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Thermal groundwater movement and radionuclide transport in SW England

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ABSTRACT. Heat flow in SW England is well above average for the UK as a whole, but northwards towards Bath and Bristol the values decrease rapidly. However, hot springs occur both in the Bath–Bristol area and in mines in Cornwall. The development of hydrothermal circulation systems is thus not controlled entirely by geothermal gradient: the presence of a suitable fracture permeability is the main requirement. The thermal 'head' produced, which nevertheless depends upon the temperature and volume of water in the system, theoretically can exceed local topographic heads even in areas of low geothermal gradient.

Thermal groundwaters usually carry above average quantities of radioelements in solution because of the long residence times involved. ^{222}Rn values are often particularly high. High concentrations of ^{222}Rn in surface waters arise from the discharge of groundwater. The results of a survey of ^{222}Rn in streams in SW England have established areas of high values which are interpreted as rising limbs of convection cells with dimensions in the order of 5–10 km.

In SE Devon γ-ray spectrometry of soils shows two E.–W. belts of high activity. The northern is coincident with the faulted southern margin of the Crediton Trough, while the southern is coincident with the westerly extension of the Abbotsbury fault system. Groundwater movement along deep-seated fracture systems is considered to be the explanation of these features. The horizontal scale of the area involved suggests that a thermal rather than local topographic head is the driving force. Groundwater circulation within fractures, driven by a thermal head, may therefore occur even in areas of low geothermal gradient and should be considered when selecting waste disposal sites.

KEYWORDS: radionuclide transport, groundwaters, SW England, radon.

THE disposal of radioactive waste by deep burial in crystalline rock such as granite, has been one of the options considered during the development of a radioactive waste management policy for the UK. Field investigations at an experimental site in the Carnmenellis granite in Cornwall have been concerned principally with fracture permeability (Heath, 1985), the results of these studies being used as part of the basis for modelling water movement through the rock under conditions of low, topographically induced hydraulic head. However, as the area of SW England underlain by granite is characterized by heat flow values considerably higher than the average for the British Isles, and by the products of a long history of hydrothermal activity, notably metalliferous mineralization as late as Tertiary, kaolinization, and the occurrence of hot springs in some Cornish mines, the possibility of an additional thermal head as an influence on modern groundwater movement, and, therefore, on radionuclide migration, should also be considered.

Although heat flow values in SW England fall rapidly away from the granite, in the Bath–Bristol area, where they are actually well below average, hot springs occur, suggesting that the influence of thermally induced head on groundwater movement may extend to areas of average heat flow where it is probably controlled by the presence of major fractures. If geological isolation of radioactive waste is in sedimentary rather than granite rocks the possibility of thermal groundwater movement, even in areas of average heat flow, should therefore still be considered.

A difficulty in assessing the importance of present day thermal groundwater movement is that evidence of such activity may only reflect past circulation patterns and not a modern dynamic system. An investigation of this problem has therefore been made, based upon the mobility of U and some of its decay products, and other naturally radioactive elements in aqueous solutions, so that circulation systems may be first identified and secondly recognized as either fossil or active.

Hydrothermal circulation

Geothermal Systems may be divided into two broad categories: Convective Geothermal Systems and Conductive Geothermal Systems, depending upon the dominant nature of the heat transfer process. Convective geothermal systems, in turn, may be subdivided into Hydrothermal and Circulation Systems, while conductive systems are subdivided into Low Temperature and Hot Dry Rock systems (Rybach, 1981).

The characteristic environments in which each of these systems occurs is relatively straightforward. Hydrothermal systems are found in areas where the rocks have high porosity and permeability and are related to shallow, young intrusions. Circulation systems occur in low porosity/fracture permeability rocks where the regional heat flow is generally above normal. Low-temperature conductive systems are found in high porosity/permeability sedimentary rocks where the heat flow is usually above normal and hot dry rock systems occur in high temperature but low permeability environments.

Convective geothermal systems manifest themselves at the surface of the Earth by fumaroles and boiling springs, and so are very apparent. Circulation systems, however, are less obvious, but discharge may be characterized by hot springs, particularly when related to faults or fracture zones in topographically low ground. Recharge may also occur along such fracture zones. The general crustal setting for circulation systems is usually recent extensional tectonism especially where this is accompanied by a high regional heat flow. In these environments fault and fracture zones are often kept open by periodic seismic activity, and basement fractures are particularly important in controlling the location of rising groundwater. Within these zones spring discharge temperatures are often strongly influenced by the admixture of cold surface waters to the ascending thermal water.

Heat flow in southern Britain. Much attention has recently been focused on SW England as a potential source of geothermal energy (Garnish, 1976). Heat flow studies by Oxburgh *et al.* (1977) and Richardson and Oxburgh (1979) have shown that the average heat flow value for the UK is about 1.43 hfu (heat flow units or 10^{-6} cal cm^{-2} s^{-1}), corresponding to a geothermal gradient of 25 °C/km which is comparable with the average value of about 1.53 hfu for continental Europe (Cermak, 1979). In a linear belt stretching approximately E.-W. from the Isles of Scilly to near Southampton, however, heat flow values are greater than 1.91 hfu and reach values greater than 2.39 hfu (associated with a geothermal gradient of up to 40 °C/km) in the zone above the SW England granite batholith (Haenal, 1980).

