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# Fault patterns in the calcareous overburden of a salt diapir: Laegerdorf, NW Germany

By **A. G. Koestler**, Oslo, and **W. U. Ehrmann**, Kiel

With 5 figures and 1 table in the text

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**Abstract:** Near Laegerdorf, in NW Germany, a block of Upper Cretaceous chalk has been pushed upwards by a salt diapir, through thick Tertiary sediments. During this movement, the homogeneous and almost monomineralic white chalks suffered brittle deformation. The single fractures and the fracture zones can be classified on the basis of mesoscopic features such as the occurrence of fault breccia, argillaceous fracture fill and slickenside striations. Normal faults on which there has been a large displacement generally show all these characteristics.

Detailed geometric analysis of the fracture patterns shows that the strain in the chalks is mainly concentrated on distinct faults and fault zones with complex internal structures. The faults strike perpendicular to the salt ridge axis and are often arranged in conjugated sets with steep dips, indicating a vertical main compression direction. The NW-SE strike of the fractures and the downstepping to the SW of tilted fault blocks seem to reflect the overprinting of a regional stress field on the local one due to diapirism.

**Zusammenfassung:** In NW-Deutschland wurde bei Lägerdorf oberkretazische Schreibkreide durch Aufstieg des Salzstockes Krempe an die Oberfläche gebracht. Dabei reagierten die homogenen und annähernd monomineralischen Kalke mit Bruchbildung. Mesoskopische Merkmale der Einzelbrüche und Bruchzonen erlauben eine Klassifizierung nach dem Vorhandensein von Brekzien, mergeligen Bruchfüllungen und Harnischen. Abschiebungen mit großem Versatz weisen meist alle diese Charakteristika auf.

Die geometrische Analyse des Bruchmusters zeigt, daß sich die Deformation in den Kalken auf einzelne Brüche und Bruchzonen mit komplexem Interngefüge konzentriert. Die Störungen streichen senkrecht zur Achse des Salzrückens. Oft sind sie steilstehende konjugierte Brüche, die eine vertikale Hauptkompressionsrichtung anzeigen. Das NW-SE-Streichen der Brüche und das Abtreppen der Verwerfungsblöcke nach SW spiegeln das regionale Streßfeld wider, welches das lokale, durch Diapirismus bedingte Streßfeld überprägt.

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## 1. Introduction

Investigations of fractures and fracture zones in a relatively homogeneous and almost monomineralic rock complex allow qualitative correlations between macro-structures and mesoscopical features. Comparisons of geometrical patterns and deformational features can be used to establish a classification of fractures independent of petrographic variations.

Upper Cretaceous chalks, pushed by a salt diapir through Tertiary sediments to the surface and exposed in quarries near Laegerdorf (NW Germany), open the unique possibility to study deformation features in the overburden of a diapir. The chalk has reacted to the superimposed stress due to diapirism by brittle fracturing, which is mostly concentrated on distinct fault zones. It is the aim of this study to identify different fracture types by mesoscopical observations and to establish a correlation between these types and the degree of deformation measured by displacement amounts on the faults.

A geometrical orientation analysis of fractures and slickenside striations was carried out to investigate relationships between the top shape of the salt ridge, the regional geologic situation and the observed fracture patterns (Koestler & Ehrmann 1985). For this purpose some nine hundred fractures were measured and typified by fracture surface features. Individual fracture zones have been mapped in detail to get an idea of the geometry of different fracture types and of internal features. In addition, several subareas were chosen for geometrical and mesocopical studies to cover the whole area exposed in the quarries.

## 2. Regional geology

### 2.1 Geological setting

In the North German Lowlands salt diapirs bring geological formations close to the surface which are normally hidden below a thick Quaternary and Tertiary sediment cover. Thus, the SW-NE striking salt diapir of Krempe lifts Upper Cretaceous sediments near Laegerdorf by more than 1000 m and makes them accessible to industrial exploitation and to geological investigations.

The quarries of the Laegerdorf area in SW Holstein are situated some 45 km NW of Hamburg (Fig. 1). The investigated area is part of the "Unterelbe-Trog", a basin which subsided since Permian time and in which the maximum sediment thickness of the whole Northern Germany is found: The Permian, Mesozoic and Cenozoic epicontinental sediments reach a maximum of more than 10 000 m in thickness (Hähnel 1982).

