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Geological control of fracture permeability in the Carnmenellis granite, Cornwall: implications for radionuclide migration

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ABSTRACT. Multi-packer hydraulic tests and radioactive tracer experiments carried out in boreholes in the Carnmenellis granite have shown that the flow of water through the rock is largely confined to narrow zones separated by zones of very low permeability. Correlation of the hydraulic data with geological data from oriented cores has shown that most of the flow is associated with discrete geological features, including pegmatitic and other veins, and elvan (quartz-feldspar porphyry) dykes, characteristic features of the granite of the area. Joints have also been found to conduct water, particularly in the upper 250 m of the granite. The permeability of the granite has been found not to be simply a function of fracture frequency, long sections of highly fractured rock having no associated flow under test conditions. While flow paths have been found to become less frequent with depth, flow rates do not vary over the depths studied, the highest flow rate recorded at the site being associated with a vein at 637 m. Water-conducting fractures have been found to have certain preferred orientations which vary with depth. A set striking 155° is particularly well developed in the upper 250 m of the granite. This orientation is significant in that it is parallel to the cross-courses in the nearby mineralized belt with which the younger (Tertiary) mineralization tends to be associated and from which thermal brines issue into several local mines. These fractures are also approximately parallel to the maximum horizontal stress which affects the granite and which appears to be responsible for the selective opening of joints of certain orientations.

KEYWORDS: granite, Carnmenellis, Cornwall, fractures.

DEEP burial in crystalline rock such as granite has been one of the options considered for the disposal of radioactive waste. Ground water movement in crystalline rocks is largely confined to fracture networks which will form the main flow paths for the migration of buried radionuclides to the surface. Field investigations at an experimental site at Troon in Cornwall, involving multi-packer hydraulic tests and radioactive tracer experiments in boreholes drilled in granite, have been directed towards the acquisition of data relating to the fracture permeability of the rock; correlation of the geological features seen in the core allow individual flow paths to be identified. Retardation of radionuclides transported along these fracture systems by sorption and diffusion has been investigated in the laboratory (Lever and Bradbury, 1985). The data obtained from these permeability and retardation studies are forming the basis for mathematical modelling aimed at predicting the migration of radionuclides following their release from buried waste.

A statistical approach to flow network modelling has been adopted in which it has been assumed that fractures are planar, occur randomly in the rock mass, are of finite extent, and have the following characteristics for which probability distributions can be determined: frequency, orientation, dimensions, and effective hydraulic aperture (Robinson, 1982). Using these statistics it is possible to generate a model rock mass within which fracture connectivity, flow and hydrodynamic dispersion may be calculated. Incorporation of the results of network modelling with those of the retardation studies is hoped to produce an integrated model capable of predicting radionuclide migration following release from its buried containment.

Geological framework

The experimental site is situated within the Hercynian (Variscan) Carnmenellis granite, approximately 1 km from its NW margin. The granite is part of a single large intrusion, irregularities in the roof of which are exposed as a series of granite plutons extending some 200 km from Dartmoor in the north-east to the Scilly Isles and beyond in the south-west (fig. 1). The batholith is post-orogenic and has been dated at about 290 Ma. The Carnmenellis granite intrudes Devonian sedimentary and basic igneous rocks; the latter were deformed and metamorphosed to the lower grades of regional

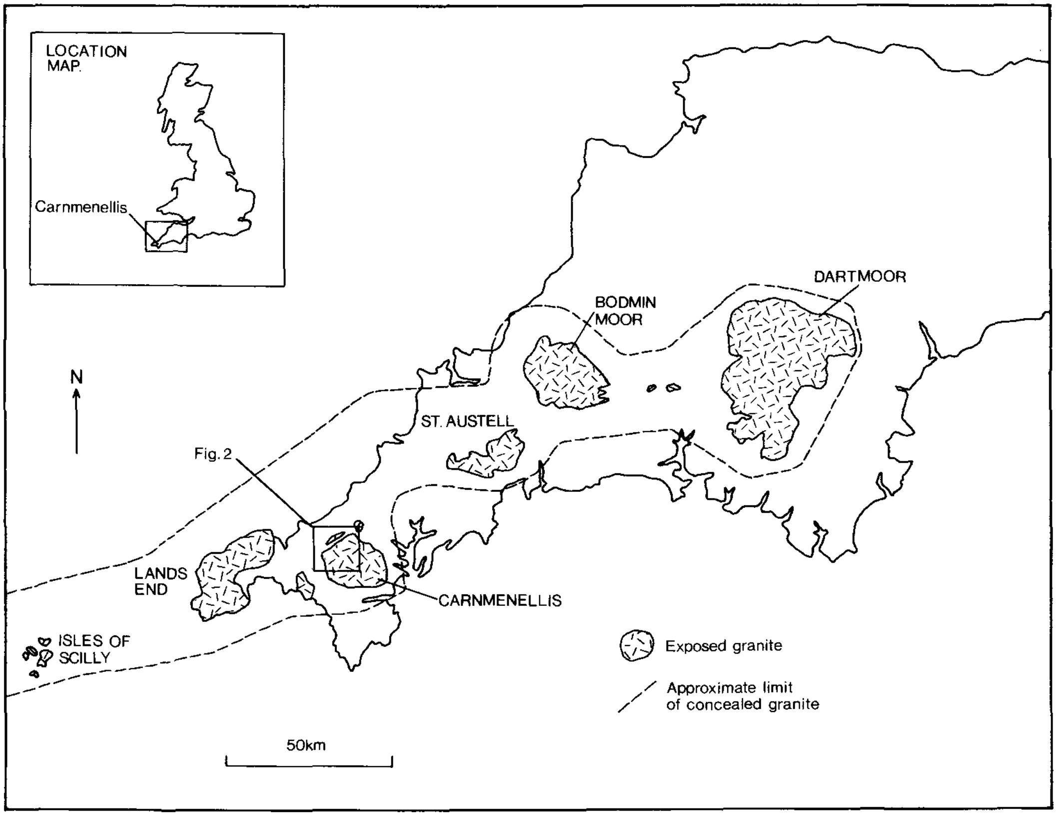

FIG. 1. The south-west England granite batholith.