The high heat flow of SW England was believed by Richardson and Oxburgh (1979) to be due to the presence of granite bodies within the upper crust, which carry above average concentrations of heat-producing radioactive elements. They therefore envisaged essentially a hot dry rock system within the granite areas, but considered that limited circulation systems could locally modify the heat flow distribution.

Rock permeabilities. The ability for mass transfer to take place within rock is determined by both the intergranular permeability of highly porous rocks and the presence of fractures in rocks which can have a great range of inherent porosities. Fluid flow in fissured rocks differs in several important respects, however, from the more pervasive percolation that takes place in competent porous rocks. Garg and Kassoy (1981) listed three main areas of difference:

(1) Fracture-induced permeability is usually much greater than permeability due to interconnected pore spaces. Louis (1970), in fact, noted that the matrix permeability of rock becomes important only in the absence of continuous joints or for joint apertures less than 10 μm.

(2) Fracture permeability is usually anisotropic.

(3) Fracture porosity (and hence permeability) is much more sensitive to fluid pressure and rock stresses than matrix porosity (Wittke, 1973; Duncan *et al.*, 1972).

The spacing of fractures is an important factor when describing the characteristics of flow. For if the fracture spacing is close in terms of the total linear dimensions of the system considered, then processes which are dominantly fracture controlled on a small scale may be better explained in terms of pervasive flow when considered on a large scale.

In terms of flow in single fractures, the pipe flow model of Donaldson (1968) is most appropriate. With direct connection down from the surface, the thermal hydraulic heads produced may be very large. For example, Elder (1981) has calculated that in the Wairakei geothermal field (New Zealand), where the temperature is about 250 °C at a depth of about 5 km, the equivalent head produced is as great as 1 km.

In established geothermal fields Elder (1981) has also noted that a permeability of 0.1 d is more than adequate to permit all the hydrothermal phenomena observed, but that the contribution of the intergranular permeability to this is negligible. He made the interesting order of magnitude calculation of the permeability afforded by fractures, by considering a system in which the rock is a cubic array of blocks of width Δ_1, with narrow spaces of width Δ_2 separating them. Then if $\Delta_1 = 1$ m and $\Delta_2 = 0.1$ mm a permeability of 0.2 d results, but if $\Delta_1 = 100$ m and $\Delta_2 = 0.5$ mm we still get 0.2 d, and 0.2 d is also found if $\Delta_1 = 1000$ m and $\Delta_2 = 1$ mm. It is thus easy to see that the occurrence of the occasional fracture (which need not even be large) gives a very significant permeability to the rock mass as a whole.

Kassoy and Zebib (1978) also considered the cooling of a rising column of water in a vertical channel of porous material with impermeable walls, and found that typical vertical convective rates were about 6×10^{-3} m/d. Even at this speed the loss of heat by conduction from the fault zone was very little compared with the convective heat transfer.

Fault controlled charging of a geothermal reservoir has been studied by Goyal and Kassoy (1977) and Goyal (1978). The model they chose considered a fracture zone which extended down through a surface impermeable layer, then through an interbedded permeable and impermeable series of layers, ending finally in a layer of basement rock. As in the Kassoy and Zebib (1978) model, the fault zone was taken to be charged with hot water flowing from the fractured basement rock. In this model it was found that hot water rose through the fracture, as before, but the presence of the surface impermeable cap suppressed vertical transport so that water was pushed out of the fault zone by the thermal head and into the permeable horizons in the interbedded series. Horizontal flow in these permeable horizons then became dominant. It was found that in this system horizontal distances away from the fault zone of 5–10 fault depths had to be traversed before the aquifers ceased to be affected by the outflow from the fault zone. This clearly shows that fault zones can provide a mechanism for charging shallow geothermal aquifers.

Convective circulation of water in the granite of South West England

Framework for convective groundwater circulation. In considering the possible existence of convective water circulation it must first be established that the physical requirements for such circulation are satisfied and that circulation is theoretically possible, given the properties of the crust in that region. Secondly, the effects of such circulation should be investigated, particularly in terms of the transport of heat and certain mobile elements as reflected in their distribution at the surface. Such a twofold approach has been adopted in the area underlain by the Dartmoor granite and it appears that modern hydrothermal circulation may indeed be of significance in this and the other granite plutons of the region.

The requirements for convective water circulation in the crust are, first, that a source of heat is available; secondly, that there is sufficient permeability within the required vertical range, and thirdly that groundwater is present. That a heat source is available has been established (Wheildon *et al.*, 1980). The anomalously high heat flow of the area underlain by granite in SW England (up to 3.0 hfu) is believed to be due largely to the heat generated by the decay of radioelements in the granite (notably U). Although fabric permeabilities for the granite of SW England are as low as 100 pd (Batchelor, 1980), the highly fractured nature of the granite produces an *in situ* permeability many orders of magnitude higher. Thus, the hydrogeological investigations in a 700 m borehole in the Carnmenellis granite (Heath, 1985) have shown that major water-bearing fractures exist at depths of at least 650 m. Indeed, Alderton and Sheppard (1977) reported hot springs issuing from depths of up to 900 m below Ordnance Datum in certain Cornish mines. Many of these thermal waters have high salinities (up to 1.5% by weight total dissolved solids) although their hydrogen and oxygen isotopic compositions indicate a meteoric origin. The high salinities therefore result from ion-exchange processes in the aquifer system and the presence of deep groundwater in the granite is indicated.

