# The 3-D structural geology of the PRZ

## Proof of Evidence
## of
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**Professor David Kenneth Smythe will say:**

## 1. WITNESS DETAILS

1.1 I hold the Chair of Geophysics in the Department of Geology and Applied Geology at the University of Glasgow. My expertise relevant to the Inquiry is in *applied geophysics*, particularly applied seismology and potential field methods.

1.2 I gained an Upper Second Class Honours BSc in Geology from the University of Glasgow in 1970, and a PhD in Geophysics from the University of Glasgow in 1987. I am a Fellow of the Geological Society, a Fellow of the Royal Astronomical Society, and have held the title of Chartered Geologist from the inception of the title in 1989. Following PhD research using the seismic reflection technique onshore and offshore, I was employed by the British Geological Survey, Edinburgh, from 1973 to 1987 in various posts within its Marine Division. Much of my work entailed seismic reflection interpretation, expand-ing into seismic (re-)processing of problematic or interesting sections of oil industry data. Interpretation often involved quantitative modelling and integration of the seismic data with gravity and magnetic data.

1.3 All my work up to 1986 was funded by the Department of Energy as part of a Commissioned Research programme on the geology of the offshore UK region. I also gave geological advice to the Foreign and Commonwealth Office on matters pertaining to UK territorial claims offshore. During this period I was involved in studies of the continental margin west of the British Isles, and also became a founder member of the British Institutes Reflection Profiling Syndicate (BIRPS), a research group which became the world leader in marine crustal seismic reflection techniques. I was awarded the Lyell Fund of the Geological Society in 1985.

1.4 Since 1988 I have held the Chair of Geophysics in the Department of Geology and Applied Geology, University of Glasgow. My research has become focused on land rather than offshore seismic methods.

1.5 I served on the BNFL Geological Review Panel from 1990-91. I was invited to join the panel by one of its members, Prof John Lloyd, a hydrogeologist from the University of Birmingham. The panel comprised four university professors, with expertise in hydrogeology (Lloyd), structural geology (Coward), sedimentology (Williams) and geophysics (myself). I served on this panel to support BNFL's case for a Sellafield site for a PRZ, at the time when Nirex was investigating both Dounreay and Sellafield. I resigned from the panel after the case for Sellafield had been successfully made.

1.6 I proposed, planned and executed a trial 3-D seismic survey of the PRZ for UK Nirex Ltd in summer 1994 (University of Glasgow 1994) [FOE/3/14]. Results of the fieldwork and data processing have been disseminated at scientific meetings and lectures (Smythe *et al.* 1995) [FOE/3/12], but to date the geological interpretation of the 3-D data has not been publicly discussed in detail.

## 2. SUMMARY OF EVIDENCE

### Scope of evidence

2.1 I summarise in Chapter 3 why I have been commissioned by Friends of the Earth to provide expert opinion and advice on the geological and geophysical interpretation of the Sellafield area. The scope of the proof is then outlined.

2.2 The scope of Chapter 4 is to explain why we need an accurate geological structural model, and why the current model is not yet robust.

2.3 The scope of Chapter 5 is to review for the lay person how and why the seismic reflection method is used in two dimensions, and to point out its limitations. This is followed by Chapter 6, the aim of which is to reveal the limitations and internal inconsistencies in the Nirex interpretations to date.

2.4 The scope of Chapter 7 is to review the three-dimensional seismic reflection technique and briefly to give evidence of the oil exploration industry's favourable experience of its adoption. The scope of Chapter 8 is to demonstrate the inconsistencies of Nirex's attempts to characterise the structure of the BVG in three dimensions, as a consequence of not using the 3-D seismic method.

2.5 The scope of Chapter 9 is to highlight the differences between the Nirex and the oil industry's approach to their respective subsurface targets, and to follow through the implications of the differences for the correct siting of an RCF. The scope of Chapter 10 is to summarise the current deficiencies.

### Introduction

2.6 Accurate geological understanding of the proposed repository site is required because the safety of nuclear waste disposal rests on the ability of the geological regime to contain the radionuclides. Therefore the precise location of the excavations within the chosen regime must be identified with due caution. Geological understanding develops over time as the subsurface data concerning a particular regime is accumulated. When sufficient measurements have been taken the understanding of the subsurface geology in a particular region will stabilise. When such a stage is reached, the geological interpretation is *robust*.

2.7 Since about 1988 new surveys have yielded a radically improved picture of the subsurface. However, the geological interpretation is still subject to substantial revision every year or so, right up to the latest version of July 1995. There is therefore no reason to expect that the current version is close to the true picture.

2.8 Nirex proposes to construct a nuclear waste repository at Sellafield. It will be demonstrated below that the current geological interpretion of the subsurface geological regime is not robust. It is proposed that this situation should be addressed through the adoption of best practice from the geophysical community.

### Two-dimensional seismic surveys

2.9 The three-dimensional (3-D) structure of the Earth can sometimes be approximated by two dimensions (2-D). In reconnaissance exploration, 2-D seismic reflection surveys are carried out on the surface along regular survey grids. A necessary assumpion is that the geological structure is essentially 2-D. Echoes produced by a surface sound source are recorded and processed to image subsurface geological structure. Processing to improve the picture is only effective on 2-D seismic data in certain simple circumstances. In the complex Sellafield area subsurface imaging using the 2-D seismic method is of limited use, so that interpretations based on 2-D data are likely to be seriously in error.

**Geological interpretations of Sellafield based on 2-D data**

2.10 Nirex has shot nine 2-D seismic lines in the PRZ area. None of the reports describing the 2-D seismic data contain any seismic data. The maps and cross-sections are *interpretations*, so it is impossible to make any judgement about the quality of the 2-D seismic data. Nirex reporting methods do not comply with standard scientific practice.

2.11 Interpretations of 2-D tomographic data from the RCF area have been presented in an acceptable form for the data to be evaluated. Some of the data suffer from a survey design weakness. The tomograms have a similar interpretation limitation to that of 2-D surface seismic reflection sections, viz. that we have to assume that the images represent geological features in the plane of the section.

2.12 One way of cross-checking the validity of 2-D tomograms would be to shoot tomograms crossing each other. The tomograms should match along the line of intersection. However, none of the six reported tomogram surveys intersect each other at any point. An estimate of the reliability of the existing tomograms, obtained by abutting pairs of tomograms sharing a common borehole, reveals severe mismatches. In conclusion, the current tomographic surveys are inconclusive and inconsistent.

2.13 The coverage of 2-D seismic reflection data over the PRZ is clearly inadequate for the purpose of mapping accurately the complex pattern of faults. The current interpretations cannot be reconciled adequately with the 2-D tomograms. Since the current Nirex interpretation is internally inconsistent it must be regarded as very provisional. There are fundamental problems with the 2-D imaging methods used, and important faults may have been missed. It is possible that some of the faults mapped have been mis-correlated across the PRZ, as suggested both by the survey grid limitations and by the frequent and substantial revisions of the interpretation.

**Three-dimensional seismic surveys**

2.14 The raw data from a 3-D survey fills a complete volume with two horizontal spatial directions and a third, vertical time dimension. This concept is fundamentally different from 2-D seismic surveying, in which there is no reliable way to interpolate information from one vertical plane to another. The smallest scale of interpretability of 3-D data is five times smaller, and therefore better, than that for 2-D interpretation. Additional aspects of a 3-D volume can be characterised to aid interpretation.

2.15 Conversion of a 2-D seismic dataset into an accurate geological depth model is not achievable in complex geological situations. This problem may be addressed through the application of 3-D techniques.

2.16 3-D seismic exploration is the most important technological breakthrough in oil exploration and exploitation in recent years. Even when employed late in the development of a field, 3-D seismic is demonstrated to be cost-effective. The recent concept of time-lapse 3-D demonstrates that repeated 3-D surveys can reveal changes within the rockmass during depletion of the reservoir.

**The 3-D characterisation of the Sellafield site**

2.17 Although Nirex planned in early 1992 to carry out a trial 3-D survey, it was not until 1994 that such a survey was done. A dynamite source for a 3-D survey was considered to be logistically impracticable as well as being prohibitively expensive. Provisional results of interpretation in progress suggest that structure is clearly three-dimensional; the reflection stratigraphy within the BVG dips 20-30° SE. The previous 2-D surveys had been unable to image the BVG as clearly. The results confirm the feasibility and cost-effectiveness of carrying out such 3-D vibroseis acquisition.

2.18 Dips within the uppermost 500 m of the BVG, interpreted independently from three different geophysical datasets (the 3-D trial seismic survey, magnetic modelling and 2-D tomograms) are generally consistent with each other but in conflict with detailed Nirex structural maps constructed by interpolation between PRZ boreholes. These comparisons suggest that Nirex's attempts to map complex BVG structure in the RCF area are currently invalid, and that the geological interpretation of the PRZ area needs to be completely revised. The three-dimensional geological problems outlined above are unlikely to be confined to the PRZ. It is likely that the Site and the District scales will also require to be surveyed by the 3-D seismic method.

**Implications for the RCF**

2.19 The subsurface geological modelling of the Sellafield site must be made robust before construction of an RCF. A stable interpretation of the subsurface geology is required in order to provide a reliable basis both for the hydrogeological models and for the RCF siting. However, the current structural interpretation is not robust against further substantial revision, and therefore does not provide a reliable basis for hydrogeological modelling. Best practice would be to employ 3-D seismic reflection surveys, which may remove the major inconsistencies in the present geological interpretation. This reinterpretation should be demonstrated to be robust before the results are used in modelling.

2.20 Nirex has chosen a PRZ on factors other than solely hydrogeological considerations. The early definition of a PRZ makes its scientific task more difficult; it has to demonstrate that a particular volume of rock is suitable. This approach does not comply with best practice, as exemplified by the approach that the oil industry takes to site selection.

2.21 Nirex's geological scale is two to five times smaller than the typical hydrocarbon exploration scale, and the BVG is a crystalline layered rock, but these differences are not fundamental. Scaling comparisons show that most oil companies nowadays routinely employ the 3-D seismic method at the oil industry equivalent of the Nirex Site scale.

2.22 The close focusing of Nirex's work on a single 'prospect' may have led already to an inappropriately restricted approach to the search for a suitable repository location. The choice of Longlands Farm for the RCF was largely based on pre-war geological knowledge, thus it is unlikely that Nirex has already discovered the best location. The approach taken by Nirex carries a high risk of failure. Site characterisation must follow best scientific practice; this requires 3-D surveys, which must be interpreted and included in the site selection process.

**Deficiencies in the Nirex case**

2.23 Inconsistencies in the current interpretation of the PRZ show that *major faults,* as well as minor geological structures, are likely to have been misinterpreted and/or not identified. There are currently major conflicts of basic interpretation of the BVG structure. *The current geological interpretation is simply not robust*, and will therefore not provide a reliable foundation for hydrogeological modelling.

2.24 Best practice in analogous geological situations is to employ 3-D seismic reflection surveys. Geological models derived on the basis of 2-D data alone are likely to require substantial revision. A baseline set of geophysical, geological and hydrogeological data must be in place before underground construction perturbs the present PRZ hydrogeological flow. The 3-D structural re-interpretation should be completed before the results are passed to a 3-D hydrogeological modelling stage. The 3-D seismic dataset available to Nirex should be processed and the results used to derive a revised interpretation of the PRZ. Further surveys should be commissioned as required. Sufficient time must be permitted for evaluation and peer review of results.

2.25 3-D seismic surveys should be properly completed before the hydrogeological model work is completed and before the location of the RCF is finalised.

## 3. SCOPE OF EVIDENCE

3.1 I have been commissioned by Friends of the Earth to provide expert opinion and advice on the geological and geophysical interpretation of the Sellafield area, with respect to the Appeal by UK Nirex Ltd against the decision of Cumbria County Council not to grant planning permission for its proposed Rock Characterisation Facility. The scope of my evidence includes:

- Outlines of the seismic reflection method in two and three dimensions, and
- A review of the Nirex geological and geophysical interpretations.

3.2 The scope of Chapter 4 is:

- To explain why an accurate geological structural model of the PRZ is required prior to RCF construction,
- To demonstrate that Nirex's interpretation of the subsurface geological structure changes substantially every time a new interpretation is published, and
- To outline the objectives of the remainder of the proof.

3.3 The scope of Chapter 5 is:

- To review for the lay person how and why the seismic reflection method is used in two dimensions, emphasising only those aspects relevant to the Inquiry,
- To outline in a simple way the geometry of 2-D surface seismic reflection surveys, and
- To explain the limitations on possible interpretation of 2-D techniques when the geological structure is complex.

3.4 This is followed by Chapter 6, the aim of which is:

- To reveal the limitations and internal inconsistencies in the Nirex interpretations to date,
- To review the main alternative geophysical methods that Nirex has used in support of its current interpretations of the subsurface geology at the location of the proposed RCF,

- To point out the gap in public data availability, and
- To demonstrate that the 2-D tomographic surveys are significantly inconsistent with each other.

3.5 Chapter 7 summarises the 3-D seismic method:
- To demonstrate why the addition of the extra dimension is fundamentally better for geological interpretation,
- To review the three-dimensional seismic reflection technique, and
- To supply evidence of the oil exploration industry's favourable experience of its adoption of the 3-D method as a standard survey technique.

3.6 The scope of Chapter 8 is to demonstrate the inconsistencies of Nirex's attempts to characterise the structure of the BVG in three dimensions, as a consequence of not utilising the 3-D seismic method.

3.7 The scope of Chapter 9 is:
- To highlight the differences between the Nirex and the oil industry's approach to their respective subsurface targets,
- To explain why the oil industry should provide a suitable model for Nirex to emulate, and
- To assess the implications of the differences for the correct siting of an RCF.

3.8 The scope of Chapter 10 is to summarise the current deficiencies in the Nirex case, and to draw an appropriate conclusion.

## 4. INTRODUCTION

### Current understanding of the geological regime at Sellafield

4.1 Nirex proposes to dispose of radioactive waste in a subsurface repository. Prior to construction of such a repository the subsurface geology at the site of the proposed repository must be well understood. This geological understanding is required for two main reasons.