metamorphism during the Hercynian orogeny, producing mainly slates. Geophysical (gravity and seismic) evidence suggests that the granite extends to a depth of at least 10 km (Bott and Scott, 1966; Holder and Bott, 1971). The dominant N.-S. compression associated with the Hercynian earth movements is reflected in the dominant E.-W. trend for major structures and outcrop patterns in the region (locally ENE-WSW) (fig. 2). This ENE-WSW trend is reflected in the distribution of mineral veins (lodes) in the intensely mineralized zone 3-4 km to the north of the test site and in the distribution of quartz-feldspar porphyry ('elvan') dykes which intrude the granite and its host rocks and which occur at the site.

The granite exposed at the site is a coarse-grained two-mica adamellite (quartz-monzonite) with K-feldspar megacrysts up to 30 mm in length ('megacrystic granite (small megacryst variant)') (Dangerfield and Hawkes, 1981). Much of the rock has been affected by hydrothermal alteration in the form of chloritization of biotite and kaolinization and sericitization of feldspars. Hematitic staining is widespread, while the limonitic staining seen at the site is largely, but not exclusively, confined to shallower depths. Tourmaline veins, with associated brecciation in places, are also common. Minor lithologies include dyke-like elvans and narrow, steeply dipping pegmatitic veins. Mineral veins, including those of quartz, fluorite (some with pyrite) and some carrying metalliferous ore minerals, are also seen.

The pattern of joints seen in the granite at the surface at the test site is dominated by two steeply dipping sets striking 015 and 105°, with an additional set striking 060 and 150°. There is also a sub-horizontal set of joints which, while closely spaced at the surface (*c.* 1 m), diminish in frequency with increasing depth.

Hydrological investigations

The first stage of hydrological investigation at the Troon test site has involved hydraulic testing of

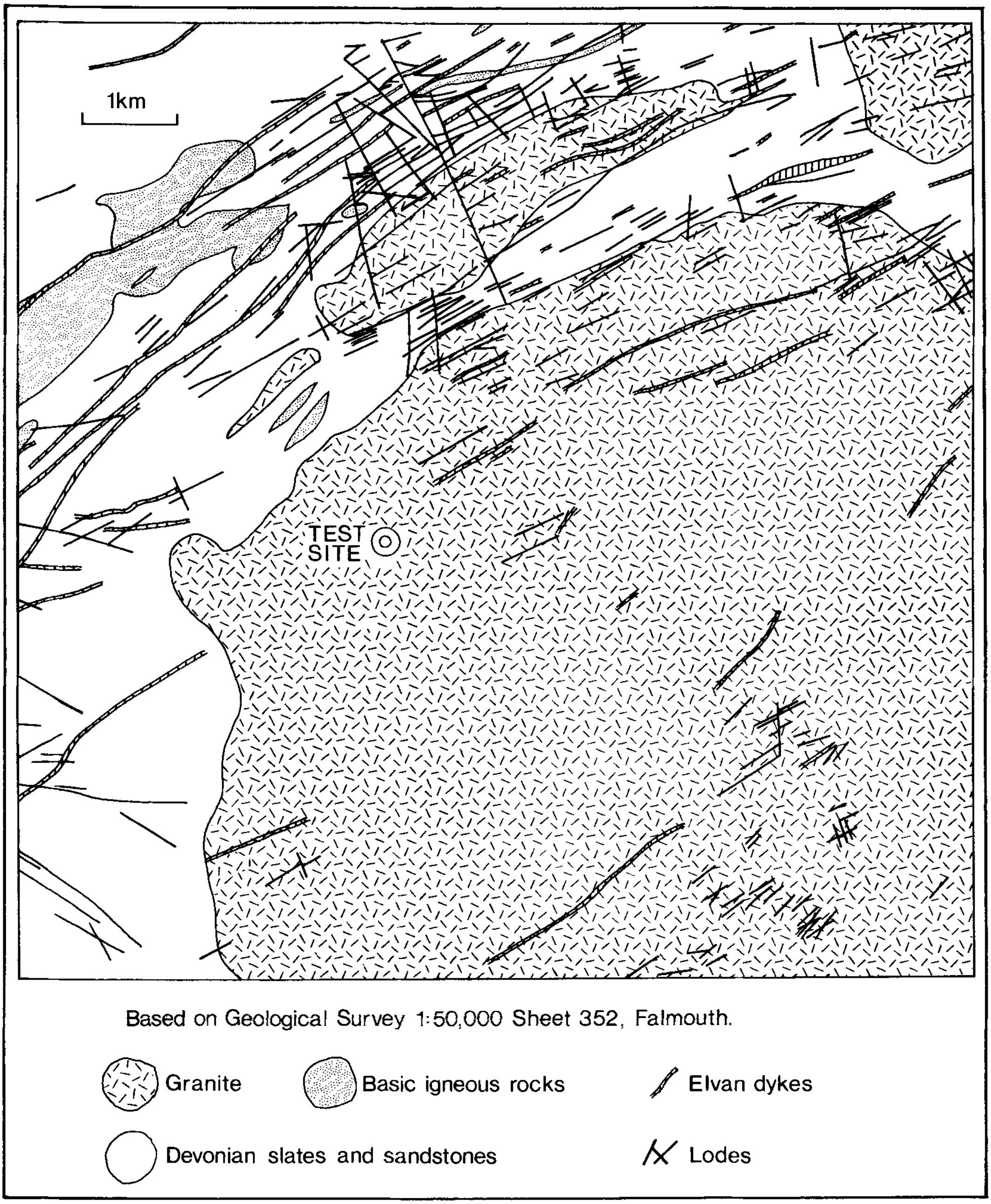

FIG. 2. Geology of the area around the Troon test site, Cornwall.

