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Sulfate deformation in the upper Triassic of the Belchen tunnel (Jura Mountains, Switzerland)

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ABSTRACT

SEM photographs of upper Triassic Belchen tunnel samples reveal several aspects of sulfate behavior during deformation of the host rock. Some of the ptygmatic folds are diagenetic and due to differential compaction between water-filled mudstones and sulfate veins. These, originally probably gypsum, are now anhydrite with a fabric suggesting static recrystallization. During Late Miocene Jura folding the compacted mudstone at first underwent brittle deformation with small-scale Mohr-type thrusting and, particularly on the flanks of anhydrite folds, boudinage with tension cracks. These faults were the site of ubiquitous sulfate deposition, solution transport setting in as soon as crack permeability was initiated. The sulfate probably was initially mostly gypsum although now it is partly anhydrite. Subsequent deformation was largely in the sulfate veins, and the sulfate-supported mudstone breccia became the most incompetent member of the formation, more incompetent than the solid anhydrite beds. These in turn deformed by some sort of flow whose original mechanism has been largely obscured by recrystallization. However, in view of the low T (~ 50° to 80 °C) it is conjectured, in analogy to the observations on the mudstone, that cracking-solution-precipitation and possibly concentration of deformation on metastable gypsum linings played an essential role, dislocation creep in anhydrite being present

ZUSAMMENFASSUNG

REM-Photographien von Handstücken der oberen Trias des Belchentunnels zeigen verschiedene Aspekte des Verhaltens der Sulfate während der Deformation des Gesamtgesteins. Einige der ptygmatischen Anhydritfalten sind diagenetisch, das Resultat von differenzieller Kompaktion zwischen wassergesättigten Peliten und Sulfatadern. Diese, ursprünglich wohl Gips, sind nun Anhydrit mit einem Gefüge, das statische Rekristallisation vermuten lässt. Während der spätmiozänen Jurafaltung wurden diese nun kompaktierten Pelite zuerst im Sprödbereich deformiert, wobei vor allem kleine Überschiebungen und – vor allem an den Schenkeln von Anhydritfalten – Zugrisse gebildet wurden. In beiden Fällen wurden reichlich Sulfate abgelagert, und es scheint, dass Lösungstransport einsetzte, sobald tektonische Permeabilität geschaffen wurde. Die Sulfate waren ursprünglich wohl meist Gips, sind aber jetzt teilweise Anhydrit. In der Folge konzentrierte sich die Deformation vor allem auf diese Sulfathäute, und deren Netzwerk führte dazu, dass tektonische Pelitbreccien die inkompetentesten Glieder der ganzen Formation wurden, inkompetenter noch als die kompakteren Anhydritintervalle, obwohl auch diese geflossen sind. Deren Fliessmechanismus hat sich bis jetzt nicht klar erkennen lassen, da das heutige Gefüge zum Teil statisch rekristallisiert scheint. Es ist jedoch zu vermuten, dass in Anbetracht der niedrigen Temperaturen (ungefähr 50–80 °C) das bei höheren Temperaturen beobachtbare Versetzungskriechen wenig konkurrenzfähig war und dass dafür – in Analogie zu den Beobachtungen an den Peliten – ein zusammengesetzter Mechanismus aus Rissbildung–Lösungstransport–Rekristallisation die entscheidende Rolle übernommen hat. Dabei ist es denkbar, dass metastabile Gipshäute, jetzt fast vollständig in Anhydrit verwandelt, wie in den Pelitbreccien die Deformation auf sich konzentrieren konnten.