Hydrogeochemistry and convective groundwater movement in the Dartmoor granite. A hydrogeochemical survey was carried out in the Dartmoor area in connection with an investigation into the distribution of U in the granite (Heath, 1982). Surface waters from 538 localities (391 within the area underlain by granite) were analysed for ^{222}Rn by scintillation counting following degassing of radon, while 222 of these samples (185 from within the area underlain by granite) were analysed for U by laser-induced fluorimetry.

The observed distribution of Rn and U in Dartmoor stream waters was found not to be related entirely to the known distribution of U in the underlying rocks. Rn distribution was shown to be controlled largely by hydrological factors unrelated to the U content of the bedrock, and many of the well-developed Rn anomalies may be attributed to the influx of groundwater (Mogro-Campero and Fleischer, 1977) in a pattern not related to topography.

Of most significance is the observation that the high Rn concentrations of the streams of central Dartmoor (Vitifer) occur in a zone where particularly high permeability of the granite is indicated by electrical resistivity work (Durrance *et al.*, 1982), and in an area of very high heat flow (Wheildon *et al.*, 1980). This suggests the possibility that the high Rn levels reflect water movement in a deep fracture system, with upwelling by thermal convection. Similar upflows appear to occur in the area south of Okehampton, in NE Dartmoor and in S. Dartmoor.

If the areas of convective ascent are associated with transport of Rn and U to the surface it is likely that areas of convective drawdown are characterized by a surface environment depleted in these elements. It is of interest, therefore, that the area between 5 and 10 km north of the Rn anomaly around Vitifer is characterized by low stream Rn and U concentrations and is also traversed by the Sticklepath fault zone (Dearman, 1963). It is possible that this represents the descending limb of the convection cell, the ascending limb of which occurs around Vitifer. Similar drawdown may be taking place along a topographically-inferred fracture zone west of Vitifer with corresponding ascent south of Okehampton. Thus, in northern Dartmoor at least two convection cells may be postulated with dimensions of approximately 5 km.

In SW Dartmoor the area in which the granite is known to be kaolinized is also typified by generally low stream Rn and U concentrations. This is consistent with the known leaching of U from the granite during kaolinization. However, in the light of the evidence from N. Dartmoor this association may be more significant. The kaolin deposits of SW England usually occur in upward-facing funnel-shaped structures which, although possibly initiated by partial alteration soon after granite emplacement, are related largely to the effects of meteoric waters (Bristow, 1977; Sheppard, 1977). The association of kaolinization with major faulting in SW Dartmoor (the Calisham Down-Cornwood fault, plus many others inferred on topographical grounds) is significant in this connection. It is suggested, therefore, that this area is the site of convective drawdown in a cell the ascending limb of which is probably reflected in the high Rn concentrations of the streams immediately north of the kaolinized granite.

A summary map of Dartmoor, showing some of the evidence on which this interpretation is based, is given in fig. 1. Three areas of hydrothermal discharge (ascent) and three associated areas of recharge (descent) are indicated. Using flow data from Fehn *et al.* (1978) and assuming an average *in situ* permeability of 100 μd and cell dimensions of 5 km, the residence time of circulating water below the surface of the granite can be estimated as 10^5-10^6 years. Evidence from Cornish mines regarding the flow of thermal waters from cross-courses and from the electrical resistivity survey of Dartmoor (Durrance *et al.*, 1982) suggests that the main orientation of flow paths in these hydrothermal systems is N.-S. to N.-NW—S.-SE; that is approximately parallel to the maximum horizontal stress which tends to keep E.-W. fractures closed.

In plutons of uniform permeability convection cells may migrate with time but, where the granite is structurally inhomogeneous, systems become anchored to major structural features and remain in the same location for long periods of time (Mogro-Campero and Fleischer, 1977). Assuming that the major requirements for convective circulation (a heat source, sufficient permeability and the presence of groundwater) have been satisfied, the convective systems postulated from Dartmoor may have been active for a considerable period of geological time.

Thermal groundwater movement in SE Devon

Hydrogeochemical evidence. High values of stream water ^{222}Rn occur near the mouth of the Exe Estuary (from samples collected on both sides of the valley) and in a zone which extends northwest to beyond Kennford (Durrance, 1978). The anomaly thus trends diagonally across the New Red Sandstone outcrop from the Littleham Mudstone Formation to the Kennford Breccias (fig. 2) and is parallel to the set of NW-SE trending transcurrent faults which affect SW England (Dearman, 1963). As for Dartmoor, it is concluded that the most likely mechanism that will allow the formation of the observed ^{222}Rn anomaly is the discharge of groundwater. The groundwater discharge, in turn, is considered to be controlled by the presence of a NW-SE fracture zone passing through Kennford towards Exmouth. Here, however, the driving force for the groundwater flow could be either a topographic head or a geothermal head, and although modern groundwater flow must be taking place to account for the presence of the radon anomaly, it cannot be determined for how long this has happened.