During both the Rotliegend and the Zechstein an intense deposition of salts occurred in this Unterelbe trough (Ziegler 1982). The Laegerdorf area was situated at that time very close to the centre of the Southern Permian Basin, where maximum salt thicknesses are found.

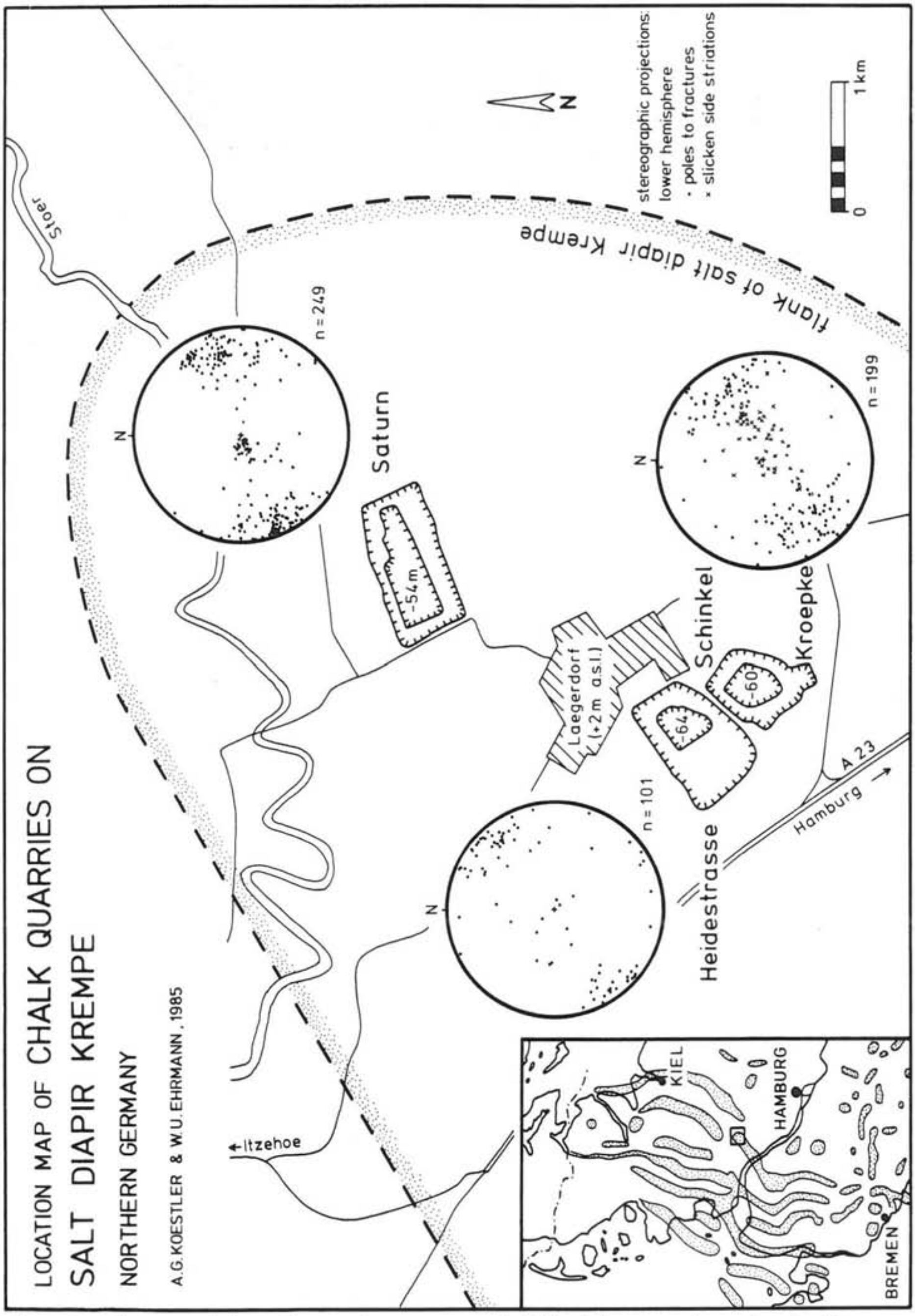


Fig. 1. Location map of the chalk quarries near Laegerdorf. The index map shows the salt ridge configuration of Northern Germany (from JARITZ 1973). The circles represent stereographic projections of fractures measured in the individual quarries.