the granite in vertical boreholes (BH) 1 (200 m deep), 2c (153 m), and 8 (700 m), and inclined (45°) borehole 9 (200 m long). The top of each of these boreholes is approximately 10 m below the natural surface, and all depths given have been measured from the top of the hole. Quadruple packer tests, employing a 1 m test section pressurized to a constant head of 7 bar, have been carried out at 1 m intervals in each of these holes below a depth of 50 m. Areas of interest have been re-tested using a

7 m test section while double packer tests, employing a zone 'zero' of variable length (between the lower packer and the bottom of the hole), have also been carried out in BH1 and BH9. Tests of this type have allowed the positions of fractures capable of conducting water under the test conditions to be identified, and an indication of their hydraulic aperture to be obtained.

Although hydraulic tests reveal the presence of water-conducting fractures, they do not provide information on specific flow routes away from the borehole or on water transit times. Radioactive tracers have therefore been employed as a second stage of hydrological work (Evans, 1982) and a three-dimensional map of flow routes in the volume of rock bounded by the boreholes has been constructed. ^{82}Br (half-life 35.4 h) in aqueous solution, has been injected into flow positions in certain boreholes and its breakthrough monitored in adjacent boreholes. The short half-life of this tracer has allowed frequent tests to be carried out without contamination from earlier tests. A total of twenty flow connections have been mapped between five boreholes in the depth range 65–155 m. At a number of points, tracer breakthrough does not correlate with zones of high permeability, reflecting the greater sensitivity of tracer tests to low rates of flow.

The hydraulic tests and tracer experiments have revealed a permeability characterized by zones of high hydraulic conductivity separated by zones of very low permeability which do not permit flow of water into the rock under normal experimental conditions (fig. 3). The geological features responsible for flow have been identified by reference to the core recovered from the diamond-drilled holes 1, 8, and 9. Orientation of these features has been carried out using the results of seisviewer (BHTV) logging in these holes.

Although generally well jointed, many long sections of BH1 and BH8 have no associated flow. The flow rates recorded in BH8 are generally much higher than those observed in BH1 using an identical test procedure (high flows of 1.0 l/min at 7 bar rather than 0.1 l/min), and the frequency of hydraulic features is much higher in BH8 over the same depth range. These differences may reflect the experimental history of BH1 (the site of early equipment tests and pilot studies at high pressures), the results for BH8 reflecting more accurately the hydraulic characteristics of the granite at the site. With increasing depth, the frequency of hydraulic features in BH8 decreases, so that very long sections of the deeper parts of the borehole have no associated flow. However, flow rates do not decrease with depth. Indeed, the highest flow recorded in any test at the site was at a depth of 637 m in BH8.

The high flow rates recorded in BH8 are also characteristic of BH9. This inclined (45°) hole was drilled to intersect more of the steeply dipping joints which dominate the granite than are seen in vertical boreholes, and the frequency of hydraulic features is accordingly higher.

Geological analysis of fracture permeability

The geological work undertaken at the experimental site in Cornwall has been aimed at the identification of those properties of fractures in the granite which are relevant to large-scale flow systems, thus enabling those systems to be modelled realistically. The site lies in an area of considerable structural complexity, reflecting a long and complex history of thermal and tectonic activity. Fracturing of the granite is accordingly complex and of diverse type and origin, but has nevertheless developed in response to well-defined geological processes. The fracture pattern is therefore not random.

Fracture types

As there is a wide variety of types of discontinuity in the Carnmenellis granite it is convenient to use the term 'fracture' loosely to refer to any natural break in the rock. It is, however, possible to recognize a number of distinct discontinuity types.

The simplest fracture type is the joint in which the break represents failure of the rock with no associated displacement. At the surface two groups of joints are commonly observed, one steeply dipping or vertical, the other sub-horizontal. The steeply dipping joints normally occur in sets of parallel fractures, perhaps 1 m apart, two sets at right angles to each other (forming a conjugate set) being commonly observed. Two conjugate sets are seen at the Troon test site, striking 015 and 105°, and 060 and 150°, the latter being parallel and perpendicular, respectively, to the main structural trend of the rocks to the north of the Carnmenellis pluton. The sub-horizontal joints (floor- or sheet-joints) may be very closely spaced at the surface but become less frequent with increasing depth (becoming rare below about 50 m). A third group of joints with angles of dip intermediate between those of the other two groups are also seen, and account for most of the joints encountered in the boreholes at the test site.