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Introduction

The role of evaporites in décollement of the Jura Mountains had been recognized as early as 1907 by BUXTORF. He thought that salt was the main plastic horizon, but LAUBSCHER (1961) argued that salt layers, although probably the weakest part, were too discontinuous for the large-scale décollement to function properly, and tried to find other sufficiently incompetent and more abundant material for that process. Impressed by the experimental results of HANDIN & HAGER (1957) who found that at room temperature dry anhydrite was stronger than dolomite, he at first rejected anhydrite as a possible candidate. However, after having seen in 1964 the extremely incompetent behavior of upper Triassic anhydrite layers in the Belchen tunnel (eastern Jura Mountains; for location and cross section see FRÖHLICHER & KEHRER 1968), which was being perforated at the time, he concluded that the experiments by HANDIN & HAGER (1957) did not portray natural conditions, and postulated that anhydrite would be abundant and apparently weak enough to permit décollement (LAUBSCHER 1967, p. 26). As there were ubiquitous manifestations of vein fillings he further conjectured that pressure solution had played an essential role (LAUBSCHER 1967, 1975), and he expanded this notion to include the metastable precipitation of gypsum or hemihydrate as thin, mechanically weak films. This in effect would mean dynamic metamorphism in anhydrite deformation, as a chemically active fluid phase and various crystalline phases are involved. This postulate seemed justified not only for general reasons but also because of the experimental results obtained by RUBEY & HEARD (1965), wo found that gypsum at elevated temperatures did not convert directly into anhydrite plus water but that metastable hemihydrate was formed in an intermediate step. Even short-lived incompetent metastable phases would be important for deformation. Subsequently MÜLLER & BRIEGEL (1977, 1978) published the results of tests up to 450 °C and deformation rates of the order of 10^{-7}/sec. They found that under these circumstances a power-law creep was operative and extrapolated that for geologically slow deformation this rheology would suffice for décollement of the Jura at temperatures above 180 °C. However, the upper Traissic anhydrites of the Belchen tunnel had never been buried more than 1100 m to 1500 m, which even at a high geothermal gradient of 50 °C/km would not amount to more than 85 °C and probably much less. Doubtless the observed flowfolds imply mechanisms other than power law creep, which at the low temperatures and strain rates become competitive.

This article is based on a series of SEM (scanning electron micrographs) of material originally collected by M. Wohnlich in the Belchen tunnel. A small number of observations, thought to be particurlarly interesting at this time, were selected, although it is hoped that in the near future a more complete analysis will be possible.

Observations in various deformational regimes

1. Diagenetic deformation of gypsum veins in a compactable host rock

Figure 1 shows a weakly deformed portion of the upper Triassic in the Belchen tunnel. Diagonally across the center of the photograph there is a band of dark dolomitic mudstone overlain by thinner layers of mostly impure anhydrite. Perpendicular to

Fig. 1. Tunnel exposure of upper Triassic with location of specimen 372 W. Length of marker is 3.75 cm. Explanations in the text.

