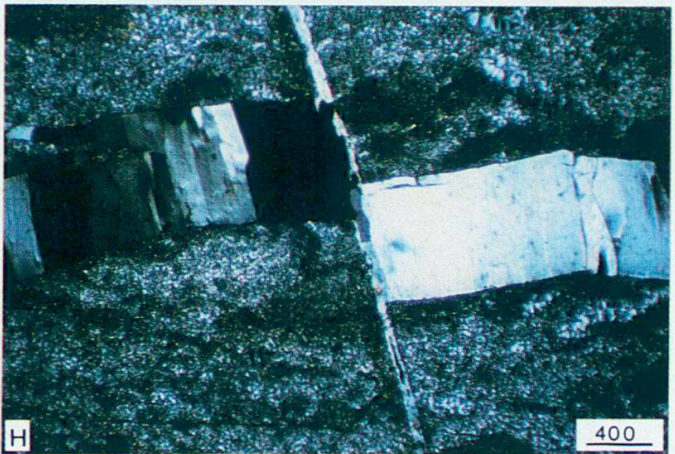
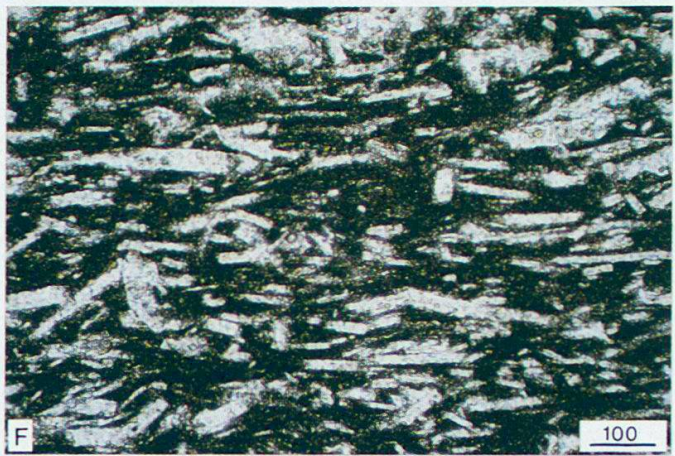
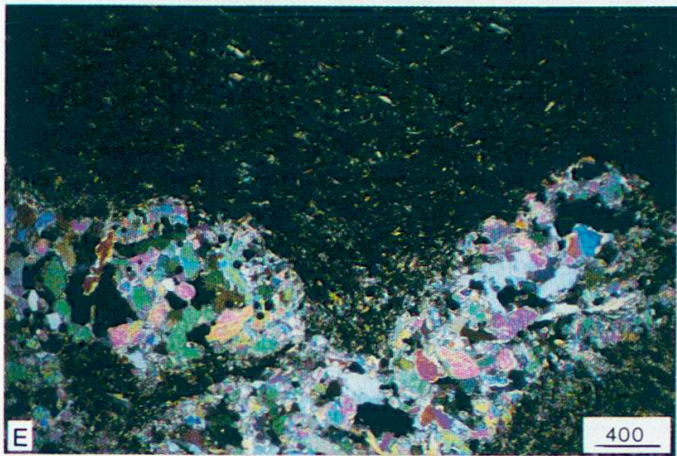
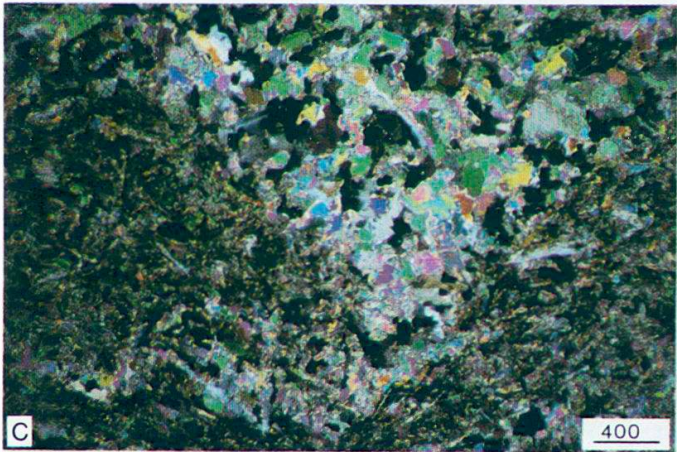
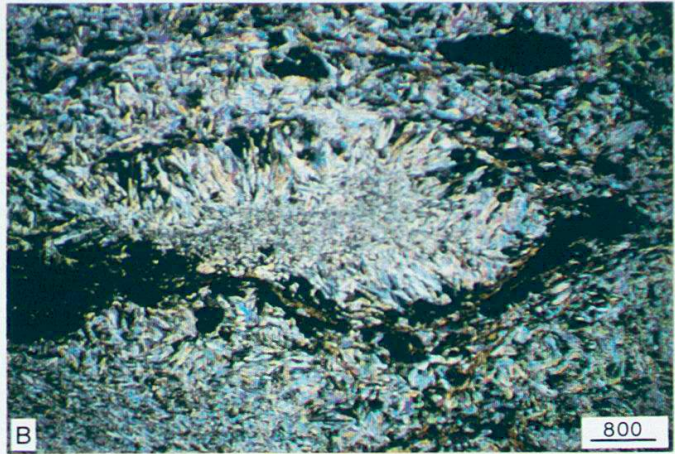
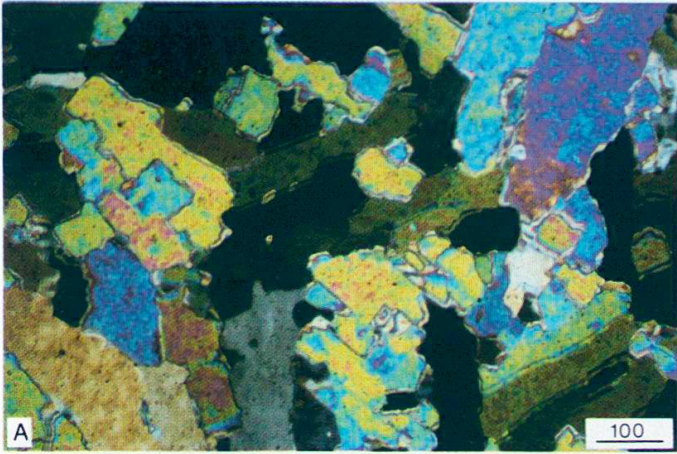