Careful observation of many 'joints' reveals displacement (of perhaps only a few mm) with the development of slickensides on joint faces. Where displacement has occurred, the discontinuity is a fault, though it may simply be a joint along which minor adjustment has taken place. Evidence for faulting on a larger scale in the Carnmenellis

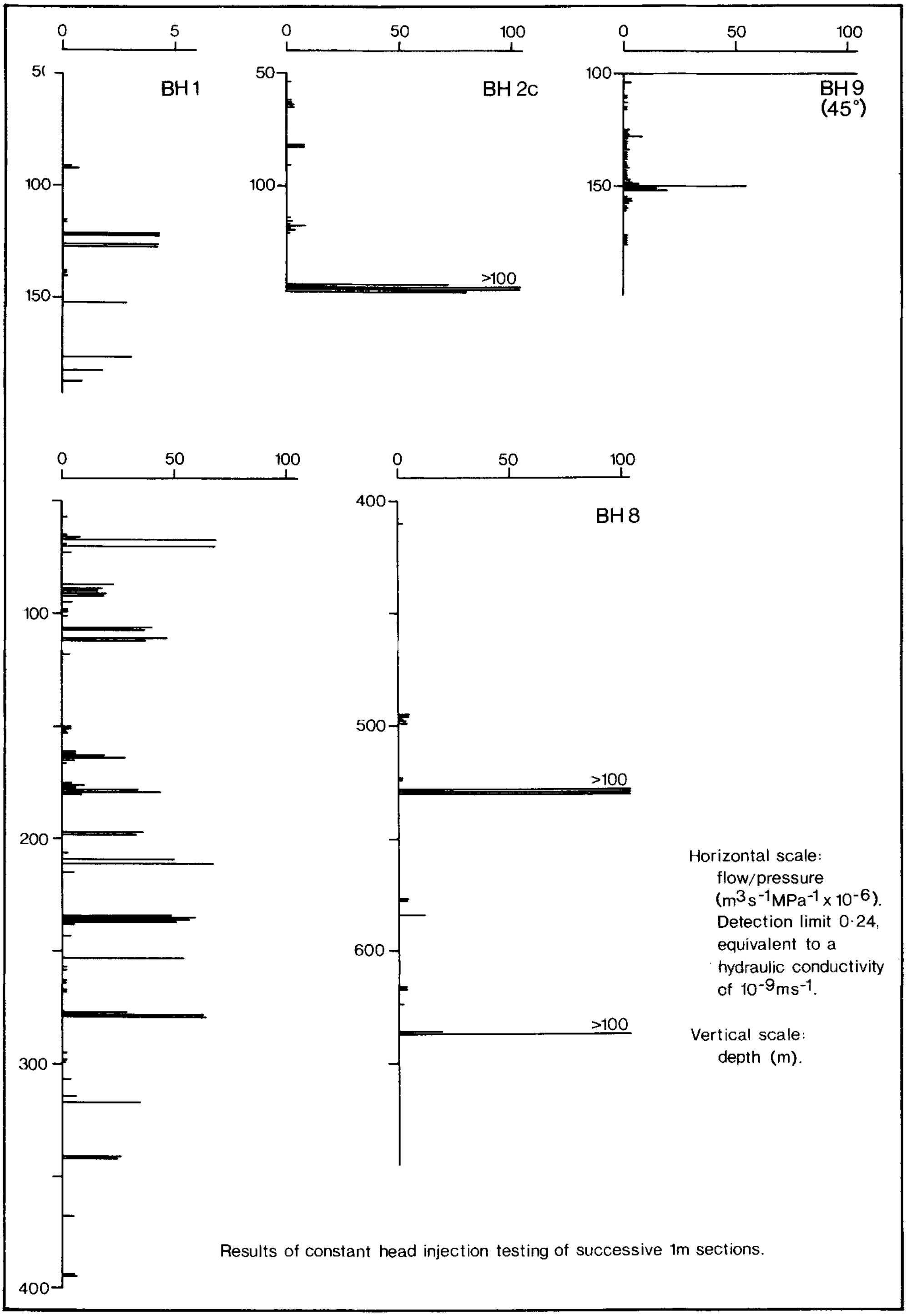

FIG. 3. Results of hydraulic tests, Troon test site.

granite is to be found in the development of topographical linearity, commonly exemplified by the courses of river valleys. Faulting on a major scale usually involves the development of fault zones in which intense fracturing occurs, rather than discrete fault planes.

Joints and faults have, at various stages of their history, been exploited by magmatic and hydrothermal fluids from which minerals have crystallized to form a variety of veins and lodes. Where narrow and only intermittently mineralized, veins are often difficult to distinguish from joints. At the test site, veins generally contain quartz or fluorite, the latter often accompanied by pyrite. Clearly distinguishable from joints are the abundant tourmaline veins, often in parallel sets. While normally very narrow (*c.* 1 mm), these veins sometimes develop into tourmaline breccias. Veins of this type are normally completely infilled and cemented by minerals. In other veins tourmaline is accompanied by quartz in open-textured (vuggy) fractures about 1 cm wide, while quartz may also occur alone in such structures. Vuggy pegmatitic veins containing mainly quartz and feldspar, also about 1 cm wide, are also commonly developed. The main area of metalliferous mineralization lies 3–4 km to the north of the test site but some tin has been worked within 2 km and some of the veins encountered at the site carry metalliferous minerals, including pyrite, chalcopyrite, sphalerite, and cassiterite. In the mineralized belt to the north many lodes have been followed for several kilometres, suggesting that the metalliferous veins at the test site may extend for considerable distances.

Though not strictly a fracture type, elvans may be included here as they represent intrusion of granitic material along fractures generally parallel to the main lode systems of the area with which they are closely associated, spatially and temporally. Where seen at the test-site these steeply dipping dyke-like bodies, up to 3 m wide (wider elsewhere in the area) are characterized by a high joint frequency and, in contrast to some elvans in the region, little alteration.

Origin of fractures

Fractures represent failure of rock under conditions of stress. Such applied stress can have a number of possible origins and the complexity of fracture systems in the Carnmenellis granite reflects its complex stress history, beginning with initial crystallization and cooling of the granite and continuing through repeated earth movement until the present day.