4.2 (1) The safety of nuclear waste disposal rests on the ability of the geological regime to contain the radionuclides. This ability is assessed through the application of numerical hydrogeological models. Such models are reliant on the existing understanding of the subsurface geology. Therefore if the understanding of the subsurface geology is not robust, then the resulting quantification of the safety of the proposed repository will also not be robust.

4.3 (2) Following the selection of a particular geological regime for repository construction it is of great importance that the precise location of the excavations within the chosen regime is identified with due caution. In addition to the financial implications of mislocation, inappropriate excavation within a potential repository zone also has safety implications. Selection of a rock zone for excavation, prior to the establishment of a robust subsurface geological interpretation, could result in the adoption of a location that was hydrogeologically inappropriate.

4.4 Our understanding of the geological subsurface is in a state of continual evolution and development. This is due to both the ongoing data collection work that is being carried out, which permits greater and greater degrees of resolution of our picture of the subsurface, but also, more importantly, it is due to the adoption of more sophisticated techniques for data collection and interpretation. At some stage in this process the understanding of the subsurface geology at a particular region will stabilise. Once the interpretation of the geology has stabilised the interpretations will be consistent between interpretations derived from different surveying techniques. In addition the interpretations will also be consistent over time, such that the interpretation is not subject to radical revision as further surveys are undertaken. If and when such a stage is reached, the geological interpretation may be said to be *robust*.

### Evolution of the interpretation of the PRZ

4.5 Over 60 years ago it was known that:

- The PRZ was underlain by SW-dipping Permo-Triassic rocks,
- The subcropping Carboniferous pinched out just to the NW,
- The Permo-Triassic rested directly on the BVG in the PRZ area, and
- The main structure was a NW-SE trending horst block.

These inferences were made on the strength of surface geological mapping and boreholes sunk for hematite (Smith 1924 [FOE/3/11]; Trotter *et al.* 1937 [FOE/3/13]). One of these early boreholes (Boonwood) lies near the centre of the proposed RCF. The geological cross-section along Nirex cross-section 17 {S/95/005}, as it was understood in 1937, is shown in Figure 1a.

4.6 The advent of two-dimensional (2-D) seismic imaging, together with more drilling, has resulted in a radically improved and more detailed, but not fundamentally different picture of the subsurface, as illustrated in Figure 1. Figure 2 is the corresponding location map. The epochs at which the cross-sections of Figure 1 were reported, and the respective information sources are as follows:

a. 1937-1988 (approx.): Trotter *et al.* 1937, plate V [FOE/3/13].
b. 1990 August: *Nuclear Engineering International*, reproduced in GOV/616.
c. 1991 August: Hooper (1991), reproduced in GOV/616.
d. 1993 December: Nirex Report no. 524, Vol. 1, fig. 3.6 [COR/524].
e. 1993 December: Nirex Report no. 525 fig. 6 [COR/505]
f. 1995 July: Nirex Report S/95/005 drawing no. 010061.

Figure 2 shows the location of Cross-section 26 (Nirex Drawing no. 010062) {S/95/005}, running NW-SE, along which the sections of Figure 1 are aligned for comparison.

4.7 The early cross-section (Fig. 1a), based on a structural map of the Site, remained a valid picture until around 1988, when the extensive new surveys began. The section of Figure 1b follows the ENE end of vibroseis line BGS-88-01, whereas those of Figures 1c, 1d and 1e lie along the line of the 1990 vibroseis profile GDGG-01, which runs very close to boreholes 10, 2 and 4. The source of Figure 1d (Nirex Report no. 524, Vol. 1, fig. 3.6) [COR/517] also figures a very small-scale line drawing interpretation of the migrated seismic data, but this differs significantly from the cross-section published at around the same time in Nirex Report no. 525, fig. 6, [COR/505] which is the source of Figure 1e. The latest version of the geological interpretation (Fig. 1f) is based on Nirex Drawing no. 010061 (Cross-section 17 through the PRZ) {S/95/005}.

4.8 It may be seen from Figure 1 that the geological interpretation is being substantially revised every year or so. There is therefore no reason to expect that the current version (Fig. 1f, July 1995) will turn out to be close to the true picture. It is important that this problem is resolved through the interpretation of all available survey results and the completion of additional geophysical surveys until a stable interpretation is established.

**Objectives of this proof**

4.9 Nirex proposes to construct a nuclear waste repository at Sellafield in Cumbria. It will be demonstrated below that the current geological interpretion of the subsurface geological regime at Sellafield is not robust, and therefore is not sufficient for either:

- Reliable hydrogeological modelling, or
- Correct siting of subsurface excavations.

4.10 In this proof it is proposed that this situation should be addressed through the adoption of best practice from the geophysical exploration industry and research community. To comply with best practice:

- All relevant survey data must be utilised,
- The most appropriate survey techniques must be adopted, and
- The surveying and interpretation work should be continued until the interpretation is robust.

4.11 In the following sections the role of the seismic technique will be considered. In particular, the role that the 3-D method may play in resolving the current difficulties faced by Nirex will be discussed.

## 5. TWO-DIMENSIONAL SEISMIC SURVEYS

**Geometry of surface seismic reflection surveys**

5.1 The structure of the Earth is three-dimensional at all scales - it varies in every direction. Because folds and faults are elongated structures which often run approximately parallel to each other in a given locality, the *real three-dimensional* structure of the earth can sometimes be approximated by *two dimensions*. This is helped by the fact that *lateral* variations in thickness and composition within sedimentary layers are usually very gradual or slight (and may be neglected) compared with the *vertical* variety of layer upon layer.

5.2. In the simplest case geological structure might vary only vertically, for example a flat layer-cake pile of beds which run laterally in all directions without change. We then say that the structure is *one-dimensional*. However this simple situation is only realised in a few special instances. The information from a borehole is essentially one-dimensional; extension to two or three dimensions can only be made by *extrapolation* (for example, of measured dips within the hole or cored rock), or by *interpolation* between boreholes.

5.3 In regional or reconnaissance exploration, *two-dimensional surface seismic reflection surveys* are carried out on the surface of the earth. The words ‘reflection’ and ‘surface’ are usually taken as implicit; ‘seismic survey’ will imply the *surface reflection* method unless otherwise stated. A regular grid of lines is laid out and surveyed, usually as two orthogonal sets of equidistant parallel lines. The *dip lines* run parallel to to the perceived dip direction of the subsurface structure, whereas the set of lines at right angles - the *strike lines* - run parallel to the geological strike. The major assumption made thereby is that the geological structure is essentially two-dimensional. This implies that any change in structure between one dip line and the next is minor or negligibly small.

5.4 Figure 3a is a perspective sketch of a simple subsurface geometry. The blue layer dips in the x direction; the strike direction lies at 90° to it, in the y direction. All vertical cross-sections made in the dip direction, i.e. x-z planes, will therefore be identical.

5.5 In the seismic reflection method echoes from the surface sound source are recorded and processed. It is a way of imaging subsurface geological structure, analogous to medical CAT scanning, or to a ship's depth recorder making a profile of the sea bottom as it sails along. A key element of the seismic method is redundancy; vast amounts of overlapping data are recorded, so that although any one of the individual records will show little or nothing, their sum total reveals a lot of useful information. During the processing phase, summation of many overlapping records turns the raw data into a vertical cross-section called a *stacked section*. The reflection events (echoes) seen on this section correspond in an indirect way to the geological structure beneath the surface survey line.

5.6 The picture can be improved by *migrating* the reflectors, or moving them around within the plane of section, to create an image which corresponds more closely to the subsurface geology. This enhanced section is called a (post-stack) *migrated section*. Migration is analogous to the focusing effect of a camera lens. There are more sophisticated methods of focusing the data before stacking, called *pre-stack migration*. Versions which work by converting the vertical dimension of travel time into depth are also available. However, these methods, which are labour and computer-intensive, are of little or no value in 2-D processing unless it is known that the structure to be imaged is very two-dimensional, and we also know the P-wave velocities in each layer very accurately. A compromise, called pre-stack partial depth migration, or dip move-out, is often used (e.g. Yilmaz 1987) [FOE/3/15].

5.7 In summary, these migration methods are effective on 2-D seismic data:

- where the structure is two-dimensional,
- where there are good continuous reflectors, and
- where the velocity structure is known.

5.8 *Vertical* resolution - i.e. the detail which can in principle be distinguished in the vertical direction - is limited by the frequency content of the seismic data. For 2-D data the effective resolution is normally taken as one quarter of the wavelength. This criterion is examined further in Chapter 7 below. The *horizontal* resolution will depend very much on the migration method and how effective it is in the particular application.

**Limitations on interpretation**

5.9 The assumption has to be made with the 2-D seismic sections, whether in the dip or the strike direction, that the section is a vertical plane beneath the surface line (Fig. 3a). The vertical scale of the vertical data panels is in *two-way reflection time* down from and back up to the Earth's surface. The first problem with interpretation now arises. Stacked seismic sections 'tie' together (match up exactly with each other) at line intersections (Fig. 3b), whereas migrated sections do not (Fig. 3c) unless the structure is perfectly flat (in which case migration would not be necessary). This is because the travel path from the Earth's surface down to and back up from a reflection point is the same whether we are recording a dip or a strike line.

5.10 Some two-way (down and back up) raypaths are shown as the red lines in the 3-D depth picture of Figure 3a, each bouncing back off a circular patch on the blue reflector. The raypath shown at the corner of the cube is common to both front faces of the cube, since it can be recorded along any survey line running through the top near corner. However, on both dip and strike stacked sections such data are represented on a seismic *trace* (the individual components making up the seismic display) running vertically downward (red vertical lines in Figure 3b). When the data have been migrated the dip line geometry corresponds more closely to the structure (the green solid line in Figure 2c), but the strike line remains unaltered since there are no means of moving the data out of the 2-D vertical plane of section.

5.11 Reflectors are best 'picked' (marked in and correlated with each other and with the geology to make a map) on migrated sections, because migration makes a better image when the structure is at all complicated. But migrated sections in a 2-D survey grid can only be tied over the grid by referring back to the stacked sections. This becomes very difficult if the structure is complex, because there is not necessarily a one-to-one match between data points on a stacked section with points on its migrated equivalent.

5.12 In the Sellafield area we can define meaningful dip and strike directions locally within the Permo-Triassic sediments. Since these sediments dip generally SW in the PRZ, seismic sections running NE-SW are the dip lines, and those at right angles are the strike lines. However, the presence of many faults cutting the sediments makes tying of reflectors over the grid, even just within the sediments, unreliable. When the structure is truly three-dimensional, as with the underlying BVG, we cannot classify the grid of data into dip lines and strike lines. Unfortunately, the generalisation that there is a locally defined strike direction will tend to lead the interpreter, working on inadequate 2-D seismic lines, to see continuity of perceived structure from one dip line to the next, even where none exists. The resulting interpretation will then end up more two-dimensional than the real world, and may even supply a spurious *post hoc* justification for the use of the 2-D method.

5.13 In summary, where the structure is complex and highly faulted, such as in the PRZ area, subsurface imaging using the 2-D methods will be inappropriate. Interpretations based on 2-D data are likely to be seriously in error. In the following sections the cogency of Nirex's current geological interpretations of the Sellafield site, based on the 2-D survey data processed to date, will be examined.

## 6. GEOLOGICAL INTERPRETATIONS OF SELLAFIELD BASED ON 2-D DATA

### 2-D seismic reflection surveys

6.1 Nirex has carried out a total of three 2-D seismic reflection surveys within the Site. One vibroseis line, shot in 1988, cuts the southern corner of the PRZ (Fig. 4). Two more vibroseis lines were shot in 1990 through this area, to which were subsequently added four dip lines (dip with respect to the near-surface solid geology) trending NE-SW, tied by two strike lines trending at right angles to these. These six lines (Fig. 4, solid lines) were shot during the 1992 'dynamite infill' survey. The total line length is about 8 km within the PRZ area shown in Figure 4. The average spacing between the 2-D data lines is 200-300 m.

6.2 Scientific papers on the subject of geological structure interpreted from seismic data normally include the following essential components as standard:

- A summary of the acquisition and processing,
- Reproductions of the stacked and/or migrated sections, in both uninterpreted form, and overlain with the line drawing picks made by the interpreter,
- Details of how wells were tied to the seismic data (the problem of comparing vertical scales in depth and reflection time, respectively), and
- Discussion of migration and depth conversion methods, and examples of test panels illustrating why certain processing decisions were taken.

Unfortunately Nirex reporting methods do not comply with standard scientific practice.

6.3 Two of the three vibroseis lines are referred to in Nirex Reports Nos. 346, 520 and 524 [COR/517] which are all Region and District integrated study reports. None of these reports contain any seismic data.

6.4 Six of the total of nine 2-D seismic lines were shot during the 1992 infill survey, and are apparently described and/or reproduced in the confidential BGS Report WA/94/47C. The source of this reference is Inquiry document COR/518, which refers to Nirex Report no. S/95/005, which in turn refers to this confidential report. However, there are no publicly available reports describing their acquisition, processing or interpretation. Only the depth geological maps and cross-sections of Report No. S/95/005 are available. These maps and cross-sections are interpretations, not data, and it is therefore not possible to make any judgement about the data quality.

### 2-D tomographic surveys

6.5 Interpretations of 2-D tomographic data from the RCF area have been published by Nirex (Report. No. S/94/007) [COR/513]. These contain planar colour images of the processed data between the pairs of boreholes within which the surveys were done. Such presentations are an acceptable form for the data to be published in a scientific journal, since the raw data themselves (the seismograms between the boreholes) would indicate little or nothing without the processing. The report is also scientifically sound as it presents several possible interpretations of each image, as well as the "preferred" interpretation of each.