γ-ray surveys. An airborne γ-ray survey of SW England which extended as far east as Budleigh Salterton was carried out for the Geological Survey in the late 1950s. The main centres of high activity that were detected occur in three geographical positions: a narrow N.-S. trending zone in the Teign Valley (probably related to a U-Th mineral vein), a broad area around Kennford, the area south of Crediton and a belt trending north from Littleham Cove. Many minor, local high-activity anomalies were also discovered. Systematic interpretation of these results was difficult because of the problems caused by radioactive fall-out from the atmospheric testing of nuclear weapons that was taking place at the time of the survey. It is considered that many of the minor occurrences of high activity have their origin in radioactive fall-out. The main zones of high activity, however, occur in positions which correlate with the results of a stream water U survey (Durrance, 1984), where three belts of high activity trend N.-S. The most westerly of these is related to the breccias, the central to the Littleham Mudstone Formation, and

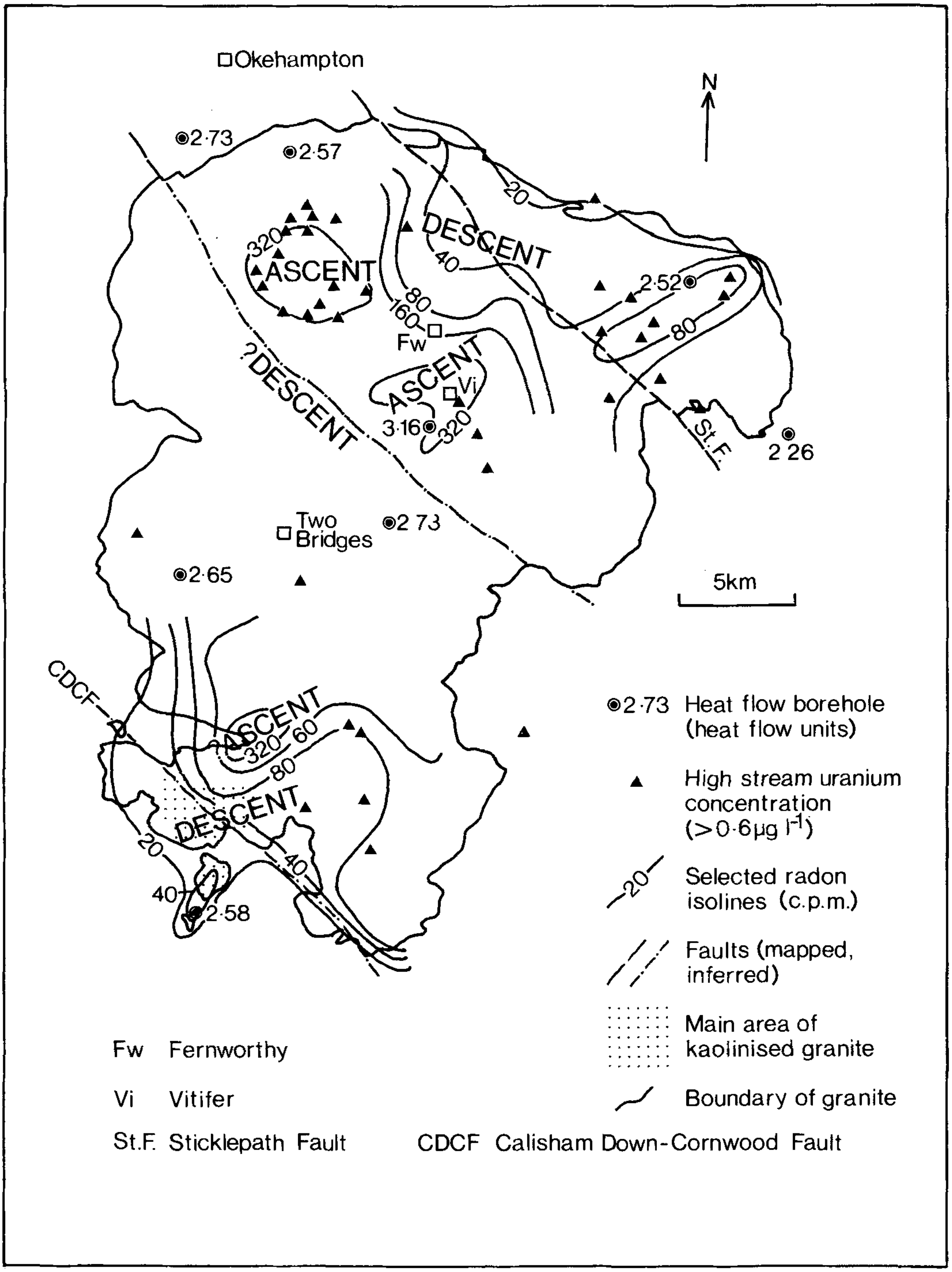

FIG. 1. Summary map of the Dartmoor granite showing possible distribution of Convective Circulation Systems.

