

Fluid flow in faults: a study of fault hydrogeology in Triassic sandstone and Ordovician volcanoclastic rocks at Sellafield, north-west England

J. C. GUTMANIS, G. W. LANYON, T. J. WYNN and C. R. WATSON

*GeoScience Limited, Falmouth Business Park, Bickland Water Road, Falmouth, Cornwall TR11 4SZ, UK
(e-mail: gutmanis@geoscience.co.uk)*

SUMMARY: The structure and hydrogeological properties of subsurface faults in the Triassic Sherwood Sandstone Group and Ordovician Borrowdale Volcanic Group at Sellafield in west Cumbria were investigated in order to develop conceptual and numerical models for input to groundwater flow modelling at the possible site of an underground radioactive waste repository. Eighteen borehole intersections of faults were studied using core, borehole imagery and hydraulic test data (single and multi-well testing). The results were integrated with data and interpretations from seismic surveys and field studies in order to prepare conceptualizations of fault architecture and hydrogeology, suitable for taking forward into numerical modelling. Hydraulic test data indicate that fault zones in the Sherwood Sandstone Group are slightly more permeable than the host rock, and geological observations suggest that flow may be focused in the fault damage zones rather than in the faultrocks, which tend to act as flow baffles. Where present in sufficient numbers, granulation seams appear to be flow inhibitors. In the volcanic rock, hydraulic test data indicate that fault zones have little permeability contrast with the host rock. However, geological observations suggest that minor reactivation may have locally disrupted the baffling effect of faultrocks, thereby creating 'leak points'. Overall, the study suggests that groundwater flow in faults at Sellafield is highly heterogeneous at the borehole scale, but at larger scales the hydraulic behaviour of faults is more homogeneous.

Between 1989 and 1997, a site near Sellafield on the west coast of Cumbria in NW England (Fig. 1) was investigated by United Kingdom Nirex Limited (Nirex) as a possible location for an underground radioactive waste repository. A key consideration affecting the suitability of any site proposed for radioactive waste disposal is the nature of the groundwater regime, including the rate, volume and direction of flow through the rock mass. Numerical modelling is normally carried out to predict flow paths, flow rates (in terms of flux), and discharge areas, which feed into the calculation of radionuclide dosage rates associated with possible future discharges from a repository. Experience in many national radioactive waste programmes, e.g. Sweden (SKB 1990) and Switzerland (NAGRA 1993), and also in industries such as geothermal energy and hydrocarbon extraction, indicates that faults often influence fluid flow paths and rates, and can act as boundaries to pressure domains. Numerical models will therefore be more realistic if the hydrogeological properties of faults are adequately represented.

This paper describes the results of a study aimed at characterizing the hydrogeological properties of faults at Sellafield (the Fault Conceptualization Study, Nirex 1997a). The potential importance of faults had been identified during previous groundwater flow studies (Nirex 1995a, b), which indicated that faults were often associated with flow entries into boreholes, but also suggested that they can act as partial barriers to flow (baffles) rather than conduits. Since faults are not exposed in the area of the proposed repository site, the work was highly dependent on sub-surface data from geophysical surveys and boreholes. Interpretation of this data was supported by studies of faults and fractures exposed in the Sellafield area, as well as reference to published fault studies. The

objective was to build conceptual and numerical models of the faults which could be used to support groundwater flow models being developed by Nirex, and underpin these with mean values and uncertainty ranges for relevant fault and fracture parameters (e.g. fault strand spacing and thickness, fault orientations and fracture apertures).

Details of the geological setting of Sellafield have been previously published (Millward *et al.* 1994; Barclay *et al.* 1994; Barnes *et al.* 1994; Akhurst *et al.* 1997). The study reported here focused mainly on three faults in the central part of the Potential Repository Zone (PRZ, Fig. 1), where the greatest density of subsurface data is available. In this area a sequence of dominantly fluvial sandstone (matrix porosities from c. 10 to 25%) belonging to the Lower Triassic Sherwood Sandstone Group overlies the Brockram, a coarse Permian breccia with a muddy, low porosity matrix. Together, these units comprise a cover sequence approximately 450m thick. The Brockram lies unconformably on a basement of Ordovician Borrowdale Volcanic Group, which here consists mainly of a succession of volcanoclastic rocks and associated intrusive bodies thought, on geophysical evidence, to be several kilometres thick.

Structurally, the PRZ is located close to the faulted boundary between the East Irish Sea Basin (Upper Palaeozoic to Mesozoic) and the Lake District Massif (Palaeozoic). The cover sequence is cut by a dominant set of NNW-striking extensional faults, with a subsidiary set of NE- to ENE-striking, steeply-dipping to vertical faults which may be transfer structures. Seismic mapping of intra-Borrowdale Volcanic Group faults is difficult due to poor reflector continuity and attenuation; however, their presence has been inferred from offsets of the base Permo-Triassic/top Borrowdale Volcanic Group reflector, and also from interpretation of downhole seismic tomograms and vertical seismic profiles. All the Nirex boreholes penetrated faults in both the cover and basement rocks, the larger of which

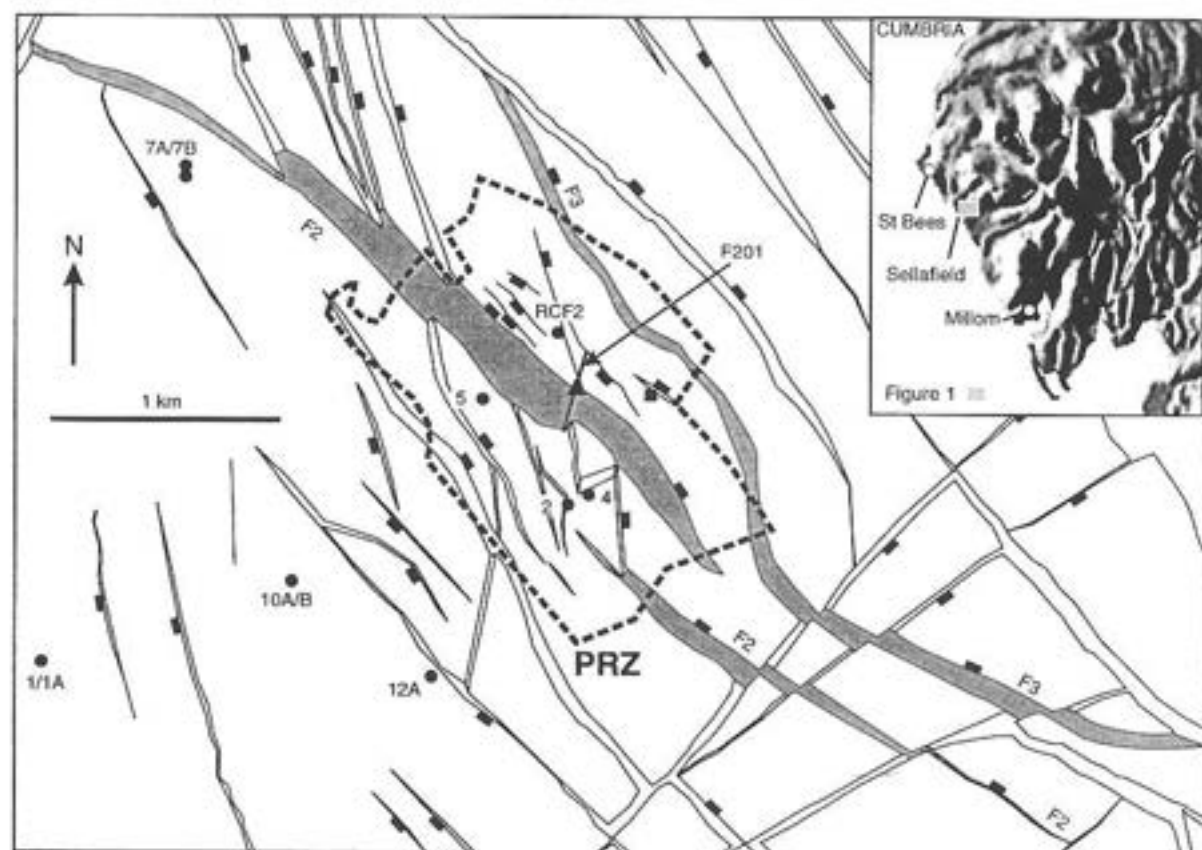


Fig. 1 Base Permo-Triassic structure map of the Sellafield Potential Repository Zone (PRZ) highlighting F2, F3 and F201. ▲, Boreholes RCF3/RCM1/RCM2; ■, Boreholes RCF1/RCM3; ●, Boreholes as numbered

were correlated with the two-dimensional (2-D) and three-dimensional (3-D) seismic interpretations to help construct a lithostructural model of the PRZ (Nirex 1997b).

1. THE FAULT CONCEPTUALIZATION STUDY

The Fault Conceptualization Study (Nirex 1997a) involved integration and analysis of borehole geological, geophysical and hydrogeological datasets, followed by application of statistical analyses and numerical modelling techniques. A total of 18 borehole fault intersections were studied in core and in borehole imagery, supplemented by analysis of hydrogeological test data across the fault zones. The terminology used in this paper to describe fault-zone structure is shown schematically in Figure 2 and the hydrogeological tests are described further in Section 3.3.1. The borehole intersections enabled 13 different fault zones to be sampled, although the majority of the data related to three specific seismic-scale (i.e. resolvable on seismic reflection data) faults: F2, F3 and F201 (see Fig. 1). F2 and F3 belong to the set of NNW-striking extensional structures and have maximum displacements of around 150 m and 30 m respectively at base Permo-Triassic level. Both structures were intersected by boreholes in the Sherwood Sandstone Group and the Borrowdale Volcanic Group, providing the opportunity to study the same fault in different lithologies and at different strain levels. F201, which belongs to the set of NE-striking faults and has a maximum displacement of around 25 m, was studied within the Borrowdale Volcanic Group.

Although the borehole fault intersections provide highly localized one-dimensional (1-D) samples of large-scale, heterogeneous structures, they are the only direct subsurface sample of the geological features (e.g. faultrocks, damage zone fractures, see Fig. 2) which control the hydraulic behaviour of the faults at the small-scale (i.e. the fault 'plumbing'). The physical characteristics, permeability, intensity, orientation, and connectivity of these features, relative to the permeability characteristics of the host rock lithology, largely determine whether fault zones are transmissive or act as flow barriers/baffles.