Early fracturing of the granite resulted from the confinement of residual aqueous fluids within the crystallizing intrusion, leading to a build-up of fluid pressure which resulted in hydraulic fracturing of the granite, often accompanied by brecciation. Tourmaline breccias of this type are seen at the test site, where they are associated with tourmaline vein systems. Fragments of broken granite, some rounded, around 5 cm in size, set in a tourmaline matrix, are seen in features up to half a metre wide.

Part of the stress responsible for fracture formation relates to post-crystallization cooling of the granite. Relief of this stress following erosion of the overlying rocks has possibly been responsible for the formation of surface-related sheet joints. The joints, usually sub-horizontal but sometimes seen to be parallel to the topography where exposed on hillsides, may have formed parallel to the roof of the intrusion (parallel to which the topography has developed) or to stress surfaces developed in the cooling pluton.

The major agent of fracture formation has been tectonic, related to earth movements that have taken place since emplacement. Major fracturing with associated mineralization (to form the main lode system of the area) and magmatic activity (to form the elvan dykes) took place some 20 Ma after granite emplacement. This fracturing developed in response to shear and, particularly, tensile stresses as the dominantly compressive stresses of the orogenesis, with which the granite is associated, gave way to a dominantly tensile stress regime. This resulted in the formation of fractures parallel to the axes of major folds produced by the orogenesis.

Crustal tension with associated rifting continued throughout most of Mesozoic time, giving way to compressive stresses with the growing influence of the Alpine orogeny (Hart, 1982). This compressive stress regime culminated, in south-west England, in the reactivation of deep Hercynian structures to form Tertiary dextral wrench faults (Dearman, 1963). These wrench faults are, in fact, complex fault zones with much associated shearing and fracturing which must extend to considerable depth.

An additional contribution to fracture formation, which may be responsible for many of the joints with angles of dip intermediate between sub-horizontal and vertical, has been suggested to be vertical compression resulting from isostatic adjustment in response to the intrusion of relatively light granitic material into denser host rocks (Hawkes, 1982).

Fracture orientation and frequency

The Hercynian orogeny in south-west England was characterized by N.–S. compression, NW–SE in the area around the Carnmenellis granite where a fold belt with a dominant NE–SW axial trend developed into which the granite was emplaced. Major fracturing parallel to this main fold trend subsequently developed. Many of these fractures were exploited by rising fluids to produce elvan dykes, which are well developed in the area around and within the northern part of the Carnmenellis granite where they strike dominantly SW-NE, and the metalliferous lode system (fig. 2). The lodes of the area are classified according to their orientation. Thus those which conform to the main SW-NE structural trend are known as normal lodes, while those which strike at right angles to these are known as cross-courses. A third group, the caunter lodes, are those of other orientations which diverge from what is otherwise a block pattern of lode development. Most lodes are steeply dipping (70° or more) but those with very low angles of dip are also developed. In the area around the Troon test site elvan dykes and metalliferous veins striking around 060° have been mapped, and some of the lodes worked for tin and copper.

The pattern of jointing in the Carnmenellis granite was first described by Ghosh (1934) who recognized two sets of steeply dipping 'master' joints developed parallel to the normal lodes and cross-courses in the nearby ore-field. An additional group of 'diagonal' joints, which may sometimes be better developed than the 'master' joints was also recognized. The main pattern of jointing is reflected in the cleaving properties of the granite long known to quarrymen. The direction along which the rock can be most easily split (the cleaving way) is parallel to the cross-courses, while the planes parallel to the main lode system are the most difficult (the tough way). The granite can also be split parallel to the sheet joints (the quartering way). The surface fracture pattern at the Troon test site is dominated by a conjugate set of 'diagonal' joints striking 015 and 105°, with subordinate sets striking 060 and 150° also well developed.

The pattern of fracture development in the Carnmenellis granite is very complex and there are many deviations from the generalized pattern discussed here. This has been demonstrated in the boreholes at the Troon test site where fractures seen in the core have been orientated using a borehole televiewer (seisviewer) system in which the borehole wall is scanned acoustically for discontinuities. It should be noted that with this technique moderately to steeply dipping fractures may be recognized and orientated without difficulty but many fractures with low angles of dip are not clearly recorded. Closely spaced fractures are also difficult to distinguish.

Fracture frequency in the granite encountered between 50 m and the bottom of BH8 (the depth range of hydraulic tests) is shown in fig. 4, while the orientation of these fractures is shown in fig. 5 (all data taken from the seisviewer record). It is clear

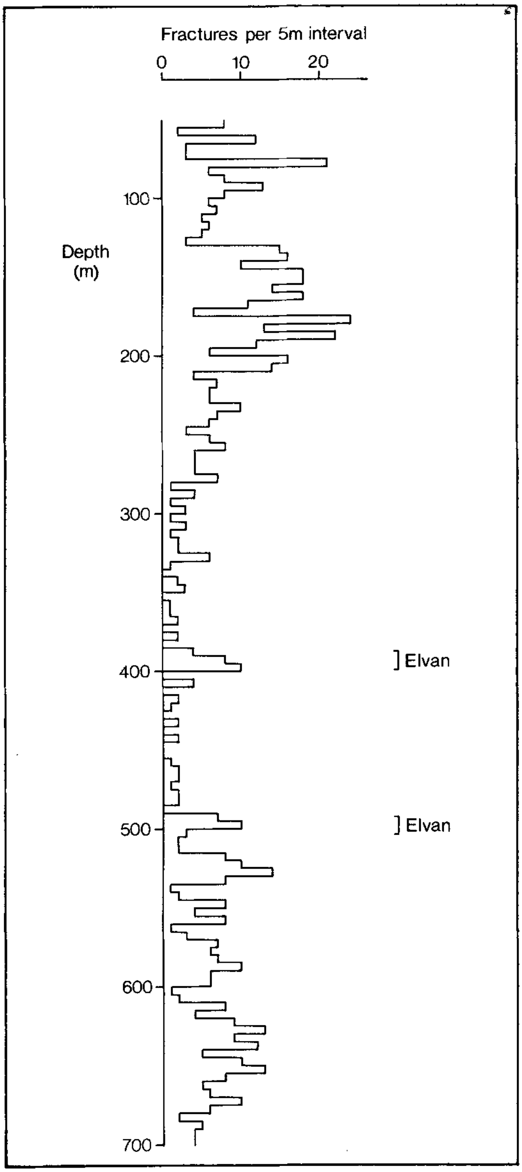

FIG. 4. Fracture frequency, Borehole 8.

