DERBYSHIRE WRENCHES AND ORES -
A STUDY OF THE RAKES' PROGRESS BY SECONDARY FAULTING

by

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Summary

The morphology of most of the Derbyshire rakes suggest that they were initiated as short primary wrench faults which were subsequently extended by a series of curved secondary faults. Geometrically they resemble fault patterns predicted by Chinnery (1966a). Using his terminology, it is suggested that in Derbyshire there are examples of the lengthening of wrench faults in the A1 and A2 modes, *en echelon* variants of these modes; and complex combinations. Complementary B type faults are rare, and it is doubtful if Chinnery's C, D, E and F type faults are represented. Propagation and lengthening is frequently from west to east and movement along the faults is small in relation to their length. Mineralisation is considered to be unrelated to the initiation and propagation of primary and secondary faults. It is ascribed to late phases of dilational reopening of primary and secondary faults and of systematic joints, possibly during periods of uplift or dilation doming during earthquakes.

Unambiguous examples of second-order faults (Moody & Hill, 1956) have not been recognised in Derbyshire and it is considered that most patterns of mineral veins in Derbyshire can be satisfactorily explained in terms of combinations of Chinnery's (1966a) primary and secondary faults and systematic joint patterns.

Introduction

In Derbyshire the widest and most continuous mineral veins are called "rakes". These have long been regarded as the main channelways for mineralising fluids (Farey, 1811). Geometrical considerations led Shirley and Horsfield (1940) to claim that Moss Rake occupies a wrench fault. More recently Ford (1969) drew attention to the prevalence of horizontal slickenside striations on walls and mineral fillings and implied that most of the Derbyshire rakes occupy wrenches. Subsequently an attempt has been made to indicate the net displacement of these supposed wrench faults (Ford and Ineson, 1971). Unfortunately the evidence is often ambiguous; horizontal slickenside striations may indicate only one component of a series of complex displacements and in the absence of near vertical 'markers' such as dykes or axial planes it is often impossible to evaluate the relative importance of strike slip movement.

In spite of these difficulties it is reasonable to assume that long, straight, vertical rakes, like Moss Rake, fill wrench faults. Others (e.g. Odin Rake, Ford 1967 Fig. 9.2) are now known to be far from straight and consequently are difficult to explain by Anderson's model (1951). Furthermore, the overall pattern of the Derbyshire rakes is quite unlike those predicted and described by Anderson (1951) in his classic publication. Thus some other explanation is required.

One explanation, examined in detail in this paper, is that the Derbyshire rakes typically consist of short straight primary wrench faults which were later extended by a series of curved secondary faults (cf. Chinnery, 1966a). If this is correct then Anderson's (1951) criteria apply only to the straight parts of the rakes and the morphology of the rest is likely to be similar to that predicted by Chinnery's mathematical model.

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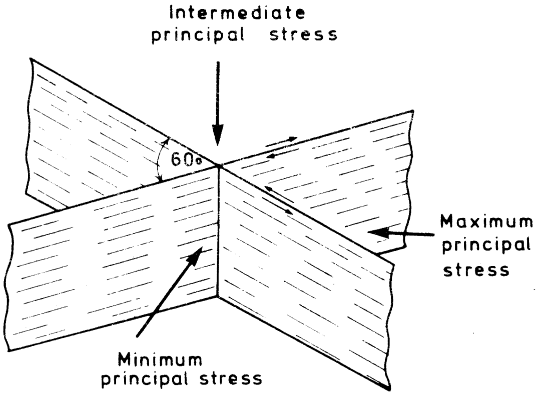
1977. pp. 81-96, 14 text-figs.

The term "secondary faults" is used in this paper exclusively to describe faults generated at the ends of wrench faults due to the build up of stress. They are confined to the *ends* of pre-existing faults and should not be confused with "second-order faults" which according to McKinstry (1953), Moody and Hill (1956) and Price (1968) may form anywhere along the length of pre-existing faults where stress concentrations developed due to friction.

In this paper the evidence for primary, secondary and second-order wrench faults is examined and the relative importance of these and systematic joints (Weaver, 1975) as channelways for mineralising fluids is evaluated.

Evidence for primary wrench faults

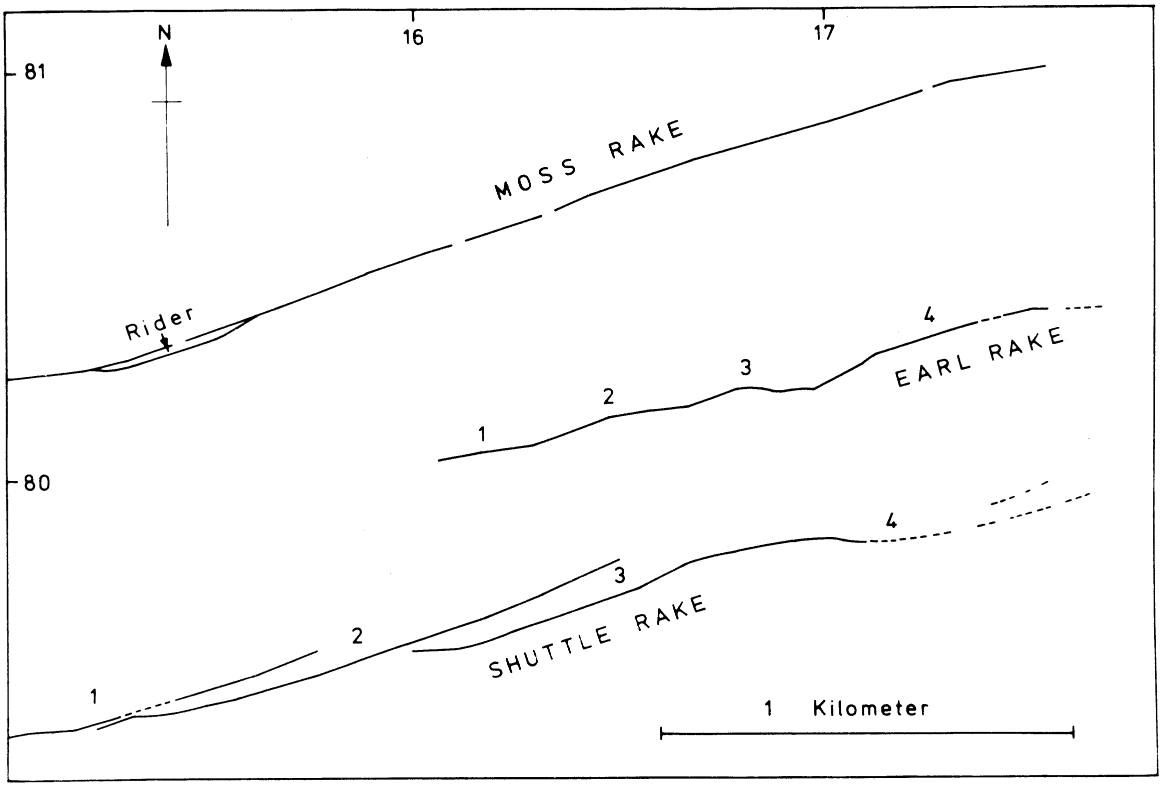
Anderson (1951) in his classic book applied the Navier-Coulomb theory of failure in brittle substances to the interpretation of faults formed in stress regimes in which the maximum and minimum principal stresses are horizontal and the intermediate principal stress is vertical (text-fig. 1).