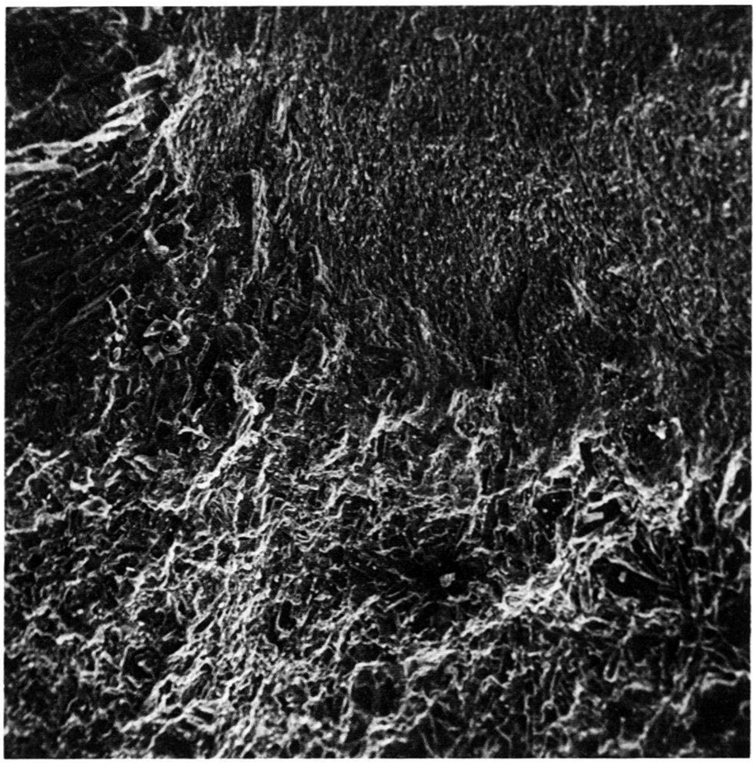

Fig. 2. SEM of core of ptygmatic fold, specimen 327 W. Length of photograph is 0.8 mm. The axial plane is vertical. Mudstone in lower left.

the layering there are ptygmatically folded anhydrite veins, whereas the mudstone of the host rock is undeformed. Consequently, the anhydrite folds must have been diagenetic and due to differential compaction of the originally water-filled mudstone. Although the veins are now anhydrite, it may be conjectured that originally and during compaction they had been gypsum.

Figure 2 is from the core of one of the diagenetic folds. The fine-grained mudstone of the core is surrounded and marginally penetrated by anhydrite laths which are more or less perpendicular to the boundary of the mudstone. As they penetrate into it the anhydrite prisms are probably the result of post-deformational static recrystallization. Consequently the deformational fabric of the original gypsum is not preserved. However, it is clear that gypsum must be extremely weak even at shallow burial and low temperature.

2. Brittle tectonic deformation of the mudstone in the Miocene and the role of anhydrite

Besides the diagenetically produced ptygmatic folds, Figure 1 shows a series of light-colored sulfate veins that mostly follow small thrusts formed during Late Miocene Jura folding, as can be observed where they displace layers. Evidently the little thrusts, though compressional features, imply dilatancy. They developed open cracks which were filled by sulfates from circulating solutions. The vein filling now is partly gypsum and partly anhydrite (analysis of scratched-off grains). The reason for this is not yet entirely clear. Some of the gypsum may have been produced at a time when due to the folding process and accompanying erosion the layer was brought close to the cool surface where gypsum is the stable phase. On the other hand, it is well known that gypsum forms metastably from solution even in the stability field of anhydrite, and there are indications that in some instances at least it has later been replaced by anhydrite (see below). Where the veins cross anhydrite-rich layers they have a tendency to disappear: In some places the anhydrite layers are sharply sheared at their boundaries, although no fault may be discerned in their interior. In other places they are bent without, apparently, internal fractures. These were either healed subsequently or they were never formed originally, at least not in sizes ordinarily recognizable. At any rate, evidence for ubiquitous solution transport in the deformed upper Traissic is compelling. Inasmuch as it stands to reason that the precipitated sulfate must have been dissolved elsewhere and that solution is enhanced by pressure, it would appear proper to speak of a pressure solution mechanism of deformation, although metamorphic phase conversions and recrystallization thus far have not permitted direct observation of solution phenomena. Doubtless it has been operative in addition to the probably still active dislocation creep mechanism observable at higher temperatures and strain rates (MÜLLER & BRIEGEL 1978).

A particularly interesting example of the mechanical role of solution transport is illustrated in Figures 3–6. Figure 3 shows the situation in the tunnel where specimen 349 W has been collected. The same dark mudstone with the diagenetic folds as in Figure 1 is recognizable at the lower left. Several small thrusts may be seen. The largest one, in the right half side of the picture and about vertical, is accompanied by some particularly interesting phenomena: 1. The overlying anhydrite of the lower plate is smoothly bent. 2. In the mudstone this bend is replaced by a sharp-hinged and broken

Fig. 3. Tunnel exposure of upper Traissic with location of specimen 349 W (Fig. 4; bottom, right of center).

