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# Arcuate hinge cleavage associated with welded contacts: an example

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**Abstract**—Arcuate hinge cleavage (a.h.c.) shows a near bedding-parallel, concentric, arcuate development within the inner arcs of hinge zones. It is favoured by alternating layers of marked viscosity contrasts with little layer-parallel shortening prior to parallel folding. A field example of a.h.c. from a greywacke/pelite sequence of the Variscan of Central Europe is presented. The a.h.c. is developed as a slaty cleavage in the inner-arc hinge zones of pelite beds close to and welded to the outer arc of greywacke layers. Microscopically it is defined by the alignment of platy minerals and oblate quartz grains. The a.h.c. ($S_a$) is cut by a divergently fanning crenulation cleavage ($S_b$) which, in turn, is cut by slip surfaces parallel to bedding. The slip surfaces are cut by a fracture cleavage which is the macroscopically observed axial surface cleavage ($S_c$). This sequence of deformational increments implies the onset of bedding slip after the formation of a.h.c. ($S_a$) and ($S_b$). We therefore suspect inhibited bedding slip by welded contacts to favour the development of a.h.c.

## INTRODUCTION

Varying lithology and competence contrast of folded beds may lead to a refraction of cleavage planes (e.g. Cobbold 1983, Treagus 1983) and to a fanning of cleavage in folds in a zone of contact strain (Ramsay 1967, p. 416). Ramsay (1967) concluded that there may be a point of no finite strain situated on the outer fold arc, the 'finite neutral point' (f.n.p.). The cleavage developed between the f.n.p. and the outer fold arc, subparallel to the arc was termed 'arcuate hinge cleavage' by Roberts (1971).

'Arcuate hinge cleavage' (a.h.c.) has been observed in the field (Roberts 1971) and modelled experimentally (Roberts & Strömgård 1972, see also Hobbs *et al.* 1976, p. 266). According to theory and experimental results (e.g. Ramsay 1967, Hobbs *et al.* 1976) the outer arc of (concentric) folds is being stretched and thus the plane normal to maximum compression, the *XY* plane of the strain ellipsoid, is subparallel to bedding (e.g. Ramsay 1967, p. 417, Dieterich 1970, Roberts & Strömgård 1972). Roberts (1971) and Roberts & Strömgård (1972) argued that such anomalous strain-patterns are likely to develop in a parallel-folded multilayered sequence with high viscosity contrasts between individual layers and minimal amount of layer-parallel shortening prior to buckling, folding and cleavage formation.

Studies by the first author on the relationship between diagenesis and tectonics (Eichentopf, work in preparation) led to the recognition of further field examples of arcuate hinge cleavage in outcrops, where layer-parallel slip between pelite and psammite beds is inhibited by welded contacts (Maxwell 1962, Powell 1969). This observation adds new perspectives to the genesis of arcuate hinge cleavage and perhaps also to the formation of concentric folds. In this contribution one of the field examples is presented and some implications for the development of arcuate hinge cleavage are discussed.

## REGIONAL EXAMPLE

The folds described below are situated in the eastern marginal part of the 'Rheinisches Schiefergebirge' about 1 km NW of the village of Scheid on a peninsula of the Lake Edersee reservoir (map-sheet Bad Wildungen, TK 25: 4820, R 3500110, H 5672605, Fig. 1). The 'Rheinisches Schiefergebirge' (Rhenish slate mountains) constitute part of the external fold and thrust belt of the

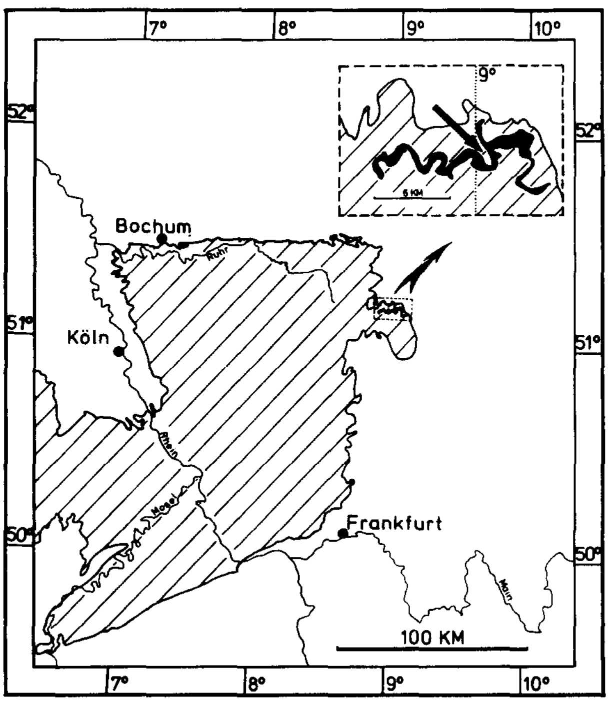


Fig. 1. Location map of the 'Rheinisches Schiefergebirge' (hatched) in Central Europe. Inset is a map of the Lake Edersee reservoir with the fold locality marked by an arrow.

