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Cleavage geometry and the development of the Church Bay Anticline, Co. Cork, Ireland

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Abstract—The Church Bay Anticline is one of a series of E–W trending Hercynian folds in southern Ireland. The fold has a crudely axial planar cleavage which was initiated early in the buckling history. The cleavage was deformed subsequently by a number of discrete bedding parallel shear zones as the fold continued to amplify. This has resulted in a characteristically sigmoidal cleavage geometry in the fold profile plane. The cleavage also displays kink bands and sharp angular changes across bedding planes in the fold hinge as a result of shearing. Within these sheared zones the cleavage is intensified indicating that conditions for cleavage formation were maintained throughout the development of the fold. No new cleavage has formed despite the rotation of the cleavage during the deformation history.

INTRODUCTION

THE HERCYNIAN orogeny in southwest Ireland deformed a sequence of Upper Devonian and Carboniferous sediments under anchimetamorphic conditions. The orogen is dominated by a number of large upright folds trending approximately E–W (Gill 1962, Naylor *et al.* 1981). The aim of this contribution is to describe the complex cleavage geometry associated with the development of one of these folds—the Church Bay Anticline. The structure is developed in alternating siltstones and sandstones of Upper Devonian age and is well exposed on two coastal sections at either side of the entrance to Cork Harbour (Fig. 1).

FOLD MORPHOLOGY

The Church Bay Anticline trends at 070° and has a half-wavelength of approximately 1.2 km, with significantly different morphologies on the two sides of Cork Harbour entrance.

On the eastern side at Roches Point (Fig. 1), the Church Bay Anticline has a wide hinge area (approximately 300 m) with dips of less than 20°. On the northern limb bedding dips at up to 50°, and on the southern limb up to 70°. The fold core, plunging 10°E, consists of gently folded red siltstones of the Ballytrasna Member (MacCarthy *et al.* 1978). The fold limbs consist of the overlying sand-dominant Gyleen Member (MacCarthy *et al.* 1978) and exhibit Z- and S-sense folds on the northern and southern limbs, respectively. The Church Bay Anticline at Roches Point thus has an overall box-fold morphology and as a result a single axial surface cannot be constructed for the structure.

On the western side of Cork Harbour entrance at Church Bay, stratigraphical relationships are the same as those at Roches Point. The Ballytrasna Member forms the core of the anticline, the Gyleen Member the limbs. However, the fold morphology has changed dramatically. The hinge is very narrow (approximately 10 m) and angular with an interlimb angle of 60°. Bedding dips are approximately 80° S on the southern limb

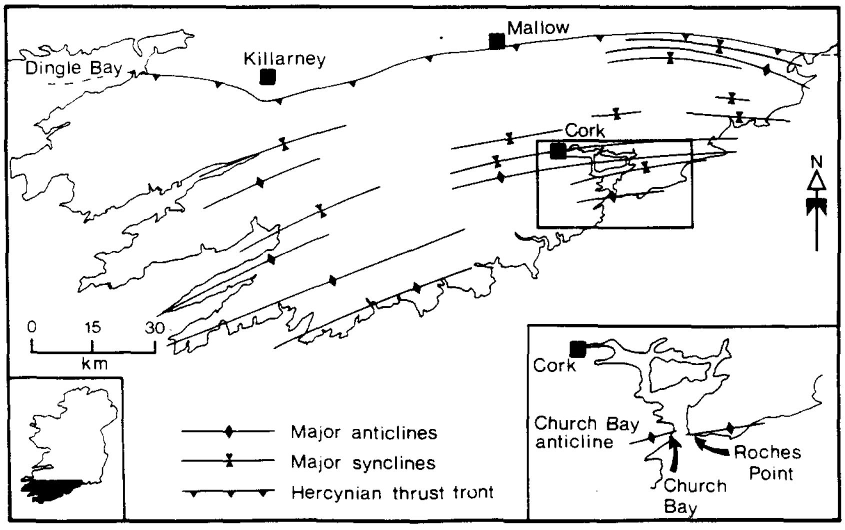

Fig. 1. Map of the Hercynian orogen in Southern Ireland showing the major structural features. The inset map shows the two localities described in this paper.

and 40° N on the northern limb. A single axial surface may be defined here dipping at 70° to the north. There are no minor folds on either limb but small-scale thrust structures resulting from accommodation during folding are commonly developed.