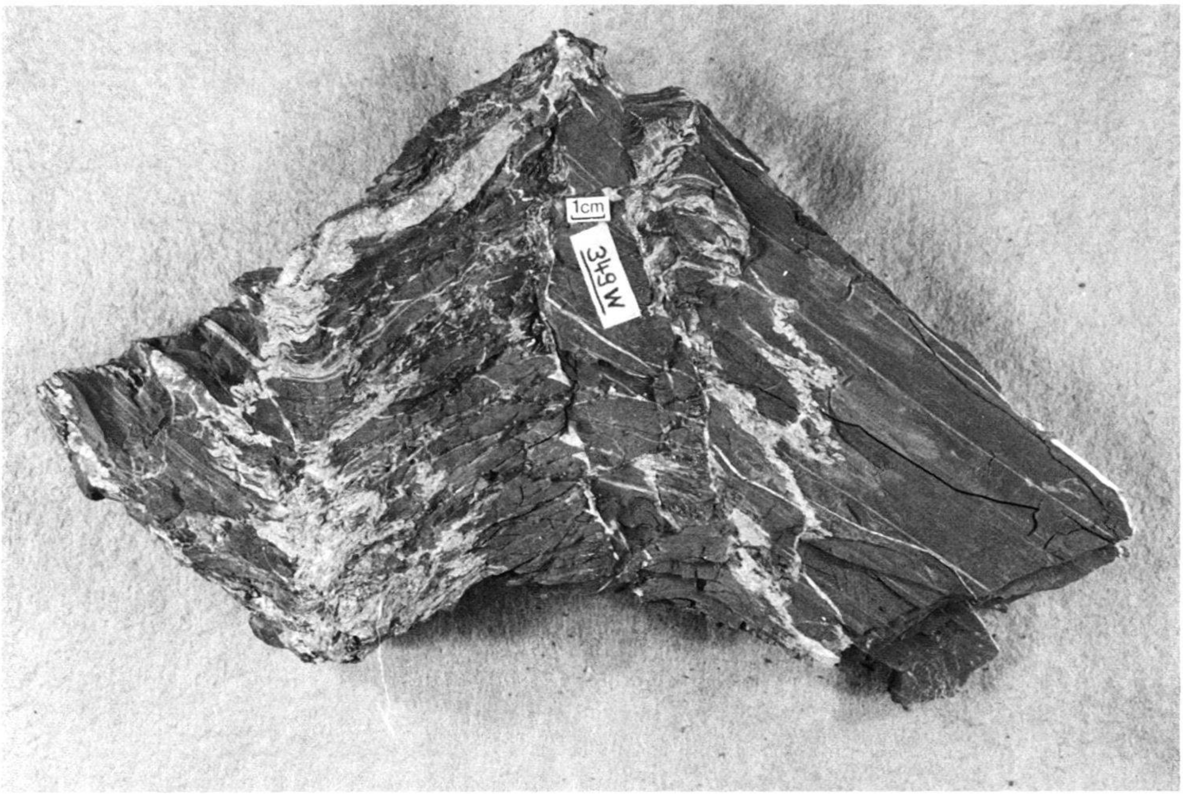

Fig. 4. Specimen 349 W (see Fig. 3). Explanations in the text.