6.6 No attempt has been made to prevent *spatial aliasing* of the tomograms. This has implications for the value of the data interpretations obtained. Spatial aliasing depends primarily upon the source frequency and the source and receiver depth interval. *Aliasing*, in time or space, is an undesirable consequence of under-sampling a periodic signal or event, so that the event appears to have a very different period (or frequency) from its true period. The apparent backward rotation of wagon wheels in cowboy films is an example of aliasing. Allowing spatial aliasing to occur is a design weakness. Some of the Nirex interpretations of the tomographic surveys assume spatial aliasing to have occurred, and include attempts to interpret the aliased data. This does not comply with good practice.

6.7 Since pairs of boreholes are not necessarily coplanar, the tomographic inversions of each pair are projected onto a best-fit plane, and travel-times corrected to the values that they would have had if the boreholes had actually both lain in this plane. This is an acceptable approach. However, even perfect coplanarity of the boreholes does not imply that the travel paths are coplanar. The problem is illustrated in Figure 5. The raypaths from source to receiver follow a path of least time, which is not necessarily the path of least distance (i.e. a straight line), and which, furthermore, may not even lie in or even near to the plane of section (Fig. 5). In essence, there is the same problem in interpreting 2-D tomograms as there is in interpreting 2-D surface seismic reflection sections, viz. that we have to assume that the events imaged (reflectors or P-wave velocities) lie in the plane of the section.

All interpretations must therefore be treated with caution.

6.8 One way of cross-checking the validity of 2-D tomograms would be to shoot tomograms crossing each other. Apart from the second-order effects such as velocity anisotropy mentioned in the report [COR/513], the tomograms should match along the line of intersection. However, none of the six reported tomogram surveys intersect each other at any point. This is a survey design shortcoming. Additional tomographic surveys of the pairs of boreholes RCF2-BH2 or BH5-RCM3 should be undertaken to provide this intersection cross-check which is currently missing. Each of these two suggested borehole pairs would be nearly coplanar, although the latter hole of each pair is deviated from the vertical.

6.9 Some check on the reliability of the tomograms of the PRZ geology, reported by Nirex, may be obtained by abutting pairs of tomograms sharing a common borehole. This has neither been done nor proposed in Report No. S/94/007 [COR/513]. Bearing in mind the cautionary note expressed in that report about absolute values of velocity being subject to anisotropic effects (which are, however, of second-order) a judgement can be made about how well or otherwise the data match at these common boreholes. This is summarised in Table 1. Figures 6-10 and Table 1 show severe mismatches in the vicinity of the common borehole. They are primary, first order mismatches, wherein the P-wave velocity apparently differs by 20-50% on adjacent panels - examples of this include Figure 6 (700-800 m), Figure 9 (around 550 m) and Figure 10 (600-800 m). It is unlikely that these differences are real, and must therefore have been produced as artefacts of the acquisition and/or processing.

6.10 In conclusion, the tomographic surveys to date are inconclusive and inconsistent.

**Comments on the current Nirex subsurface interpretation**

6.11 The density of coverage of 2-D seismic reflection data over the PRZ is insufficient. The survey profiles are spaced at 200-300 m (Fig. 4), but the faulting as mapped by Nirex is spaced at 100-400 m within the Permo-Triassic, and 20-200 m within the BVG. Thus Nirex is trying to obtain greater horizontal (map plane) resolution from the information available than the 2-D seismic grid is intrinsically capable of providing.

6.12 The attempt to reconcile the current Nirex geological picture with the 2-D tomograms is not satisfactory. This problem is illustrated below using an example taken from the tomogram between borehole 2 (BH2) and borehole 4 (BH4). I have selected this tomogram because the comparison of tomograms suggests that the upper part of this one is reliable, and because a tomogram over the small inter-well distance of 150 m or so is less likely to suffer from the assumptions about coplanarity of the data discuss-ed above than some of the other tomograms. The BH2-BH4 cross-section and interpretation features in the cross-hole hydraulic testing described by Chaplow (1995, fig. 6.6) [PE/NRX/14].

**Table 1. Tomograms having a common borehole**

| Tomogram 1 | Tomogram 2 | Common borehole | Fig. No. herein | Quality of match at common borehole |
|---|---|---|---|---|
| BH5-BH2 | BH2-BH4 | BH2 | 6 | Good except 400-470 and 700-830 m |
| BH5-BH2 | BH2-RCF3 | BH2 | 7 | Good 700-900 m; poor elsewhere |
| RCF3-BH5 | BH5-BH2 | BH5 | 8 | Good 800-980 m; poor elsewhere |
| BH2-RCF3 | RCF3-BH5 | RCF3 | 9 | Poor above 630 m; good beneath |
| RCF3-BH2 | BH2-BH4 | BH2 | 10 | Good except 600-800 m |

6.13 The interpreted tomogram (Report No. S/94/007, fig 5) is shown here as Figure 11a. Depths are in metres below the rotary table of borehole 4 (BH4). Feature A is described by Nirex as an aliased zone between 460 and 650 m. Figure 11b shows the uninterpreted tomogram, to which I have added the presumed aliased zone (the triangular area outlined in yellow). This lies to to the right of the obvious feature which I have marked and labelled AA (Fig. 11b). Nirex feature A (Fig. 11a) is tied to an apparently shallow-dipping fault at 620 m in BH4, and interpreted as a fault dipping at 73° from the horizontal. No fault has been recognised by Nirex within BH2 in the interval 350-500 m. Although preferred, this interpretation mismatches the borehole stratigraphy by up to 40 m.

6.14 The Nirex preferred version of feature A (Fig. 11a; see also Chaplow 1995, fig. 6.6 [PE/NRX/14]) is based upon:

- Interpreting aliasing in the tomogram,
- Ignoring the obvious direct unaliased image,
- Using a minor fault whose dip mismatches the inferred fault feature by 50°, and
- Permitting a gross mismatch to the borehole stratigraphy.

6.15 The alias dip limit for this tomogram is 65°. My feature AA (Fig. 11b) dips at 65° relative to BH2, and is therefore not aliased. It is parallel to other features such as B interpreted by Nirex, and corresponds to the feature A interpreted by Nirex as Option A (Report No. S/94/007, fig 3), although in the Nirex version it stops short of reaching BH2.

6.16 An alternative geological interpretation of the tomogram (Fig. 11b) assumes that feature AA is a fault zone. The minor feature A, interpretable from aliased data (Fig. 11a), is still permissible, but not shown. This interpretation implies that fault feature AA cuts BH2 within the St Bees Sandstone at around 380 m. This depth corresponds to a major zone of fracturing {Nirex Drawing No. 010133; Borehole No. 2 Summary} which has not been correlated by Nirex with any fault zone. The intersection of fault feature AA with BH4 at around 620 m depth also corresponds to a major zone of fracturing {Nirex Drawing No. 010135; Borehole No. 4 Summary}, which in this instance has been interpreted by Nirex as a fault. In summary, my re-interpretation:

- Uses the principal feature on the tomogram,
- Ignores possibly aliased events,
- Ties major zones of fracturing in the two boreholes by way of a major fault, and
- Is consistent with the borehole stratigraphy.

6.17 In conclusion, the current Nirex interpretation of its existing dataset is internally inconsistent, and must therefore be regarded as very provisional. There are fundamental problems with the imaging methods used (2-D seismic reflection and 2-D cross-hole tomography), and important faults may have been missed in the interpretation of the borehole logs. It is possible that some of the faults mapped have been mis-correlated across the PRZ, as suggested both by the survey grid limitations (Fig. 4) and by the frequent and substantial revisions of the interpretation (Fig. 1).

6.18 Thus it may be concluded that although Nirex has commissioned several 2-D seismic reflection surveys, it has been unable to generate good, unambiguous 2-D images of the PRZ target. In the following sections the possibility of addressing this problem through the use of the 3-D seismic reflection survey technique will be considered.

## 7. THREE-DIMENSIONAL SEISMIC SURVEYS

### Data volume

7.1 The raw data from a well-designed 3-D survey are not confined to particular planes. Instead they fill a complete volume with two horizontal spatial directions and the third, vertical time dimension. The data are processed in a 3-D mode, and can be displayed as a parallel set of vertical planes in one direction ('inlines'), or in another direction at right-angles to the first ('cross-lines'), or as time slices (horizontal planes one above the other), or on arbitrary user-selected planes or surfaces. Schematic locations of the Inlines (NE-SW) and the Crosslines (NW-SE) from the 1994 3-D trial survey of the PRZ are shown in Figure 4 for comparison with the 2-D survey coverage.

7.2 The discrete sampling of data within a 3-D volume is such that we can go smoothly from point to point within the volume. This concept is fundamentally different from 2-D seismic sections, where there is no reliable way to interpolate information from one plane to another, since in the 2-D case it is not known whether or not the data really belong within the vertical plane on which they are displayed.

### Resolution and interpretability

7.3 The resolution of the technique is dependent upon the frequency of the seismic energy put into the ground and returned as echoes. High frequencies (short wavelengths) are desirable because they permit greater resolution. The frequency f of the seismic sound source is related to the wavelength $\lambda$ by the P-wave velocity V through the rocks, using the formula $\lambda = V/f$. The rule of thumb for the limiting resolution in 3-D data is considered to be $\lambda/20$, i.e. 5 times smaller (and therefore better) than the quarter-wavelength criterion for 2-D interpretation. This is because the vastly greater amount of quasi-continuous data within the data volume permits much more subtle changes to be identified than could ever be seen with discrete 2-D planes.

7.4 To illustrate how this is used, two frequencies of seismic energy, 50 Hz and 100 Hz, may be considered (Table 2), assuming V = 5000 m/s, appropriate to the BVG. Table 2 illustrates how the resolution achievable may be calculated.

**Table 2. 2-D *vs.* 3-D vertical resolution**

*$\lambda = V/f$; V = 5000 m/s (assumed). res = resolution. The two right-hand columns show the scale of the smallest features that can be resolved, or separated with 2-D and with 3-D methods.*

| f | $\lambda$ | 2-D res ($\lambda/4$) | 3-D res ($\lambda/20$) |
|---|---|---|---|
| 100 Hz (optimistic) | 50 m | 12 m | 2.5 m |
| 50 Hz (pessimistic) | 100 m | 25 m | 5 m |

7.5 These correspond to frequency components towards the bottom and near the top, respectively, of a realistically achievable seismic reflection bandwidth. Bandwidth is the range, or spectrum, of frequencies contained in the seismic source, since we do not in practice use a single frequency.

7.6 Aspects of the 3-D volume can be characterised to aid interpretation. These include seismic attributes such as phase, amplitude and instantaneous frequency of a trace, but also amplitude and dip variations on a picked surface through the volume.

**Migration and depth conversion**

7.7 The primary goal of seismic reflection imaging is the conversion of a seismic dataset into an accurate geological depth model. In complex geological situations the use of 3-D rather than 2-D techniques allows a considerable improvement in the accuracy of the model derived. After preliminary processing and interpretation phases, the raypaths from every shot to every receiver of the raw 3-D dataset can be traced through a 3-D velocity model, so that the reflector elements can be positioned accurately within the 3-D depth model. This is *pre-stack depth migration*. If this sounds like the chicken and egg problem - well, it is; we cannot accurately migrate the reflectors until we know the 3-D structure, and we cannot know the 3-D structure until we have a good migrated picture. In practice the whole process is iterative, and the more information that can be brought in from external sources, such as velocity and depth information from boreholes, the better.

7.8 Vertical dip sections from a migrated 3-D survey often look remarkably similar to their 2-D equivalent shot along the same surface track. This is to be expected; the only difference will be that the out-of plane reflectors will be absent from the 3-D section, but may still be present in the 2-D section, perhaps just appearing as extra ‘background noise’.

**Growth of 3-D seismic exploration**

7.9 The seismic reflection method has long been by far the most important tool in creating images of subsurface geology within the oil industry. The extension of the method from 2-D to 3-D is now regarded as essential once the reconnaissance stage of exploration is complete.

7.10 Shell International Petroleum Company is of the opinion that “*three-dimensional seismic is the most important technological breakthrough in oil exploration and exploitation in recent years*” (Pink 1993) [FOE/3/10]. It was estimated that by 1990 some one thousand 3-D surveys had been shot throughout the world, and Shell claims at least 25% of these (Nestvold 1992) [FOE/3/9]. The average size of these surveys is 240 km$^2$, or a linear dimension (the square root of the area) of about 15 km.

7.11 3-D surveys are now becoming larger in area. A survey of onshore NW China in summer 1994 covered 743 km$^2$ (linear scale 27 km; Anon. 1994b [FOE/3/2]), and an offshore Campos Basin, Brazil, survey being undertaken in early 1995 is around 1400 km$^2$ (linear scale 37 km; Anon. 1995a [FOE/3/3]). In 1993-94 an offshore survey of 1670 km$^2$ was completed in the North Sea (linear scale 41 km; Anon. 1994a [FOE/3/1]).

7.12 Another major oil company, Amoco Production Co., has analysed the results of 115 3-D surveys (Aylor 1995) [FOE/3/6], using business concepts of ‘risk management’ and ‘expected value’. Whereas the actual added value calculations by Amoco cannot be applied in a useful way to the Nirex example, some of the comments are noteworthy. For example, although Amoco often employs 3-D late in field development after larger, less risky locations have already been drilled out, 3-D can be used to define previously unrecognized, high quality locations (Aylor 1995) [FOE/3/6].

7.13 Not only are 3-D surveys now regarded as essential in the exploration for and exploitation of hydrocarbons, but the concept of *time-lapse 3-D*, sometimes referred to as ‘4-D’ is becoming popular (e.g. Anon. 1995b, 1995c [FOE/3/4, FOE/3/5]). A 3-D survey is repeated several times within the lifetime of the field to monitor reservoir changes and therefore assist in its efficient exploitation. This demonstrates the ability of the 3-D seismic method to reveal changes within the rockmass during depletion of the reservoir.

7.14 The oil industry is a highly appropriate model for Nirex to emulate, because it is engaged in characterising in as much detail as possible *geological structure* and *fluid flow regimes.* These are essential elements of Nirex’s safety case. The role of the 3-D seismic technique in the subsurface imaging of the Sellafield geology will be considered in the next section.