Bedding planes throughout the fold are often mineralised by quartz and chlorite with slickenside fibres oriented perpendicular to the major fold axis. This suggests that flexural slip was a contributory folding mechanism.

CLEAVAGE GEOMETRY

Strong *ac* jointing has produced a number of profile sections which have aided the study of bedding/cleavage relationships. Figure 2 is a line-drawing from a photograph of one such joint surface from the hinge area at Roches Point. Sharp angular changes in cleavage orientation are seen between some beds, probably due to cleavage refraction. At other bedding interfaces, across which there are no obvious lithological changes, cleavage displays a sigmoidal geometry in the profile plane. If this were the result of cleavage refraction then it would imply that beds had coarser middles with finer grained bases and tops; no such changes in grain size can be observed. Where the bedding/cleavage angle is least the cleavage is most intensely developed. Figure 3 is a close-up of dextral shearing of cleavage at a sandstone bedding interface on the northern limb of the Church Bay Anticline at Roches Point. The cleavage is a spaced pressure solution fabric with an anastomosing character on both profile and bedding planes. It is more intensely developed, that is closer spaced, in the zone of greatest angular change. On the southern limb, where good exposures are limited, a similar geometry is observed with a sinistral sense of shear. The sigmoidal cleavage geometry is most pronounced on the fold limbs suggesting formation during flexural shear processes as the fold developed. Ideally there should be no slip in the fold

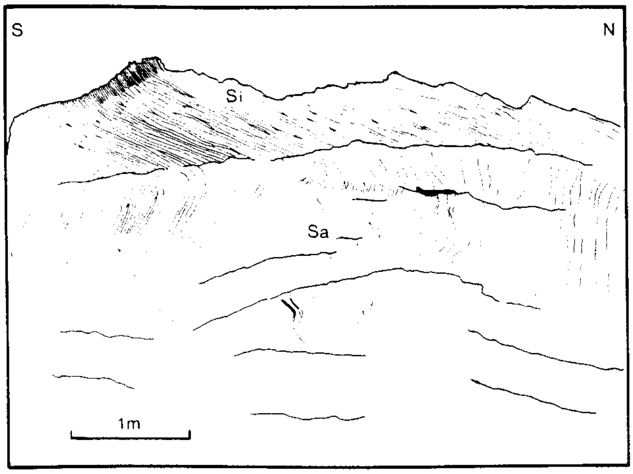

Fig. 2. Line-drawing made from a colour transparency of an *ac* joint plane in the hinge of the Church Bay Anticline at Roches Point. An abrupt change in cleavage/bedding angle occurs at the contact between the siltstone (Si) and the sandstone (Sa).

hinge, however, due to the box fold morphology at Roches Point there is also some flexural shear in the wide hinge zone (Figs. 2 and 4).

Figure 4 illustrates from the hinge zone at Roches Point the common development of kink bands deforming the cleavage sub-parallel to bedding. The kink-band axes are parallel to the axis of the Church Bay Anticline and they and the fold are considered to have developed coevally. Within many of the kink bands the cleavage is more intensely developed.

The angular variation of cleavage throughout the Church Bay Anticline is shown by a graph of the angle between bedding-normal and cleavage plotted against bedding dip (Treagus 1982). The data for Roches Point (Fig. 5a) and Church Bay (Fig. 5b) shows that for any particular bedding dip there is a large variation in cleavage/bedding angles.

DISCUSSION

Sigmoidal cleavage traces and the intensification of cleavage in discrete shaly beds have been described briefly by Cloos (1951, 1961) from the Round Top Section, Maryland, U.S.A. Using calculations of maximum slip due to flexural-slip folding, Cloos concluded that these phenomena were associated with bedding-parallel slip prior to folding. Borradaile (1982) gives a brief description of sigmoidal cleavage but further descriptions in the literature are scarce.