Structural logging of core (Nirex 1995c) provided qualitative observations on the permeability characteristics of the faultrocks (e.g. clay content, grain-size), including any disruption to them resulting from reactivation. Similarly, fracture mineralization logging of core (Nirex 1997c) provided a dataset of 'Potential Flowing Features', defined as those fractures containing both connected void space and late Quaternary or contemporary mineralization (see the Appendix for a description of Potential Flowing Features and also the mineralization episodes which have been identified at Sellafield). Logging and characterization of Potential Flowing Features was a method for sampling the distribution of potential pathways for groundwater flow along each borehole. In addition, the depths and magnitudes of fluid flow entries into each borehole (Flow Zones), as identified during production logging, was used as a valuable indicator of contemporary flow (see Appendix). It was recognized that not all groundwater flow

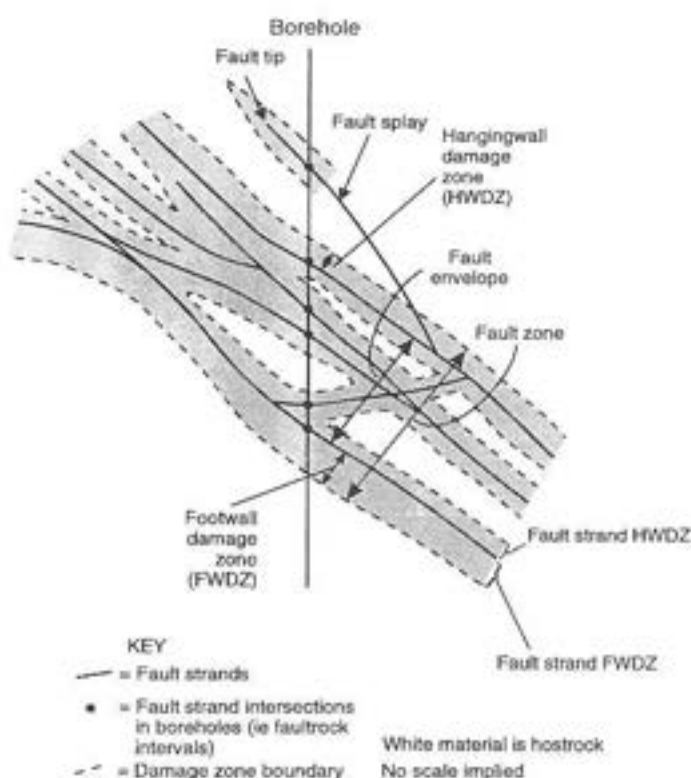


Fig. 2 Sketch showing fault terminology used in the paper.

entries could be identified due to the resolution limits of the production logging method.

The analysis of borehole data was carried out in three steps and the results used to construct composite logs of each fault intersection (e.g. Fig. 3), and also to derive fault and fracture parameter values. The first step was the interpretation of fault geometry, based on the distribution and character of the fault strands and fracture types making up the associated damage zones. The next step was to investigate correlations between the fault geometry and the distribution and character of Potential Flowing Features and Flow Zones. Finally, in order to evaluate the hydraulic character of the faults, the fault structure and associated 'plumbing' were compared with permeability values derived from hydraulic testing which had been carried out in the boreholes at a range of scales from 1.5 m (Short Interval Tests) to 50 m (Environmental Pressure Measurements) in length (see Sutton 1996).

In order to upscale from the centimetre scale of the 1-D borehole samples to the 10–100 metre scale needed to develop 3-D models of fault geometry and 'plumbing' it was necessary to integrate the results of seismic mapping (Nirex 1997b), fault analogue studies (Nirex 1997d, e) and cross-hole hydraulic testing. Seismic data enabled an interpretation of the larger-scale geometry of the faults to be made, for example identifying features such as jogs, relay ramps (Peacock & Sanderson 1991) or fault intersections (Figs 5, 7, 8), all of which may influence the bulk hydraulic behaviour. It also allowed the lithological juxtapositions across the fault plane, which may strongly influence the sealing efficiency of the fault rocks, to be mapped out (Nirex 1996). Field studies of faults and fracture systems, carried out both for this and previous studies (Ameen 1995; Nirex 1997a, e), were also essential to help understand

the geometry of the faults and aspects such as fracture lengths, connectivity, and intersection relationships. Figures 4 and 5 are examples of structures mapped in the St Bees Sandstone (lower part of the Sherwood Sandstone Group) at St Bees Head, which were directly used in developing the 3-D conceptualizations of fault geometry. Additionally, the results of cross-hole hydraulic testing carried out from boreholes intersecting the faults but separated by a few tens to a few hundreds of metres (Nirex 1997f, g) were also used to evaluate their hydraulic behaviour at that scale.

2. FAULTS IN THE SHERWOOD SANDSTONE GROUP

2.1. Fault geometry

The Sherwood Sandstone Group of west Cumbria comprises three formations, from top down the Ormskirk, Calder and St Bees sandstones (Barnes *et al.* 1994). Most of the borehole intersections in which faults were studied, including those of F2 and F3, were in the lower part of the St Bees Sandstone, which comprises fluvial silty fine-grained sandstone with minor thinly interbedded claystones. The clay content is variable from bed to bed, generally 10 to 20%. The lower 80 m are characterized by discrete claystone beds or packages of beds up to several metres thick and distinguished as the North Head Member (Akhurst *et al.* 1997).

F3 was intersected in a total of five boreholes, three of which were only 30 m apart (RCF3, RCM1, RCM2, see Fig. 1) and at depths ranging from about 90 to 160 mbGL (metres below Ground Level). At this level the St Bees Sandstone is relatively isotropic in terms of lithology, containing minimal claystone beds, and is within the zone of near-surface weathering and associated cement dissolution (Nirex 1997h). From seismic interpretation the fault displacement at the level intersected is inferred to be about 9 m (Nirex 1997h), implying that F3 is effectively a sub-seismic scale structure, where sampled by the boreholes. The fault, which has a strike length of c. 4.5 km, consists of up to two strands, dipping 40° NE, but seismic interpretation and geomorphological mapping both indicate a significant along-strike curvature. These observations, together with field analogues, suggest that along-strike and down-dip jogs, and possibly en echelon offsets may be present, as often observed in such structures (Peacock & Sanderson 1991; Childs *et al.* 1996a, b).

The two borehole intersections of F2 studied in the St Bees Sandstone (PRZ2 and PRZ3, see Fig. 1) were at approximately 350 to 430 mbGL, partly within the relatively clay-rich North Head Member, and at a level where the fault displacement inferred from seismic data is close to the maximum of 150 m observed in the Sellafield area at the base Permo-Triassic. Therefore, in contrast to the F3 intersections described above, these boreholes provided samples of a seismic-scale fault in a more anisotropic Sherwood Sandstone Group host rock. Like F3, F2 dips NE at 40° but it has a strike length of 6 km at the base of the Permo-Trias, and also comprises en echelon segments linked by relay structures (Fig. 1). Its geometry is similar to that of F3, but with up to five fault strands with associated damage zones, in a fault envelope (see Fig. 2) some 50 m wide, reflecting a greater displacement.

A conceptualization of fault geometry in the Sherwood Sandstone Group (Fig. 6) shows that the fault geometry is

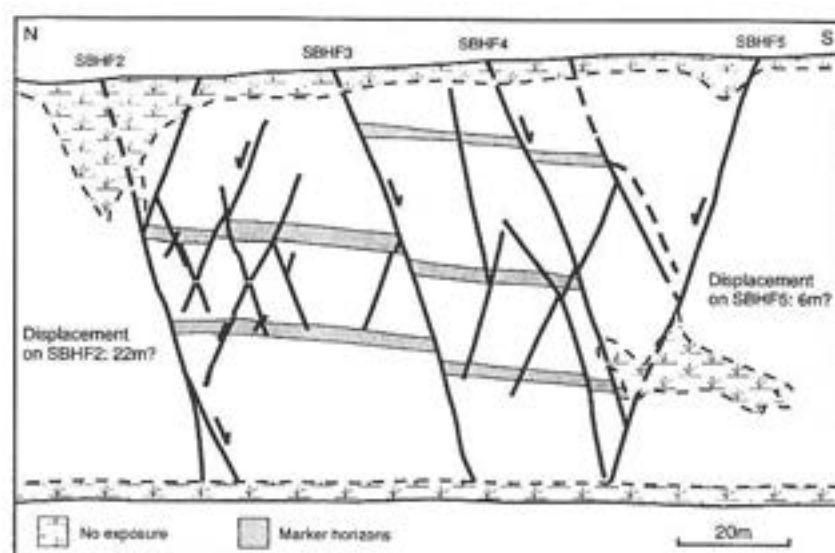


Fig. 4 Extensional faults in St Bees Sandstone at South St Bees Head cliffs.

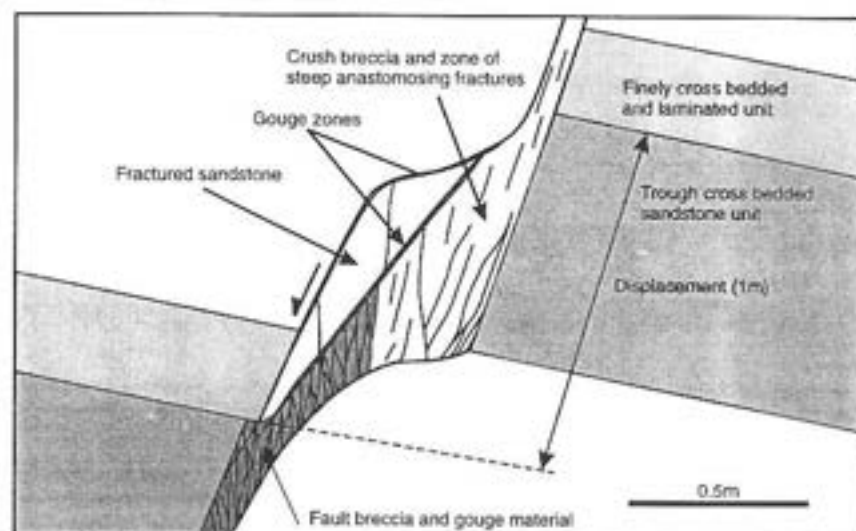


Fig. 5 Field sketch of a compressional jog structure in cliff exposure of fault SBHF 9 at St Bees Head.

variable, particularly with respect to the number of fault strands present and the thickness and spatial distribution of the damage zones. This heterogeneity, which has a potential impact on hydraulic behaviour, reflects differences in the local stress history of the faults, often related to fault geometry together with variations in the litho-mechanical properties of the host rock. For example, damage zones represent strain concentrations which are commonly best developed in brittle lithologies and at locations where stress was focused because of the fault geometry (e.g. at offsets in the fault plane, and at fault tips). The development and character of fracture damage zones around faults have been discussed in many recent publications (Scholz & Anders 1993; Caine *et al.* 1996; Knott *et al.* 1996).