## 8. THE 3-D CHARACTERISATION OF THE SELLAFIELD SITE

8.1 Nirex reported to Cumbria County Council in early 1992 its plans to carry out a 3-D trial seismic survey [PE/NRX/12/2]. The statement “*drilling in connection with a three-dimensional seismic survey*” [PE/NRX/12/2, p. 12] implies that a dynamite source would be used. However, at some later stage the plans were dropped, since a dynamite source for a 3-D survey was considered to be logistically impracticable as well as being prohibitively expensive (Smythe *et al.* 1995) [FOE/3/12].

8.2 The Swiss experience of imaging a similar target (Birkhauser 1993) [FOE/3/7] suggested that a 3-D survey using optimised vibroseis acquisition might be a way forward. A 3-D trial seismic survey was carried out by the University of Glasgow in 1994 (University of Glasgow 1994; Smythe *et al.* 1995) [FOE/3/14; FOE/3/12] over the PRZ (Fig. 4). The aim was to test the feasibility of vibroseis as a semi-high resolution source, both logistically and in terms of quality of data obtainable. Interpretation of results is in progress (Chaplow 1995, para.2.11) [PE/NRX/14]. The results of the trial confirm the feasibility and cost-effectiveness of carrying out 3-D vibroseis acquisition over complex shallow targets (Smythe *et al.* 1995) [FOE/3/12].

8.3 Provisional results from the 3-D trial have been reported as follows (Smythe *et al.* 1995) [FOE/3/12]. The structure of the subsurface geology of the PRZ is clearly three-dimensional; the reflection stratigraphy within the BVG dips 20-30° SE, unconformably below the SW-dipping sediments. Penetration is good, down to 2-3 km. The previous 2-D surveys were unable to image the BVG as clearly, and results were also complicated by out-of-plane reflections from the faults.

8.4 The reported dip direction of reflection events within the 3-D trial survey dataset is consistent with the SE dip of the base of the magnetic layer within the uppermost 500 m of the BVG, interpreted by Kimbell (1994, fig. 5c) [FOE/3/8]. This magnetic layer trends NE-SW and pinches out in the neighbourhood of borehole 5 (Fig. 12). It dips SE at about 30°, flattening out SE of boreholes 2 and 4. Both these independent geophysical sources of structural information are represented schematically by the long bold dashed arrows in Figure 12. Notwithstanding the problems inherent in the 2-D tomographic surveys, the data between BH5 and BH2 appear to be fairly consistent in the depth range 700-900 m (Table 1 above). The BH5-BH2 tomographic image (Figs. 6-8) suggests a component of dip in the SE direction of about 15°, which is fairly consistent with the other two independent geophysical methods (Fig. 12).

8.5 In contrast, the dips of the Base Longlands Farm Member and Base Fleming Hall Formation in the RCF area are interpreted on the basis of the 2-D dataset by Nirex (Nirex Report no. S/95/005, figs. 3.4 and 3.5 respectively) as varying from south to SW (Fig. 12, thin solid-line arrows). Along the BH5-BH2 section (Fig. 12) the Nirex structure contour map of the Base Fleming Hall Formation predicts that the structure is almost flat, varying only between 810 m and 825 m below OD. This information is represented schematically by the thin arrows in Figure 12, which generally trend at right-angles to the BH5-BH2 line. This is completely at variance with the tomographic image, which, if valid, shows an increase in depth of the velocity contours of around 150 m between BH5 and BH2 over the appropriate depth interval (see, for example, Fig. 6).

8.6 Substantially more effort is needed to remove these major inconsistencies within the current subsurface geological interpretation. Given the inconsistencies in the current interpretation, together with the normal experience of the oil industry when 3-D seismic data are used, it is very likely that the PRZ area geological interpretation will have to be completely revised following the interpretation of the 3-D dataset.

8.7 This re-interpretation will be restricted to the PRZ area covered by the 1994 3-D trial survey. However, the three-dimensional geological problems outlined above are unlikely to be confined to the PRZ. Therefore for any realistic hydrogeological modelling the geological model of the Site (and preferably the District as well) should also be upgraded using data from 3-D seismic surveys.

## 9. IMPLICATIONS FOR THE RCF

### Hydrogeological modelling implications

9.1 Realistic hydrogeological models require realistic geological models. Perturbation of the present PRZ hydrogeological flow by the construction of an RCF will be unavoidable (O'Nions 1995) [PE/NRX/17]. Therefore a baseline set of geophysical, geological and hydrogeological data must be in place before underground construction starts. However, inconsistencies in the current structural interpretation show that it is not robust against further substantial revision, and is therefore does not provide a reliable basis for hydrogeological modelling.

9.2 Best practice in analogous complex geological situations is to employ 3-D seismic reflection surveys, but the PRZ has not yet been reinterpreted using the existing 3-D trial survey. Reinterpretation, using existing or new 3-D surveys, may remove the major inconsistencies in the present geological interpretation. This reinterpretation should be demonstrated to be robust before the results are used in hydrogeological modelling.

### The location of the RCF

9.3 The implications of an inadequate geological basis for the hydrogeological models are considered in more detail in PE/FOE/4 and PE/FOE/5. In this section the implications of the current inadequate understanding of the Sellafield subsurface geology for the location of the proposed RCF are discussed. The Nirex process which led to the adoption of the currently proposed PRZ will be considered, and a comparison will be drawn between the approach adopted by Nirex and the approach considered as best practice within the oil industry.

9.4 The Royal Society Study Group has expressed particular concerns about the methodology adopted by Nirex to select the PRZ. "*Nirex have chosen a potential repository zone (PRZ) not only on hydrogeological considerations, but also on the basis of factors such as ownership of land and mineral rights, ease of transport and likely costs of repository construction. This early definition of a PRZ makes their scientific task more difficult; instead of being able to proceed in stages, by showing that there are locations in the area that are potentially suitable for a repository, and then determining by a process of optimization which of these processes is preferred, Nirex have set themselves the task of demonstrating that a particular volume of rock is suitable*." [COR/605].

9.5 "*The optimal siting of a repository should be determined through highly iterative interaction between the scientists and the design engineers, as the scientists' understanding of the site characterization develops. The Study Group has seen no evidence of such a close relationship*." [COR/605].

9.6 The early definition of the PRZ, on the basis of very limited data, clearly does not comply with best practice. This point may be illustrated by comparison with the approach that the oil industry takes to site selection. Within the oil industry the targeted site is selected through a process of staged data-gathering. The area covered is reduced stage by stage as it becomes possible to home in on the most appropriate site. This allows the investment in site investigation to be focused such that the best site is chosen, and detailed site investigation effort is then concentrated in this area.

9.7 The oil industry's search for hydrocarbon accumulations (oil and gas fields) begins with a reconnaissance phase. This may be trans-national or even global. Political considerations - obtaining a licence to explore, the tax regime of the host country and so on - come in at the next stage when exploration may be carried out over specified 'acreage'. Possible oil targets or 'prospects' are then identified, and drilling will start, accompanied by more and more detailed seismic and other geophysical work. The interval from identification of a prospect through to the commercial production of oil or gas can be five to ten years.

9.8 The Nirex approach to the selection of the PRZ does not match best practice from the oil industry. This may be illustrated by a comparison of the scales of the surveys undertaken by Nirex and by the oil industry. The geological scale of the Nirex search for a repository is two to five times smaller than the typical hydrocarbon exploration scale, and the BVG is a crystalline layered rock, which is not normally investigated by oil companies. These differences are not fundamental.

9.9 Nirex has commissioned geological surveys at four scales from large to small. The Nirex terms for the different scales are Region, District, Site and PRZ, respectively. Within the PRZ lies the RCF. Table 3 shows the scales involved in aerial and linear dimension, together with the oil exploration industry equivalent, obtained by multiplying the Nirex linear scale L by a factor of between 2 and 5. This empirical scaling comparison allows for the fact that Nirex's target 'reservoir' (the PRZ) is of the order of two to five times smaller in spatial scale and depth of burial than a typical oilfield.

**Table 3. Comparison of Nirex and oil industry survey scales**

| Nirex category | Area $km^2$ | Linear scale (L; km) | Equivalent oil exploration linear scale (~L × 2 to 5; km) | Oil exploration use of 3-D seismic? |
|---|---|---|---|---|
| Region | 4000 | 60 | 100-300 | No |
| District | 600 | 25 | 50-100 | Perhaps (offshore) |
| Site | 50 | 7 | 15-35 | Yes |
| PRZ | 2 | 1.5 | 3-8 | Yes |

9.10 Thus from Table 3 it may be seen that, taking the oil industry as an illustration of good practice, it would be appropriate to undertake 3-D surveys possibly at the District scale, and certainly at the Site scale, before selection of a PRZ. However, the approach which has been taken by Nirex contrasts strongly with best practice.

9.11 The Sellafield Site became one of the two Nirex targets in 1989. It was evidently not selected on the basis of especially suitable geology or hydrogeology, but on a combination of political and economic grounds. The Nirex approach to date has departed from the oil industry exploration model of homing in from the regional, reconnaissance scale towards likely targets to be drilled. Instead Nirex has started with the target at Site scale, and come down to PRZ and RCF scales while *simultaneously* filling in the regional geological background at Region and District scales.

9.12 The contrast between the Nirex and the oil industry *modi operandi* is illustrated by the Venn diagrams of Figure 13. The figure corrects for the linear scale factor of 2-5, by which oil exploration is greater than Nirex exploration. The relative scales at which the political and/or economic constraints apply are different in the Nirex and oil company examples. These are the *Site* scale and *Licensed Acreage* scale, respectively. Nirex has chosen a single Site, and within it has invested most of its effort to date in a single PRZ. An oil company, on the other hand, will take out a licence to explore a block or sector within which it hopes for a variety of *plays* (oil-bearing scenarios) and several *prospects* (specific structures prognosed to be oil-bearing). It also has the freedom to relinquish the acreage if it turns out to be unproductive or uneconomic, and to move elsewhere after fulfilling its commitments under the licence.

9.13 The oil company approach will be to drill only one or two exploratory wells in each prospect before deciding whether to invest more effort in exploiting a discovery; drilling targets are chosen in such a way that a dry hole usually means that the prospect would not be worth testing any further, even though the prospect might contain a little oil. In contrast, Nirex has already drilled nine deep holes in its single prospect, the PRZ. This is the oil company equivalent of not merely testing a prospect, but of having gone into full exploitation mode.

9.14 Nirex is focusing on a single ‘prospect’ (to use the appropriate oil industry exploration analogy), which is a structural high within the ‘play’ of onshore, coastal subcrop of the BVG at 400-700 m depth beneath a sedimentary cover. It appears to have no alternative prospects at present. The resulting close focusing of the work may have led already to an inappropriately restricted approach to the search for a suitable repository in the Sellafield district.

9.15 The choice of Longlands Farm was largely based on pre-war geological knowledge. It is therefore highly unlikely that Nirex has already discovered the best location for the RCF in the Sellafield area. The suitability of this area has not been tested through rigorous application of scientific best practice. The limited approach to data gathering adopted by Nirex carries a high risk of failure. In addition to the financial and logistical implications of mis-location of the PRZ and the RCF within this zone, there are also significant implications for the integrity of the potential repository host rock (these are considered in more detail within PE/FOE/7). It is therefore of vital importance that the scientific programme of site characterisation through site surveys is carried out rigorously and in compliance with best scientific practice. This requires that 3-D survey techniques are carried out at the appropriate scale, and that the survey results are interpreted and incorporated into the selection process.

## 10. DEFICIENCIES IN THE NIREX CASE

10.1 I support, in principle, the general concept of a nuclear waste repository sited in the Sellafield area, if a suitable repository zone can be found. I also accept that at some stage within the site investigation programme for repository development it would be appropriate to construct a rock characterisation facility. However, I consider that the current proposal is deficient in a number of respects, which I outline below.

10.2 An essential prerequisite for hydrogeological modelling is to establish the geological structure accurately both in and around the PRZ. Inconsistencies in the current interpretation show that *major faults,* as well as minor geological structures, are likely to have been misintepreted and/or not identified. There are currently major conflicts of basic interpretation of the BVG structure between geologically and geophysically based methods. Although it is possible that the BVG in the PRZ may turn out to be a suitable host rock for a repository, it is not possible to verify this from the current structural interpretation. *The current geological interpretation is simply not robust,* and will therefore not provide a reliable foundation for hydrogeological modelling of the site.

10.3 Best practice in analogous geological situations is to employ 3-D seismic reflection surveys. The oil industry experience suggests that the use of 3-D seismic data would result in considerable re-evaluation of geological models derived on the basis of 2-D data alone.

10.4 Perturbation of the present PRZ hydrogeological flow by the construction of an RCF will be unavoidable (O’Nions 1995) [PE/NRX/17]. A baseline set of geophysical, geological and hydrogeological data must be in place before underground construction starts.

10.5 The 3-D structural re-interpretation should be completed *and demonstrated to be robust* before the results are passed to a 3-D hydrogeological modelling stage (see also PE/FOE/4 and PE/FOE/5), and before the results are used for the selection of the appropriate location for an RCF (see also PE/FOE/7).

10.6 The 3-D seismic dataset available to Nirex should be processed and the results used to derive a revised interpretation of the geological structure of the PRZ. Further surveys should be commissioned and shot if required, such that a stable interpretation of the geology is achieved. The area over which the survey work is carried out must be adequate:

- To provide a sufficient framework for reliable hydrogeological models, and
- To allow the identification of the correct location for the PRZ.

10.7 Sufficient time must be permitted for evaluation of results before the next phase is planned and executed. The results and their interpretation must be subjected to a proper process of peer review.

10.8 For the reasons given above I consider that the 3-D seismic survey should be properly completed or a new survey undertaken, properly validated, and adequately peer reviewed. This work should be undertaken before the hydrogeological modelling work is completed and before the location for the RCF is finalised. The results from the 3-D seismic model and those from the hydrogeological modelling should be demonstrated to be properly compatible before work on the RCF starts.

## GLOSSARY

The context within a word or phrase is used herein is shown, where necessary, in square brackets thus [ ]. Cross-referenced terms are shown in *italics*.