The formation of salt pillows and salt diapirs began in Triassic time under a sediment overburden of about 400 m (JARITZ 1973). The salt movements continued at least to Tertiary time. SANNEMANN (1968) postulates a genetic relationship between individual salt diapirs, thus forming salt-stock families. The long North German salt ridges most probably did not ascend simultaneously over their full extension. The orientation of the ridges seems to be controlled by basement structures (PRATSCH 1979). NE-SW striking salt horsts are the typical features of salt tectonics in the central part of the Southern Permian Basin (Fig. 1, inset). The Krempe salt diapir is one of them and is thought to have existed in form of a salt pillow already in Early and Middle Triassic, and to have risen as a diapir since Late Triassic (JARITZ 1973). The top of the diapir is assumed to be at a depth of 400–800 m (JARITZ 1972) or about 500 m (BEST 1980). Our own gravimetric field investigations (unpublished data) suggest a depth of 450–550 m close to the Laegerdorf quarries.

## 2.2 The Cretaceous chalks of Laegerdorf

The Upper Cretaceous chalks of Laegerdorf are well exposed in the large quarries Saturn, Heidestraße, Schinkel and Kroepke which are some 60 m deep (Fig. 1). The quarries are situated near the NE end of the Krempe salt ridge (JARITZ 1973, HINSCH 1977) and relatively close to the salt ridge axis. An additional quarry near Hemmoor (some 35 km SW of Laegerdorf) also exposed Upper Cretaceous chalks on top of the same salt ridge, but today it is flooded.

As a result of the doming beneath, the bedding dips with about 10° to the NW. This tilting gives the possibility of overlooking a large part of the stratigraphic column. The sedimentary sequence is biostratigraphically very well studied and zonated (e. g. ERNST 1963, SCHULZ 1978, SCHULZ et al. 1984). It ranges from Middle Coniacian to Lower Maastrichtian. The combined section has a thickness of ca. 420 m.

Numerous nodular chert layers, some marl beds and pyrite impregnated beds allow a very detailed lithostratigraphic subdivision of the chalk sequence (e. g. ERNST 1963, SCHULZ 1978). These layers serve as excellent markers for displacement measurements at the individual faults.

The chalks are very homogeneous throughout the whole exposed stratigraphic profile. Representing a pelagic facies they consist almost entirely of calcareous components, mainly calcareous nannofossils (coccoliths). The carbonate contents of the very finegrained (usually $<5$ μm) sediments is about 95 % in the lower part of the profile, 98 % in the middle part and 94 % in the upper part. The acid insoluble residue of the chalks consists mainly of montmorillonite and quartz. Illite, kaolinite, chlorite and zeolites may occur in smaller quantities. The chalks are thought to be extremely bioturbated (SCHULZ et al. 1984), so that hardly any bedding planes are visible.

Permeability measurements indicate very low values (2–10 mD) for the chalks of Laegerdorf. According to SCHOLZ (1973) the porosity is about 40–50 %. These data fit quite well with those from other localities (HARDMAN 1982, SCHOLLE 1974).

## 3. Structural geology

The chalk of Laegerdorf is brittle deformed due to salt diapirism. The strain is mainly concentrated on distinct fractures and fracture zones. A geometrical analysis of fracture orientations makes it possible to correlate the interpreted stress field with the shape of the salt diapir and the regional geologic situation. An initial description of the structural elements and an analysis of the pattern is presented by GRUBE (1955). However, an interpretation and discussion in terms of diapirism-induced fracturing is not given there.

### 3.1 Methods

The mapping of structural features in the chalks was intended to establish a classification of fracture types and to give the data base for a geometrical analysis. Mesoscopical features, such as brecciation, slickenside striations and/or clay enrichment were the basis for establishing five fracture classes (Table 1). In addition, the fractures are subdivided into six orders by means of their extension in the outcrop, from order 1, penetrating the whole quarry wall, to order 6 as internal structures in fracture zones. During the geometrical analysis this distinction revealed correlations between large fault zones and mesoscopical zone internal structures, and interpretations of stress field variations on different scales.

Seven subareas (Fig. 3) were chosen for data collection to cover the whole area of chalk outcrops accessible in the four quarries. For discussion, the data of GRUBE (1955) of quarries Schinkel and Hemmoor are incorporated. A 150 m long profile section at the W-wall of quarry Saturn (subarea 1, Fig. 3) was studied in detail. It cuts the faults with a low angle and therefore allows a detailed description of single fractures, their surfaces and fracture fills as well as a wide variety of mesoscopical zone internal features (Fig. 2). Subarea 2 in the same quarry (Fig. 3) shows a few major fault zones with displacement amounts in the range of several meters. In the deepest parts of quarry Kroepke, subarea 7 was studied to quantify the extension due to normal faulting over a length of a few hundred meters. At each of the other subareas some hundred structural elements were measured in their orientation; they were described and analysed relating displacement amounts to special mesoscopical features. Usually, displacement amount (a few centimeters to tens of meters) could be measured in the outcrops; however, for the higher and inaccessible parts of the quarry walls, photographs were used.