2.2. Hydrogeological characteristics

Evidence from core observations and petrography of St Bees Sandstone faultrocks (Nirex 1995c) indicates that they have lower permeability than the host rock due to cataclastic grain-size reduction during deformation, and the development of secondary clay minerals. Where the host rock has a higher clay content than the normal sandstone, as for the F2 intersection in the North Head Member, the faultrocks are also likely to have a higher clay component due to the dragging of claystone beds along the fault plane ('clay smearing').

Faults in the St Bees Sandstone are commonly associated with granulation seams, which are cataclastic slip planes generally associated with porosity and permeability reduction (Aydin & Johnson 1978) and thought to represent early phases

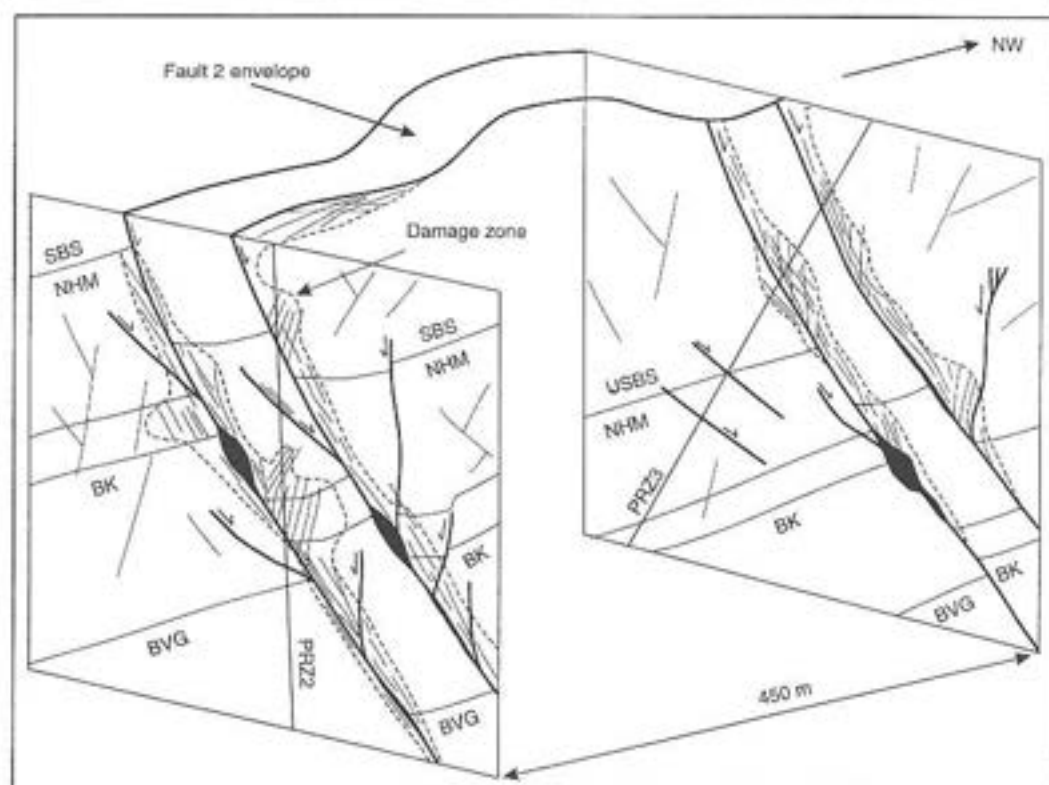


Fig. 6 Conceptualization of Fault 2 structure in the North Head Member/Brockram interval based on integration of borehole intersections, seismic mapping and field data. Key: SBS, St Bees Sandstone; NHM, North Head Member; BK, Brockram; BVG, Borrowdale Volcanic Group.

of fault growth. Where intensively developed, they have the capacity to act as baffles to flow, affecting sandstone reservoirs by creating permeability anisotropy or helping to compartmentalize them (Edwards 1996, Fossen & Hesthammer 1998).

Composite borehole logs for F2 in the North Head Member revealed a generally strong negative correlation between Potential Flowing Feature intensity and the presence of granulation seams (e.g. see Fig. 3 at c. -300 to -314 mO.D.) suggesting that flow has been inhibited or channelled by the presence of granulation seams. However, Figure 3 also indicates a reasonably strong positive correlation between granulation seams and Flow Zones (see Appendix), which would appear to contradict the negative correlation between granulation seams and Potential Flowing Features. This is explained by the resolution of the production logging method in porous sandstones, which records flow from broad intervals rather than from point entries. The lack of a correlation between Flow Zones and Potential Flowing Features in the interval -300 to -314 mO.D. is probably either because flow was below the resolution threshold of the production logging tools or because the Potential Flowing Features are no longer connected to the active flow system.

A model for the hydrogeology of faults in the Sherwood Sandstone Group is shown in Figure 7. Faultrocks and granulation seams are the two main elements of the fault 'plumbing' interpreted as flow baffles. Another factor enhancing the baffle effect is the likely presence of zones of enhanced cementation caused by ponding of diagenetic fluids against low permeability faultrocks. These 'cement damage zones' have been recognized in exposures adjacent to faults in St Bees

Sandstone (Nirex 1997d; Edwards 1996). Conversely, there may also be zones of cement depletion where groundwater has been introduced to the matrix along fracture walls.

Conduits for fluid flow are represented by the Potential Flowing Features and, at the larger scale, by the damage zones and local fault offsets or jogs (Fig. 7). Most of the Potential Flowing Features in the Sherwood Sandstone Group fault zones are carbonate veins with some secondary porosity developed by dissolution due to groundwater flow, a process thought to be in dynamic interplay with deposition of mineral phases from the same groundwaters (Nirex 1997c).

The spatial distribution of Potential Flowing Features (Nirex 1997c and see Fig. 3) indicates that flow has been focused in the fault damage zones compared with both the faultrocks and the host rock, although Potential Flowing Features also occur in the host rock and not all faults in the Sherwood Sandstone Group are associated with Potential Flowing Features. There is also a tendency for Potential Flowing Features to be clustered, but there is no consistent relationship to the fault structure. Hydrotesting data (Environmental Pressure Measurements) indicate that the larger-scale Sherwood Sandstone Group fault zones have slightly higher permeabilities than the host rock, assumed to be due to the damage zones. In addition, cross-hole hydraulic testing results (Nirex 1997f) indicate that the faults may act both as baffles to transverse flow and as flow conduits parallel to strike or dip. Thus, observations made at both small-scale and large-scale appear to be consistent in suggesting that fluid flow is likely to be mainly fault-parallel, focused in the damage zones and highly heterogeneous, whereas flow normal to the fault plane will be

tortuous and restricted, especially for the larger-displacement faults.

The permeability axes inferred from the above observations and inferences, for both isotropic and anisotropic host rocks, are shown on Figure 7. The field observation that the vertical extent of damage zone fractures tends to be limited by termination at bed boundaries, together with the presence of strike-parallel jogs (Peacock & Sanderson 1991; see Fig. 5), imply that the maximum permeability axis (K_{max}) is parallel to the fault strike (Fig. 7). The orientation of the minimum (K_{min}) and intermediate (K_{inter}) permeability axes are likely to be dependent on the permeability characteristics of the host rock. In a lithologically homogeneous host rock with isotropic matrix permeability, as at the F3 intersection in the upper part of the St Bees Sandstone, K_{min} is expected to be normal to the fault. However, in an anisotropic sequence such as the North Head Member, permeability normal to bedding (and approximately parallel to fault dip) is likely to be inhibited. This will compound the effect of the limited fracture height and result in K_{min} being dip-parallel (see Fig. 7), with K_{inter} normal to the fault plane.

3. FAULTS IN THE BORROWDALE VOLCANIC GROUP

In the PRZ the Borrowdale Volcanic Group is dominated by massive, densely welded tuff and lapilli-tuff, interpreted as thick ignimbrites, with subordinate units of volcanoclastic rocks and acid, intermediate, and basic dykes and sills (Millward *et al.* 1994). In general, these rocks have very low matrix porosity (<1%). The sequence is affected by secondary alteration, especially close to the top, in some volcanoclastic units, and in association with fault zones. Apart from the fault-rocks (see below) these intervals tend to have slightly higher matrix porosities, up to 4%. The Borrowdale Volcanic Group is also affected by a complex fracture system, with several episodes of fracture mineralization identified from the core fracture logging (Nirex 1995a; 1997c; and see Appendix).

3.1. Fault structure

Fault 2 was studied in five borehole intersections (RCF1, 2 and 3, RCM1 and 3), and Fault 201 in three (RCF1 and 3, and RCM1; see Fig. 1). The intersections were all located at a depth of c. 525 to 740 mbGL, within the top 200 m of the Borrowdale Volcanic Group and immediately below the unconformity. In parts of this interval the tuffs are sufficiently altered to reduce the strength of the host rock. Fault 2 in the Borrowdale Volcanic Group is a complex structural zone, with typically 4 to 6 main strands but up to 11 in some boreholes. These strands are of variable orientations, but contained within a fault envelope whose orthogonal thickness ranges from 16 to 71 m. This variation in fault envelope thickness is interpreted as a jog or offset in the strike of F2 (Nirex 1997b), coincident with the location of the ESE-dipping F201 (discussed below). F2 is interpreted as a braided fault system, containing internal lozenges of less deformed host rock, with a multi-phase movement history which is dominantly dip-slip but may also have involved some lateral movements. Many of the F2 strands are coincident with alteration zones, and some are associated with a coarse breccia which is interpreted as an early faultrock or fault-related rock (Nirex 1997b). Most of the

strands are associated with fracture damage zones in their own right, and in some cases these damage zones merge.