**3-D** [seismic survey] Three-dimensional configuration in which there are two horizontal spatial directions parallel to the earth's surface and one vertical time or depth dimension.

**Alias** [discrete sampling theory] Representation of a periodic event at a false period due to undersampling of a continuously varying (analogue) signal.

**Anisotropy** [seismic] Variation of seismic velocity depending upon the direction in which it is measured.

**Common mid-point** [seismic survey] The geometric half-way point between the *source* and *receiver* positions. In reflection processing, the subsurface location of reflections on a seismic trace is initially assumed to be at this point (often abbreviated CMP).

**Geophone** [seismic survey] Light, portable sensor connected to the ground to measure the ground motion (usually the vertical component of ground velocity, converted to a low-impedance electrical analogue signal).

**Geophone string** [seismic survey] Set of *geophones* connected together in series.

**Play** [hydrocarbon prospecting] Potentially oil-bearing geological scenario.

**Potential Repository Zone** Region in which it is considered that a deep radioactive waste repository might be located.

**Prospect** [subsurface exploration] The locality or *target* zone of the survey.

**Receiver** [seismic survey] The instrument (usually a *geophone string*) which picks up the reflected waves from the subsurface. It can also be put down a borehole.

**Robustness** [modelling] The property that a model can stand firm, with only minor alterations required, when new data are added to it.

**Rock Characterisation Facility** The test site at which subsurface investigations of the Potential Repository Zone are carried out.

**Shooting** [seismic survey] The process of setting off the *source* in a seismic survey; although referring originally to dynamite shots, it is also used in *vibroseis*.

**Shot-point** [seismic survey] The place at which a seismic shot (pulse source) is to be fired; used also loosely for *vibroseis* work.

**Source** [seismic survey] The origin of the signal used to generate seismic reflections from the subsurface.

**Target** The zone of the subsurface in which the survey is to be concentrated.

**Tomography** [seismic survey] A method for finding the velocity and reflectivity distribution from a multitude of observations using combinations of *source* and *receiver* locations.

**Vibrator** [seismic survey] Servo-hydraulic device mounted on a truck to generate sweeps transmitted into the earth.

**Vibroseis** [seismic survey] The technique of using a quasi-sinusoidal low-power but long-duration burst of energy into the earth using a *vibrator*.

## ABBREVIATIONS

| | |
|---|---|
| **BGS** | British Geological Survey |
| **BNFL** | British Nuclear Fuels [plc] |
| **CAT** | Computer-aided tomography |
| **CMP** | Common mid-point |
| **FoE** | Friends of the Earth Ltd |
| **Nirex** | United Kingdom Nirex Limited |
| **OD** | Ordnance Datum |
| **PRZ** | Potential Repository Zone |
| **RCF** | Rock Characterisation Facility |

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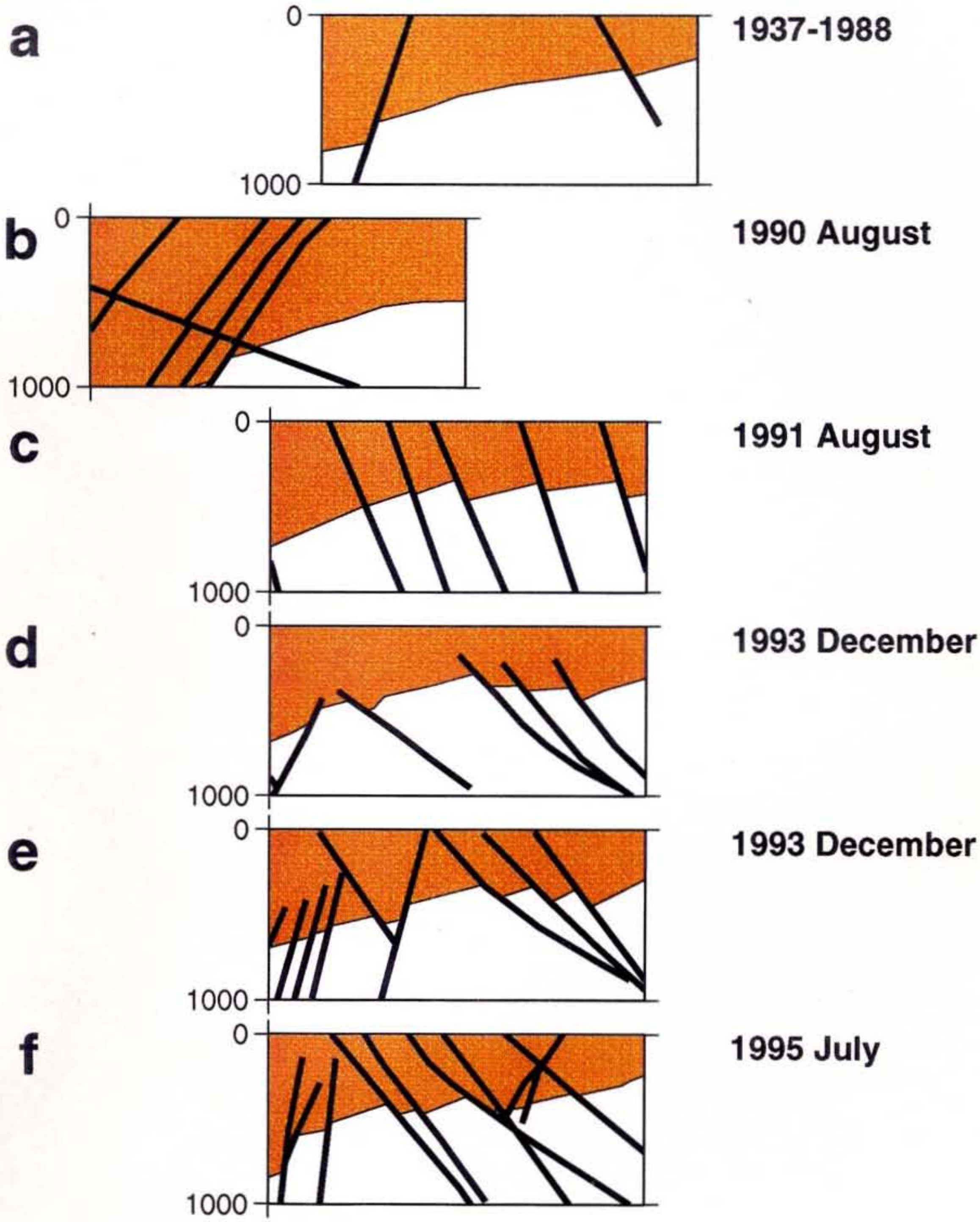



**Fig. 1. Interpreted cross-sections through the PRZ at several epochs.**
Only the major faults (solid black lines) and post-BVG sedimentary cover (colour) are shown. All sections are 2200 m long, located in Figure 1(key map). The sections are aligned vertically along Cross-section 26 {S/95/005; Drawing No. 010062}. Epochs and information sources are as follows:

**a.** 1937-1988 (approx.): Trotter *et al.* 1937, plate V [FOE/3/13].
**b.** 1990 August: *Nuclear Engineering International*, reproduced in GOV/616.
**c.** 1991 August: Hooper (1991), reproduced in GOV/616.
**d.** 1993 December: Nirex Report no. 524, Vol. 1, fig. 3.6. [COR/517]
**e.** 1993 December: Nirex Report no. 525 fig. 6. [COR/505].
**f.** 1995 July: Nirex Report S/95/005 Cross-section 17; Drawing no. 010061.

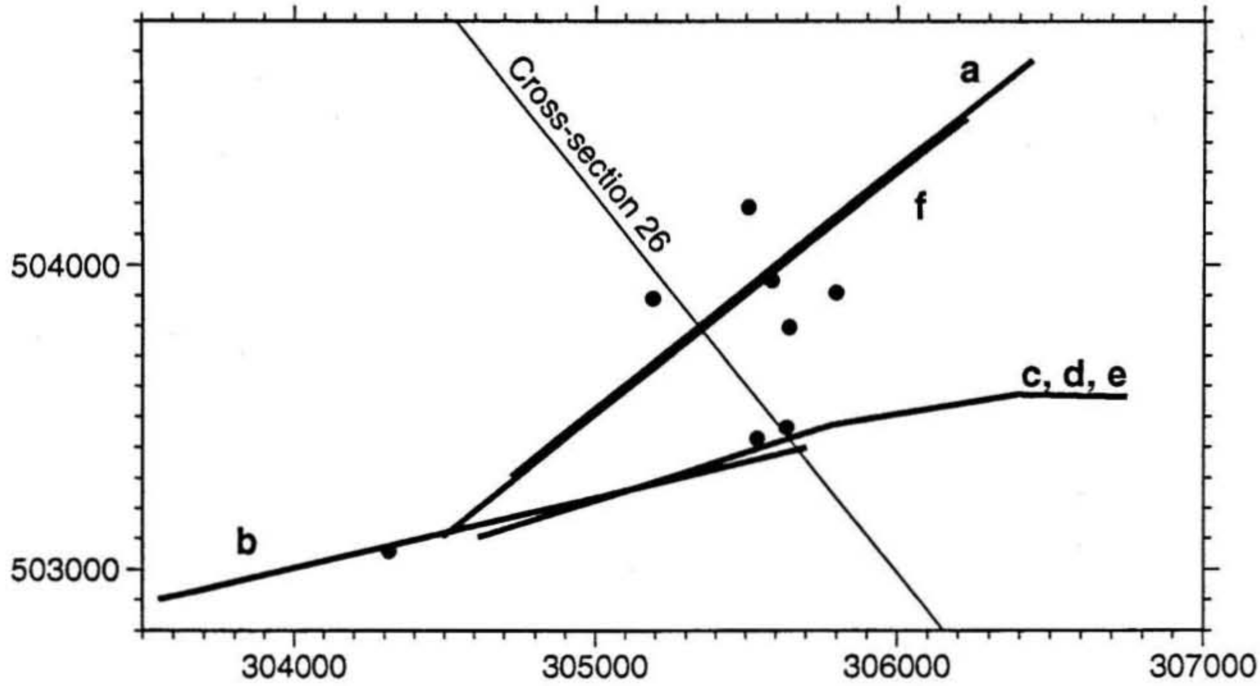
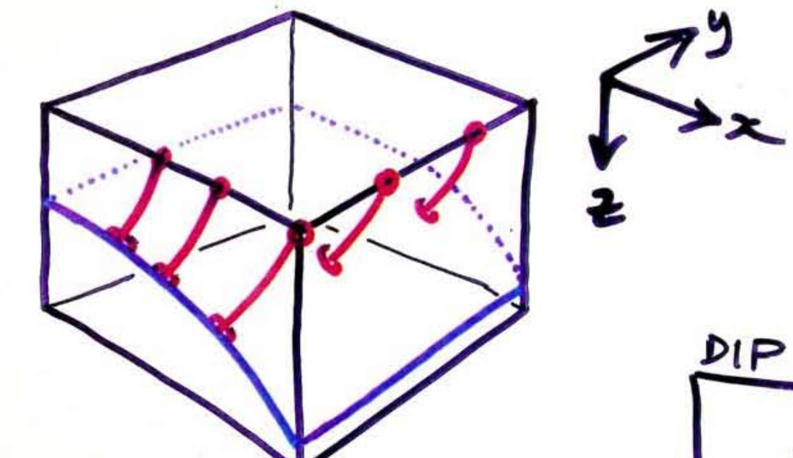
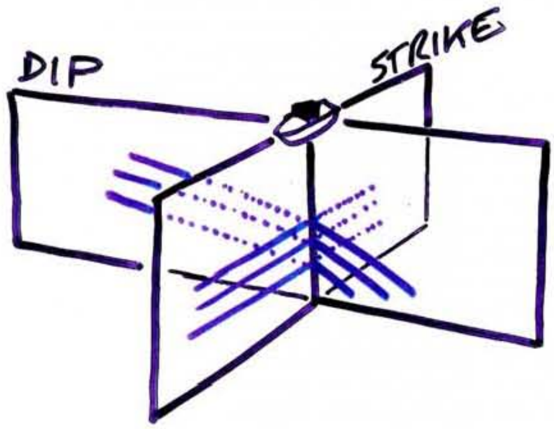



**Fig. 2. Locations of interpreted cross-sections through the PRZ at several epochs.**
Scale 1:25,000. National Grid coordinates in metres are labelled every 1000 m, with tick marks every 100 m. Black solid circles are principal boreholes. Epochs and locations are as follows:

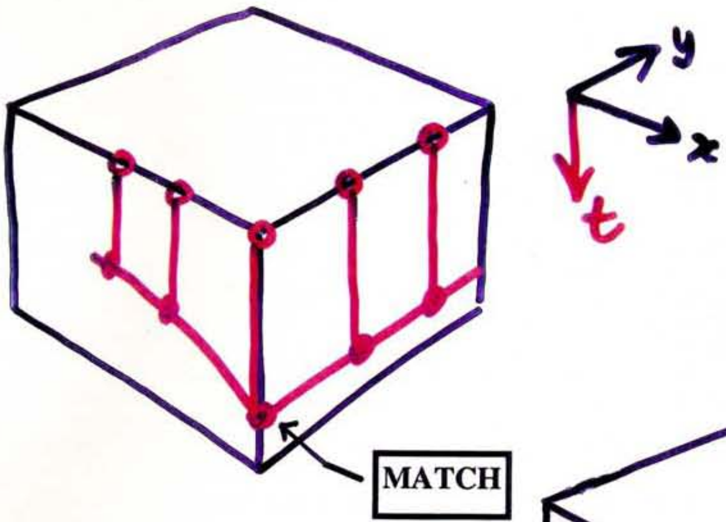
**a.** 1937-1988 (approx.): drawn from the subsurface map of Trotter *et al.* 1937, plate V [FOE/3/13], along line of Cross-section 17.
**b.** 1990 August: based on seismic line BGS-88-05.
**c.** 1991 August: based on seismic line GDGG-01.
**d.** 1993 December: based on seismic line GDGG-01.
**e.** 1993 December: based on seismic line GDGG-01.
**f.** 1995 July: Cross-section 17; Drawing no. 010061.