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Variscan orogen in Central Europe. Exposed sedimentary successions range in age from Devonian in the centre to Early Carboniferous at its eastern margin and Late Carboniferous towards the north. Deformation took place during a time interval of about 30 Ma around the Early/Late Carboniferous transition and proceeded from the SE (about Frankfurt) to the NW (N of Bochum, Ahrendt *et al.* 1983). The structural style is characterized by open to tight, rarely isoclinal folds with NW vergence and associated thrusts, dipping SE (Weber 1978).

## *Field description*

The outcrop shows an alternating sequence of greywacke and pelite of Late Viséan age (Horn *et al.* 1973). Decimetre thick greywacke beds show flysch-type grading (fining upwards) Bouma sequences a b c e (Bouma 1962) and are frequently interlayered with cm-thick greywacke layers composed exclusively of Bouma c. The sequence is folded into NW vergent m-scale nearly concentric folds. Layer-parallel 'slip surfaces' are different from lithological layering interfaces (Fig. 2). An apparent single bed may comprise several greywacke and mudstone layers with their contacts tightly welded. Slip surfaces generally are developed within pelite layers (Fig. 3). Similar features have also been observed elsewhere in the northeastern 'Rheinisches Schiefergebirge' by H. Eichentopf. Bedding slip during folding is documented by lineations on slip surfaces (Fig. 6).

Competent, thick greywacke beds show convergent fans of fracture cleavage, whereas in the incompetent beds a slaty cleavage is developed as weakly divergent fans (Figs. 2 and 5). Refraction is obvious at greywacke–pelite boundaries (Fig. 3). Close inspection of the pelite layer shown in Fig. 3 revealed a weak cleavage that could be followed from the limb to the hinge of the syncline. The angle between bedding and cleavage decreases towards the fold hinge. At the hinge itself no cleavage has been observed macroscopically apart from the few axial planar surfaces visible in Fig. 2 (compare with Fig. 4).

In the adjacent syncline to the SE a similar fracture cleavage is developed in greywacke beds. A pelite interlayer is divided into three 'beds' by layer-parallel slip surfaces, carrying 'bedding'-slip lineations (Figs. 5 and 6). These slip surfaces delimit zones of different cleavage development. Close to the lower greywacke bed (L in Fig. 5) cleavage is broadly continuous from greywacke to pelite; it does not continue, however, across the lower slip surface where the cleavage is aligned subparallel to the slip surface in the fold hinge and fans convergently towards the limbs. In the pelite bed adjacent to the upper greywacke layer (U) the arcuate hinge cleavage is more clearly developed with transitions to a 'regular' cleavage towards the fold limbs. The upper greywacke layer shows an axial planar fracture cleavage.

Weathering has apparently accentuated the structural elements for the macroscopic view but has precluded the collection of good samples. In contrast, the syncline described previously (Fig. 2) has yielded specimens well-suited for the preparation of thin sections.

## *Microscopic observations*

The hinge area of the syncline in Fig. 2 was studied microscopically. A weak but clear arcuate hinge cleavage (a.h.c.) is developed (Fig. 4), defined by the alignment of platy minerals (mainly illite and muscovite) and oblate quartz grains. No recrystallization of these minerals has been observed. This implies a purely mechanical origin of the a.h.c. A fine, primary lamination may sometimes be disturbed or cut by the cleavage surfaces.

The detection of the a.h.c. ($S_a$ in Fig. 4a) is easy where it forms an angle to the primary lamination (Fig. 4a–c). It may be difficult, however, to distinguish between a.h.c. and lamination where these two are parallel (Fig. 4a).