Fault 201, which consists of two distinct, sub-parallel strands and associated damage zones, is steeply dipping and belongs to the family of approximately NE-striking structures. The observed spatial relationship with F2 described above suggests that it may be an accommodation structure.

A model illustrating the structure of Faults 2 and 201 at the stratigraphic level of the borehole intersections is shown in Figure 8. Although fault damage zones, in which the intensity of fracturing is higher than in the host rock, have been identified from the borehole data, the host rock itself contains a complex fracture system with a long history of mineralization. This has implications for the hydrogeological behaviour of the faults, as discussed below.

3.2. Hydrogeological characteristics

As noted above (Section 1), Potential Flowing Feature distributions are considered to be the best indicator of potential hydraulically active fractures. Evaluation of along-borehole Potential Flowing Feature distributions in the Borrowdale Volcanic Group (Nirex 1997c, i) indicates a partial correlation with fault zones. Some fault zones are associated with Potential Flowing Feature clusters, especially within the damage zones, although others are not; Potential Flowing Feature clusters commonly also occur in the host rock apparently not in association with faults. Additionally, Potential Flowing Feature clusters are inconsistently distributed in relation to fault geometry and are not always present at intersections of the same fault zone in other boreholes. Although these observations suggest heterogeneous fluid flow, they also indicate that fault zones have, in the past, and potentially at the present day, the capability to act as conduits within the larger-scale fracture dominated flow system in the Borrowdale Volcanic Group.

The majority of Borrowdale Volcanic Group faultrocks studied are not associated with Potential Flowing Features. They are, therefore, interpreted as low permeability features which, in general, appear to have been hydraulically inactive. However, some faultrocks do contain Potential Flowing Features and in these cases the Potential Flowing Feature intensity is often higher than seen in the damage zones or host rock. This observation suggests that some faults have undergone minor local reactivation, possibly in response to Cenozoic uplift, creating fracture space and allowing fluid flow. These may effectively be 'leak points' in otherwise low permeability flow baffles. Evidence of variations in faultrock permeability comes from the contrasting responses of the two F201 fault strands during hydraulic cross-hole testing (Nirex 1997g). During drawdown the upper strand, which is not associated with Potential Flowing Features, appeared to be hydraulically less active than the lower strand where Potential Flowing Features are present, although the different responses may also be partly due to different distances from the source zone. Therefore, localized reactivation and 'leak points' were incorporated into the conceptual model of Borrowdale Volcanic Group fault 'plumbing' (Fig. 9).

Conduits for fluid flow in the Borrowdale Volcanic Group fault zones, as indicated by the Potential Flowing Feature types identified, are in general a pro-rata subset of the fracture population and also include reactivated faultrocks as discussed above. Many appear to have been formed by the dissolution

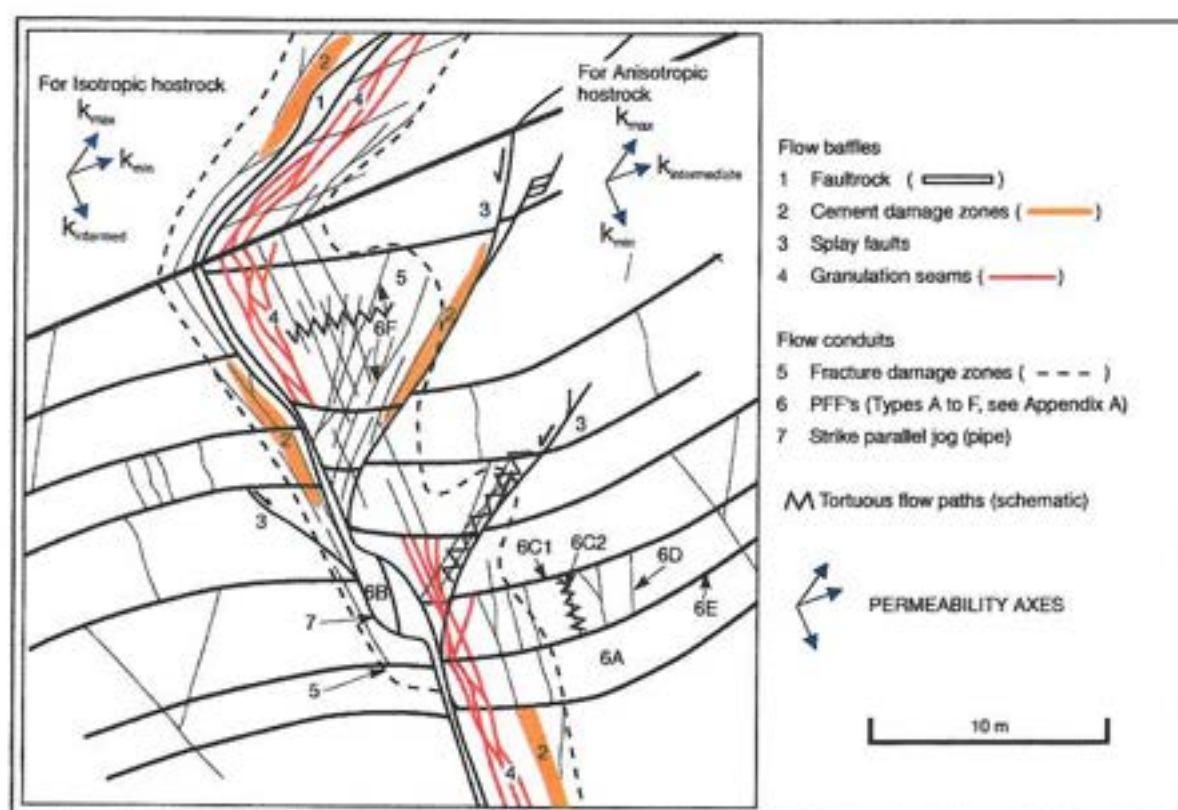


Fig. 7 Conceptualization of fault structure and 'plumbing' in the Sherwood Sandstone Group.

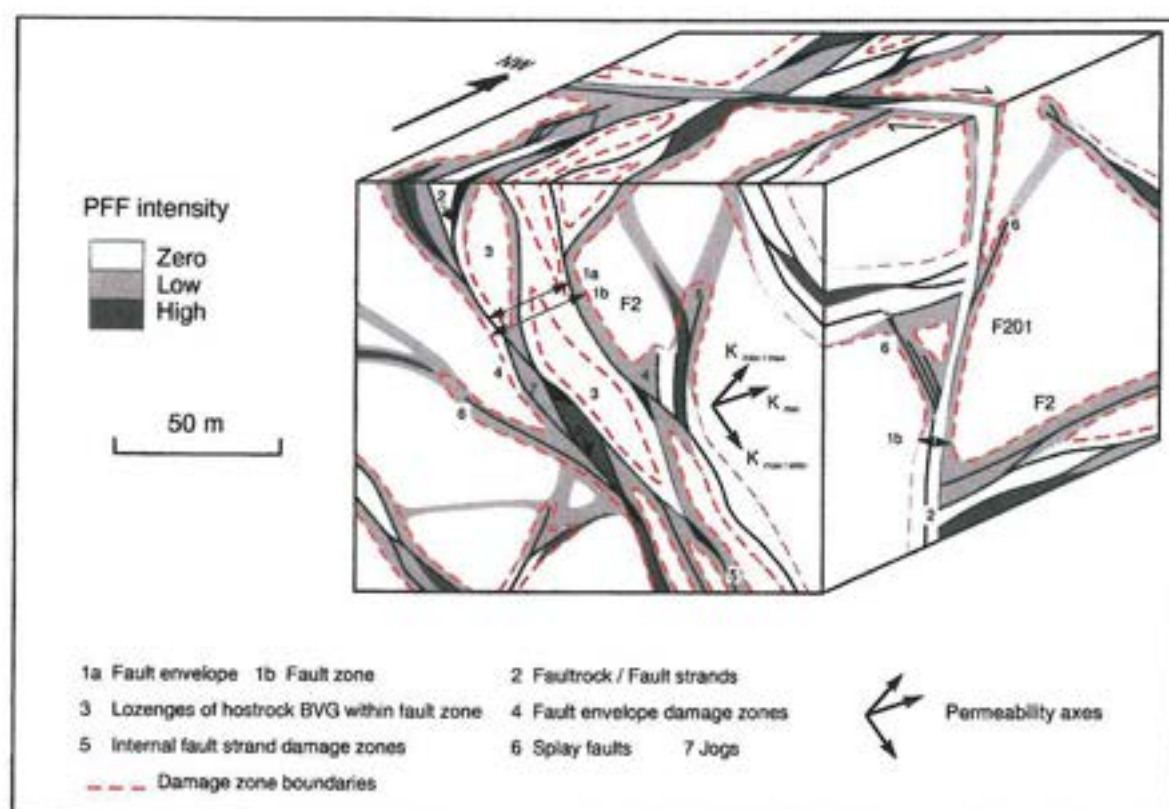


Fig. 8 Conceptualization of Fault 2 and Fault 201 structure in the Borrowdale Volcanic Group based on integration of borehole intersections and seismic interpretation, showing interpreted distributions of Potential Flowing Features.