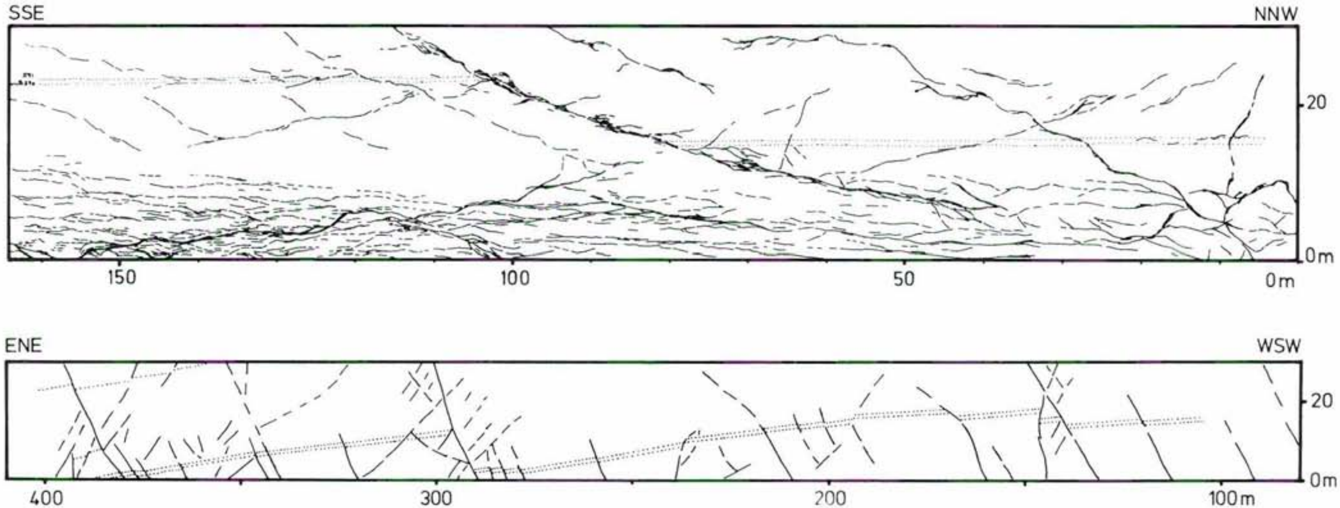


Fig. 2. Fracture mapping in the quarry Saturn. The W-wall section (above), subparallel to fault orientations, shows the detailed pattern and indicates a highly deformed rock complex. The S-wall section (below) perpendicular to the fault orientation shows the SW-ward downstepping of the tilted fault blocks.