Text-fig. 1. Orientation of the principal stresses and shear planes during wrench faulting. Note that the fault planes may be curved or corrugated in the vertical profile but take a straight course along the direction of movement. Slickenside striations are often developed as shown and the dihedral angle between the fault planes is often about 60° but depends on the internal coefficient of friction of the rocks traversed.

In such conditions the wrench fault surfaces would tend to be vertical and to develop horizontal slickenside striations. Along the direction of movement the fault is likely to follow a straight course and hence have a straight outcrop but it may have a more sinuous vertical profile (Anderson, 1951).

Straight outcrops, near-vertical fault surfaces and evidence of strike-slip movement are characteristic of some, but by no means all of the Derbyshire rakes. In some instances only parts of a rake are straight; others are gently curved; some seem to consist of a series of short curved faults, which may be inter-connected or *en echelon* (text-fig. 2), and others (discussed later) are considerably more complex. Some rakes may be depicted as straight lines on the geological map solely because of a lack of evidence of their true course. Nevertheless many rakes are straight and Farey's (1811) contention that "rake veins generally preserve a pretty straight course," is broadly true. Thus although many Derbyshire rakes and veins conform with Anderson's (1951) description of wrench fault morphology there are several whose horizontal profile is unlike the wrench faults described by him but which nevertheless exhibit evidence of strike slip movement.

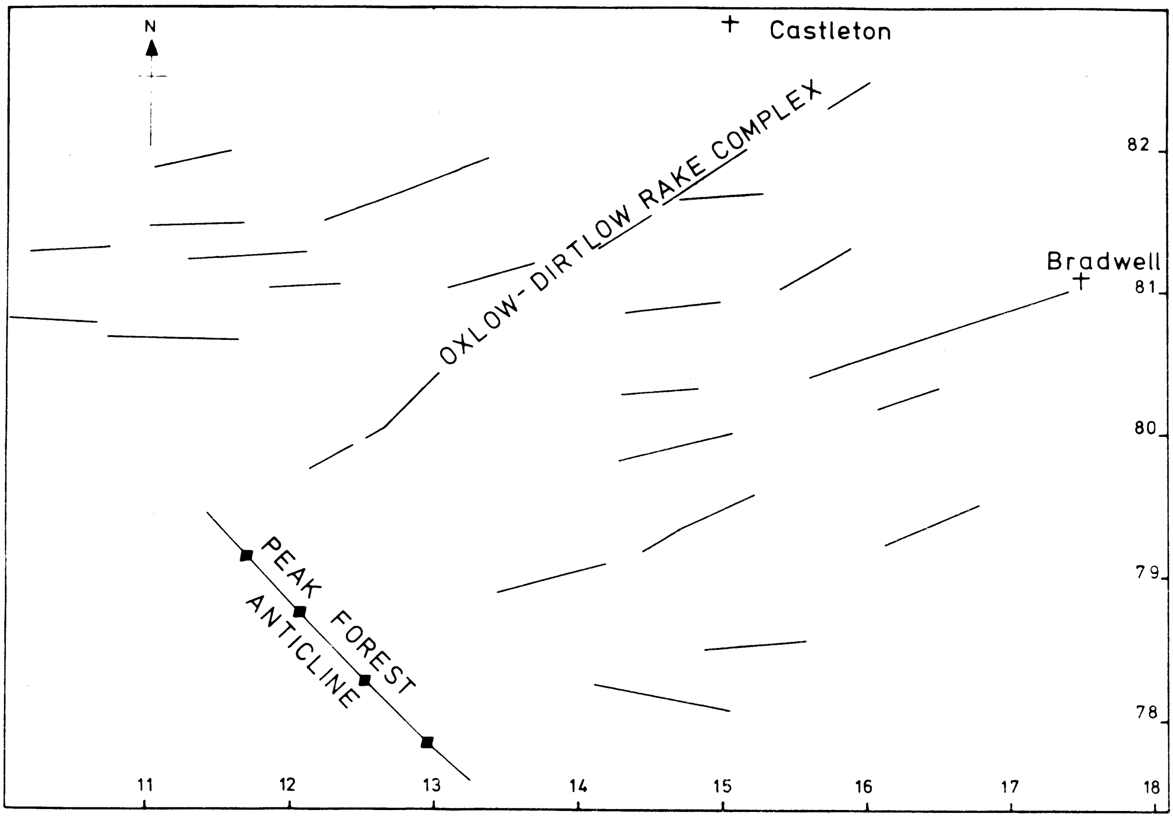


Text-fig. 2 Three parallel faults in the Bradwell area showing markedly different morphologies. Moss Rake is essentially straight, but encloses a limestone 'rider' or 'horse'; Earl Rake appears to have been propagated by a series of curved fractures apparently convex to the north, and Shuttle Rake consists of a series of *en echelon* curved shears convex to the south. Based on I. G. S. six maps SK18SE and SK17NE.

Other discrepancies are noted when the overall pattern of rakes is considered. It is not easy to identify complementary wrench fault patterns, nor is the probable direction of movement along the faults consistent with that predicted by Anderson.

Anderson's simple classical concept cannot therefore be applied to all the Derbyshire rakes. Admittedly Anderson's simple pattern applies only to isotropic conditions and stresses produced in a heterogeneous basement and during folding might be expected to modify profoundly this pattern. Nevertheless the variability of the pattern of rakes contrasts with the simple pattern revealed by the systematic joints (Weaver, 1975) and, in the writer's opinion, the hypothesis that the rakes are compounded of primary and secondary wrench faults has much to commend it.

Text-fig. 3 attempts to identify primary faults in the Bradwell area. With the exception of the Dirtlow and Oxlow Rake complex these have a fairly consistent east and west orientation which contrasts with the greater variability of the curved portions of the rakes. It is not the purpose of this paper to explain the generation of the primary shears but it is interesting to note that Stevenson and Gaunt (1971 p. 34) suggest that the Dirtlow Rake Fault may have been active during B_2 - P_1 times. Thus it appears possible that its anomalous trend may be due to reactivation of a basement fault.