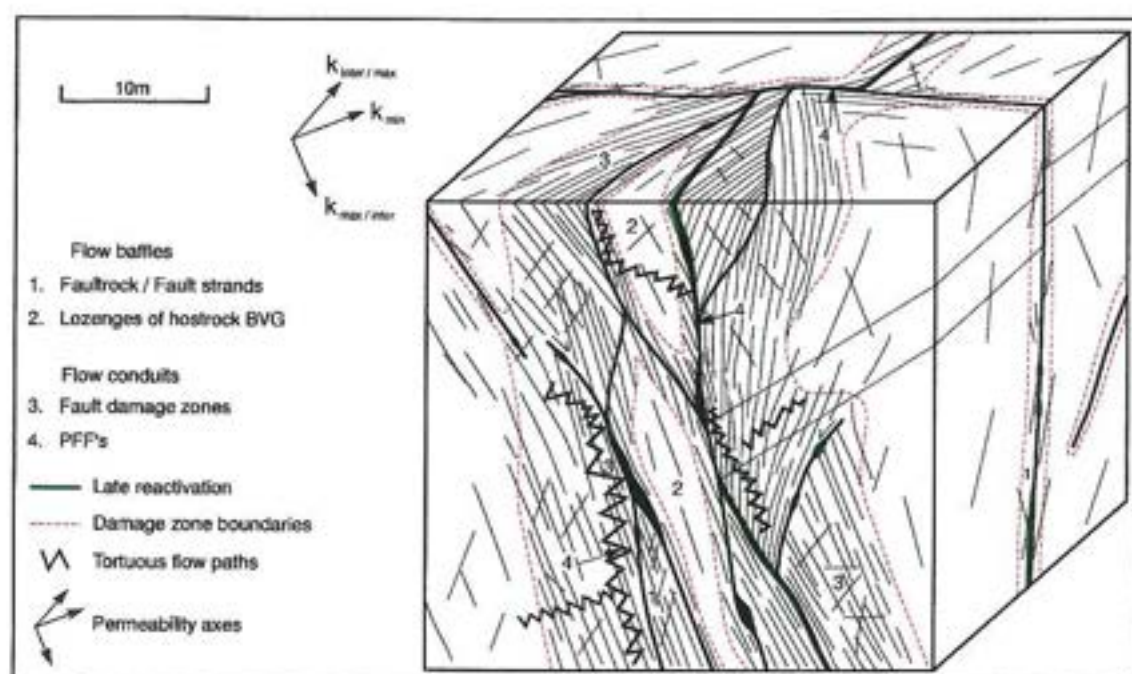


Fig. 9 Conceptualization of fault structure and plumbing in the Borrowdale Volcanic Group.

of carbonate veins, mainly of Triassic age (Nirex 1997c). Orientation analysis indicates a wide scatter of fracture dip azimuths in the Borrowdale Volcanic Group host rock; however, this tends to be overprinted in the fault damage zones by a dominance of synthetic (fault-parallel) fractures.

The permeability axes inferred from the above observations are shown on Figure 9. K_{min} is likely to be orientated normal to the fault plane because of the flow baffling effects of the low permeability faultrocks (except where reactivated). K_{max} is considered to be within the plane of the fault zone, reflecting the dominance of synthetic fracture orientations. The Potential Flowing Feature distributions, as discussed above, indicate that fault damage zones are likely to be the focus of tortuous flow, reflecting their higher intensity of fracturing compared to host rock. Field data on fractures in the Borrowdale Volcanic Group (Nirex 1997e) indicate generally short fracture lengths, variable orientations and complex intersection relationships owing to the multi-phase fracture history. Similar complexity is expected in the subsurface fault damage zones. Consequently any flow anisotropy in the plane of the fault is considered to be minimal.

Hydraulic test data derived from the 50m interval tests (Environmental Pressure Measurements) suggest that fault zone permeabilities are in general similar to those of the host rock. At the c. 1.5 m scale of the Short Interval Tests where individual Potential Flowing Features, or clusters thereof were tested, permeabilities are strongly related to the presence of Potential Flowing Features in both the damage zone and host rock with the bulk of the rock being of very low permeability (see Section 3.3.2). This relationship, which generally applies to both fault zones and host rock, is characteristic of fracture-dominated flow in a low permeability host rock.

In order to carry out numerical modelling (Section 3.4) a geological model was developed for the spatial distribution of

Potential Flowing Feature clusters within a typical Borrowdale Volcanic Group fault zone. The model was based on integration of the borehole observations described above with the lithostratigraphic and structural framework of the Potential Repository Zone (Nirex 1997b) and with the field observations of faults and fractures. Central to the model was the inference that Potential Flowing Features preferentially develop in susceptible lithological units or in zones of mineralization or secondary alteration, and also in association with faults and fault intersections. This conceptual model of intersecting pipe-like Potential Flowing Feature clusters was taken forward into the modelling (Fig. 10).

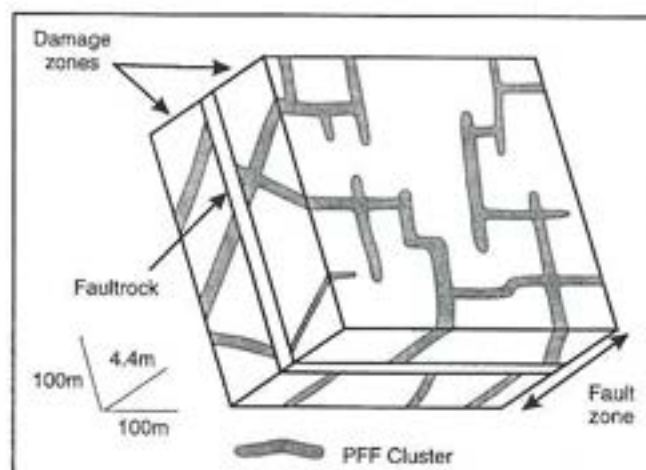


Fig. 10 Borrowdale Volcanic Group fault model showing distribution of Potential Flowing Feature clusters.

3.3. Statistical analysis of well test data

The discussion in previous sections focused on the use of Potential Flowing Features and Flow Zones as indicators of hydraulic significance.

Quantification of Flow Zone hydraulic properties from the results of fluid conductivity logs is possible (e.g. Hale & Tsang 1988) but is likely to be approximate, and the detection threshold for a Flow Zone will vary according to test conditions and the position and magnitude of other Flow Zones in the borehole. Typically low flow intervals will be more readily detected at the base of a borehole than at shallower depths resulting in a biased sample that requires careful analysis. Successful use of such a dataset requires detailed integration with well test results (NAGRA 1993).

It is not possible to directly quantify the hydraulic significance of Potential Flowing Features because of the mineralogical nature of their detection method. In order to quantify the permeability (or equivalent hydraulic conductivity) of Potential Flowing Features it is necessary to consider the hydrogeological test data over the borehole interval within which they are identified.

3.3.1. Hydrogeological test data used

Sutton (1996) describes the general testing methodology and well test procedures used at Sellafield, including the two types of test of interest here (Environmental Pressure Measurements and Short Interval Tests, see Section 1). Environmental Pressure Measurements were performed to determine estimates of *in situ* pressure and hydraulic conductivity within typically 50 m intervals. Their wide coverage, together with a relatively uniform sampling methodology, makes the results suitable for statistical analysis.

The Short Interval Tests, which formed part of the Post Completion Testing programme in Borehole RCF3 only (see Fig. 1), were performed using a wireline-conveyed testing string (the Schlumberger Modular Dynamics Tester [MDT]). The aim of the campaign was to measure the permeability of the host rock at a small scale suitable for correlation with detailed geological observations and to determine the permeability of intervals away from identified Flow Zones. No other Short Interval Test campaign was performed at Sellafield although other individual tests were performed as part of an appraisal of the Modular Dynamics Tester. The Short Interval Tests consisted of 100 short duration pulse tests, each on a 1.56 m interval, uniformly spaced over 156 m of borehole within the Borrowdale Volcanic Group (see also Armitage *et al.* 1996). The pulse tests took the form of a 20 cc injection of fluid into the packer interval followed by a recovery period during which the pressure in the interval was monitored. For a small number of the most transmissive intervals the Modular Dynamic Tester was reconfigured to perform constant rate extraction tests where fluid was pumped out of the interval over a period ranging from a few minutes to one hour. The 150 m interval selected for the campaign covered the depth range above the proposed repository depth and included faulted intervals and zones of high and low fracture density in the Borrowdale Volcanics Group.

3.3.2. Comparison of Potential Flowing Features and Short Interval Test results

The small interval length of the Short Interval Tests provided an opportunity to consider quantitatively hydraulic properties

at a scale close to that of the geological observations, especially the Potential Flowing Features. However, exact correlation may include uncertainties due to depth offsets between the testing string and the core observations. Such offsets are likely to be small because of the operational procedures used but may well be of the order of 10 cm. In addition, the core sample is of smaller diameter than the borehole so that Potential Flowing Feature structures in core are likely to be offset compared with those at the borehole wall. For example a thin planar feature dipping at 70° to a 6 1/4" diameter borehole will extend over 46 cm of the borehole wall but only 29 cm of a 100 mm diameter core from the same interval.

Figure 11 shows normal probability plots for the distribution of hydraulic conductivity from Short Interval Tests for intervals with and without Potential Flowing Features. Clearly the intervals with Potential Flowing Features are typically more permeable. Only two intervals without Potential Flowing Features have conductivity higher than 10^{-12} m/s. In both cases there are Potential Flowing Features very close to the interval (8 and 18 cm respectively). Notes from the core logging indicate that the depth of one of these features is approximate and it has therefore been assumed to be within the high conductivity interval for the analyses presented here. Given the depth uncertainties it would be entirely possible that both intervals did in fact contain Potential Flowing Feature structures. Thus all intervals without Potential Flowing Features would be of very low conductivity. In addition, a significant proportion of intervals containing Potential Flowing Features have very low conductivity.

There is a clear relationship between conductivity determined from the Short Interval Tests and the number of Potential Flowing Features in each interval (Fig. 12). Intervals with one Potential Flowing Feature are, on average, 10 to 100 times less permeable than those with two or more. The statistics are based on relatively small sample sizes and it is possible that packer by-pass effects (where a fracture might connect the test interval to the rest of the borehole) occur in zones of higher Potential Flowing Feature intensity. However, the data suggest that clusters of Potential Flowing Features are more important than individual Potential Flowing Features.

Hydraulic conductivity determined by Short Interval Tests may be compared for intervals of Borehole RCF3 inside damage zones and in the host rock. There is no statistically significant difference between the means of the two samples and the probability plots show a very similar shape below the median value of 10^{-12} m/s. At higher conductivities the distributions show a different pattern with a small number of the most conductive intervals (above 10^{-10} m/s) being found in the host rock. In the damage zones there is a higher frequency of intervals of conductivity between 10^{-10} and 10^{-12} m/s. However, the sample size is small and the differences may not be significant. High conductivity intervals in the host rock correspond to a zone within the Sides Farm Member of the Fleming Hall Formation (Akhurst *et al.* 1997) that was part of the source interval for the RCF3 Pump Test (Nirex 1997g) and also the most permeable zone in the Borrowdale Volcanic Group of RCF3.

Overall the data suggest that much of the damage zone rock is of very low hydraulic conductivity. Comparison with Figure 11 indicates that individual clusters of Potential Flowing Features both within damage zones and associated with other structures in the host rock are more permeable.