The a.h.c. is cut by an equally weak, divergently fanning crenulation cleavage ($S_b$, Fig. 4a–c). $S_a$ and $S_b$

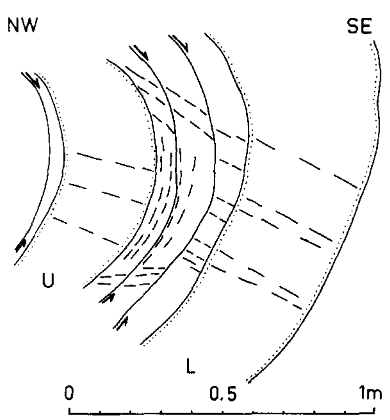


Fig. 5. Field sketch showing a synclinal hinge of a NW-vergent fold in greywacke (stippled margins, U—upper, L—lower bed) and pelite interlayers. Slip surfaces (marked with half-arrows), developed exclusively in pelite layers and not at lithological boundaries. Cleavage (broken lines) is mostly axial planar, but close to the outer arc of the upper greywacke layer an arcuate hinge orientation is clearly seen in the shale. Different cleavage domains are bounded by slip surfaces.

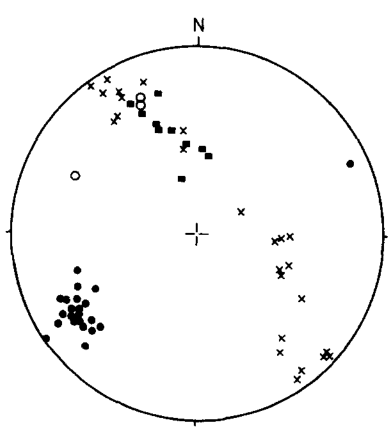


Fig. 6. Equal-area stereographic diagram (lower hemisphere) showing structural elements of the described folds: bedding plane poles (crosses), cleavage plane poles (squares), fold axes (dots) and flexural slip lineations (circles). A concentric fold shape is suggested by the almost full girdle of bedding plane poles.

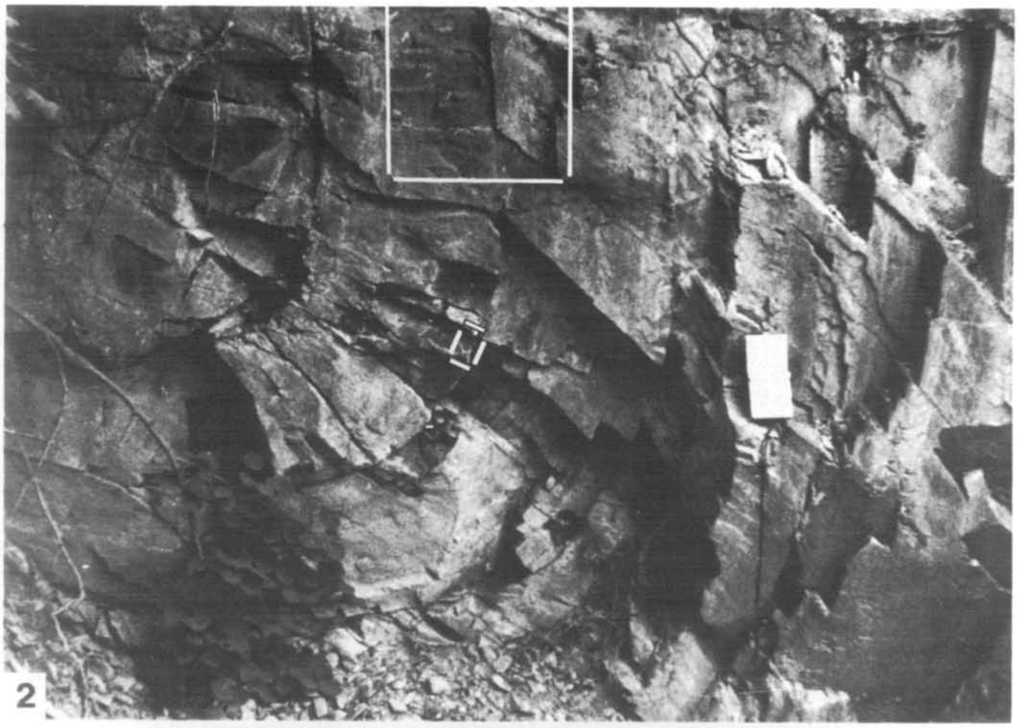

Fig. 2. NW-vergent fold in alternating greywackes and pelites with gently convergent and divergent cleavage fans, respectively. Cleavage refraction is obvious at lithological boundaries. However, flexural slip surfaces are different from lithological boundaries (see detail outlined at the top, shown in Fig. 3). The small white rectangle (centre) outlines the part of the fold hinge area that is shown on Fig. 4. This part is different from the fold hinge proper. Compass (7 × 14 cm) for scale.

Fig. 3. Detail from Fig. 2. A prominent slip surface (near vertical, centre, marked by pencil) developed within a pelite bed during flexural slip. Note, that the slip surface is cut by the cleavage. No slip occurred at the boundary (shown by white dashes) between greywacke (left) and pelite (centre), that is distinguished by a marked cleavage refraction.