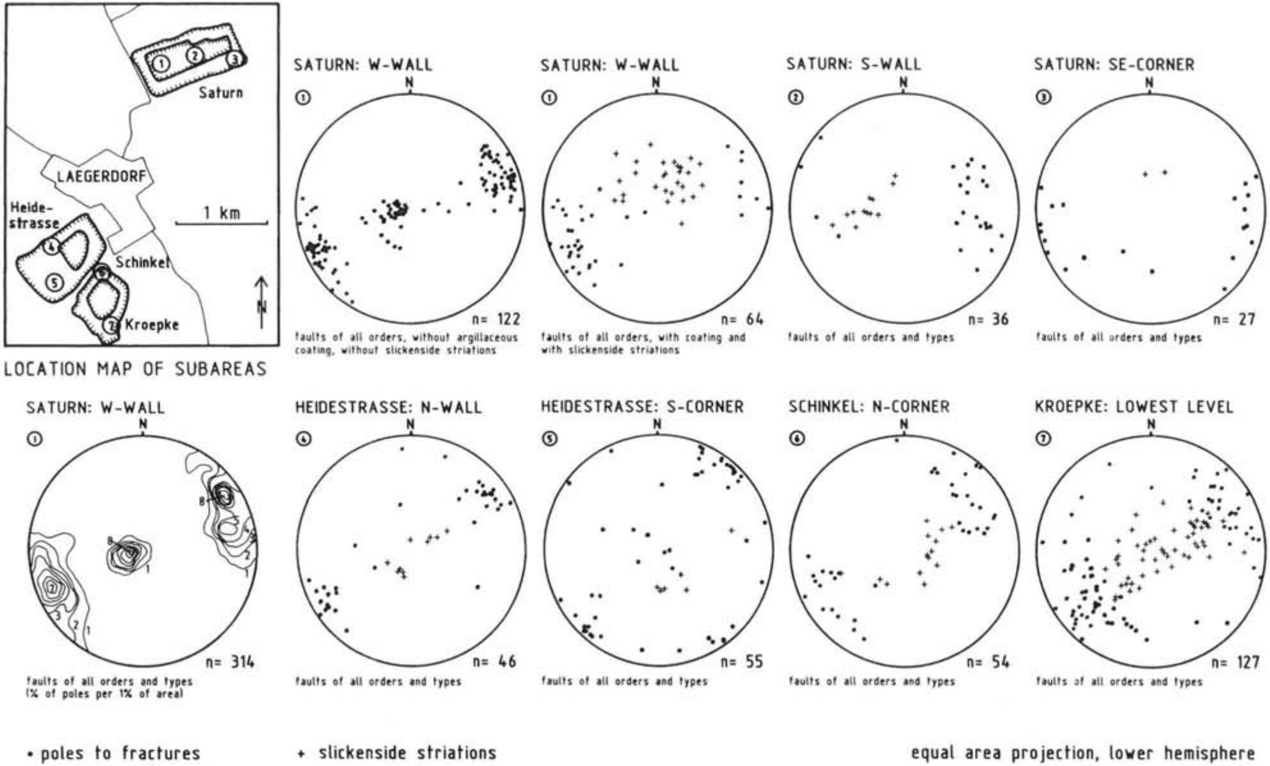


Fig. 3. Stereographic plots as equal area projections of the seven subareas indicated on the index map.

The orientation data of the structural elements (fracture planes and slickenside striations) are presented as pole plots in the lower hemisphere of equal area nets (Fig. 3).

The progressive exploitation of chalks causes ever changing outcrop conditions. However, the intense weathering of the outcrop walls, their overgrowth by algae and covering by Fe-hydroxides due to the running water quickly obliterate interesting structural information.

### 3.2 Description of fractures

Characteristics of fracture surfaces and zones were used to establish a classification (Table 1). Joints (type I) show neither slickenside striations nor argillaceous coating and occur mainly in subhorizontal orientation (central maximum in Fig. 3a, subarea 1), but also in the orientations of all other fracture types. Fractures with slickenside striations (type II), but without any argillaceous coating, look like polished surfaces; their displacement ranges from no visible amount to several decimeters. However, fractures with striated and clay-coated surfaces are the most common types (types III, IV). Their displacement amounts cannot directly be correlated with the thickness of argillaceous fracture fills and/or distinctness of slickenside striations. Breccias (type V) are often bordered by distinct fault planes and are composed of small chalk fragments and a clay-rich matrix containing pyrite concretions. Usually, breccia zones characterize faults with larger displacements.

Table 1. Classification of fracture types according to mesoscopic features.

| fracture type | slickenside striations | argillaceous coating and fills | brecciation |
|---|---|---|---|
| I | – | – | – |
| II | + | – | – |
| III | + | + | – |
| IV | ++ | + | – |
| V | +++ | ++ | + |

Single fracture planes show a wide variety of shape characteristics (Fig. 4). Type I fractures are very irregular in the joint surface topography on large, as well as on small scales. Planar fractures with few irregularities have a large penetrancy and have usually high dip angles. On these planes slickenside striations have a constant orientation. Another type of fault planes is a combination of several differently oriented planes with more or less parallel intersection lines, which also are parallel to the striation (Fig. 4a). On these planes the displacement direction is parallel to the intersection lines. More irregular and slightly to strongly undulatory planes show a high variation of striation orientations. Fig-