from fig. 4 that fracture frequency is not constant over the length of the borehole, there being a zone between 280 and 515 m in which fracture frequency is very low. Whether or not the observed pattern is part of a large-scale periodicity of fracture frequency with depth is not known.

The orientation of the dominant fracture sets also varies with depth, as shown in fig. 5 where BH8 has been divided into three zones. The fracture pattern seen at the surface is also observed at a

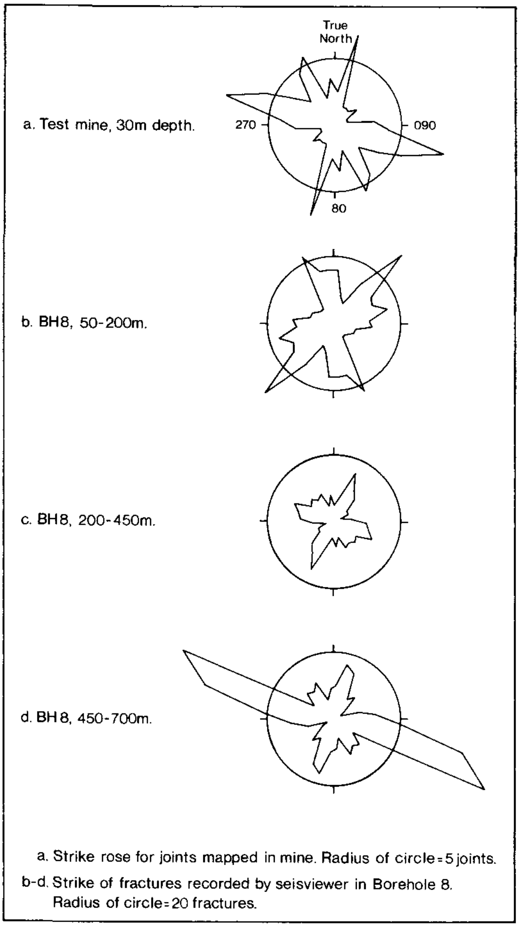

FIG. 5. Fracture orientation, Troon test site.

depth of about 30 m in the mine at the test site where dominant sets striking 015° and 105° are supplemented by a third striking about 150° (the SW-NE set being poorly developed here). Between 50 and 200 m in BH8 the fracture pattern is dominated by those striking 045 and 155°; between 200 and 450 m by those striking 025 and 115°; and between 450 and 700 m by fractures striking 020° and, particularly, 110°. Thus the relative importance of the 'master joints' and 'diagonal joints' of Ghosh (1934) varies with depth, while the strike of these fracture sets (around 060/150 and 020/110° respectively) also shows some variation over the depth range studied.

In situ stress

While the granite of south-west England is dominated by structures related to the Hercynian orogeny, Alpine compression also affected the batholith significantly with the development of major wrench faults. Moreover, the granite has been left with a strongly anisotropic residual horizontal stress pattern believed to be of Alpine origin. This regional stress field has been measured by hydrofracturing at depths of up to 2000 m at the Rosemanowes site in the Carnmenellis granite (Pine *et al.*, 1983*a*), where the maximum horizontal stress (σ_H) was found to be more than twice the minimum (σ_h), and by overcoring at a depth of 790 m at South Crofty mine in the nearby Carn Brea granite (Pine *et al.*, 1983*b*). At the latter site σ_H was found to be 45.6 MPa and σ_h 12.9 MPa, while the vertical stress was measured at 19.8 MPa. The principal stress directions determined at South Crofty were 129° (σ_H) and 040° (σ_h).

Fabric permeability and fracture permeability

Fabric or intact-rock permeabilities reported for the Carnmenellis granite are extremely low—among the lowest determined for any granite in the world (Brace, 1980). Values as low as 100 picodarcies (10^{-10} d) were determined by Duffy (1979) in the granite at 300 m depth at the Rosemanowes geothermal research site (corresponding to a porosity of 10^{-5}) while Batchelor (1978) gave values in the range 10^{-8}–10^{-9} d. The results of *in situ* hydraulic tests, however, give values many orders of magnitude higher as these values relate to fracture-controlled permeability.

Hydraulic conductors

It is clear from a comparison of the hydraulic test results for BH8 in fig. 3 with the fracture frequency for that borehole in fig. 4 that not all fractures conduct water. Fracture permeability is, therefore, not simply a function of fracture frequency. The alteration and mineralization of many 'dry' fractures, however, demonstrate that they have conducted water in the past, but the geological conditions then prevailing may have been quite different to those of the present. It is, therefore, necessary to investigate the factors which control whether a fracture provides a flow path through the granite or not. Examination of the core from sections of borehole where flow was recorded during hydraulic tests, has enabled most of the features responsible for that flow to be identified. Unfortunately, where fracturing is intense it is not always possible to isolate individual flow paths, but sufficient data have been obtained to make some generalizations about the nature of flow paths and the geological factors controlling their distribution.