Text-fig. 3 Possible primary wrench fractures in the Castleton-Bradwell area based on the relatively straight parts of rakes as shown on I. G. S. maps (2½ inch Special Sheet Castleton and Edale.) Note the anomalous direction of the Oxlow-Dirtlow Rake fractures which may be due to basement control. (see text pp. 87-88).

Evidence for Chinnery's Type A secondary faults

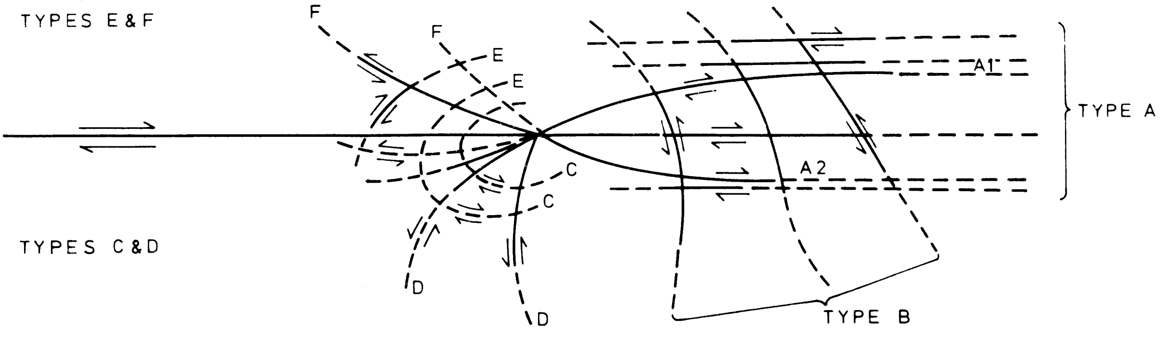
The assumption that only the straight portions of strike slip faults in the Carboniferous Limestone were primary implies that they were subsequently extended along a series of short, frequently curved, fracture surfaces often about 0.5 to 1 km long. Of all the mathematical studies of wrench faults which have been published only one (Chinnery, 1966a) predicts that wrench faults are likely to extend themselves along curved surfaces. This analysis, confirmed Anderson's contention (1951 p. 164) that only at the ends of wrench faults could sufficiently strong concentrations of shear stress be built up to produce secondary faults. Anderson (1951) realised that his model, based as it was on a fault of infinite depth, was not sufficiently refined to allow more than a qualitative explanation of "splays" commonly observed at the end of wrench faults but Chinnery's (1966a) more rigorous analysis permits a more precise definition of the localisation, size and shape of secondary faults.

Chinnery (1961, 1963) had previously used the "elasticity theory of dislocations" as developed by Steketee (1958) to calculate the stress changes which accompany strike-slip faulting. Subsequently (1966a) he argued that, since Steketee (1958) had shown that the displacements and stress changes are independent of the initial stress, the calculated changes in the stress components *during* faulting could be added to the initial stress components to obtain the stress distribution *after* movement had ceased. The pattern that Chinnery obtained showed "that although the initial stress is reduced over most of the length of the fault there are strong concentrations near the ends" which could cause secondary faults. Chinnery (1966a) suggested that secondary faulting was likely where the maximum shear stress after faulting was equal to, or in excess of, the maximum shearing stress which existed before faulting and was also very likely in regions of tension. In regions of compression the secondary faults were assumed to be aligned at about 30° to the principal axis of compression whilst in regions of tension the fractures were expected to develop approximately parallel to the planes of maximum shear stress. Using these assumptions Chinnery was able to predict the geometry of secondary faults (text. fig. 4) from the stress distribution after faulting.

Chinnery (1966a) showed that the pattern of stress distribution and of predicted secondary faults should be symmetrical only when the principal stress axes are inclined at 45° to the primary fault. According to him this corresponds to the classical case of "pure shear" and might be an appropriate model to describe the relative movement of continental blocks. However, all the examples given by him (Chinnery 1966b); by Moore and Shanti (1973) and the Derbyshire rakes described in this paper, are asymmetric and it appears that his "uniaxial compression" model which assumes that the maximum principal compressive stress was at 30° to the primary fault is the most appropriate model for general use (text-fig. 4). In theory the pattern of predicted secondary faults will be more symmetrical than shown in text-fig. 4 as the angle between the fault and the maximum principal stress approaches 45° and more asymmetric if less than 30°, but the changes are slight.

One possible objection to applying Chinnery's model to Derbyshire is that his calculations were based on a fault model 200 km long, 10 km deep with a net displacement of 5 m. Although, this is too large for Derbyshire it may be scaled down without altering the geometry of the predicted secondary faults. For example a fault 2 km long, 100 m deep with a net displacement of 50 mm should produce the same array of secondary faults as those predicted for the larger model. However, although the straight and presumably primary, portions of the Derbyshire rakes rarely exceed 2 km (text-fig. 3) lead mines often are more than 100 m deep and some were worked below 300 m. It seems probable that most faults are much deeper and therefore in Derbyshire the ratio of length to depth is much less than the 20:1 ratio of Chinnery's model. According to Chinnery (1966a) this should not alter the geometry but should cause the secondary faults to extend further from the ends of the primary wrench faults. Field evidence seems to support this assertion since in Chinnery's model, type A secondary faults lengthen the primary fault by about one eighth of its total length whereas in Derbyshire the lengthening appears to be approximately equal to the length of the primary fault. Apart from this difference Derbyshire wrench fault extensions fit exceedingly closely to those predicted by Chinnery (1966a) - indeed the fit is closer than many examples quoted by Chinnery (1966b) himself.

The complete range of secondary faults predicted by Chinnery (1966a) is very complex (text-fig. 4) but in practice it is most unlikely that they will all form at the end of any one fault. As indicated in the caption to text-fig. 4 different shears require different stress



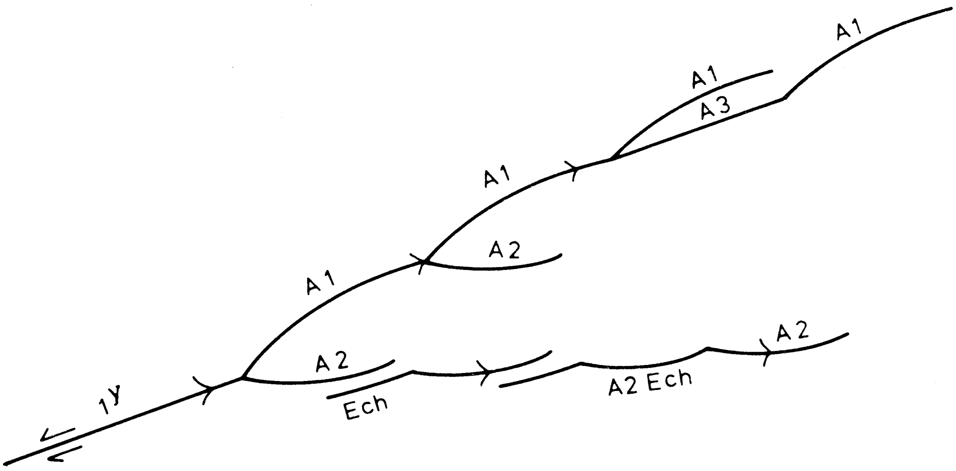
Text-fig. 4 Likely directions for secondary faulting under uniaxial compression (after Chinnery 1966a). According to Chinnery types A and B require high shear stress; types C and D form in regions of overall tension and types E and F need both high shear and high compressive stress conditions.