3.3.3. Comparison of Environmental Pressure Measurement derived hydraulic conductivities and faults

The scale of Environmental Pressure Measurement testing (normally 50 m in length) makes investigation of the hydraulic properties of faults difficult. Of the 44 Environmental Pressure Measurements performed in the Fleming Hall Formation only seven intervals did not contain a fault strand. No statistically significant difference could be identified between the means of the hydraulic conductivity of intervals with and without faults. Given that some of the intervals without fault strands most probably contained damage zone intervals and/or fault intersections not classified as significant, this is not surprising.

However, statistically significant differences were found between the mean hydraulic conductivity in the Fleming Hall and the Bleawath Formations. The latter underlies the Fleming Hall Formation, at a depth of c. 1000 mbGL (Millward *et al.* 1994, Fig. 2), and is considerably less fractured and faulted than the former (where penetrated by boreholes). It is not possible to determine whether the difference in conductivity is due to lithological or depth influences, which may also control the apparently lower intensity of faulting within the Bleawath Formation.

The conclusion from analysis of the Environmental Pressure Measurement data is that a significant proportion of both host rock and fault damage zone rock is of low conductivity. The scale of the Environmental Pressure Measurement tests does not allow more detailed comparison with regard to the influence of faults and their damage zones in the Fleming Hall Formation which, where penetrated by the boreholes examined, is a relatively highly faulted part of the Borrowdale Volcanic Group. However, very low hydraulic conductivities have been measured in the less faulted Bleawath Formation.

3.3.4. Conclusions from statistical analyses

A reasonably consistent pattern of hydraulic properties emerges from the analyses:

- The hydraulic conductivity of both host rock and damage zones is heterogeneous with a large proportion of rock with low hydraulic conductivity at the Short Interval Test scale;
- higher hydraulic conductivity intervals occur within damage zones and the host rock;
- Potential Flowing Features are strongly associated with these intervals of higher hydraulic conductivity;
- the conductivity of intervals containing Potential Flowing Features appears to be related to Potential Flowing Feature spatial intensity suggesting that Potential Flowing Feature clusters may be the most hydraulically conductive features.

The strong association of Potential Flowing Features, and clusters of Potential Flowing Features, with the most conductive intervals suggests that it is these structures that are the most appropriate basis for hydrogeological modelling. Potential Flowing Features occur in association with parts of some faults usually in fault damage zones, but may also occur in zones between faults. The heterogeneity within, and between, damage zones suggest multiple controls on hydraulic conductivity. Hydrogeological models of the Borrowdale Volcanic Group should therefore not be based on fault geometry alone.

3.4. Numerical models of flow in faults and damage zones

As part of this study numerical models of faults in the Borrowdale Volcanic Group were developed. The purpose of this work was to identify ways of integrating the geological knowledge derived from the study and to suggest appropriate models for use in further hydrogeological modelling. The development of numerical models ensured that all the important hydraulic properties of the faults were addressed within the geological studies. In particular, it was important to develop concepts concerning the distribution of Potential Flowing Features and Potential Flowing Feature clusters away from the boreholes. Therefore, the aim of the modelling performed within this study was to identify suitable methodologies for representing faults in groundwater models, rather than to build models and make predictions from them.

In order to simplify the task only a single Borrowdale Volcanic Group fault strand was considered. Models of features with multiple fault strands can be developed from those described here but special consideration would be required for fault intersections. The treatment of such intersections would be a source of uncertainty as only very limited data concerning such zones are available.

Following from the observations and concepts presented in previous sections, all the models described are based on Potential Flowing Features or Potential Flowing Feature clusters and their distributions. The conceptual model of flow in a Borrowdale Volcanic Group fault strand and associated damage zones considered here is that flow occurs in a network of Potential Flowing Feature structures (Section 3.2), which are a subset of the total fracture population. In addition flow occurs preferentially within clusters of Potential Flowing Features (Fig. 10) which were sufficiently well connected in the past to allow the passage of fluids responsible for the fracture mineralization. The distribution of the Potential Flowing Feature clusters is thought to be related to the geology, but is predominantly channelled so that the bulk of the fault rock and damage zones do not contain Potential Flowing Feature clusters. Flow within the host rock has not been considered, apart from locally within Borehole RCF3 (see above), but might be expected to show a similar pattern that would involve additional lithological controls. Three numerical implementation methods are considered:

- Heterogeneous porous medium models.
- Discrete Fracture Network models of the Potential Flowing Feature network.
- Discrete Fracture Network models of networks of Potential Flowing Feature clusters.

The first two models are considered appropriate for small scale models of say 10m to 100m in extent, whereas the third model could be used for larger scale applications. The observed heterogeneity requires that all the suggested models are stochastic with inputs based on probability distributions and statistical relationships. Outputs from the models are based on multiple realizations of these probability distributions and need to be analysed using statistical methods. Each of the modelling methodologies is illustrated in Figure 13.

The heterogeneous porous medium model (Fig. 13a) is based on division of the model volume into relatively small cells in which the hydraulic properties are a function of local Potential Flowing Feature intensity. The inputs to this model

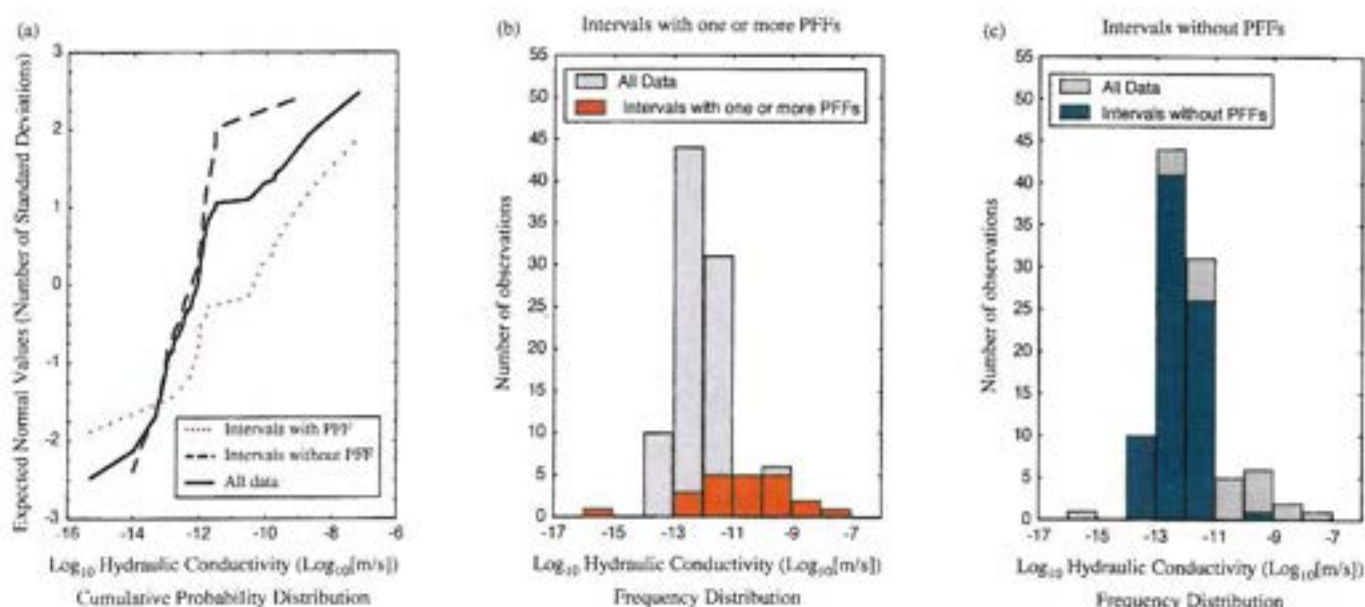


Fig. 11 Probability plot (a) and histograms of Log_{10} hydraulic conductivity (m/s) of Short Interval Test intervals with (b) and without (c) Potential Flowing Features.

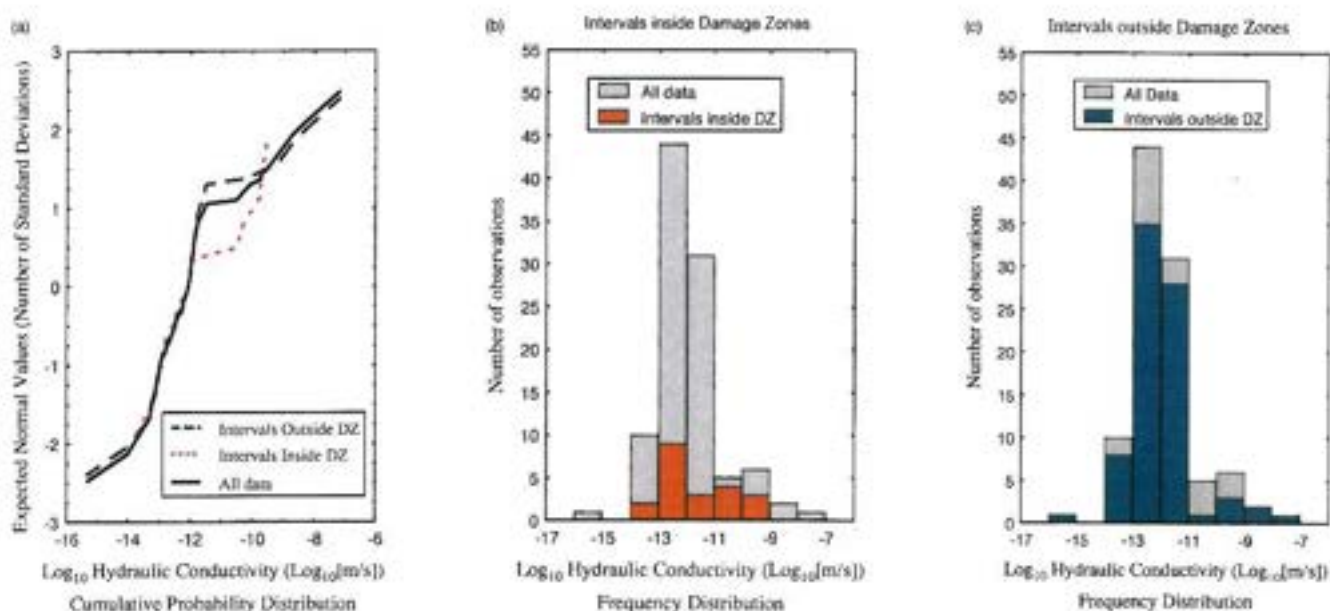


Fig. 12 Probability plot (a) and histograms for Log_{10} hydraulic conductivity of Short Interval Test intervals within damage zones (b) and outside damage zones (host rock) (c).

are the distribution of Potential Flowing Feature intensity within the fault zone and the statistical relationship between Potential Flowing Feature intensity and hydraulic conductivity derived from the analysis of Short Interval Tests (Fig. 14). Some upscaling of effective hydraulic conductivity may be required if the porous medium cell size is significantly different from the scale of the tests. The distribution of Potential Flowing Feature intensity in relation to fault framework is uncertain due to the one-dimensional sampling from boreholes. The method used in this study, and recommended for future use as a means of incorporating geological understanding, was based on the use of geological drawings (see Fig. 9)

and their generalization into numerical images of Potential Flowing Feature intensity. Geologists provided drawings of the predicted spatial layout of Potential Flowing Feature clusters within the fault strand (Fig. 10) and these were digitized after ensuring that they were consistent with the borehole data in terms of the relative frequency of Potential Flowing Features. Figure 15 shows a sample heterogeneous model of a fault strand and the cells corresponding to high intensity Potential Flowing Feature clusters within it (Fig. 15b).