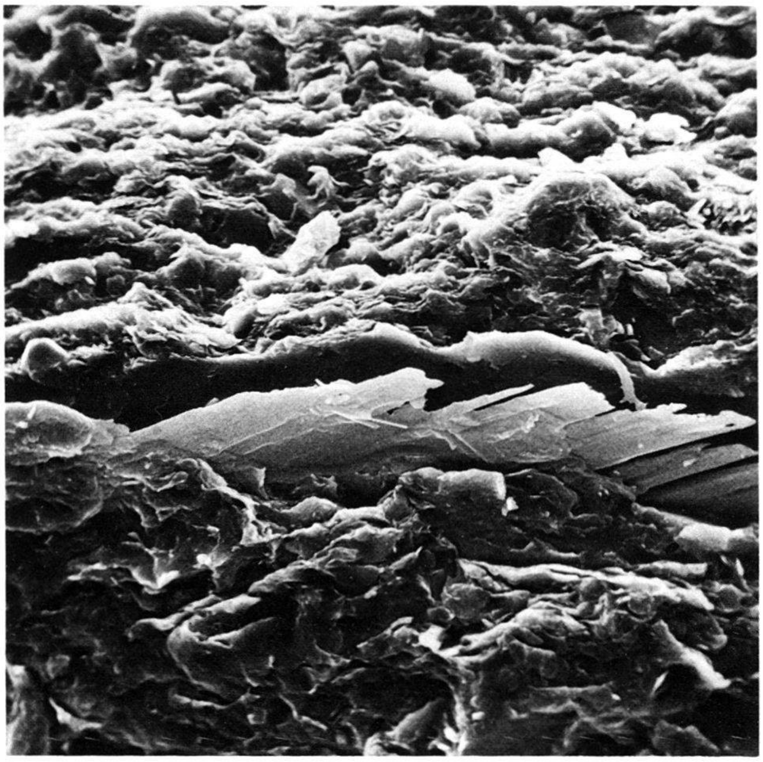

Fig. 5. SEM of gypsum lining on shear plane in mudstone, specimen 349 W (see Fig. 4 and text). Lenght of photograph is 0.09 mm.

Fig. 6. SEM of gypsum lining on shear plane in mudstone, specimen 349 W (see Fig. 4 und 5, and text). Length of photograph is 0.04 mm.

kinkband. The details of this kinkband may be seen in Figure 4 (sample 349 W). Mudstone within the kinkband is intensely sheared, with the shearing surfaces slightly inclined to the layering and tending to dissect the mudstone into lenticular bodies. These surfaces are invariably lined by sometimes very thin and discontinuous films of sulfate. The hinge fault had originally been a Mohr-type thrust. Within the kinkband the lenticular shear bodies have been rotated and sheared in the sense required by the rotation. Thereby triangular holes developed along the hinge fault which are now filled by sulfates. To judge from grains scratched from the filling of these holes they are mostly gypsum with some anhydrite.

Figures 5 and 6 are SEM pictures of the thin films lining the shearing surfaces (compare WOHNLICH 1967 and LAUBSCHER 1975). Evidently sulfate saturated water percolated along the shearing surfaces as soon as permeability had been established. The sulfate films seem to be mostly gypsum. Figure 6 is particularly interesting as it shows a composite gypsum step of a shape comparable to that of calcite steps on limestone shearing surfaces. The motion of the removed upper plate would be diagonally from the lower right to the upper left. A strongly oriented fabric seems to be associated with the precipitation mechanism. The impression is that during that motion the discontinuous film of gypsum moved like a migrating dune: it was dissolved in the rear and reprecipitated frontally. It may be surmised that there were two lubricating processes at work simultaneously: dislocation creep in the gypsum and solution redeposition. If the latter process was sufficiently fast, it kept the possibly metastable gypsum from being converted into stable anhydrite.

If we now reconsider Figures 3 and 4 it becomes evident that the formation of the kinkband in the mudstone was a strongly nonlinear process. Immediately after initiation of shearing in the mudstone gypsum lubrication took over, converting the mudstone into an extremely incompetent material. Indeed, fine-grained mudstone or shale breccia with gypsum linings is the most incompetent material in the tunnel outcrops, much more so than the solid, flow-folded anhydrite layers (WOHNLICH 1967, LAUBSCHER 1975).

Figure 7 is a detail from the hinge vein of Figure 4. It documents shearing between the fibrous sulfates and the mudstone. The sulfates are mostly gypsum, but some of the grains scratched off in the hinge vein are anhydrite. The mudstone is undeformed and unfaulted except for the immediate neighborhood of the contact where dextral drag may be observed. Consequently, in the hinge itself as well in the kinkband movement was concentrated in the sulfates, initially mostly gypsum.