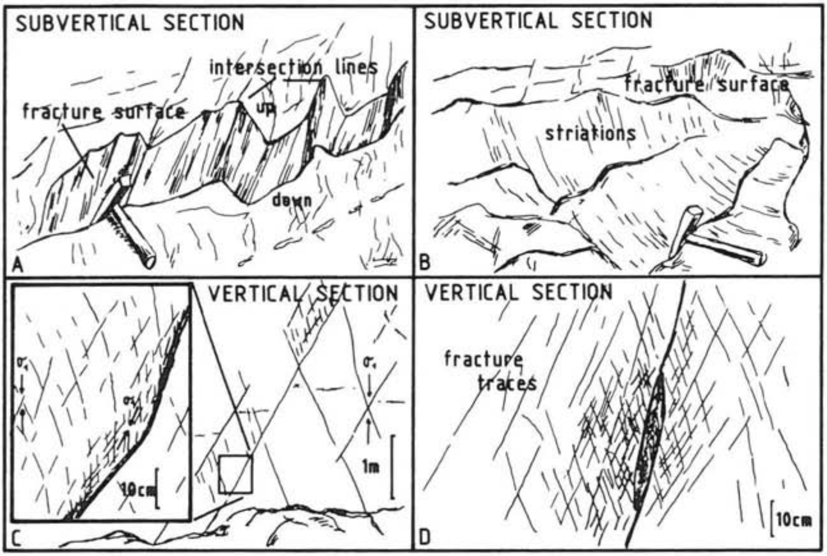


Fig. 4. Mesoscopical features of fracture planes and fracture patterns. a) Single fracture composed of different planes intersecting in parallel lines, which are also parallel to slickenside striations. b) Slickenside striations on a fracture surface indicating a rotation of about 70° of the adjacent blocks. c) Principal compressional direction indicated by orientation of acute angle at different scales. Note the rotation of $\sigma_1$ close to the larger fault. d) Lense shaped deformation pocket formed as pull-apart gap in vertical section. The immediate surroundings are highly fractured.

ure 4b illustrates a situation where slickenside striations indicate a rotation of two adjacent blocks by about 70°. Often slickenside striations of different generations can be observed.

Large fault zones indicate a more or less vertical orientation of the principal compressive stress axis $\sigma_1$ and fault internal structures strongly mirror the expected pattern produced by normal faulting processes. In small areas however, variations in the orientation of the largest stress axis ($\sigma_1$) can deviate more than 20 degrees from the vertical. Because of the homogenity of the chalk, stress field variations have to be responsible for the differently oriented small scale structures. Fig. 4c shows an example where the subvertical stress axis rotated several degrees towards the bordering fault plane. Displacement, which is concentrated on this fault plane, may be responsible for the tilting. Conjugate sets of internal structures show an acute intersection angle and indicate a lower dip angle for $\sigma_1$ – orientation compared with that of the large scale conjugated fault zones. However, it may be that faulting slightly different in relative age can have rotated pre-existing orientations of the earlier fractures.

Clay enrichment in lensoid shaped pockets is a commonly observed feature (Fig. 4d) which usually can be used to measure the displacement amount. These pull-apart pockets in the vertical direction are bordered by the overlapping fault planes and equal the displacement in length. Often, the immediate surroundings of such lenses are highly fractured indicating stress concentrations around these pockets.

### 3.3 Analysis of the geometric patterns

In total, some nine hundred orientations of fractures and slickenside striations were measured and plotted in stereographic projections (Fig. 3). There are conjugated fracture sets of all orders and types in almost all subareas. This can easily be recognized on the plots by the two maxima situated symmetrically to the centre of the stereographic net. The dip angle of the fractures normally varies from 50° to 90° with an concentration around 75–80°. The subhorizontal fracture system is an exception which has been observed in all subareas, but they were only measured and plotted for subarea 1 (Fig. 3). The fractures generally show a NNW-SSE strike direction. This orientation pattern is very homogeneous for all the subareas, perhaps with a slight rotation to NW-SE in quarry Heidestraße. Obviously, the single fractures show a wide range in strike directions, which may be explained by the internal pattern of fracture zones, because fractures of all orders are plotted together.

The NNW-SSE striking steep fractures comprise all types, with or without slickenside striations, with or without clay smearing and argillaceous coating. On the other hand, the subhorizontal fractures are restricted to the simplest type without striations and without argillaceous coating.

Statistically, fractures of different orders show the same orientation pattern. This means that in outcrop scale small fractures and fracture zones are generated by the same stress field. Based on the geometric fracture pattern the orientation of the three main stress axes can be given as vertical for $\sigma_1$, as NNW-SSE and horizontal for $\sigma_2$ and ENE-WSW and horizontal for $\sigma_3$.

The orientation of slickenside striations varies between 60° and 90° in plunge and shows trend variations according to the orientation of the corresponding fractures. The striations seldom correlate with the dip direction of the corresponding fracture. Fractures without any striation occur in all observed orientations, but mainly in the subhorizontal one.