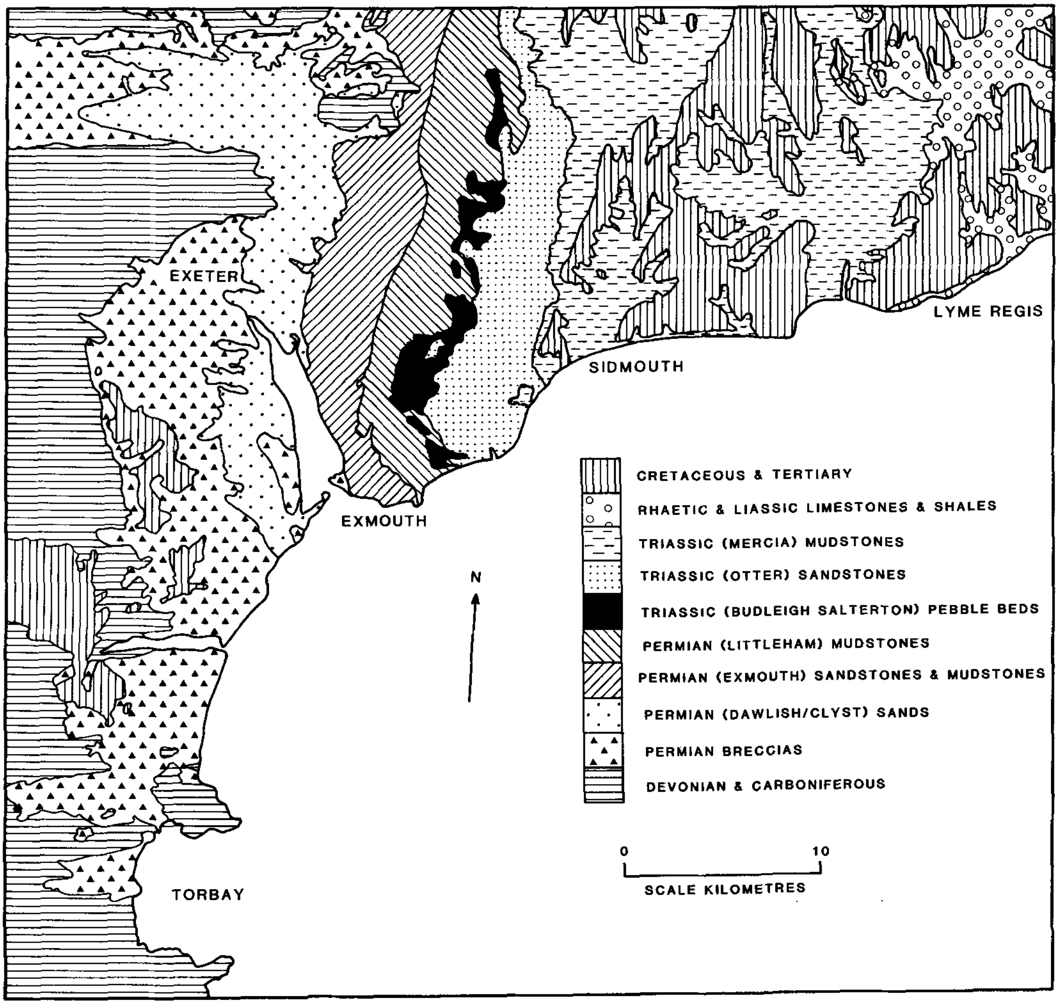

FIG. 2. Geology of SE Devon.

the eastern to the lower part of the Mercia Mudstone Formation.

Ground-based γ-ray spectrometry of soils at 559 sites in SE Devon (Durrance, 1983), using a Geometrics DISA 400A and a count-time of five minutes at each site (Lovborg *et al.*, 1971; Lovborg, 1972; Cassidy, 1982), also shows that the main areas of high activity recorded by the airborne survey are not the results of short-lived fall-out (fig. 3*A*). However, the area north of Littleham Cove is not characterized by soils with high activity, although clearly having U enrichment in the form of the concretionary nodules. The discrepancy is explained as a product of the different sampling techniques used in the various surveys, and their interaction with the sporadic nature of the occurrence of the U-bearing nodules. Thus, whereas the airborne and stream water U surveys considered samples which 'averaged' effects from a wide area, because the DISA 400A detector was placed directly on the ground during counting, the soil survey considered only a small volume of material at each site, so the chance of finding any influence of a U-bearing nodule was small. The main additional feature shown by the distribution of the Total Count values in the results of the soil survey is the presence of easterly trending zones of high activity. One zone passes close to Feniton and continues east of Honiton; another, more complex, zone is in the Exmouth–Sidmouth area.