Water-conducting fracture types

The fracture types with which flow is associated include joints and veins, with elvan dykes sometimes forming major permeable features. Water-conducting joints often have little to distinguish them from 'dry' joints, though recent water movement has often left them limonite-stained. Veins are particularly important at depth, accounting for most of the flow paths below a depth of about 250 m. Of major importance as hydraulic conductors are the pegmatitic and similar veins which are commonly developed in the granite. The incomplete growth of crystals into open fractures has left many of these veins with large cavities (vughs) which, where interconnected, form major flow paths. Other water-conducting veins with similar textures include those of quartz and those carrying metalliferous minerals. A 1 cm wide vuggy vein carrying quartz, chlorite, fluorite, sphalerite, and galena at 111.5 m in BH8, for example, is a major hydraulic feature found during tracer tests to connect with three other boreholes at the site. The highest flow rate recorded during any hydraulic test carried out at the site correlates with a 2–3 mm wide, heavily limonite-stained, vuggy quartz vein with an interconnecting joint, also limonite-stained. Other important water-conducting veins include those of fluorite, sometimes very narrow with thin patchy development of the mineral on 'joint' planes, often accompanied by pyrite. The intersection of individual, steeply dipping veins with the borehole accounts for many of the double 'spikes' on the hydraulic logs for BH1 and BH8 (fig. 3). Elsewhere, double or multiple 'spikes' are related to groups of fractures. In some cases, joints connecting a major hydraulic feature with the borehole appear to have extended the influence of that feature along the borehole beyond its 'outcrop'. Many of the elvans encountered in the boreholes are important hydraulic features. This may be attributed to their highly fractured nature combined with the lack of alteration to joint faces commonly observed, fractures remaining open while in the altered granite most are closed by the products of alteration. The permeable nature of many elvans is significant with regard to radionuclide migration as these dykes are often very extensive, some being traced at the surface for several kilometres.

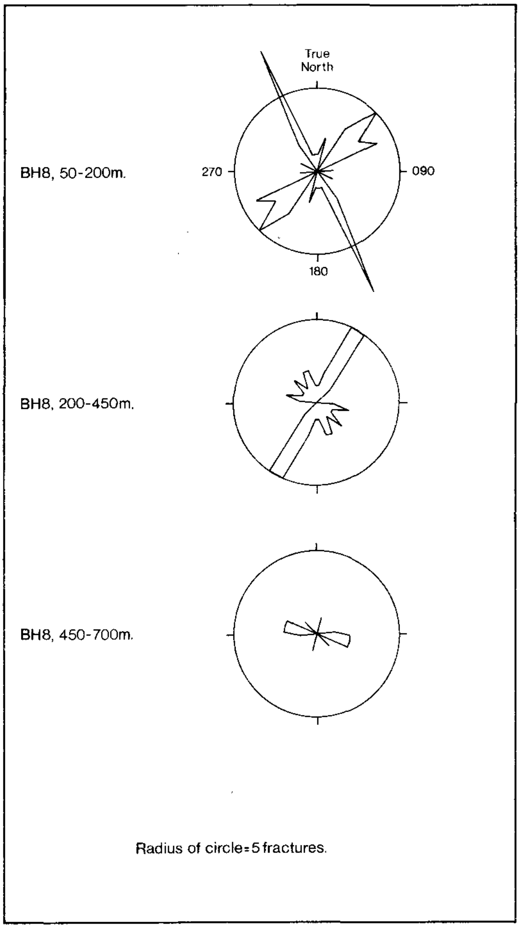

FIG. 6. Orientation of water-conducting fractures, Troon test site.

Orientation

The orientation of hydraulic conductors in BH8 is shown in fig. 6. Early work in the 200 m deep BH1 showed that most of the major flow paths into the granite can be correlated with discrete geological features: a highly fractured elvan dyke and two pegmatitic veins. It is difficult to orientate elvans in boreholes as their contacts with the granite are often irregular, but most strike parallel to the main lode trend of the area (*c.* 60°) where seen at the surface. The pegmatitic veins in BH1 were found to strike approximately E.–W. Other hydraulic features in BH1, with generally lower flow rates, appear to be associated with joints. Of six such features observed, four appear to be correlated with joints dipping steeply to the NE, striking approximately 140°. An apparently simple pattern of hydraulic conductors therefore emerged from BH1; one set associated with veins and elvans approximately parallel to the main structural trend of the area, and one set associated with joints striking parallel to the cross-courses. The hydraulic test results for BH8 (fig. 3) are rather different from those for BH1 (those for BH8 being considered the more reliable as discussed earlier) but the pattern of flow paths suggested for the same depth range (50–200 m) is very similar. Again, two major sets, approximately at right angles to each other, are seen, one striking parallel to the main lode system (*c.* 055°) and one parallel to the cross-courses (*c.* 155°). In the case of BH8 veins and joints are associated with each of these sets. At greater depth, however, the orientation of major flow paths is found to be different. In the depth range 200–450 m flow is mainly associated with narrow veins striking *c.* 030°, while between 450 and 700 m the few flow paths that do occur are dominated by a set striking around 110°.