Note that the south-western halves of sections **a** and **c-f**, together with the north-eastern half of section **b** are 500 m or less apart.




**3a.** 3-D perspective view (above) showing zero-offset raypaths (red) from the surface to a curved, 2-D dipping surface (blue). Horizontal directions are x, y; vertical depth is z, positive downwards. Dip and strike directions are depicted in diagram at right, showing seismic ship or other source at intersection of two planes at right-angles.




**3b.** The blue reflector in Figure 3a above is displayed on **stacked seismic sections** as the red reflector (diagram at left), with the raypaths *assumed* to be vertical. Vertical scale is unmigrated two-way reflection time. Dip and strike lines match at intersections.

**3c.** Stacked sections can be migrated to give a more accurate image in the dip direction. Vertical scale (green) is now **migrated two-way time**. Dip and strike lines no longer match at intersection, since the strike line data cannot be moved out of the plane to their correct positions as shown in Figure 3a above.

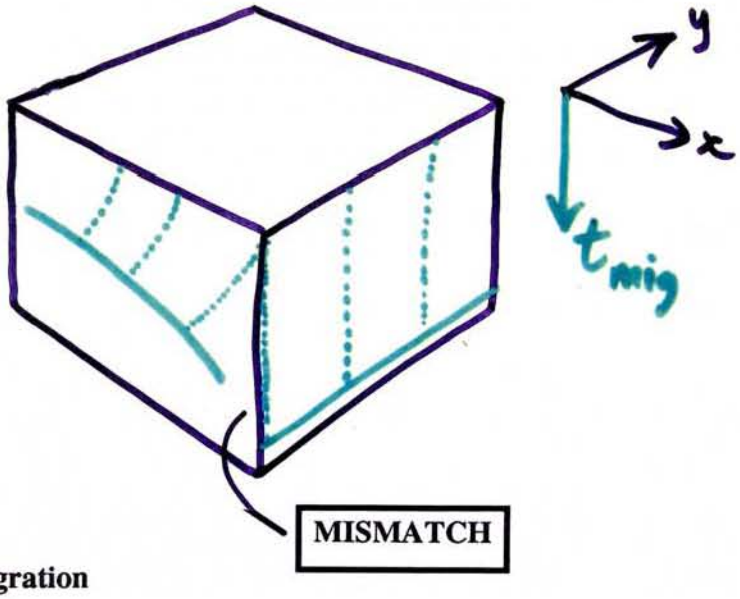



**Fig. 3. Geometry of post-stack time migration**

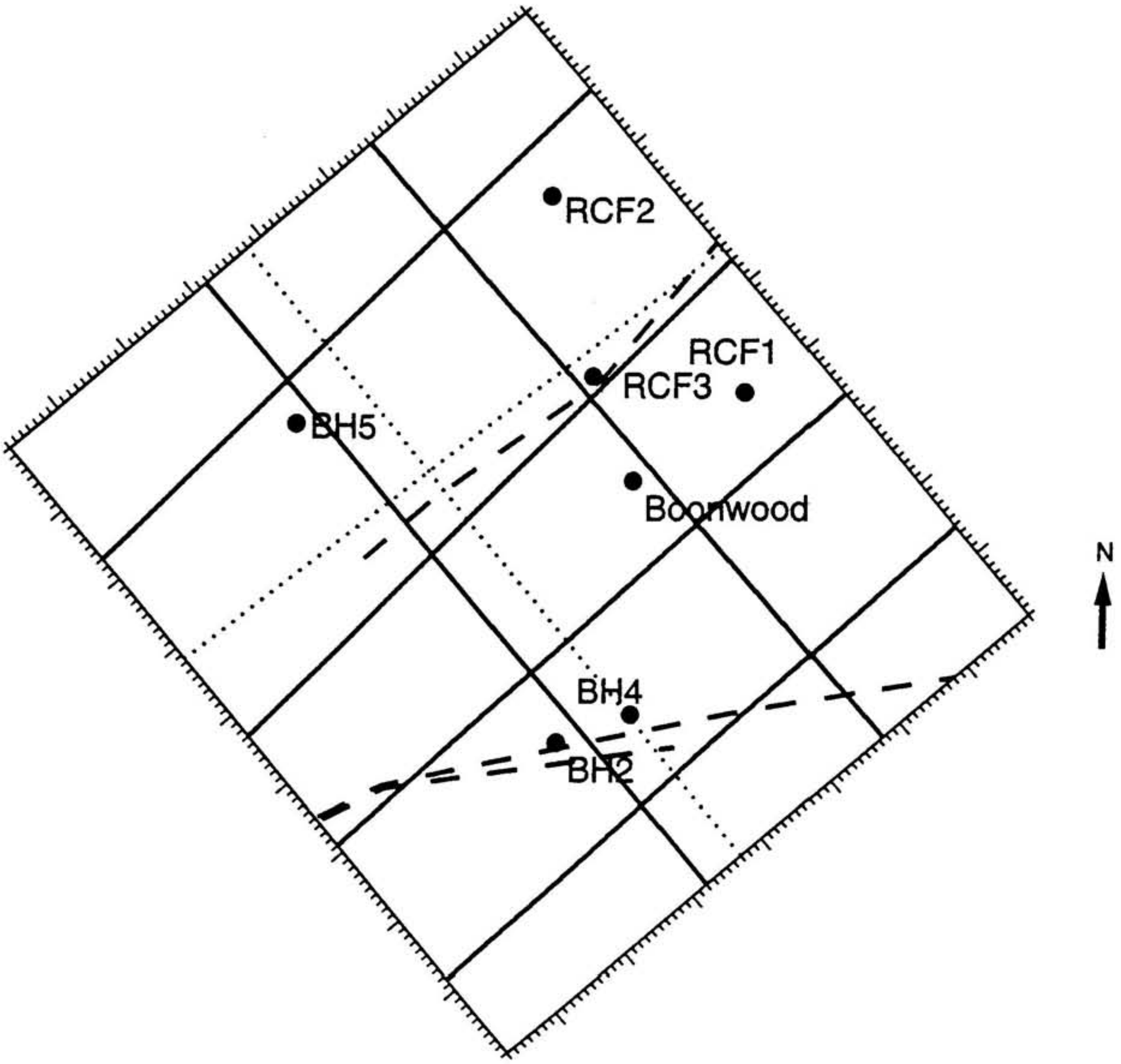



**Fig. 4. Seismic lines and boreholes in the PRZ (scale 1:10,000).**
Dashed lines - vibrator surveys 1988, 1990; solid lines - dynamite survey 1992. Dotted lines are locations of Cross-sections 17 (NE-SW) and 26 (NW-SE) shown in Nirex Report no. S/95/005 (Drawing nos. 010061 and 010062 respectively). Rectangle shows approximate area of subsurface (CMP) coverage of the 1994 3-D trial survey. Ticks around the edge of the rectangle are spaced at 12.5 m, which is the spacing of the processed data. The 3-D dataset can therefore be viewed as:

- 80-90 vertical seismic sections in the NE-SW direction, spaced at 12.5 m, and as
- 70-80 lines in the NW-SE direction similarly spaced, and, in addition, as
- a set of horizontal 'time slices', each covering the area of the rectangle, stacked one above the other at a depth spacing of about 3 m, from the surface to about 3 km depth.

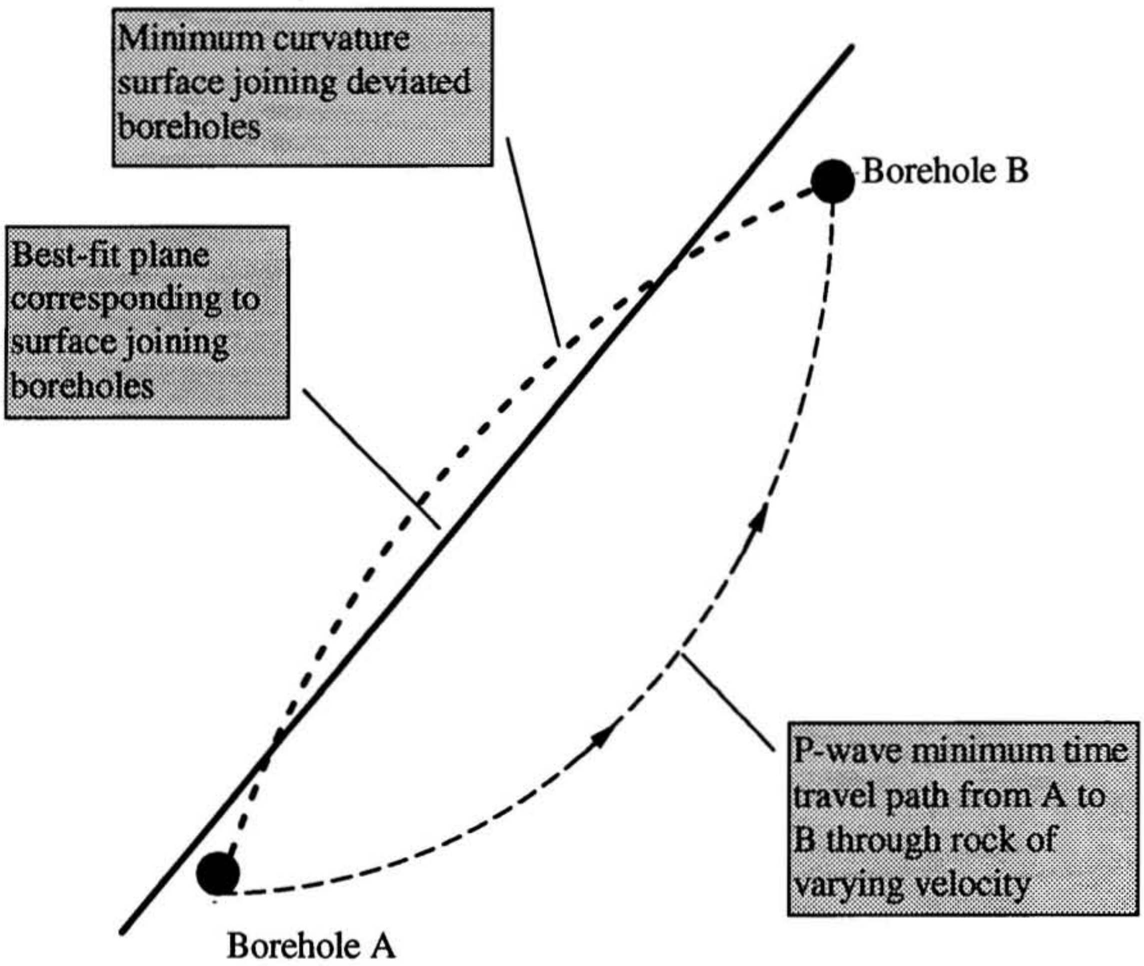



**Fig. 5. Non-planarity of transmission paths in a 2-D tomogram.**
This is an arbitrary planar cross-section through area of two deviated boreholes A and B. The 'best' surface connecting the boreholes is one of minimum curvature (heavy dashed line). This is in turn represented by a best-fit plane (solid line) on which 2-D tomographic data are plotted. However, the actual ray travel path could be as shown by the fine dashed line.

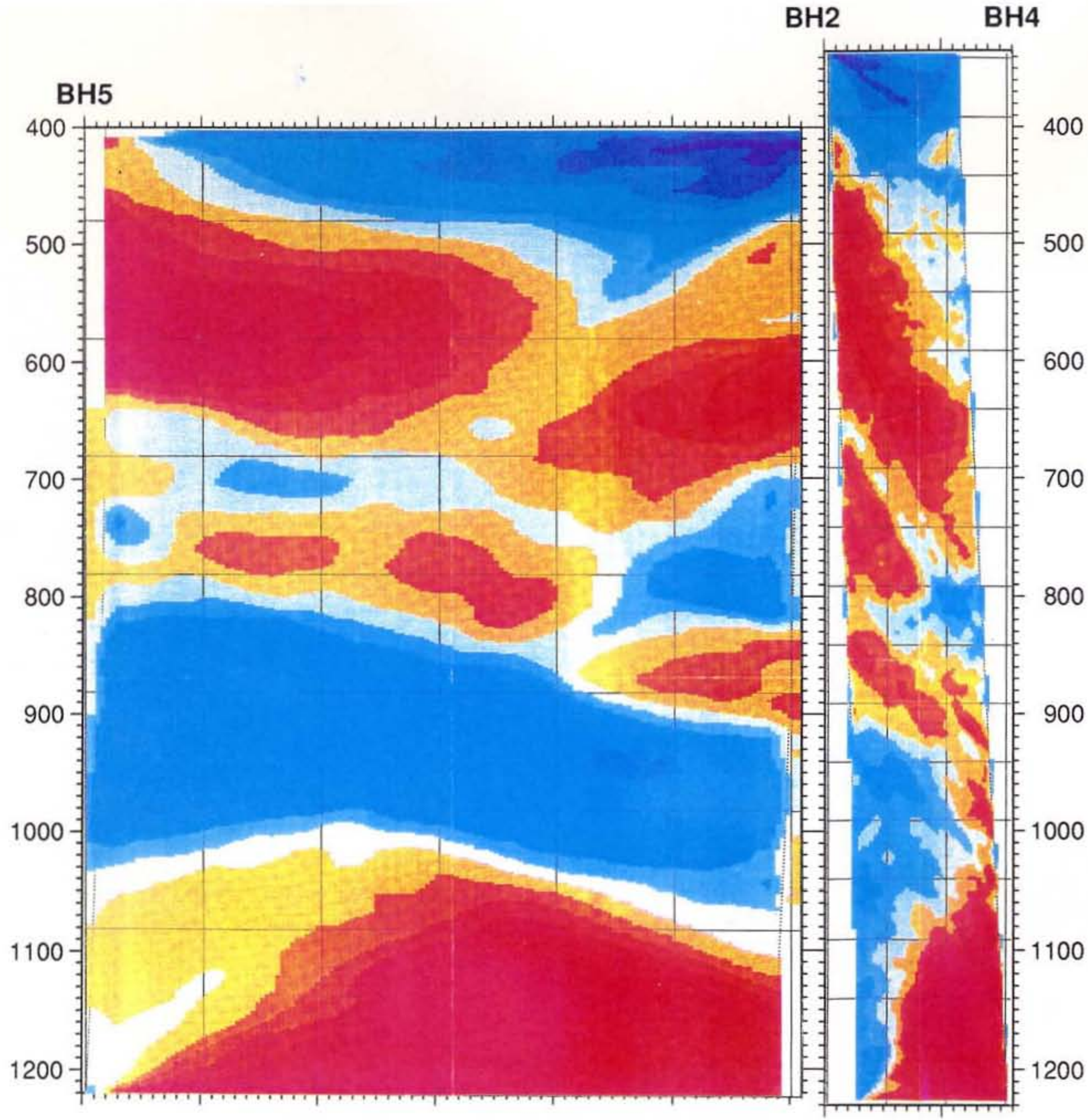



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**Fig. 6. Tomograms BH5-BH2 and BH2-BH4 meeting at common borehole BH2.**
Depths are in metres below rotary table of BH2.
A guide to the colour coding of this and other tomograms is as follows (units of velocity in m/s):

| | |
|---|---|
| White | No data |
| Dark blue | 4000 |
| Royal blue | 5000 |
| Sky blue | 5500 |
| Vermilion | 6000 |
| Scarlet | 6500 |
| Dark red | 7000 |