conditions for their formation and in addition the formation of one secondary shear may sufficiently reduce the accumulated stress to prevent the formation of complementary shears. Thus in Derbyshire, types A and B, which according to Chinnery (1966b) form in conditions of high shear stress, are far more common than all others and of these, type A, which has the effect of lengthening the fault, is far more common than the complementary type B set. This latter observation may be biased by the fact that most of the complementary fractures can only be recognised, in Derbyshire, when they have been mineralised. Because type A fractures are extensions of the main fault they are much the most likely of all Chinnery's predicted faults to be mineralised and hence the most likely to be shown on old mine plans or by surface evidence of old workings. Nevertheless Chinnery himself (1966b) commented that in New Zealand type A faults are common and type B apparently absent.

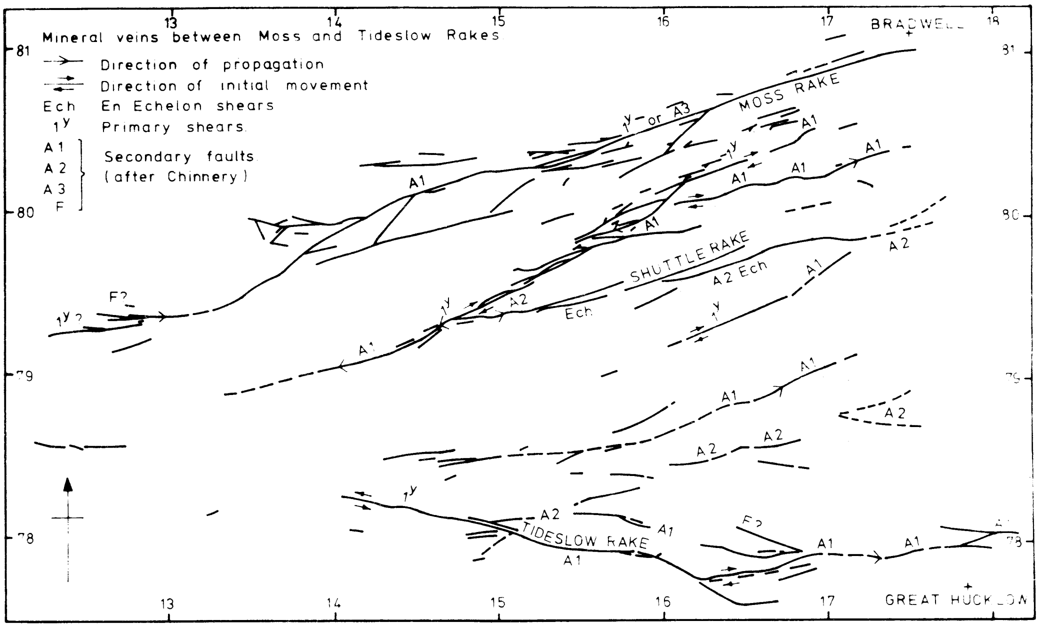
A geometric similarity between those faults predicted by Chinnery and those observed in Derbyshire is illustrated by several subsequent text figures. In the absence of any alternative explanation it is accepted in this paper that the curved portions of the rakes were generated as secondary faults and the reader is left to judge from the following examples how closely the geometry fits that described by Chinnery.

According to Chinnery (1966b p. 183) in conditions of uniaxial compression the A1 mode of lengthening is more likely than the A2. Text-fig. 5 shows the theoretical orientation a dextral wrench fault, formed in response to an east-west regional stress, and extended in the A1 and A2 modes respectively.

The Bradwell area provides good examples of wrench faults which appear to have extended themselves along curved fractures analogous to Chinnery's type A faults. Here the relatively simple pattern exemplified by text-fig. 5 is analogous to many of the veins which radiate from the Peak Forest Anticline (text-fig. 6). Moss Rake (West), Earl Rake, Nether Water Vein and High Rake (I. G. S. six sheets SK18SW, SK18SE and SK17NE) exhibit a geometry consistent with an eastward propagation and extension of dextral wrench faults in the A1 mode; Shuttle Rake appears to represent an *en echelon* extension in the A2 mode as on text-fig. 6, and less convincingly the White Rake - Tideslow Rake system appears to be a sinistral fault with both A1 and A2 components.



Text-fig. 5 A possible example of the lengthening of a dextral primary wrench fault by the different types of secondary faulting suggested by Chinnery's model. Legend as in text-fig. 6.