The small scale Discrete Fracture Network model (Fig. 13b) includes elements for each Potential Flowing Feature. The inputs to this model are the distribution of Potential Flowing

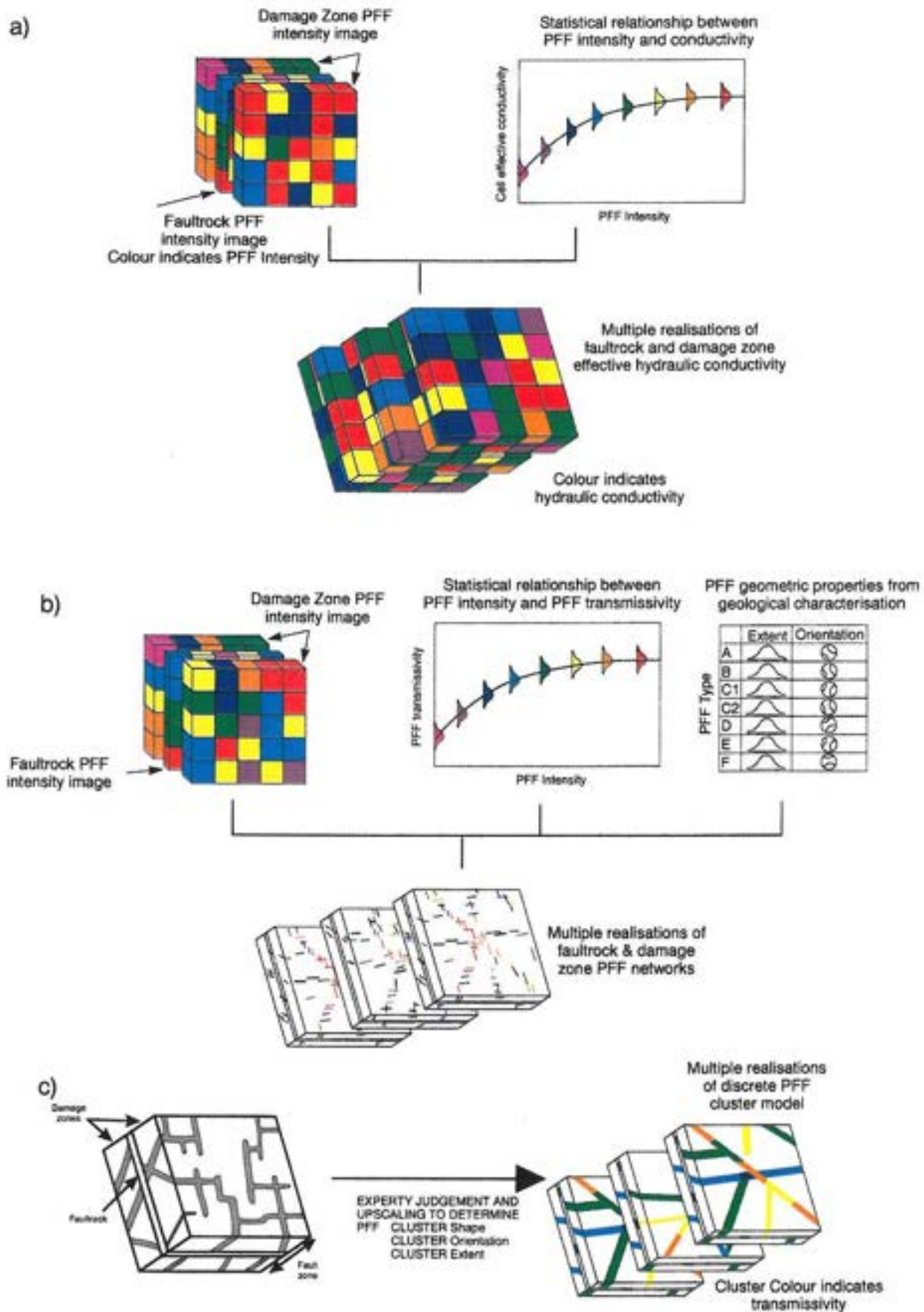


Fig. 13 Schematic diagram of suggested numerical representations of fault strands and their damage zones in the Borrowdale Volcanic Group. (a) Small-scale, heterogeneous porous medium model of fault. (b) Small-scale, discrete fracture network model of Potential Flowing Features within a fault. (c) Large-scale, discrete fracture network model of Potential Flowing Feature clusters within a fault.

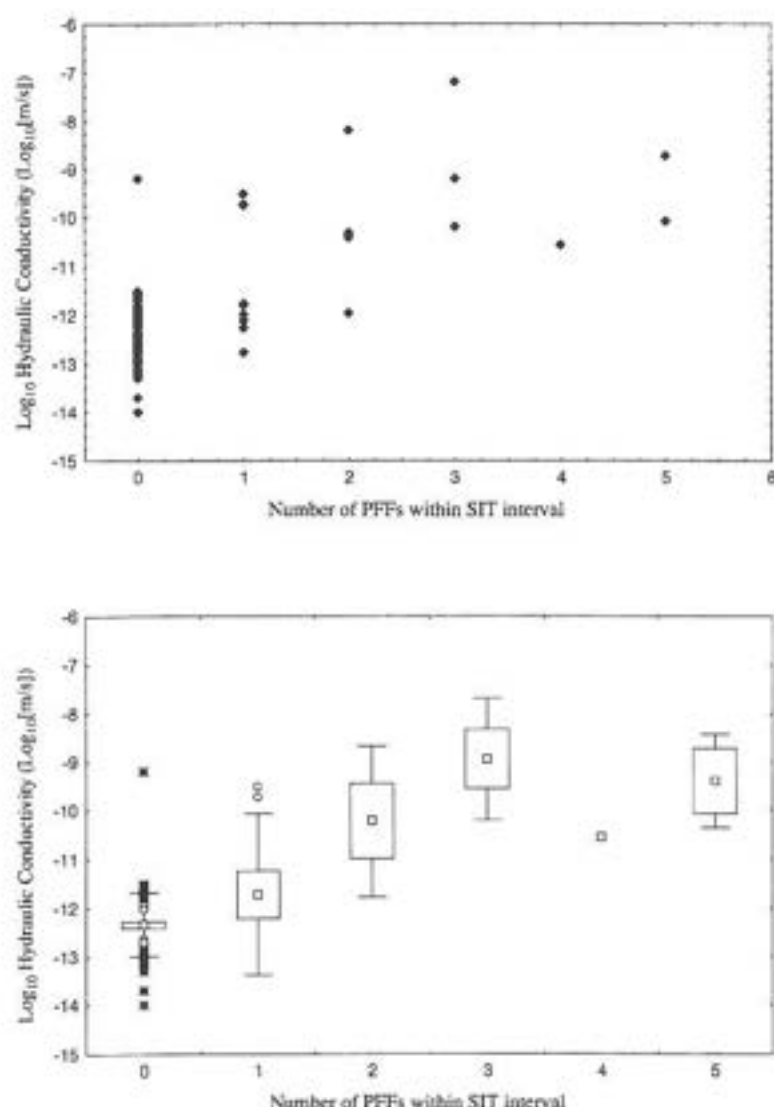


Fig. 14 Scatter plot and box plot of Log₁₀ hydraulic conductivity (m/s) against Potential Flowing Feature count for Short Interval Test intervals.

Feature intensity within the fault zone, transmissivity distributions for individual Potential Flowing Features and the geometric properties of the different types of Potential Flowing Features. The transmissivity distribution is dependent on Potential Flowing Feature intensity (Fig. 14) and would need to be derived in a manner consistent with the well test results (see Herbert *et al.* 1991). The geometric properties of the Potential Flowing Features' length, orientation and shape are derived from core measurements, outcrop mapping and geological judgement (Nirex 1997e) and are dependent on Potential Flowing Feature type. The spatial organization of the Potential Flowing Features is again derived from the Potential Flowing Feature intensity image (Fig. 10). A key input to the model is the Potential Flowing Feature intensity image, because this defines the channelling of flow within the fault and damage zones that are being modelled.

The larger scale Discrete Fracture Network models (Fig. 13c) include model elements corresponding to Potential Flowing Feature clusters. The inputs to the model describe the hydraulic and geometric properties of the PFF clusters. Hydraulic properties can be derived from upscaling the Short Interval Tests or from analysis of larger scale well tests. The

geometric properties of the clusters would need to be based on the geological concepts developed and would need to be augmented with relevant uncertainties and probability distributions. Cluster orientation, extent and connectivity are defined not by individual Potential Flowing Feature characteristics but from the Potential Flowing Feature intensity image. Thus Potential Flowing Feature cluster orientation may not be the same as the individual Potential Flowing Features (see for example discussions in Martel & Petersen 1990). The transmissivity and its heterogeneity within each cluster would need to be consistent with the smaller scale models and might be derived from calculations using such models.

The models described above rely on the extrapolation of borehole data into the rock volume. The method selected for the basis of this extrapolation is the use of quantified images of the rock volume derived from geological conceptualizations constructed in the manner described in previous sections. It is felt that this is a useful way of capturing and documenting geological expertise and of testing it against observation. The Potential Flowing Feature intensity image was calibrated and tested against borehole data to ensure consistency with the available data.