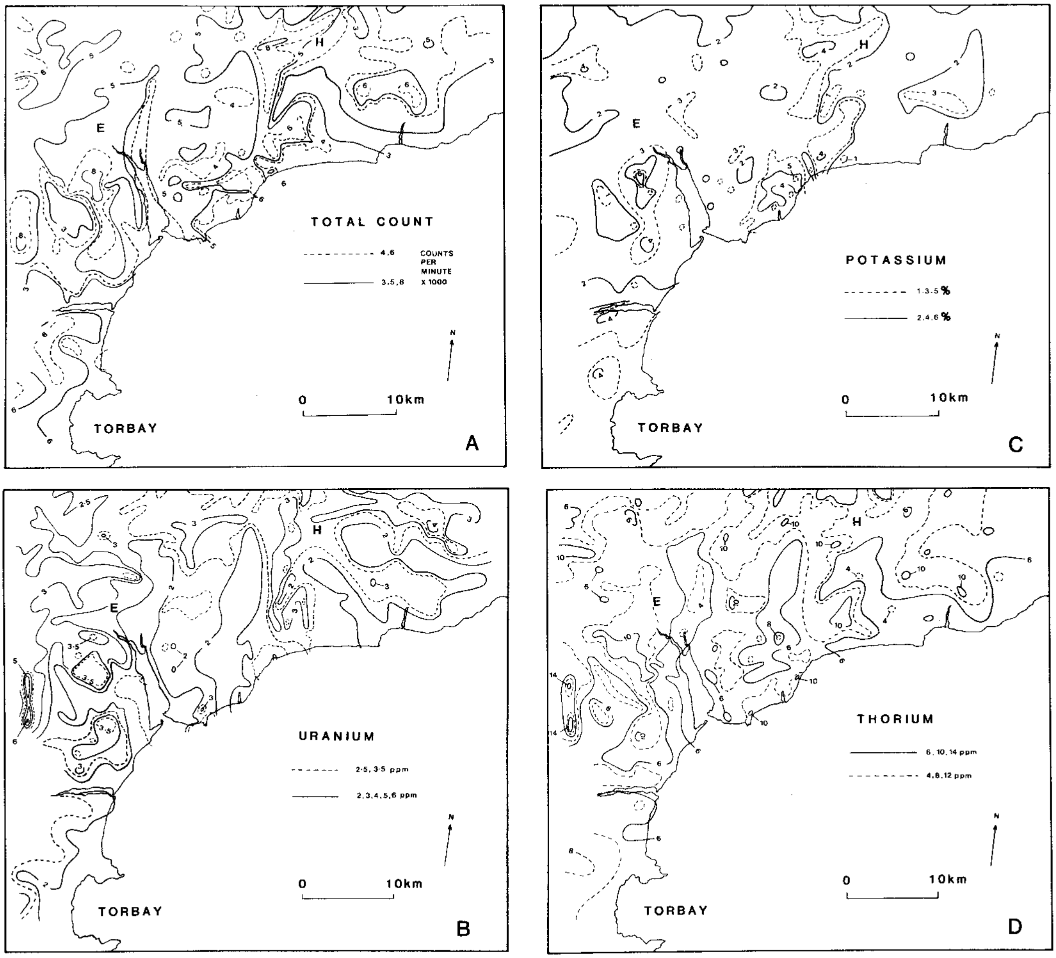

FIG. 3. SE Devon: (*A*) Total γ-ray activity of soils; (*B*) U content of soils; (*C*) K content of soils; (*D*) Th content of soils.

The U content of the soils, shown by the activity of ^{214}Bi in the γ-ray spectrometer survey, is also high in the easterly trending zones of high Total Count (fig. 3*B*). The extent of the zone passing through Feniton is shown by the U values to be particularly impressive, the line continuing from Exeter to north of Axminster. High U values also occur in the Teign Valley (where they are related to the mineral vein detected by the airborne survey), and in the NW-SE trending zone through Kennford. U values are not high in the soils over the Littleham Mudstones or the Exmouth Sandstones and Mudstones, again probably reflecting the sporadic distribution of the U-bearing nodules. The lower part of the Mercia Mudstones, however, shows soils in which the U content is consistently above average. This suggests that U-bearing nodules which occur in these strata are much more widely distributed than in the Permian formations. U levels in the soils on the Tertiary flint gravels and the Cretaceous strata are low. They are also low in the soils which overlie the Bovey Formation.

The total γ-ray activity and U distribution in the soils of SE Devon thus generally confirm the picture given by the results of the stream water U survey, but additionally provide evidence for the presence of approximately E.-W. lines of U enrichment. These lines probably indicate the positions of deep-seated fractures which act as channelways for moving groundwater.

K distribution in the soils of SE Devon (shown by the activity of ^{40}K in the γ-ray spectrometry survey) closely follows that of U and total γ-ray activity, except that the mineral vein in the Teign Valley does not appear as a K high (fig. 3*C*). The main occurrences of high K values are found in the area around Kennford, with extensions to the NW and SE, in the E.-W. zone passing through Feniton and in the Exmouth-Sidmouth area. K enrichment in these zones is probably the result of upflow of groundwater carrying K as well as U, in solution. Both U and K are highly mobile elements in aqueous solution and their association in low-moderate temperature hydrothermal systems is expected from their geochemical characteristics.

Th is generally immobile in low moderate-temperature aqueous environments, and the distribution of Th in the soils of SE Devon (shown by the activity of ^{208}Tl in the γ-ray spectrometer survey) reflects the levels of Th in the underlying rocks (fig. 3*D*). With the exception of Th occurrences in the Teign Valley, the highest Th concentrations are found in association with the mudstone formations in the New Red Sandstone. The N.-S. mineral vein in the Teign Valley, however, is shown by soils with very high Th contents indeed. An association of high U and high Th with low or normal K levels in this feature suggests that the vein carries pitchblende. It is thus similar to other U mineralization in SW England, where N.-S. veins (cross-courses) are often of Tertiary age.