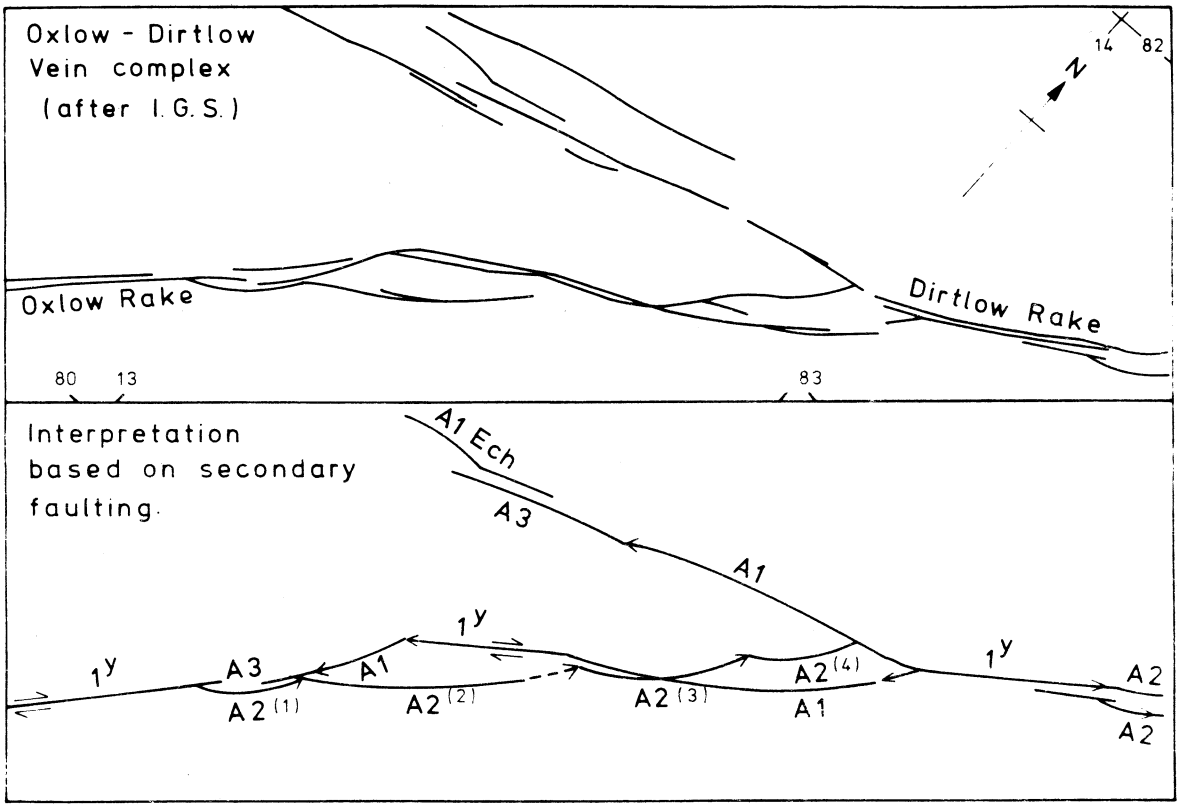


Text-fig. 6. A tentative structural interpretation of the mineral veins between Moss Rake and Tideslow Rake. Note that the arrows indicate the *initial* movement implied by the geometry and *not* the net displacement. Although generally similar to the pattern shown in text-fig. 5, the actual pattern above as mapped (I. G. S. $2\frac{1}{2}$ inch Special Sheet Castleton and Edale) is more complicated because of a greater number of primary fractures and because of westward as well as eastward propagation. Tideslow Rake appears to be part of a sinistral fault system. If this is correct the dihedral angle between complementary wrench faults is much less than 60° in the Bradwell area.

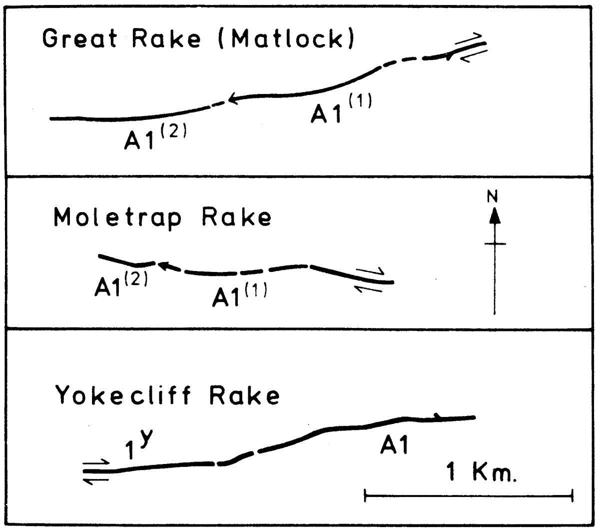
Considering this evidence only, a very good case could be made for faults being initiated and propagated from the crest of the Peak Forest Anticline in response to stresses associated with the formation of that anticline. However, applying Chinnery's secondary fault geometry to other mineral veins suggests that several fractures originated on the flanks of the anticline (text.fig. 3) and were then extended up the eastern limb from east to west. Amongst these are the western end of Shuttle Rake and parts of the Oxlow-Dirtlow fracture system. This latter vein complex is much more intricate than any other in the Bradwell area. By no means can all fractures in this belt be satisfactorily explained by Chinnery's hypothesis. Nevertheless if it is postulated that master faults with slightly different orientations were initiated in several places along the Dirtlow-Oxlow line and secondary A type faults spread out north-eastward and south-westward from these small primary faults much of the complex geometry can be satisfactorily explained (text-fig. 7). Other fractures may have formed during re-shearing.

Probable type A secondary faults occur elsewhere in Derbyshire but less prolifically than in the Bradwell area. Good examples, traced on the I. G. S. special $2\frac{1}{2}''$ to 1 mile Matlock Sheet include Great Rake (Matlock), Moletrap Rake and Yokecliff Rake in the southern part of Derbyshire, (text-fig. 8).

Detailed underground surveys frequently demonstrate that where surface mapping has indicated a straight vein it actually consists of a series of curved fractures (e.g. Mandale Rake, Tune, 1969; and Odin Rake, Ford, 1967 and Ford & Rieuwerts, 1976). The geometry of Odin Rake is particularly interesting since it is possible that the rake changes direction with each change of limestone lithology. Theoretically a fault will extend, "until the fault reaches a region where the initiating conditions are modified" (Anderson, 1951 p. 66).

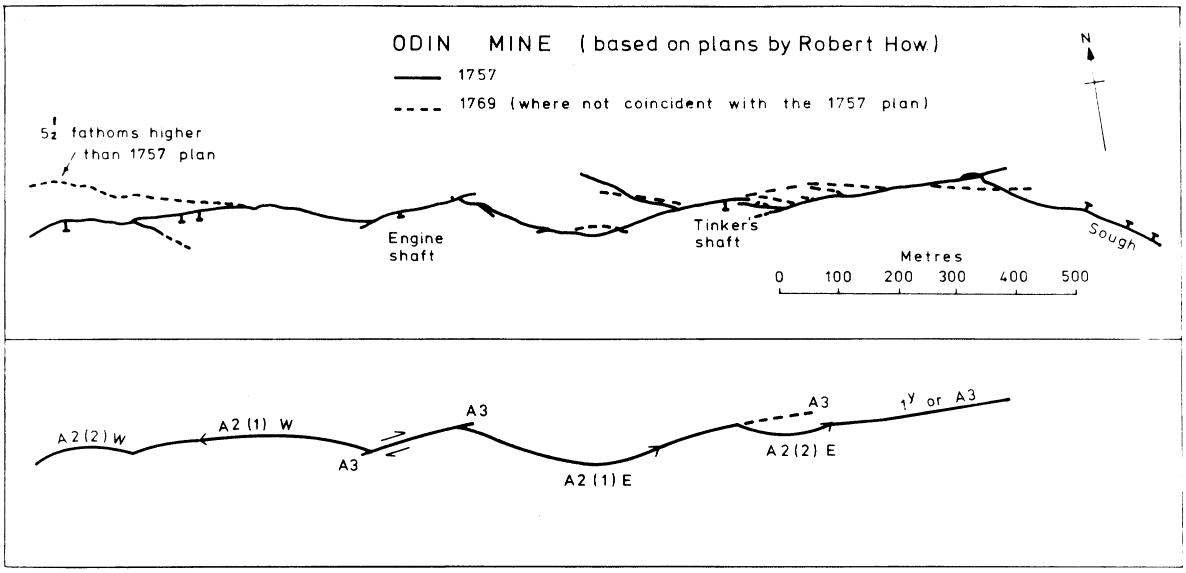


Text-fig. 7 A portion of the Dirtlow-Oxlow Rake complex as shown on the I. G. S. six-inch map (SK18SW) together with a tentative interpretation based on the assumption that the complex developed from a few short primary wrench faults which were extended both north-eastward and south-westward by secondary faults.