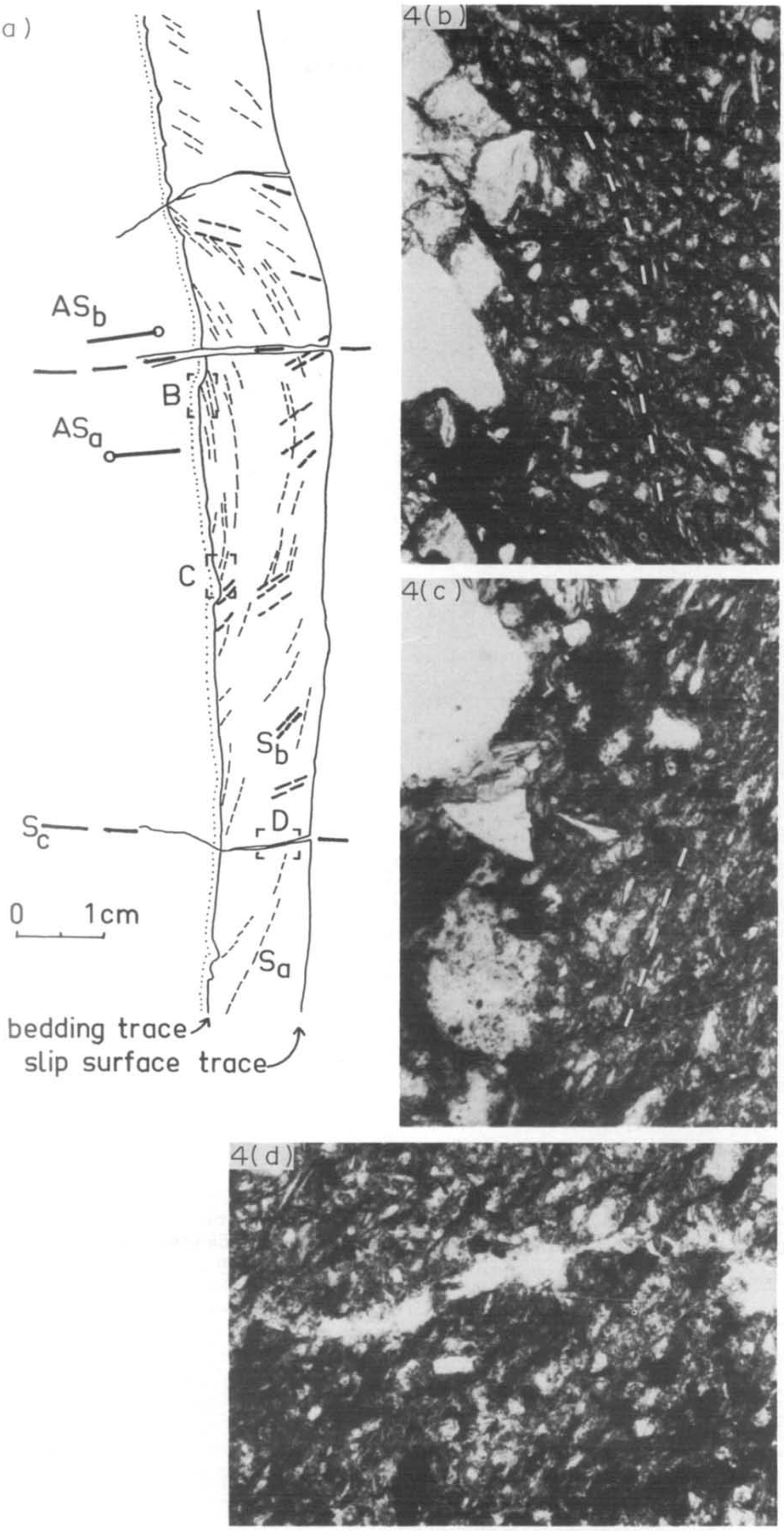


Fig. 4. (a) Detail of synclinal fold hinge (location indicated on Fig. 2) with arcuate hinge cleavage ($S_a$) and divergently fanning axial surface crenulation cleavage ($S_b$) developed in pelite close to psammite (left, dotted). The boundary to the right is a slip surface within the pelite. Cross-cutting relationships show $S_a$ to predate $S_b$ that, in turn, is cut by the macroscopically visible cleavage ($S_c$). Axial surface traces, shown schematically as $AS_a$ and $AS_b$, respectively, are different for 'increments' a and b. Axial surface trace 'c' is situated below the lower margin of the figure. (b)–(d): Photomicrographs (positive prints) showing examples of the fabric outlined in (a) (at locations marked by B, C and D). Quartz grains and fresh feldspar grains appear white, mica minerals and weathered feldspar grains appear dark. Most of the photographs are pelite, the lowermost part of the overlying psammite bed is visible to the left. The bedding surface is approximately vertical. (b) Upper part of $S_a$ arcuate development. $S_a$ (marked by white lines) forms an acute angle with the bedding trace. $S_a$ is cut by a (somewhat irregularly developed) crenulation cleavage ($S_b$) that is approximately horizontal. (c) Lower part of $S_a$ arcuate development. $S_a$ is cut by the $S_b$ crenulation cleavage, dipping steeply to the left. (d) The $S_b$ crenulation cleavage (dipping moderately to the left) is cut by a fracture cleavage ($S_c$, approximately horizontal). $S_c$ open fractures show up white.

are cut by a slip surface (Fig. 4a). Both this surface and $S_a$ and $S_b$, in turn, are cut by the macroscopically visible axial planar (fracture) cleavage ($S_c$, Figs. 2–4a & d). Figure 4 shows that the locus of the fold axial surface has migrated during the time of development of the fold axial cleavage ($AS_a - S_c$). Thus the a.h.c. axial plane is not located at the hinge of the present, macroscopically visible fold. This fact may account for the preservation of the early a.h.c. in moving it from the locus of subsequent intensive cleavage formation. $S_a$ and $S_b$ could not be followed from the fold hinge to the limbs. As is evident from Fig. 4, $S_a$ and $S_b$ become subparallel towards the fold limbs, so that an exact distinction is no longer possible.

### *Time sequence and interpretation of deformational increments*

In contrast to the model of tension fracture development as a response to stretching at outer fold arcs (e.g. Ramsay 1967, p. 401) in competent brittle rocks, in our example cohesion in pelite beds and between incompetent pelite beds and competent psammite beds apparently precludes fracture initiation and propagation. Instead, ductile deformation leads to the