In the Church Bay Anticline it appears that modification of cleavage/bedding angles is solely due to flexural-slip and flexural-shear processes during folding. The intensification of cleavage in kink bands and along bedding interfaces suggests that the conditions necessary for cleavage formation were present throughout the development of the fold. It must also be concluded that cleavage formation began early in the fold's development and that the cleavage was subsequently rotated by flexural shear operating along discrete zones parallel to bedding.

In similar deformation sequences reported in the literature (e.g. Boulter 1979, Mitra & Elliott 1980), a second cleavage is developed. Mitra & Elliott (1980) postulate successive cleavage development with successive thrust movements in an imbricate stack of thrust sheets. Lower thrusts fold earlier, higher thrusts and their associated cleavage, producing a new axial planar cleavage. Boulter (1979) described the production of two inclined cleavages during a single folding event from the Stirling Range, southwestern Australia. There, the initial phase of folding was dominated by layer-parallel shortening, producing a spaced mica-band cleavage. Body rotation of limbs resulted in a 70° angle between cleavage and bedding on fold limbs which was preserved by flexural slip until the fold had tightened to about 100°, when flattening rapidly became important. During this later stage a second cleavage developed, approximately axial planar to the fold.

Fig. 3. Intensification and dextral shearing of the cleavage at the contact of two sandstone beds on the north limb of the Church Bay Anticline at Roches Point. The lower bed does not fine upwards.