Text-fig. 8 Examples from the south-eastern part of the limestone outcrop, of rakes probably propogated eastward and westward in the A1 mode by secondary faults. (I. G. S. 2½ inch Special Sheet. Matlock).

At Odin, the modified condition may well correspond with varying lithology since changes in fault orientation seem on the 1757 plan by Robert How to correspond to reefs rising from the general level of the limestone. Unfortunately most of the Odin Mine is inaccessible and differences between 1757 and 1769 editions of mine plans by Robert How are sufficient to throw doubt on their accuracy. Nevertheless these plans (xerox copies of which were kindly lent by Dr. Trevor Ford) can plausibly be interpreted in line with Chinnery's hypothesis (text-fig. 9).



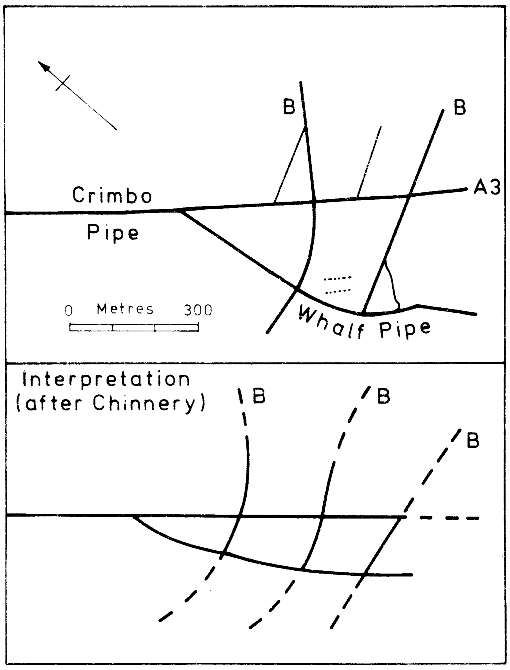
Text-fig. 9 A plan of the Odin Rake (based on surveys by Robert How) with a possible structural interpretation involving both eastward and westward propogation in the A2 mode from a short primary fault. Like the west end of Moss Rake and Whalf Pipe (text-fig. 10) the curvature on the early A type fractures is greater than that predicted by Chinnery for secondary faulting under conditions of uniaxial compression and approaches the curvature postulated by him for pure shear.

Thus fractures analagous to Chinnery's type A faults appear to be very common in Derbyshire. They are particularly abundant in the northern part of the limestone outcrop and are rare in the south where the majority of veins appear to fill the systematic joints (Weaver 1974) which are much more numerous than mineralised wrenches and associated secondary faults. The curvature along most of the supposed type A faults is comparable to that predicted by Chinnery (1966a) for shearing under uniaxial compressive stress when the maximum principal stress was at 30° to the resulting shear. The greater curvature, exhibited, for example, by the western end of Moss Rake and Long Rake, near Yougreave, could, if Chinnery is correct, be due to a more deep-seated origin in conditions approaching pure shear. However, the majority of the Derbyshire "rakes" appear to have been initiated as shallow wrench faults which were subsequently extended by a series of type A secondary faults. The total strike slip movement was insignificant and often so masked by later strike-slip and dip-slip displacements that the original direction of movement cannot be determined.

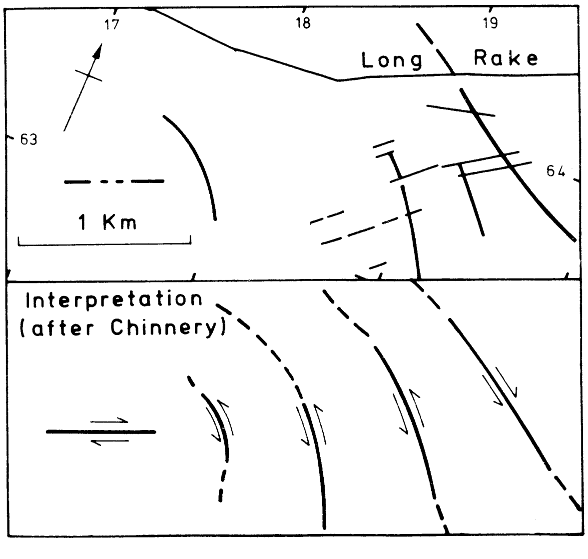
Examples of complementary secondary faults

(Chinnery's type B)

Secondary faults complementary to type A faults are rare, possibly because they have not been subsequently mineralised and hence remain undetected, but more probably because the formation of type A faults sufficiently relieved the stress to inhibit their formation. The examples illustrated in text-figs 10 and 11 are similar, but not identical to those forecast by Chinnery (1966a) and moreover include a number of other mineral veins (possibly joint fillings) which obscure the pattern.



Text-fig. 10 Crimbo and Whalf pipes and associated veins based on surface and underground information (after Robey, 1969).

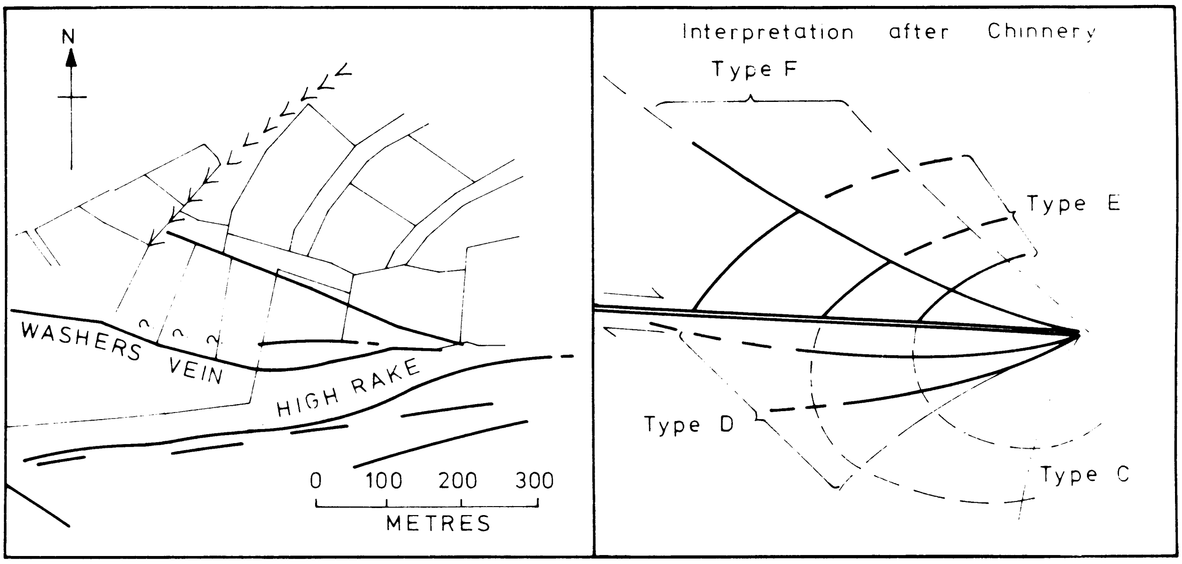


Text-fig. 11 Possible type B faults in the Long Rake area (Author's mapping).