Figure 8 is a specimen where a reddish anhydrite layer across a thrust is typically folded and thinned out but continuous, whereas the underlying and overlying mudstones are sharply sheared. Newly precipitated colorless sulfate, much of it anhydrite but also some gypsum, is found along the thrust in the projection of the displaced anhydrite bed. Shale seams in the anhydrite fold are broken and rotated as rigid fragments. Figure 9 is from this recrystallized anhydrite. It shows multiply kinked fibrous sulfate, possibly already anhydrite, with the jagged hinge zone and the irregular boundary of the fibrous sulfate healed by a mosaic of anhydrite. It appears that two processes were at work: 1. Kinking of a fibrous sulfate which may originally have been gypsum. 2. Solution transport and precipitation of sulfate particularly into the voids left by kinking, with eventual static recrystallization as anhydrite.

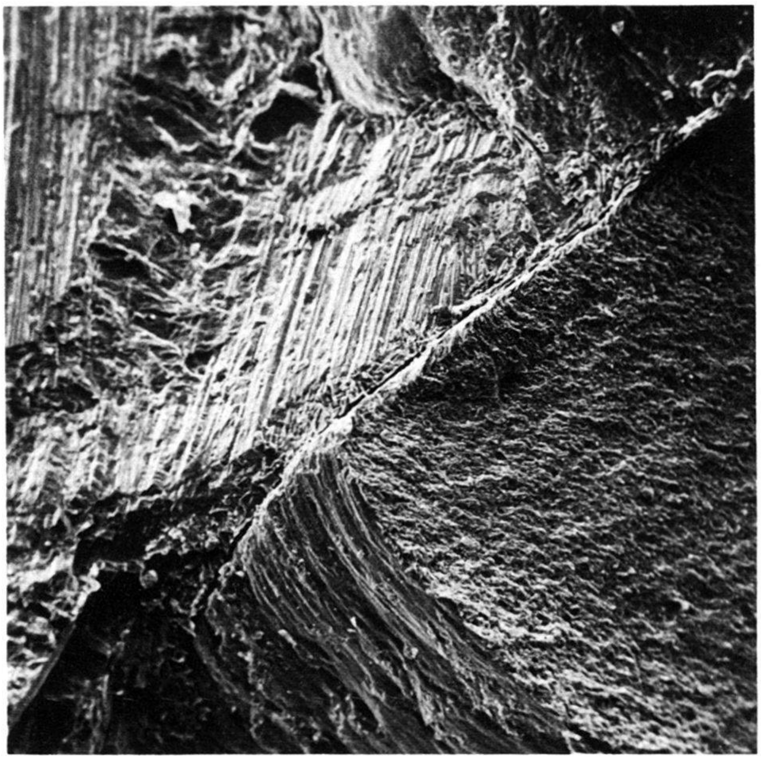

Fig. 7. SEM of sulfate-mudstone contact, specimen 349 W (see Fig. 4). Lenght of photograph is 0.9 mm. Explanations in the text.