The general distribution of U, K, and Th thus probably results from the original concentrations of these elements in the detrital minerals of the sedimentary succession in SE Devon, but upon this there appears to have been superimposed the effects of mobilization, transport, and precipitation of elements derived from outside the succession. The character of these secondary enrichments varies according to the geochemical properties of the elements concerned, the temperature and chemistry of the mobilizing system and the nature of the host rocks. Thus, Th appears to have been mobilized only in the formation of the Teign Valley mineral vein, but U and K have a more extensive spatial record of mobilization, which probably also reflects a more extensive temporal record of mobilization.

Disequilibrium in the ^{238}*U Decay Series.* Secular equilibrium within any decay series is achieved by the growth of abundance of the various daughter products in a closed chemical system. This growth is exponential with respect to time so that, theoretically, equilibrium is reached only after an infinite period of time. In practice, therefore, equilibrium is assumed at the 95 or 99 % level. Decay of ^{40}K is simple and not liable to disequilibrium, and the ^{232}Th decay series, although long and composed of many daughter elements, is characterized by short half-lives, so that disequilibrium is unlikely. The ^{238}U decay series, however, also has a long and complex decay chain, and some of the daughter products have long half-lives. It is these circumstances which make the ^{238}U decay series very susceptible to disequilibrium when taken in conjunction with the chemical mobility of the parent and some of the daughters (Adams and Gasparini, 1970).

For the ^{238}U decay series, 99 % secular equilibrium is reached after about 1.66 Ma. Thus if disequilibrium in the decay series, resulting from the gain or loss of any daughter (or the parent) in an open chemical system, is found, it implies that these changes have occurred in the recent past, because of the short (geologically speaking) time needed to establish equilibrium. Indeed, if substantial disequilibrium is present, it is the result of processes that have probably operated in about the last 2.5 ka, and may, therefore, still be acting today.

A Disequilibrium Factor has been established, using the results of the γ-ray spectrometer survey of the rocks and soils of SE Devon, in which comparison is made between the Total Count recorded at a particular site, and the count expected from the K, U, and Th concentrations at the site with the ^{238}U decay series in equilibrium (Durrance, 1983). Because the Total Count additionally records the essentially low energy (0.1-1.25 MeV) part of the γ-ray spectrum not covered by the separate channel windows, the main contributor in the ^{238}U decay series is ^{234}Th, but this will be in equilibrium with ^{238}U. Thus where the Total Count is less than expected (negative Disequilibrium Factor) loss of U or addition of Rn has occurred in the soil, and, conversely, where the Total Count is greater than expected (positive Disequilibrium Factor) there has been recent U addition or Rn loss. The pattern of Rn loss from the soils in SE Devon, however, shows no association with the distribution of positive and negative values of the Disequilibrium Factor and it is therefore concluded that the Disequilibrium Factor indicates U mobility (Ostrihansky, 1976). Negative values of the Disequilibrium Factor dominate the results from SE Devon, showing loss of U by modern leaching to be widespread, but positive values occur in a NW-SE trending zone through Kennford, along an E.-W. line passing through Feniton and in the area between Exmouth and Sidmouth (fig. 4).

Convection Systems in SE Devon. Whereas negative values of the Disequilibrium Factor probably result from the downward percolation of groundwater, positive values are interpreted as indicating upflow. The spatial association between the occurrence of positive values of the Disequilibrium Factor and the distribution of high values of U and/or K suggests that, with the possible exception of a short interval during the Upper Cretaceous, groundwater was available to participate in circu-

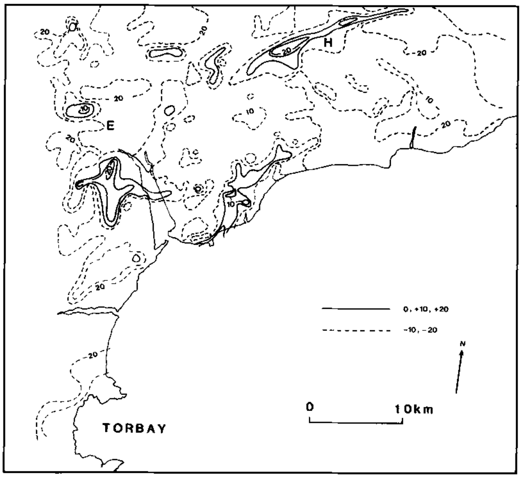

FIG. 4. SE Devon: Soil Disequilibrium Factor Values (ψ). $\psi = \{\text{Total Count (5 min)}/100\} - \{43.95 \times \text{K (\%)}\} - \{25.11 \times \text{U (ppm)}\} - \{11.45 \times \text{Th (ppm)}\}$.

lation systems at all times. The upflow pathways in the groundwater movement pattern for SE Devon occur along major basement fracture systems. The E.-W. zone through Feniton is coincident with the position of the faulted southern margin of the Crediton Trough, the zone between Exmouth and Sidmouth occurs along the line of a westerly extension of the Abbotsbury fault (Melville and Freshney, 1982), and the NW zone through Kennford has already been discussed in terms of the transcurrent faulting of SW England. For movement on such a large geographical scale, the presence of a widely distributed driving force is required for the maintenance of circulation. This is in keeping with the system of groundwater circulation expected to be produced by a geothermal head.