Possible examples of other types of secondary faults

Faults shown on text-fig.12 are the most convincing examples, known to the writer, of mineral veins which could possibly represent some of Chinnery's other types of secondary faults. None will convince the sceptic and indeed it appears more probable that either Chinnery's types C, D, E and F did not form in Derbyshire or if they did they were not mineralised and hence cannot be seen where the limestone is not exposed. Curved geomorphological features emphasised by the curved walls in the Tideslow Rake area may be a fortuitous coincidence and not as tentatively implied in text-fig.12, type E secondary faults.

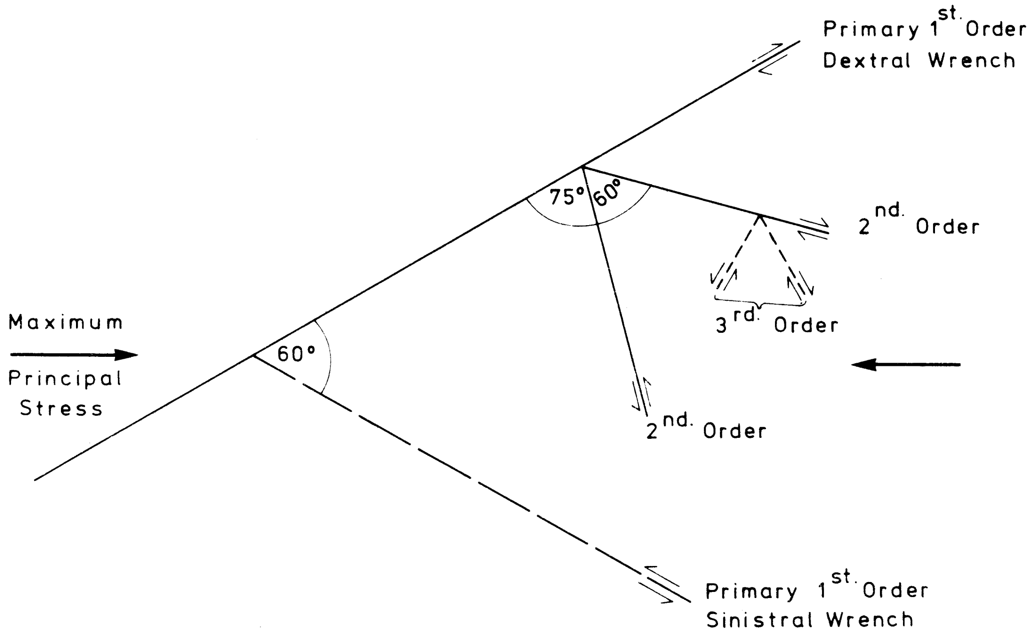
Whatever the true status of types C, D, E and F secondary faults the writer is of the opinion that there are sufficient examples of types A and B to strongly suggest that they are prevalent in Derbyshire.



Text-fig.12 A possible example of types D and F faults near Washers Vein, Tideswell. Geomorphological features exemplified by the valley and emphasised by curved walls could conceivably be controlled by type E secondary faults. (Based on I. G. S. map SK17NE).

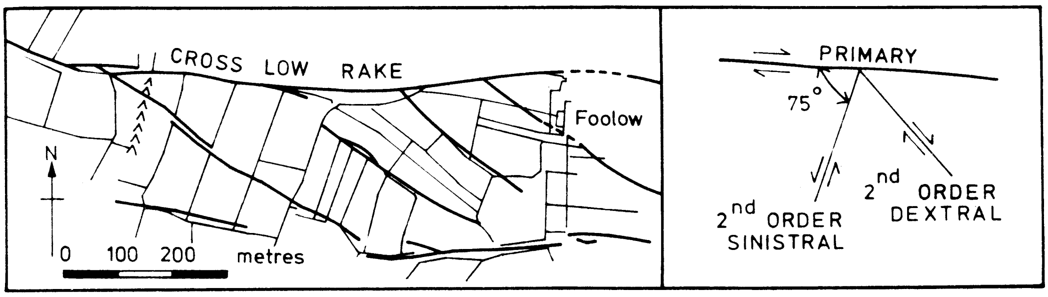
Second-order faulting

Second-order faulting caused by the frictional forces generated by wrench faults was first proposed by McKinstry (1953) and elaborated by Moody and Hill (1956). The latter authors suggested that further movement along second-order faults would generate third-order faults orientated as shown on text-fig.13. Both McKinstry, and Moody and Hill have been severely criticised by Chinnery (1966b) who maintains that their arguments are mechanically unsound and that in any case stress concentrations sufficient to cause faulting can only build up at the ends of major faults. However fault patterns similar to those predicted by Moody and Hill (1956) have been recorded from many parts of the world and have been attributed by many authors to second and third-order wrench faulting. A radically different explanation for second-order faults was proposed by Price (1968). He suggested that earthquake shock waves generated by the incremental movements of wrench faults may cause momentary and transient modifications of the static stress field sufficient to cause fractures to form adjacent to the major faults with orientations similar to those forecast by Moody and Hill (1956). These fractures might later be extended during renewed movements of the primary fault.



Text-fig. 13 Primary, second- and third-order fault systems expected from an east-west maximum principal stress system as predicted by Moody and Hill, 1956 (cf. text-fig. 5, p. 86).

It is not the purpose of this paper to evaluate the relative merits of the static theories of McKinstry, and Moody and Hill, compared with Price's dynamic theory, but merely to ascertain whether there are any fault patterns in Derbyshire which geometrically resemble second-order faults. One feature of many second-order fault patterns described in the literature is that fractures tend to be developed on one side only of the primary wrench. Using this feature the obvious candidates are fractures adjoining Coast Rake, Long Rake and Crosslow Rake (text-fig. 15). If these fractures were initiated as second-order faults, then only one of the two complementary directions is present. Weaver (1975) has shown that the mineral veins trending south-south-east from the Coast Rake are parallel to the systematic joints. Observations by the writer demonstrated that the same relationship holds south of Long Rake where joints in Shining Bank Wood Quarry and adjacent to the Bowers Vein form a rectilinear pattern parallel to the principal veins other than Long Rake itself. It thus seems most likely that the mineral veins adjoining Coast Rake and Long Rake fill systematic joints and not second-order faults as previously suspected (Firman and Bagshaw, 1974). Owing to lack of rock exposures the Crosslow area is more difficult to evaluate. Curiously one set of stone-walls and a valley are parallel to the theoretical direction of the complementary second order fault. It is therefore possible that the veins south of Crosslow Rake do fill one set of second-order faults but in the absence of measurable joints this is difficult to prove (text-fig. 14).