The strong development of flow paths with a NNW–SSE orientation in BH1 and the upper part of BH8 is believed to be significant, as these features are parallel to the cross-courses in the nearby orefield with which the younger (Tertiary) mineralization is associated and from which hot springs issue into several local mines. This orientation has also been found to be important in the Dartmoor granite where the results of electrical resistivity surveys have suggested that fractures trending approximately N.–S. tend to be open while those tending E.–W. tend to be closed (Durrance *et al.*, 1982). Enhancement of the permeability of these fractures is thought to be related to the regional stress field in which the maximum horizontal (compressive) stress tends to keep fractures of this orientation open. However, the relationship between stress and permeability is not simple. In the upper part of BH8, for example, fractures striking at right angles to this preferred orientation are also of major importance. Some of these flow paths are veins relating to the main stage of mineralization which, having developed in a tensile stress regime, may now simply be held open by their infill. Others may be faults which cannot be closed because their faces no longer 'match'. Many flow paths striking at right angles to the maximum horizontal stress (around 040°) may be the result of shearing in the strongly anisotropic stress field, particularly where the vertical stress is reduced near the surface. The orientation of flow paths between 200 and 450 m in BH8 also deviates from the simple pattern, though again most of these 030°-trending fractures are veins. The 110°-trending flow paths between 450 and 700 m in BH8 may form a set complementary to the 155° set in the upper part of the hole, the 129° maximum stress direction approximately bisecting the acute angle between the two. In each of the three depth zones in BH8 the orientation pattern for hydraulic conductors (fig. 6) reflects to some extent that of the total fracture population (fig. 5). The role of present-day stress conditions as a controlling influence on permeability may therefore be limited by the fracture pattern itself so that water is simply forced to flow along available fractures regardless of their orientation relative to the stress field. The fracture pattern is the product of a long stress history involving the repeated application of compressive and tensile stress in a direction approximately parallel to the present maximum horizontal stress. It is therefore difficult to differentiate the role of stress in keeping existing fractures open from its role (and that of older, parallel stress fields) in creating those fractures. Whatever the mechanism responsible, hydraulic conductors have well-defined preferred orientations which vary with depth, factors of great importance to the modelling of flow networks.

Channel flow and aperture

When modelling the flow of water along fractures it is often assumed that flow paths are planar and parallel-walled. Observation of fractures at the surface and in the core recovered from boreholes shows that this simple two-dimensional model is not always applicable. Fracture surfaces are normally very complex with many small-scale irregularities and larger-scale undulations which produce a highly variable aperture, especially if displacement has occurred. Fracture infill is also commonly irregularly distributed, as illustrated by the metalliferous vein at 111.5 m in BH8. This major hydraulic feature, where seen in the core, has a measurable aperture ranging between zero and *c.* 1 cm. Flow paths along this vein consist of a series of interconnected cavities bounded by zones in which the vein is completely infilled with mineral material. Many other major hydraulic features encountered in the boreholes have a similar form, while in other places identical veins are not associated with flow, a feature attributable to a lack of interconnection between cavities so that no flow paths (intersecting the borehole) are created. Channel flow is probably the normal flow condition in fractures in the granite studied and flow rates will vary considerably between one channel and another. The possibility of preferred channel orientation (where fractures have developed under conditions of shear, for example) also has important implications for network modelling.

Conclusions

Any assessment of a crystalline rock mass as a site for the underground disposal of radioactive waste must involve investigation of water movement through fractures in the rock. Flow networks can be modelled mathematically but it is essential that such modelling is based on realistic geological assumptions and is furnished with relevant geological data. Geological work at an experimental site in the Carnmenellis granite has therefore been directed towards determination of the major geological controls of permeability as a contribution to the development of a model capable of predicting radionuclide migration in fractured crystalline rock.

Hydrological investigations have shown that the flow of water through the rock is largely confined to narrow zones separated by zones of very low permeability. The rock is therefore characterized by a fracture permeability, the intact rock being of very low permeability indeed. Many long sections of fractured rock have also been found to be impermeable under test conditions, indicating that permeability is not simply a function of fracture frequency.

Over the depth range studied in a 700 m borehole, fracture frequency has not been found to be uniform, there being a zone of very few fractures between 280 and 515 m in which flow paths are correspondingly infrequent, except where highly jointed elvan dykes intersect the hole. Whether or not this pattern of joint frequency reflects a large-scale periodicity with depth is not known. The frequency of flow paths appears to decrease with depth but flow rates do not.

Much of the flow through the granite can be correlated with discrete geological features, including pegmatitic and other veins and highly jointed elvan dykes, and with joints, the latter being particularly important in the upper *c*. 250 m. These water-conducting features exhibit distinct preferred orientations which vary with depth. The strongly anisotropic horizontal stress field is believed to influence the orientation of hydraulic features but the relationship is not simple.

The lengths of individual flow paths in the granite may be considerable. Many of the lodes and elvan dykes of the area can be traced for several kilometres at the surface, while topographical linearity within the area underlain by granite suggests the presence of narrow fault/fracture zones of similar lengths. Individual fractures at the site, where exposure is limited, can only be traced for 20 m or so, but an elvan dyke exposed at the surface can be traced for at least 2 km to the NE. The irregular distribution of vein-filling minerals and the uneven nature of fracture faces causes aperture to be extremely variable along individual fractures and water movement to be characterized typically by channel flow. The assumption that flow paths are planar and parallel-walled is, therefore, not valid while the possibility of preferred channel orientation is also important.

Alteration of the granite adjacent to fractures has implications for diffusion and sorption, the processes by which radionuclides are retarded during transport along fractures. The mechanical breakdown that accompanies alteration may increase the micro-permeability of the wall rock, creating many 'dead-end' pores and cracks into which diffusion may occur. The clays produced during alteration may, however, clog those pores and cracks, reducing diffusion but providing ion exchange sites which increase retardation by sorption. The latter will also be affected by the precipitation of limonitic material commonly observed on the walls of water-conducting fractures.

The hydraulic characteristics of the Carnmenellis granite have been shown to be subject to well-defined geological control. Many of the controlling factors, such as the non-random fracture pattern, the development of veins and dykes, alteration of the granite and the regional stress field, are characteristic of the granite of south-west England, where they are well documented. Many geological factors must therefore be taken into account when modelling the hydraulic properties of granite. These factors may be of regional significance and may be different from those affecting other granites of different origin and evolution.

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