reorientation of oblate mineral grains to form an a.h.c. ($S_a$ in Fig. 4). Progressive deformation induced a second step of cleavage formation ($S_b$ in Fig. 4) different from $S_a$ in both direction and type of deformation. Whereas the a.h.c. ($S_a$) is a penetrative, slaty cleavage, $S_b$ is a spaced, crenulation cleavage (Fig. 4). The geometry of $S_b$ implies the presence of a finite neutral point, although different from the locus of the f.n.p. during $S_a$ formation (Fig. 4). Observed slip surfaces cut both $S_a$ and $S_b$ and are cut, in turn, by a fracture cleavage ($S_c$). $S_c$, the macroscopically visible cleavage is only weakly fanning. No f.n.p. is developed.

Microscopic observations imply the onset of bedding slip first after $S_b$ cleavage formation. We therefore suspect inhibited bedding slip by welded contacts to favour the development of a.h.c. and the peculiar pattern of principal strain axes around a finite neutral point. In fact, the experimentally produced buckle folds described by Roberts & Strömgård (1972) and the finite-element work of Dieterich (1970) imply a similar interpretation. Welded contacts may also be suspected from field examples of a.h.c. shown by Roberts (1972, figs. 8 and 10a).

Boulter (1979) argued that operation of flexural slip preserved the bedding/cleavage angle during fold limb rotation, a situation similar to that of Fig. 5. However, the early history in Boulter's (1979) example with prefolding bedding-slip is distinctly different from fold formation as envisaged above. Otherwise, the authors found little reference as to the importance of bedding-slip for cleavage or a.h.c. formation, although it has been discussed in detail in the 1950s in the context of concentric fold formation (e.g. Cloos 1950, Hoeppener 1953, 1956, Nabholz 1956, De Sitter 1964, Hills 1972).

## CONCLUSIONS

Arcuate hinge cleavage (a.h.c.) is an exceptional type of cleavage restricted to multilayered sequences of considerable interlayer competence contrast with little layer-parallel shortening prior to parallel folding (Roberts 1971). As argued above, there is also a close genetic relationship between inhibited bedding slip and a.h.c. formation. Bedding slip may be inhibited by welded contacts between competent and incompetent layers. Relative scarcity of welded contacts could be an explanation for the scarcity of a.h.c. Furthermore, a.h.c. is likely to be overprinted by a later axial-planar cleavage during progressive deformation. In the present example a.h.c. escaped overprinting because the fold hinge migrated during fold formation so that the early hinge area with a.h.c. is now distinct—and distinguishable—from the axial-planar cleavage at the present (late) hinge.

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