Based on displacement observations at subarea 7 at the bottom of quarry Kroepke, the calculated extension is in the order of 3–5 percent. The same results from the S-wall section of quarry Saturn (subarea 2 and Fig. 2).

### 3.4 Discussion of the fracture pattern

The chalk at Laegerdorf may have been deformed by two different types of movement: ice loading and/or salt diapirism. For the described deformation features ice tectonics can be excluded: possible features of Quaternary origin, such as weathering and fracturing on a small scale, can be found only near the surface in the uppermost 10 m of the chalks. Therefore, all features discussed below are interpreted as fracturing caused by salt diapirism.

The strike direction of the salt ridge Krempe in the area of Laegerdorf is NE-SW according to gravimetric and seismic investigations (JARITZ 1972, 1973). A few kilometers NE off the quarried area, the salt ridge seems to end (Fig. 1).

From the extensional regime on top of a salt ridge, fractures striking parallel to the ridge axis are expected and normally observed (CLOOS 1955, 1968). However, the fractures in the Laegerdorf chalk on top of salt ridge Krempe strike perpendicular to the ridge axis (Fig. 5; KOESTLER & EHRMANN 1985). Therefore, a correlation between this pattern and the nearness to the ending of the diapir to the NE seems to be obvious. However, almost the same situation has been recorded in quarry Hemmoor on the same salt ridge some 35 km to the SW (GRUBE 1955). Furthermore, an analysis of up and down displaced blocks in quarry Saturn (Fig. 2) shows a consistent downstepping towards the SW, and not towards the dipping flank of the salt ridge, as would be expected. This means that the fault pattern is not related to the contour lines of the ending ridge, but rather to local depressions in the top shape. GRUBE (1955) proposed a slight culmination of the ridge axis striking NNW-SSE and running through the centre of quarries Heidestraße, Schinkel and Kroepke. This culmination is based on detail measurements of the bedding, which never exceeds 10° in dip and may be difficult to observe exactly. Such a local culmination may explain the fault orientation pattern in the quarries Heidestraße and Schinkel, but is difficult to correlate with the consistent pattern from the whole area. The downstepping of tilted blocks in quarry Saturn and a possible interpretation of own gravimetric investigations indicate rather a depression in the ridge crest between the quarries Saturn and Heidestraße/Schinkel. Probably seismic data could shed light on the possibly very complex topography and shape of the salt ridge, but unfortunately were not available to us.

The influence of regional stress situations on fracture orientations in the overburden due to doming ridges was studied by WITHJACK & SCHEINER (1982) in clay experiments. They showed that a regional compressive stress field oriented perpendicular to the ridge axis induces fracture sets mainly parallel to this stress direction. In addition, conjugated fracture sets with an acute angle pointing in the direction of maximal stresses were observed. The fracture pattern described here from Laegerdorf with a strike direction perpendicular to the ridge axis is quite similar to the pattern of their clay experiments. How far these