Plate 3

Microfacies of Triassic evaporite rocks. Cathodoluminescence microscope photographs of thin sections from Nagra well material. Scale bar in micrometers.

- A Dark radial (spherulithic) calcite crystals and bright anhydrite cement. Gipskeuper IV, Weiach 809.65, x polars
- B Multiphase pore fill with dolomite (from brown, over red to yellow) and fluorite (blue) that have replaced original anhydrite. Muschelkalk Dolomit der Anhydritgruppe, Beznau 300.98, cathode luminescence
- C Zoned dolomite rhombs in dolomitic corrensite/illite matrix. Gipskeuper II, Weiach 764.70, x polars
- D Same as C. Zoned dolomite rhombs (in shades of red) and black anhydrite (luminesces dark blue). Weiach 764.70, cathodoluminescence
- E Dolomiticite (M) at nodule margin, dolomite (D) that replaced anhydrite, megaquartz (Q) that replaced anhydrite, chalcedony (C) replacing dolomite and fluorite (F) that was redistributed after replacement of anhydrite. Some relict anhydrite lath's are preserved in the megaquartz. Muschelkalk Dolomit der Anhydritgruppe, Beznau 300.98, x polars
- F Same as E. Dolomiticite luminesces orange to red, mega quartz is nearly black, chalcedony is beige brown and fluorite is bright blue. Muschelkalk Dolomit der Anhydritgruppe, Beznau 300.98, cathodoluminescence
- G Open pore lined by dolomite crystals (D) that have been corroded by chalcedony (C) on the rock side. Muschelkalk Dolomit der Anhydritgruppe, Beznau 300.98, x polars
- H Same as G. Open pore (P) lined by multiphase orange to red dolomite crystals (D) that have been corroded by very dark brownish chalcedony (C) on the rock side. Muschelkalk Dolomit der Anhydritgruppe, Beznau 300.98, cathodoluminescence