The localization of Rn anomalies along the NW-SE line through Kennford, suggests that the speed of groundwater movement up this fracture zone is more rapid than along the E.-W. lines. In turn, this may indicate some element of residual E.-W. tensional stress acting in SE Devon. Certainly the *in situ* stress anisotropy in the Carnmenellis granite is in keeping with this concept of E.-W. tension (Durrance *et al.*, 1982). However, the occurrence of the highest Rn values in the streams near the mouth of the Exe Estuary suggests that fracture flow in this area is very rapid, and some control might be exercised by formation of an intense fracture zone where NW-SE and E.-W. lines meet. Moreover, flow along a fracture zone in the pipe flow model is not two-dimensional. Along any fracture zone, areas of high upwelling activity and areas of downflow or no activity, are to be expected. The pattern of distributions seen along the E.-W. and NW-SE lines in fig. 5 could merely reflect this variation.

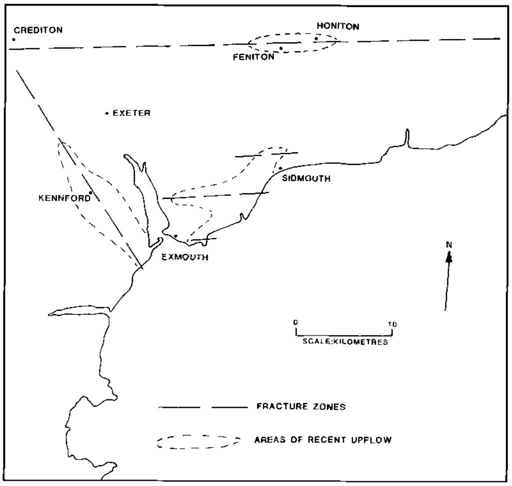

FIG. 5. Summary map of SE Devon showing possible major fracture zones and areas of recent groundwater upflow.

Implications for radionuclide transport. While it is recognized that the foregoing discussion is based on investigations carried out in specific study areas in specific geological environments, it is believed that the implications of the work outlined are important in the selection of any site for the geological disposal of radioactive waste. The important conclusion in this respect is that the main control of convective groundwater circulation appears not to be a heat source producing local enhancement of the geothermal gradient, but permeability over a sufficient vertical range to allow normal geothermal gradients to act as the heat source.

Enhancement of heat flow will, however, increase the potential for convective groundwater circulation. The possibility of a thermal component to the total head in groundwater systems is therefore greater in the two belts of high heat flow in the UK outlined by Richardson and Oxburgh (1979). The first of these belts, in northern England, occupies a NW-SE trending area between Cumbria and the Wash in which a maximum heat flow of 2.51 hfu has been recorded. The second of these belts, in which heat flows as high as 3.0 hfu have been recorded, occupies an E.-W. trending area extending from the area underlain by the SW England granite batholith to the Hampshire Basin. Within these areas permeability is still the major control of thermal groundwater movement, deeply penetrating fault-fracture systems acting as the main conduits for deep water movement.

Away from these areas of high geothermal gradient, permeability is the only control of convective water circulation. That it exists in areas of normal heat flow is exemplified by the thermal waters of the Bristol–Bath area where heat flow values are actually below average. Here deep fracturing with a long history and a strong influence on Mesozoic sedimentation in the region has allowed waters to rise from considerable depth. Residence time for water in this system has been estimated as less than 10 ka but some water could be much older (Andrews *et al.*, 1982).

Deep sedimentary basins also commonly exhibit associated geothermal phenomena. In the Paris Basin, for example, groundwater in high porosity sedimentary strata has provided the basis for a small urban heating system at Melun. In Britain, the Hampshire Basin may also have geothermal potential, as permeable sedimentary strata extend to depths of several kilometres (Garnish, 1976) while the deep sedimentary basin of Lincolnshire and E. Yorkshire is an extension of the North Sea Basin in which many high-temperature oil-field brines have been observed (Garnish, 1976). In any deep sedimentary sequence interbedding of permeable and impermeable strata presents the possibility of extensive horizontal water movement where vertical systems are interrupted by barriers of impermeable rocks.

Thus, in a number of areas in Britain, the possibility of a thermal head in addition to any topographically induced head that may be present should be considered. In an area of generally low relief (as is much of Britain) topographically induced hydraulic head values are likely to be low. Thermally induced head may therefore make a significant contribution to the total head and thus to groundwater movement. The maximum topographic head that is present in SE Devon, for example, is of the order of 250 m. If a similar calculation to that of Elder (1981) for the Wairakei geothermal field is carried out for this area, with a geothermal gradient of around 30 °C/km and a temperature differential of 150 °C maintained over a depth of 5 km, then a geothermal head in the order of 500 m results. This is a maximum value developed over that depth range. The effective head at shallower depths will be reduced by cooling effects during ascent. It should be emphasized that this head is developed on a large horizontal scale and, in the presence of deep fractures, may be very effective in producing major groundwater movement.

Selection of sites for the geological disposal of radioactive waste must take into account the consequences of leakage of radionuclides from their containment. The major mechanism for the return of these toxic substances to the biosphere is transport in moving groundwater, and models are being devised to predict groundwater movement over long time scales in the region of a depository. It is normally assumed that the major driving force for water movement is topographically induced hydraulic head. This assumption may not always be justified. An additional, thermally induced head may also be present and should be taken into consideration during the early stages of site assessment.

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