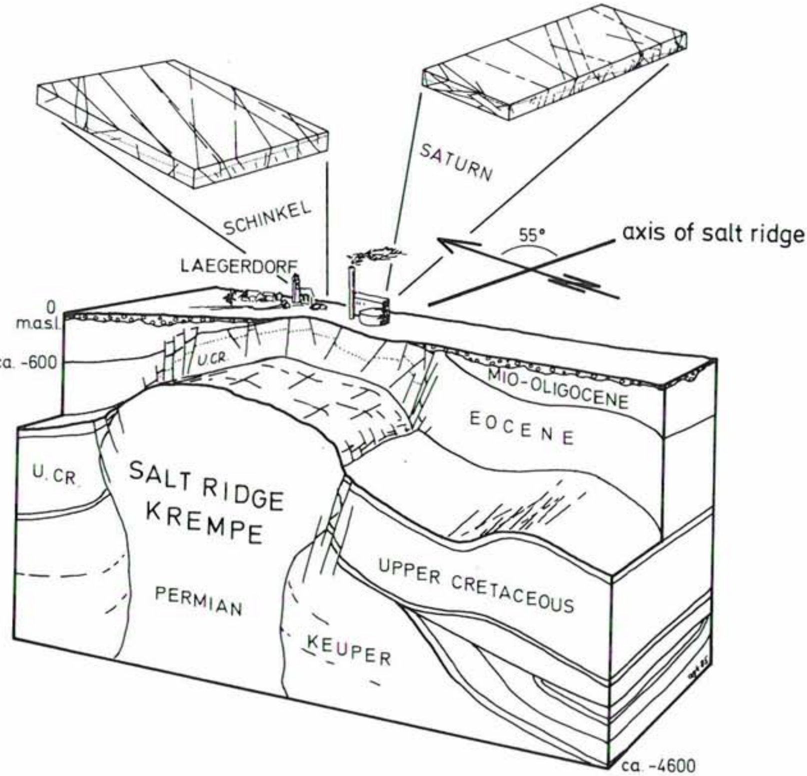


Fig. 5. Schematic block diagram of the tectonic situation of the quarries on salt ridge Krempe (geologic section redrawn from GRUBE 1955).

experiments can be extrapolated from the study scale of a few centimeters to the actual situation of several kilometers is very uncertain.

A regional stress field overprinting local salt tectonics could provide an explanation of some features of the local fracture pattern. In addition, the regional set of parallel salt ridges in the northernmost Germany with a NE-SW strike direction (Fig. 1, inset) is quite conspicuous, and suggest the operation of a large scale stress field for this phenomenon, as well. A major tectonic lineament, the Tornquist Zone (e. g. TORNQUIST 1908, BAARTMAN & CHRISTENSEN 1975, PEGRUM 1984) farther to the N strikes NW-SE and can be followed at least from the Norwegian sector of the North Sea through southern Sweden into the lowlands of Poland. The Tornquist Zone (Fennoscandian Border Zone) is a complex zone of parallel major lineaments separating grabens and highs. Wrenching in different areas of these lineaments induced the development of sedimentary basins.

Reactivating pre-Cambrian structures the zone was active in periods during all the three Eras (e. g. BAARTMAN & CHRISTENSEN 1975, PEGRUM 1984, ZIEGLER 1985). The polarity of shear displacement changed several times. Late Paleozoic and Late Cretaceous to Early Tertiary dextral shear displacements are reported. The Tornquist Zone was also subjected to transpressional stress and tectonic inversions. These dextral shear regimes, possibly reactivating basement structures, can be made responsible for the major compressional components in NW-SE direction. This may be the reason for the configuration of the salt ridges and for the fracture pattern in the chalk overburden. A subparallel lineament has been postulated to be situated beneath the salt ridge Krempe striking parallel with the river Elbe (e. g. ARTHOUD & MATTE 1977, PILGER 1976), but is not seismically confirmed.

However, the regional stress field and its effects on structural regimes has not yet been studied in the detail necessary to confirm the proposed interpretation of the observed fracture pattern. Further mapping of structures at all scales and correlations of geophysical data and surface-geological phenomena are necessary to follow up this hypothesis.

## 4. Conclusions

The investigations and descriptions of the fractures in the four quarries near Laegerdorf reveal some preliminary correlations between fracture types, internal structures and displacement amounts. While the subhorizontal joints lacking striations and argillaceous coating, do not show any displacement, the other four types are connected with displacement in the range of millimeters to tens of meters. However, a quantitative correlation between fracture surface features and displacement amounts could not yet be established. The width of fractures, the thickness of argillaceous fracture fills and the distinctness of striations are not proportional to the amount of displacement. In general, wider zones with complex internal structures and brecciation indicate faults with large displacement in the range of several meters.

The fracture orientation generates a pattern which strikes perpendicular to the salt ridge axis. The principal compressional stress component ($\sigma_1$) is oriented subvertical. The intermediate ($\sigma_2$) and the smallest ($\sigma_3$) are oriented NW-SE and parallel to the ridge, respectively, both in a subhorizontal plane. This situation reveals a faulting of the Upper Cretaceous chalks with an extension in NE-SW direction. The downstepping of the tilted fault blocks is mainly to the SW.

To provoke during diapirism an extension direction parallel to the ridge axis a regional stress field is proposed with a compressional component in NW-SE direction. This regime can be made responsible for the parallel configuration of the N German salt ridges and for the fracture pattern in their overburden. The existence of dextral sense major lineament some hundred kilometers to the N of the study area with large strike slip displacements can be the plausible cause for this regional stress regime.

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A. G. KOESTLER, GEO-RECON A. S., Bernhard Herres vei 3, 0376 Oslo 3, Norway.
W. U. EHRMANN, Geol.-Paläont. Institut und Museum, Olshausenstr. 40, 2300 Kiel, F. R. Germany; present address: GEO-RECON A. S.