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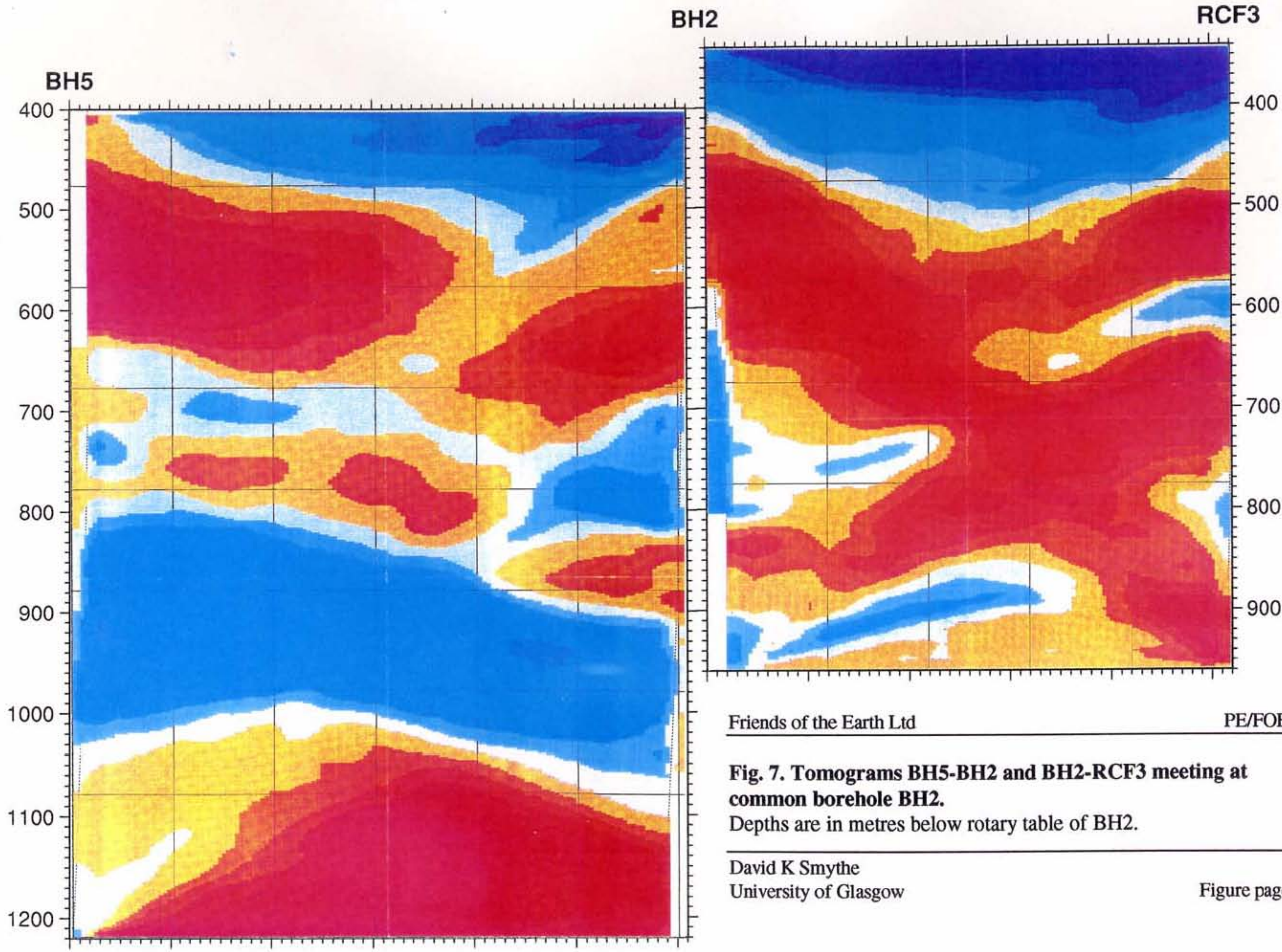


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**Fig. 7. Tomograms BH5-BH2 and BH2-RCF3 meeting at common borehole BH2.**
Depths are in metres below rotary table of BH2.

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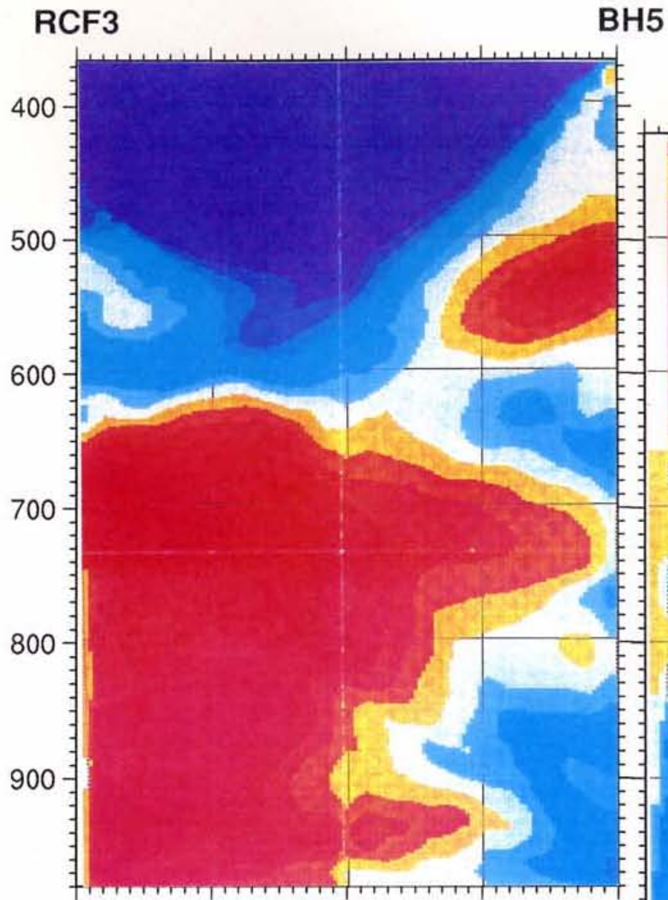


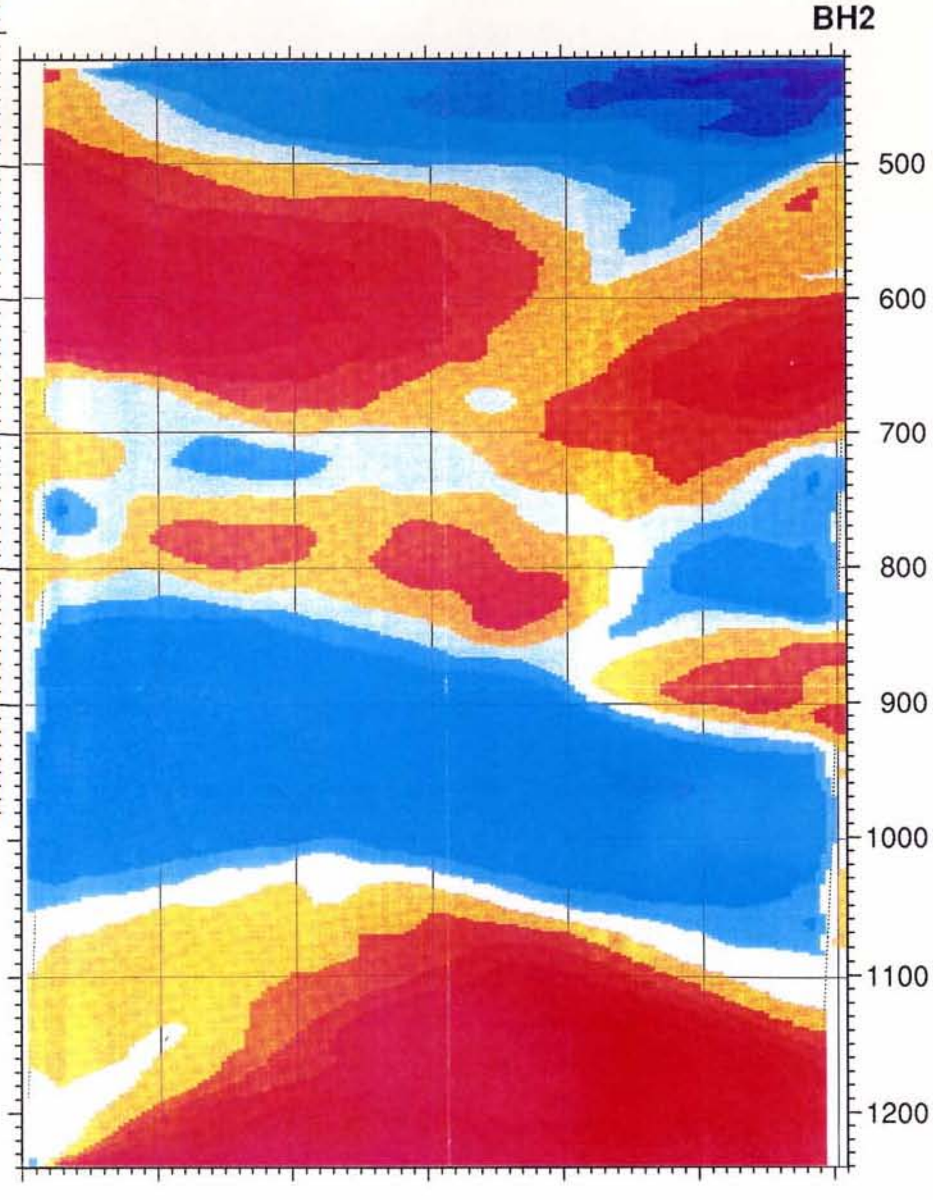


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**Fig. 8. Tomograms RCF3-BH5 and BH5-BH2 meeting at common borehole BH5.**

Depths are in metres below rotary table of BH5.

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**Fig. 9. Tomograms BH2-RCF3 and RCF3-BH5 meeting at common borehole RCF3.**

Depths are in metres below rotary table of RCF3.

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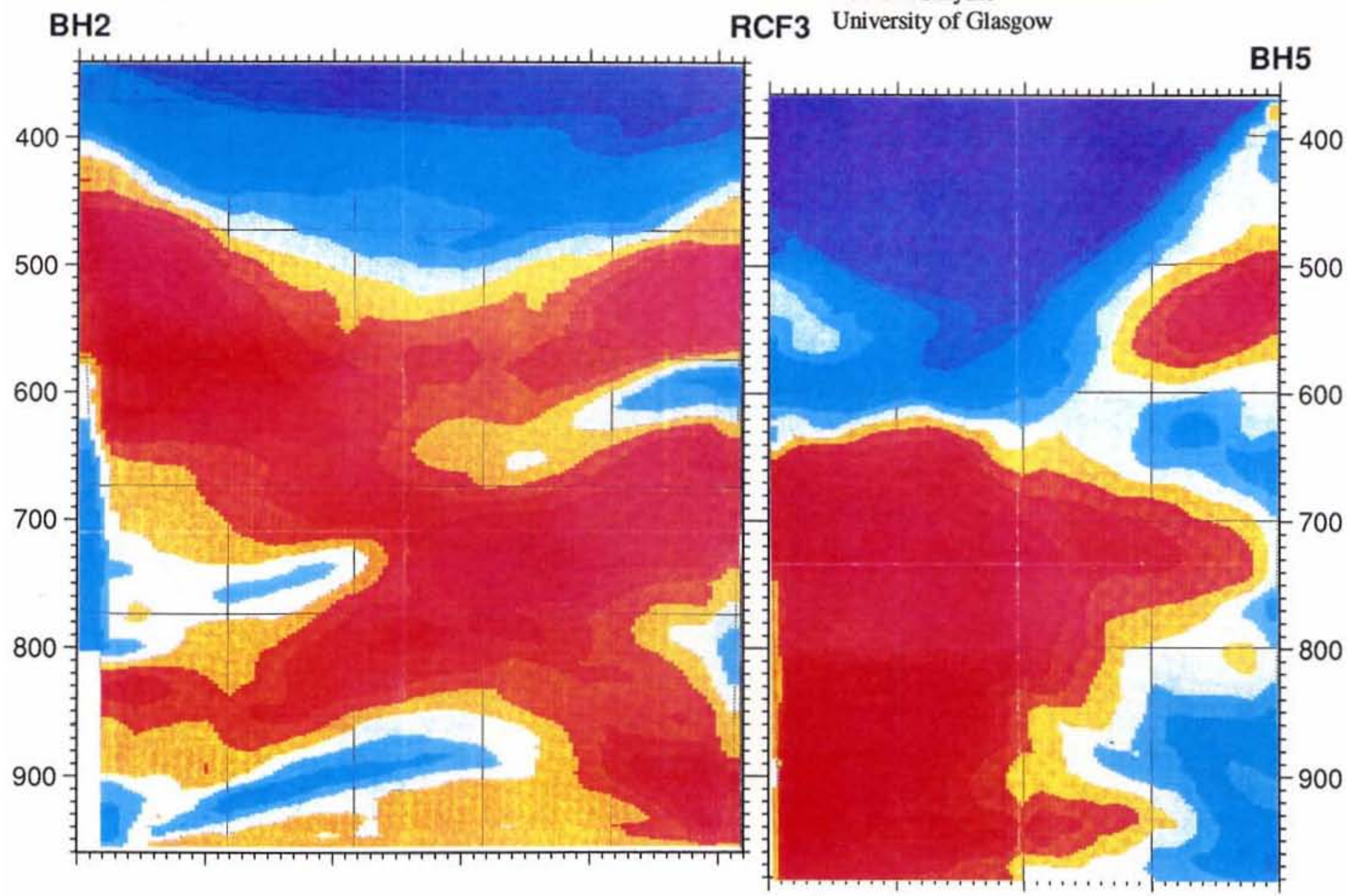