Text-fig. 14 Veins adjacent to Crosslow Rake - a possible example of second-order faults. Based on I. G. S. six-inch map, (SK17NE).

Thus, in Derbyshire, the evidence for "second-order faults" is weak whereas the case for "secondary faults" is strong.

Mineral veins, wrench faults and systematic joints

Weaver (1975) has demonstrated convincingly that in the south-eastern part of the Derbyshire Dome the majority of mineral veins shown on Geological Survey maps fill systematic joints. His illustrative rose diagrams show the close comparability between vein and joint patterns but this statistical approach obscures the fact that some of the widest and historically the most profitable veins (i.e. the "rakes") do not conform to the systematic joint pattern. Morphologically Great Rake (Matlock), Moletrap, Yokecliff and several other rakes appear to be primary wrench faults extended in the A mode (Chinnery 1966b) by secondary faulting. Their curved segments contrast markedly with the predominate rectilinear mineral vein patterns; therefore, the south-eastern part of the mineral field is compounded of veins filling primary and secondary wrenches *and* systematic joints. This contrasts with the Bradwell area (text-fig. 6) where mineral veins in wrench faults predominate and only very thin uneconomic veins (scrins) or joint coatings occur in the systematic joints.

The arguments for the rakes as primary and secondary wrench faults should not be allowed to detract from Weaver's clear evidence of mineral veins filling systematic joints. In some areas such as Crich, Ashover and Bonsall Moor the mineral veins in systematic joints were economically very important and at Millclose (Traill, 1939) the value of minerals filling joints, albeit widened by corrosive waters, was probably in excess of all the minerals won from the Derbyshire rakes.

To explain the complete pattern of Derbyshire mineral veins the mechanism of both faults and joints needs to be considered.

Mineralisation

Mineralisation in Derbyshire is not confined to faults and joints and is not restricted to one period of time (see Firman and Bagshaw, 1974, for a fuller discussion). Nevertheless fault and joint fillings account for a substantial part of the Derbyshire mineralisation and many of the major fluorspar replacement ore bodies are adjacent to major rakes. Intuitively it might be expected that much of the mineralisation of the rakes coincided with their initiation and extension, perhaps by hydraulic mineralisation (Phillips, 1972). Several lines of evidence suggest that this is incorrect.

(a) Many faults were propagated from west to east whereas evidence (reviewed by Firman and Bagshaw, 1974) suggests that the minerlising fluids tended to move up dip from east to west.

(b) Mineral zoning does not coincide with stages in the extension of wrench faults.

(c) Wrench faults and joints are not necessarily contemporaneous (Price, 1966) yet in many areas they contain the same mineral assemblages suggesting that both structures opened simultaneously during mineralisation.

(d) Euhedral minerals are often found growing on horizontal slickenside striations which developed in the wall rock prior to mineralisation.

Such arguments do not preclude some mineralisation coinciding with the initial propagation of primary and secondary wrench faults but they do strongly suggest that the bulk of the mineralisation was due to the reopening, probably by hydraulic fracturing, of pre-existing primary and secondary wrench faults at a late stage after both the faults and systematic joints had fully developed.

The timing and mechanism of this reopening and mineralisation is uncertain but the textures and structures in the veins indicate that it was episodic and that dilational periods were interspersed by periods of renewed strike-slip and oblique-slip movements often accompanied by brecciation (Firman and Bagshaw, 1974). Slickenside striations on the mineral fillings are often differently orientated from those on the wall rocks (e.g. Ford, 1976), indicating a reorientation of the stress system between phases of mineralisation. Ford's contention (1976, p.36) that slickenside striations on the wall rocks of the Odin vein are probably evidence of a late phase of movement of the opposing walls as they ground against the sides of the mineral fill is at variance with the evidence here and elsewhere in Derbyshire that the minerals nucleated on an already slickensided surface. Wall rock slickenside striations in the writer's opinion almost invariably formed before mineralisation began.

Dilational reopening of pre-existing fractures, both before and between periods of mineralisation, might result for instance from uplift, renewed folding in anticlinal areas or dilation doming during shallow earthquakes. Circulation of mineralising brines could result from processes analogous to the seismic pumping suggested by Sibson, Moore and Rankin (1975) but whatever the true explanation the mineralisation appears to be largely unrelated to the initiation and propagation of the primary and secondary wrench faults.

Conclusions

The geometry of most of the Derbyshire rakes strongly suggests, in the writer's opinion, that they were initiated as short primary wrench faults 0.5 to 1 km long which were subsequently extended along a series of curved secondary faults similar to those predicted by Chinnery (1966a). The commonest means of extension is, as forecast by Chinnery, in the A1 mode; but the A2 mode is frequent and extensions in both the A1 and A2 modes of *en echelon* shears has also been observed. This latter means of extension was not suggested in either of Chinnery's papers (1966a and 1966b) and has not been recorded in any subsequent papers by other authors but seems to be a legitimate addition to the modes of extension suggested by Chinnery. As in the examples quoted by Chinnery the complementary type B secondary faults are uncommon. No wholly convincing examples of Chinnery's types C, D, E and F secondary faults have been located and thus secondary faulting in Derbyshire is virtually limited to the types A and B. This, according to Chinnery (1966a), implies high shear stress conditions without the accompanying high compressive stress required for types E and F or the overall tension needed for types C and D.

The reasons for one mode of extension being adopted in preference to another is not understood and is apparently not predictable from surface lithologies or published gravity and magnetic data. If the mode of extension, curvature and length of secondary faults could be related to measurable parameters a useful means of predicting the course of the rakes eastward under the Namurian cover would be available to the prospector. Much more research is needed to solve this problem.

Second-order faults, as defined by Moody and Hill (1956), appear to be rare or absent and most vein patterns reminiscent of second-order faults are more plausibly attributed to mineralised systematic joints.

Mineralisation appears to be unrelated to the initiation and propagation of the primary and secondary wrench faults. It is attributed to periods of tensional reopening of these faults and systematic joints and not to hydraulic mineralisation accompanying the initial opening. The Derbyshire wrenches and ores are thus not contemporaneous and the wrenches have a long history of initiation, propagation and extension before the ores were formed. The wrenches' progress is thus not synonymous with the rakes progress, although it is a necessary prerequisite.

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