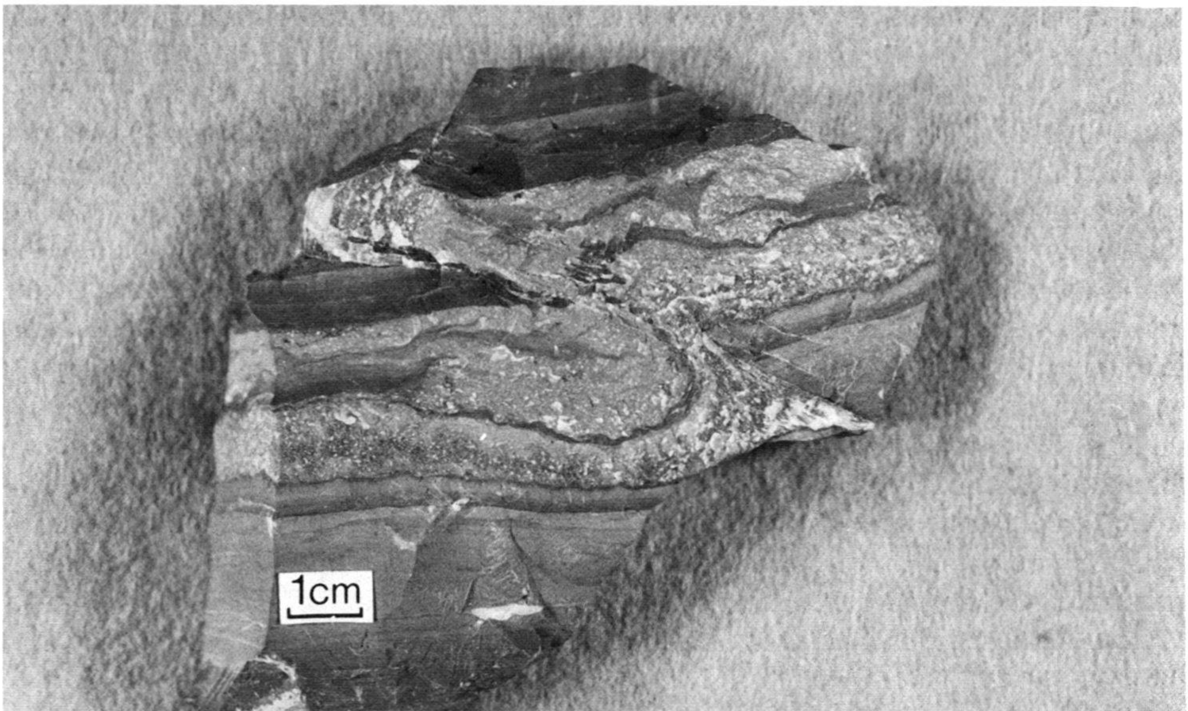

Fig. 8. Specimen 1000, upper Triassic, Belchen tunnel.

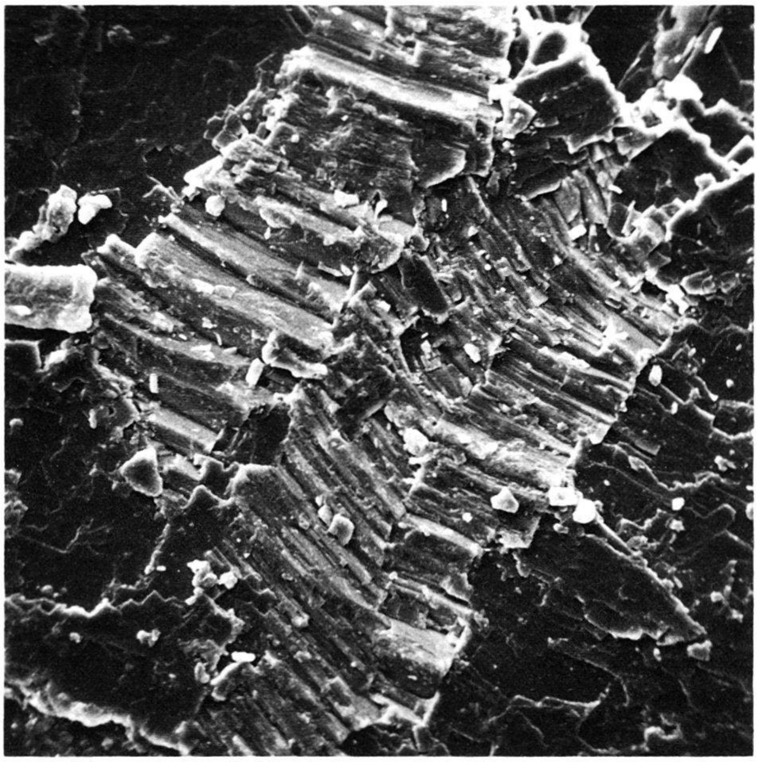

Fig. 9. SEM from redeposited sulfate, lower right of specimen Figure 8. Lenght of picture is 0.18 mm.