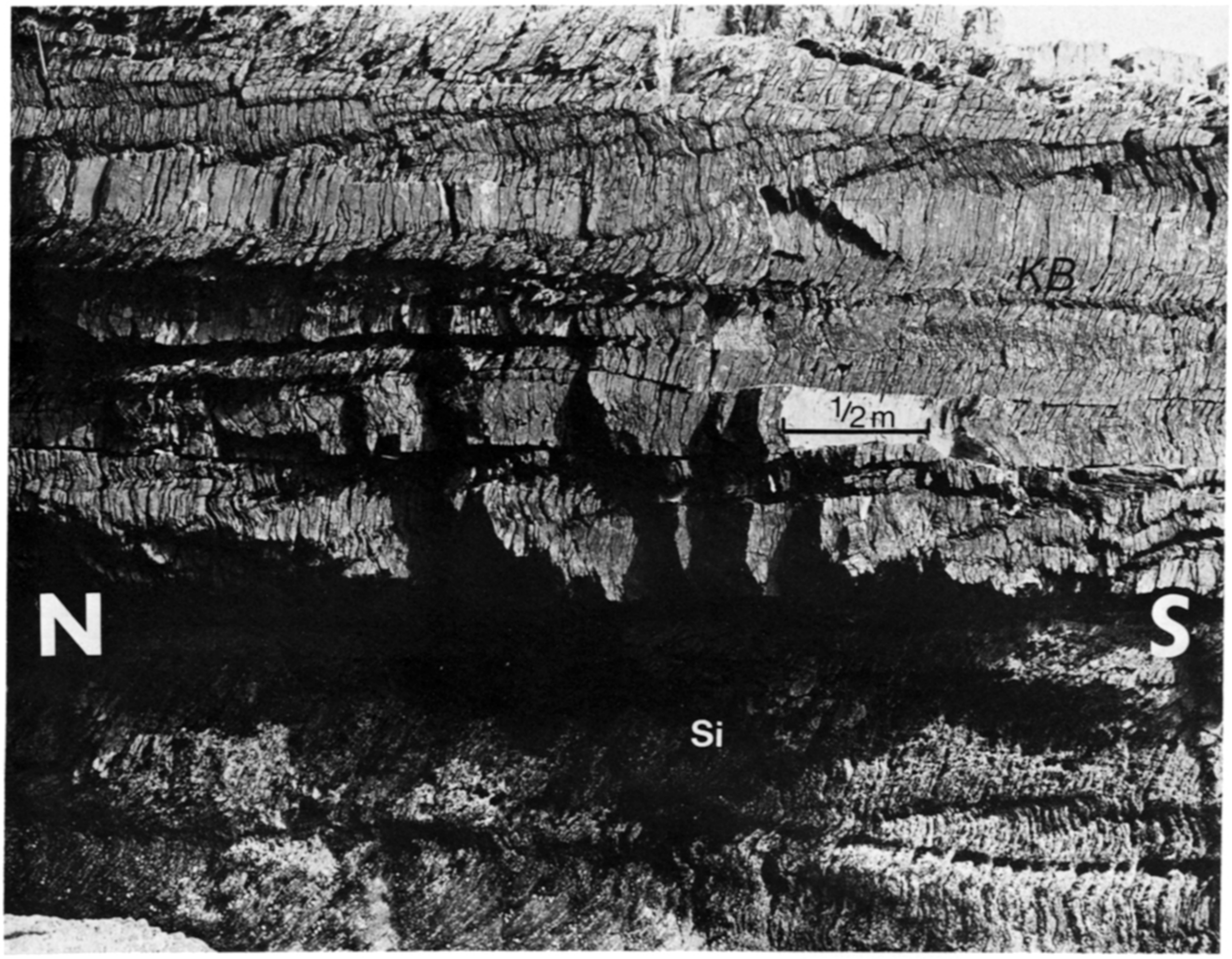

Fig. 4. View of an *ac* joint plane in the hinge of the Church Bay Anticline at Roches Point. Note the number of kink bands which are approximately parallel to bedding (e.g. KB). The siltstone bed (Si) at the base shows sigmoidal cleavage traces resulting from dextral shear.

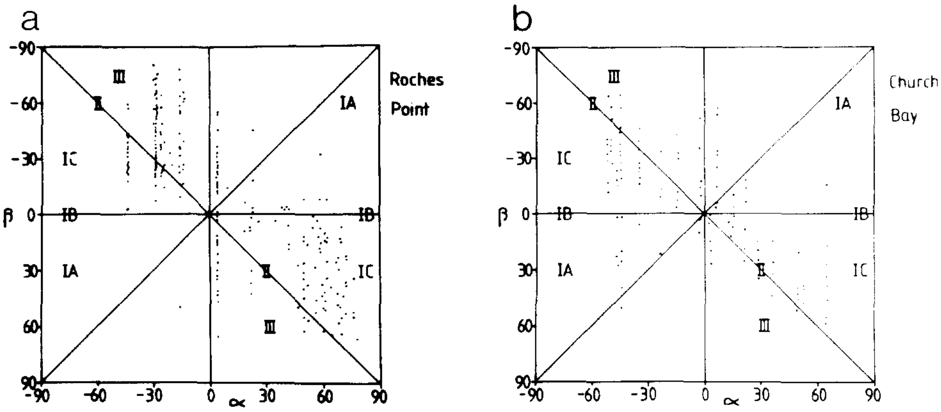

Fig. 5. Treagus plots of the bedding/cleavage data from (a) Roches Point and (b) Church Bay. α is bedding dip normalised to the plane bisecting the fold limbs. β is the angle between bedding pole and cleavage trace. The plots illustrate the wide variety of bedding/cleavage angles for any given bedding dip.

Although conditions for cleavage formation were present throughout the development of the Church Bay Anticline there is no evidence of a second cleavage. There does not appear to be a phase of homogeneous flattening, in contrast to the Stirling Range example (Boulter 1979). It seems probable that once initiated, cleavage planes accommodated all subsequent strain by passive rotation, recrystallisation and localised intensification.

The marked change in fold morphology is not reflected by the cleavage geometry. The change in fold style could be the result of two factors. (1) The presence of sandstones of variable thickness in the Roches Point section may have caused instabilities in the chevron-type structure at Church Bay (Ramsay 1974). (2) Cooper *et al.* (in press) have recognised that there is probably a frontal ramp to the south of the Church Bay Anticline and hence we think that changes in ramp height could have resulted in changes of fold style along the strike. Work currently in progress should help to resolve the cause of the change in fold style. Additional work is also in progress to determine whether the sigmoidal cleavage geometry in the Church Bay Anticline is typical of folds in the Irish Hercynian fold belt.

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