The Discrete Fracture Network models were not implemented within this study, however the relevant input parameters were identified and associated with borehole measurements. The major uncertainties relate to properties away from the boreholes, such as length scale and connectivity, rather than properties such as orientation that are easily measured at the borehole. All models require a description of the distribution of the Potential Flowing Features and Potential Flowing Feature clusters away from the borehole. Without suitable outcrop or underground exploration such extrapolations must be uncertain and this uncertainty may be an important factor in any estimates of the effective permeability of both fault zones and the host rock.

4. CONCLUSIONS

The results of the Fault Conceptualization Study provided a firm starting point for more accurate representation of faults in groundwater flow models at Sellafield. Borehole, reflection seismic, and outcrop data were used to constrain and develop parameters for conceptual models of fault geometry and hydrogeology. Preliminary numerical models based on the observed relationship between Potential Flowing Feature intensity and hydraulic conductivity have also been developed.

The main conclusions for NNW-striking, seismic scale faults in the Sherwood Sandstone Group are as follows:

- (a) The faults are commonly multi-stranded, with along-strike and down-dip jog structures, a geometry which is typical of extensional structures. Damage zones are commonly developed, but are heterogeneous in terms of thickness and spatial distribution.
- (b) A good correlation is observed between fault zones and Potential Flowing Features, implying that flow has been focused in the fault zones. Potential Flowing Feature distributions imply that heterogeneous flow occurs within the fault zones. The relationship with Flow Zones is less clear because of the effects of matrix flow from the sandstones.
- (c) Faultrocks and granulation seams are interpreted as low permeability flow baffles, whereas the damage zones are identified, from both Potential Flowing Feature distributions and from hydrotesting, as having higher permeability than the host rock. Granulation seams appear to have been particularly responsible for inhibiting groundwater flow.
- (d) $K_{\max}$ is interpreted as being parallel to fault strike, while $K_{\min}$ may be normal to the fault or aligned down-dip, dependent on the degree of permeability anisotropy within the host rock.

The main conclusions for NNW- and NE-striking, seismic-scale faults in the Borrowdale Volcanic Group are as follows:

- (i) The geometry of the large displacement, NNW-striking fault zone studied (F2) is highly complex, with anastomosing fault strands, internal lozenges of less deformed host rock, and well developed damage zones which commonly merge. The small displacement, NE-striking fault studied (F201) appears to be a less complex, semi-planar structure but also with damage zones.
- (ii) A correlation is observed between fault zones and

Potential Flowing Features, but it is weaker and less consistent than that observed in the Sherwood Sandstone Group. Faultrocks are generally considered as flow baffles, but there is evidence that the integrity of these baffles has been locally breached by minor fault reactivation. As a result, $K_{\min}$ is inferred to be normal to the fault plane. However, there is little evidence for flow anisotropy within the fault plane. The difficulty of imaging fault zones within the volcanic rocks and limited exposure data make any conclusions about anisotropy within the fault plane uncertain. The damage zones contain Potential Flowing Features which are a subset of the fracture population, and these damage zones may be a focus of hydraulic activity.

- (iii) Potential Flowing Feature clusters are considered to be the best guide of potential hydraulic activity at the larger scale, both for the faults and the host rock. A geological model to describe their spatial distribution in relation to faults is based on the fault framework and the distribution and characteristics of lithological units in the host rock, including zones of alteration and mineralization.
- (iv) The distribution of Potential Flowing Features and, more ambiguously, permeabilities derived from 50 m-scale hydrotesting suggest that, at the larger scale, there is little hydraulic contrast between the fault zones (including their damage zones) and the host rock. In contrast, the higher permeabilities observed at the 1.5 m-scale hydrotesting are typical of fluid flow in a fracture-dominated, low permeability rock. Faults in the Borrowdale Volcanic Group, therefore, appear to be simply one component of a complex fracture system whose flow characteristics largely depend on the connectivity of Potential Flowing Features.

APPENDIX

Definition of Potential Flowing Features, Mineralization Episodes, and Flow Zones

This Appendix provides a brief explanation of Potential Flowing Features, Mineralization Episodes and Flow Zones, all of which were fundamental to the Fault Conceptualization Study but which, because of space limitations, could not be described here in detail. They are discussed more fully in Nirex (1997c).

1. Potential Flowing Features

These are discontinuities and discrete zones, identified in the Nirex borehole cores, as being capable of conducting groundwater flow at the present day. The two criteria necessary for identifying Potential Flowing Features are firstly some degree of demonstrable connected porosity at the core scale, and secondly the presence of mineralization or rock-water interaction (a 'Mineralization Episode', see below) that can be attributed to the present-day, or relatively recent, groundwater system. The implication is that Potential Flowing Features are a record of contemporary or recent hydraulic activity, and therefore indicate potential active groundwater flow conduits. Potential Flowing Features were identified by detailed fracture and mineralization logging of the Nirex core by geologists at the British Geological Survey under the direction of Mr Antoni Milodowski.

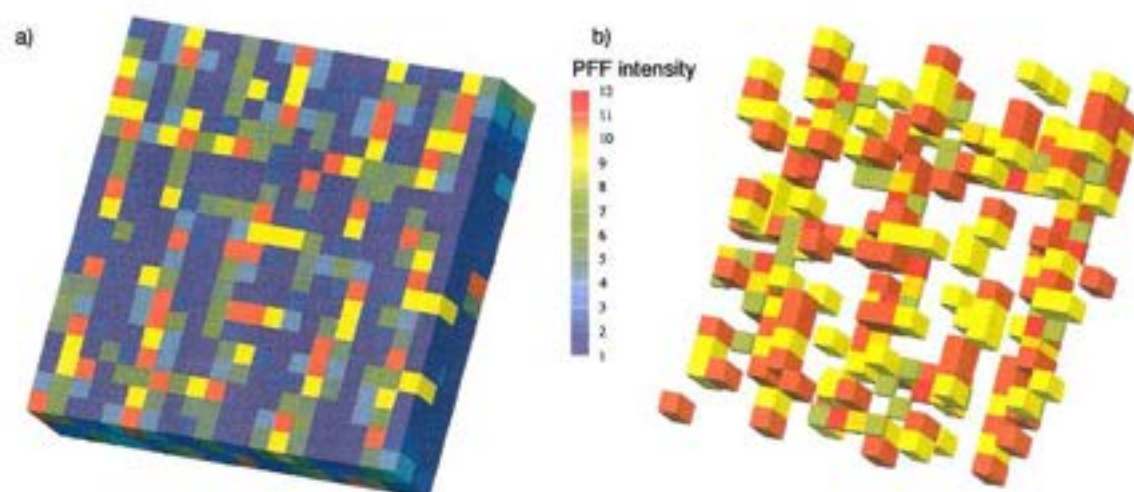


Fig. 15 Sample realization of equivalent porous medium model of a single fault strand and damage zone. Elements coloured by Potential Flowing Feature intensity. (a) Fault strand – all elements. (b) Fault strand – high Potential Flowing Feature intensity elements only.

In the Fault Conceptualization Study the along-borehole distributions of Potential Flowing Features in relation to fault architecture were examined by means of borehole composite plots, an example of which is given as Figure 3. Six end-member types of Potential Flowing Feature were recognized, based on a combination of physical attributes, origin of the structure and origin of the porosity. These are summarized as follows:

- Type A:** Permeable rock matrix (i.e. flow from intergranular and interclast porosity)
- Type B:** Fault planes (i.e. flow from either porous faultrock or intra-faultrock discontinuities)
- Type C:** (two sub-categories):
 - C1 – Reactivated fractures (normally at vein margins or at 'slip planes')
 - C2 – New fractures (i.e. unmineralized and with fresh wallrocks)
- Type D:** Steep to vertical dilational fractures controlled by bounding 'slip planes'
- Type E:** Bedding-parallel fractures in the sandstone sequences (related to erosional unloading)
- Type F:** Fractures with clear evidence of porosity formed by mineral dissolution

Within this paper the term Potential Flowing Features has been used both for particular features identified in core (Nirex 1997c) and for equivalent features within the host rock. This usage is different from that in the Nirex 1997 Safety Assessment (Nirex 1997i) where the term Potential Flowing Features refers only to those features identified in core and features that flow within the rock mass are termed Flowing Features.

2. Mineralization Episodes

A fundamental aspect of Potential Flowing Feature recognition was the construction of a chronological framework for the fracture mineralizations developed at Sellafield. Nine broad, temporally discrete, 'Mineralization Episodes' were identified from detailed core logging by the BGS supported by petrographic and fluid inclusion studies, isotopic analysis, and radiometric dating. Full details of this paragenetic framework can be found in Nirex (1995a) and Mildowski *et al.* (this

Volume). For the purposes of the Fault Conceptualization Study only the three most recent mineralizations (ME7, ME8 and ME9) were correlated with other geological and hydrogeological data on the borehole composite plots (e.g. see Fig. 3) because of their relevance to the present groundwater regime. These are summarized as follows:

- ME7:** Dominantly illitic clay minerals and hematite either as late fracture infills or within fault gouges. Probably late Triassic to Tertiary in age.
- ME8:** Mn- and Fe-oxides, which are alteration products occurring as surface impregnations and stains, thin films and dendritic coatings on fracture surfaces. Typical of near-surface alteration associated with an oxidizing groundwater regime, and found only in the upper few hundred metres of the Sellafield sequence. Presence of ME8 and open porosity suggests that fractures are hydraulically active.
- ME9:** Dominantly calcitic mineralization, almost always associated with open fractures. Its habit is closely associated with present-day groundwater chemistry, and changes with depth accordingly. Dated as very young, and believed to be produced by deposition from the active groundwater system.

3. Flow Zones

The term Flow Zones was used to describe points or intervals within the Nirex boreholes where flow entry from the borehole walls was identified from the interpretation of hydrogeological production logs (specifically differential temperature and conductivity logs). These production logs were run during hydrogeological testing of the boreholes (e.g. Full Sector Tests) and interpretation of Flow Zones was carried out by GeoScience Limited. Details can be found in Nirex (1995b, 1997j). Flow Zones, which represent active groundwater flow induced during pressure drawdown of the borehole, were used in the Fault Conceptualization Study to draw correlations with other geological and hydrogeological data on the borehole composite plots (see Fig. 3).

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