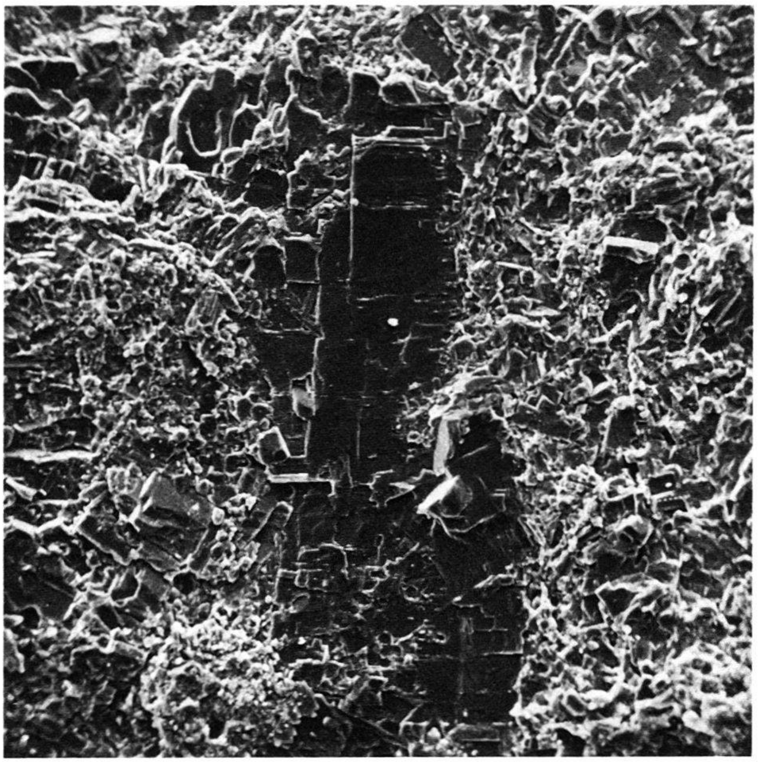

Fig. 10. SEM from external side of crest of solid anhydrite fold (specimen 321 W, not shown). Lenght of picture is 0.44 mm.

Figure 10 is from the external side of an anhydrite fold detached by means of a shear zone from massive mudstone. Macroscopically the anhydrite of the fold appears massive without any obvious internal fabric. The SEM confirms this impression. The large anhydrite crystal appears to be due to static recrystallization rather than fragmentation of an even larger grain.

Conclusions

SEM pictures presented in this article are a selection of a large number of pictures which in turn are from a tiny sample of the large collection of specimens of deformed anhydrite from the Belchen tunnel. It is hoped that a thorough analysis of a much larger and more representative selection will be possible in the near future. However, those pictures available at this time are sufficiently revealing as to the mechanism of deformation at work that a few temporary conclusions may be drawn.

1. Pressure solution and solution transport have been operative on a variety of different scales. Initiation of even vestigial permeability seems to have been followed by invasion of sulfate solution and precipitation. Anhydrite crystals often seem to be postkinematic.
2. In apparent contradiction to this, shaly layers between anhydrite are usually broken into rigid fragments which are rotated as solid bodies around the anhydrite folds. In reality this behavior conforms to that of the mudstones and shales generally: They break and the fragments are floated in a web of gypsum veins and films. It has not been possible to prove so far, but it may by surmised, that within the anhydrite layers a similar mechanism was operative. Tiny cracks in the anhydrite which develop at stress levels much below ultimate strength may be filled with films of gypsum which then carry the bulk of the deformation as they are seen to have done in the mudstones. However, conversion from gypsum to anhydrite here is easier as epitaxial overgrowth may take place on the anhydrite crystals. This mechanism would not exclude dislocation creep in the anhydrite crystals. However, it would seem doubtful whether dislocation creep would be competitive at low temperatures where anhydrite even at low deformation rates would tend to behave in a brittle manner. As solution transport and phase conversions play a role, the deformation mechanism is actually that of dynamometamorphism.

Acknowledgments

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