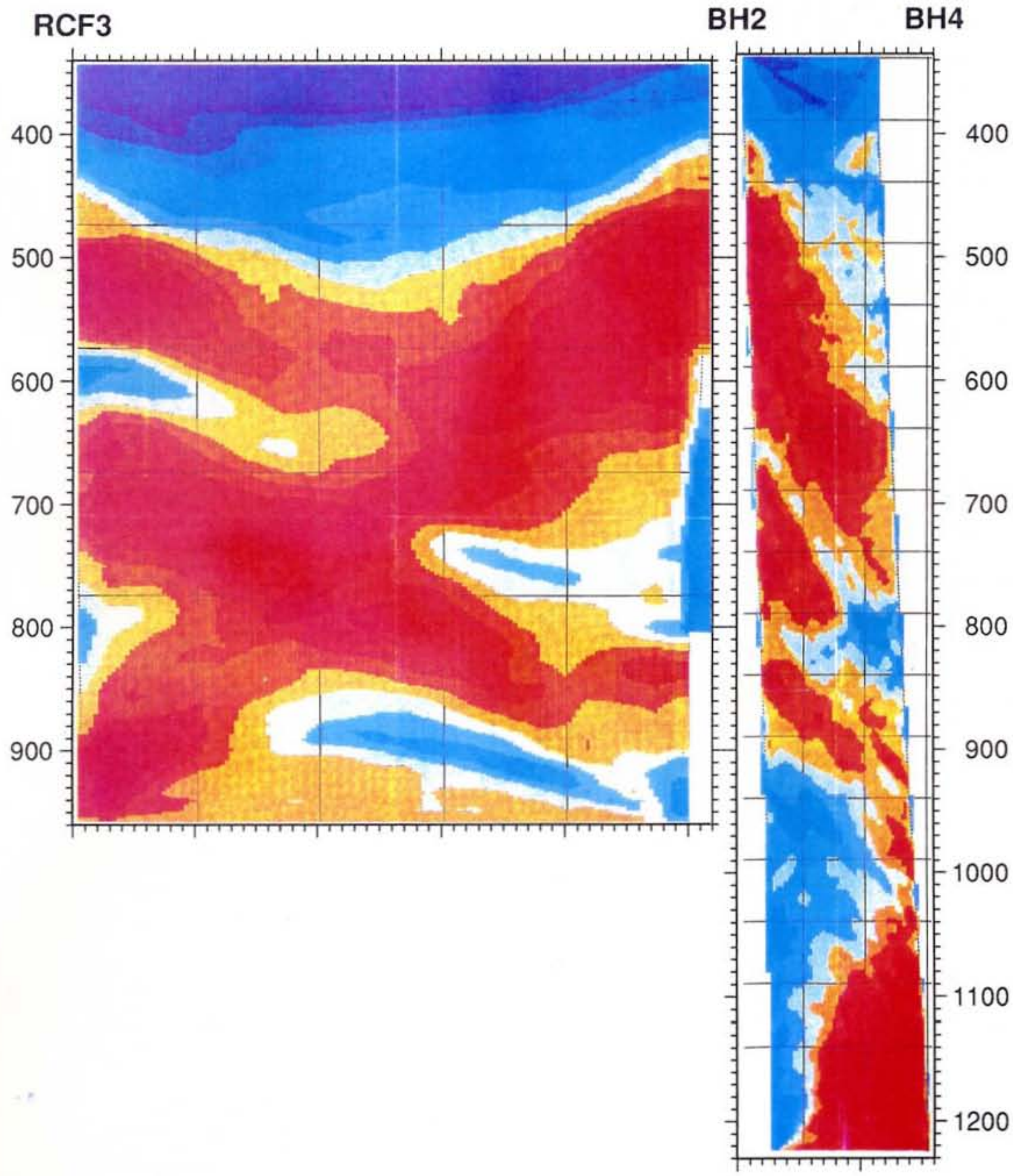


**Fig. 10. Tomograms RCF3-BH2 and BH2-BH4 meeting at common borehole BH2.**
Depths are in metres below rotary table of BH2.

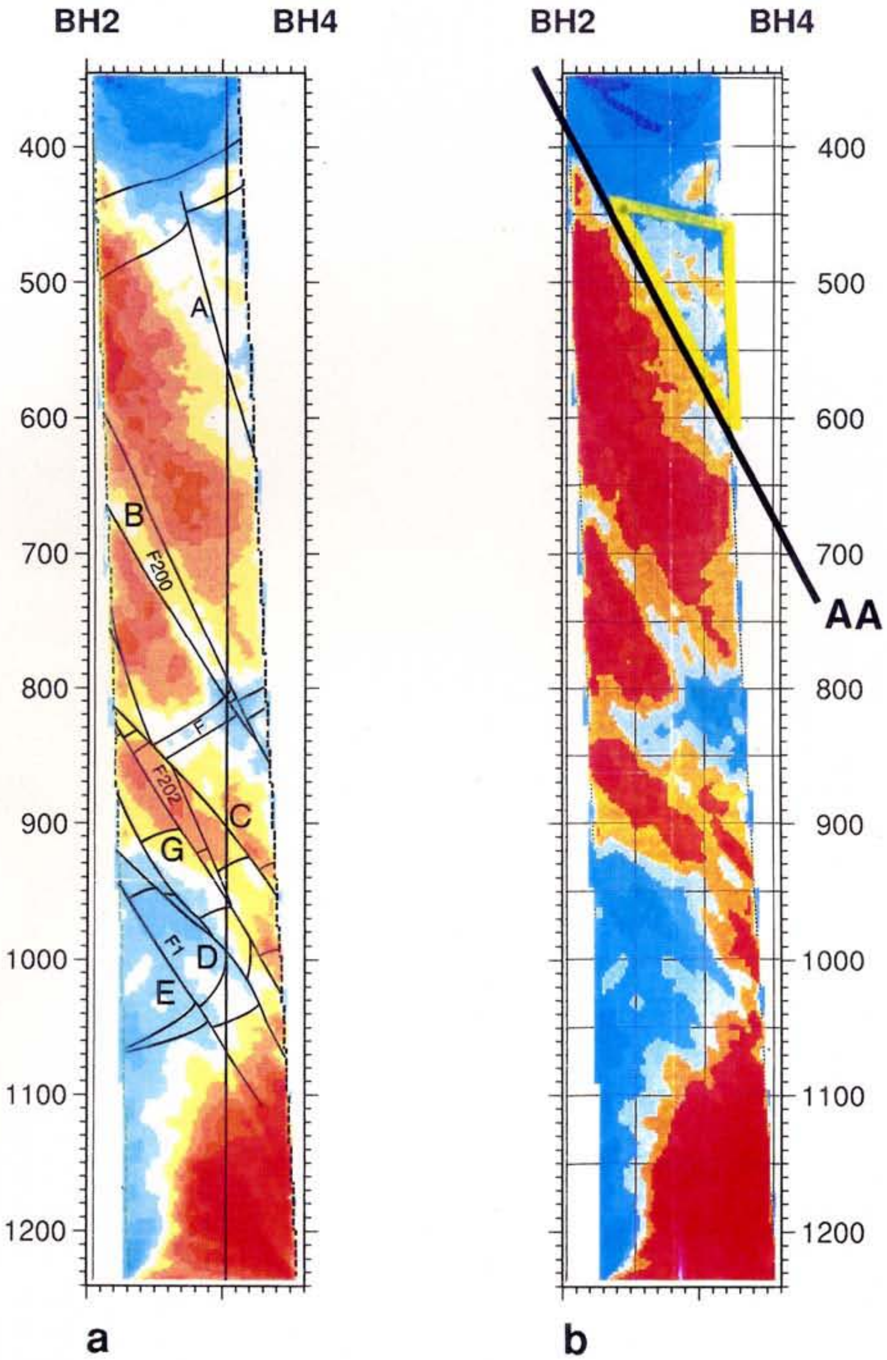


**Fig. 11. BH2-BH4 tomogram interpretations.**
**a.** BH2-BH4 tomogram (Report No. S/94/007, fig 5) showing aliased zone interpreted by Nirex as a fault feature A cutting BH4. Interpreted stratigraphy (left-dipping solid lines between 400-500 m) mismatches the borehole stratigraphy by up to 40 m.
**b.** Alternative interpretation with feature AA interpreted as a fault zone cutting both boreholes. Triangular area outlined in yellow is the presumed aliased zone interpreted as feature A in Fig. 11a.

**Fig. 12. Sketch map showing discrepancies in dip within the BVG.**

Arrows depict the true dip of horizons within the BVG as interpreted from a geological and geophysical methods. Bold dashed-line arrows are interpreted dips from geophysical surveys; the direction is compatible with the component of dip in the SE direction of about 15° within the upper BVG interpretable from the BH5-BH2 tomogram. Fine solid-line arrows are dips interpolated from borehole geological correlations.

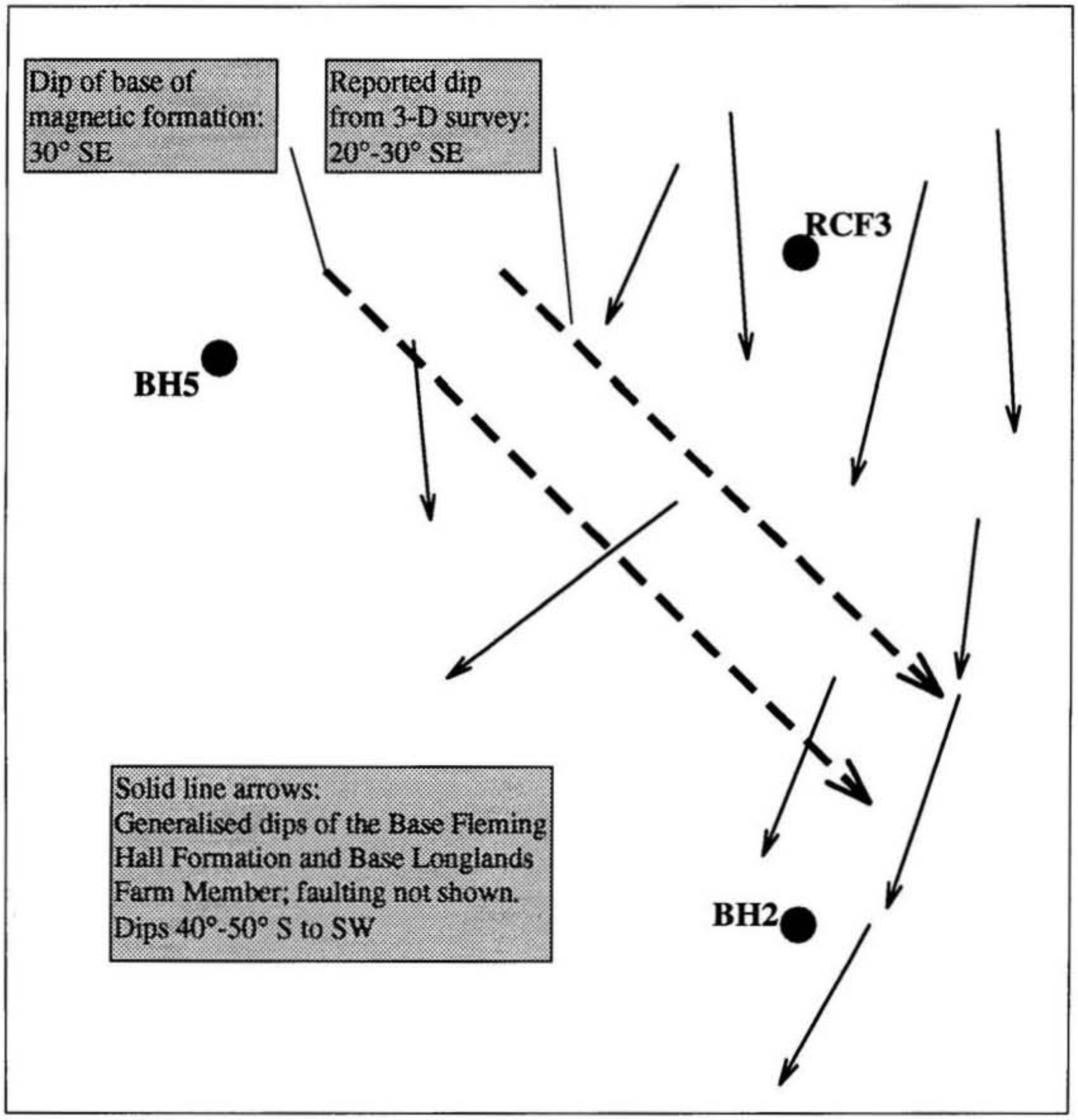

**Fig. 13. Modes of exploration: Nirex *vs.* oil industry.**
Venn diagrams illustrating the difference between the Nirex mode of geological exploration and characterisation *vs*. the standard oil industry mode. Arrows show time progression of exploration from one scale to another. Italics indicate scale at which political and economic considerations restrict the area. Note that in the oil example a specific prospect (P3 in the lower figure) may be grouped under more than one play.