THE MODELLING OF GROUNDWATER FLOW PATTERNS IN THE UPPER PALAEOZOIC COAL BASINS OF THE MIDLAND VALLEY OF SCOTLAND

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ABSTRACT

A paucity of deep geological information in the Midland Valley of Scotland has been partially overcome by the consideration of palaeogeography in order to create a geological model to 4km depth. A simple groundwater flow model is superimposed upon the geology, in sympathy with topographical, geophysical, petrological (from core specimens) heat flow and hydrochemical evidence. Deep groundwater circulation is likely to be moderate in volume and limited to selected pathways. The Stratheden Group contains the best developed aquifer (the Knox Pulpit Formation) in the Midland Valley and is used as an example of the modelling techniques that have been applied.

INTRODUCTION

The Midland Valley is the major hydrogeological province in Scotland. It is a complex graben containing several, sometimes partly superimposed, Upper Palaeozoic (Devonian, Carboniferous and Permian) sedimentary basins, some in excess of 6km thick (Figure 1). Excluding the Quaternary, the rocks present at surface range in age from Ordovician to Permian. The Midland Valley is about 90km wide and over 300km in length. The trend of the graben is ENE. The Midland Valley is flanked to the north by the Dalradian metamorphic rocks of the Scottish Highlands and to the south by the Ordovician to Silurian greywackes of the Southern Uplands, from which it is separated by the major fracture systems of the Highland Boundary Fault and Southern Upland Fault respectively.

The coal and oil-shale bearing formations which are of Carboniferous age, have supported major extractive industries. Coal extraction is still much in evidence but increasingly uses opencast rather than deep mining methods.

A survey of the low enthalpy geothermal prospects of the Upper Palaeozoic sediments in the Midland Valley has recently enabled a regional study of the basins to be carried out (Browne and others 1986). The work included an evaluation of relevant borehole data and also available geophysical, petrological and hydrogeological evidence, so that a model of the structure and geology at depths down to 4km could be devised. Hydrogeological units have been assigned to the model and regional and deep-seated groundwater flow patterns superimposed according to aquifer configuration and heat flow anomalies.

GEOLOGICAL MODEL

Surface and near surface geology of the Midland Valley is well documented (Browne and others 1985). Coal mines penetrate down to about 1km below sea level. The structural geology observed in the mines combined with scattered deep borehole (<2.5km) and geophysical information enabled a three dimensional picture of the geology of the coal basins to be devised to a depth of 4km. Lower Devonian sandstones and lavas are known almost exclusively at outcrop and have only been penetrated by one or two of the deeper boreholes. Proof of the depth to and nature of these strata in subcrop relies on geophysics or speculation.

The complexity of the Devonian and Carboniferous rocks is illustrated in Figure 2. The more permeable strata occur in the Upper Devonian and Lower Carboniferous where there are several well-developed sandstone horizons in particular the Knox Pulpit Formation. Rhythmic sedimentation in the Carboniferous restricts the development of thick aquifer units and promotes the occurrence of numerous thin, isolated potentially permeable sandstone and carbonate horizons.

The geological model is dependent on available data and on the distribution of lithofacies and predictive interpretation of palaeogeography (Browne and others 1985), in particular those areas where thick, permeable sandstones might occur. For example, the aeolian or beach environment produces well-sorted sandstones, low in fine-grained components and where the individual grains may have a high sphericity. Such deposits are likely to occur in thicknesses of the order of 10s to 100s of metres.

Fluviatile, channel-fill sequences also contain medium to coarse-grained sandstones, arranged in upward-fining units. The stacking of the units, together with erosion of the upper, finer-grained portion of the sequence may potentially build medium to coarse-grained sandstone bodies of the order of 10s of metres thick.

Deltaic sequences seem less attractive in that the sandstone bodies built by this process are medium to fine grained, coarsen upwards and while commonly attaining significant thicknesses of the order of 10s of metres, are often interbedded with silt and mud grade sediments.

Figure 3 (Browne and others 1986, Fig. 5) is an example of one of the paleogeographical reconstructions, that for the late Fammenian to early Tournasian Series. Groupings of lithofacies can be assembled in order to provide isopachyte maps of lithostratigraphic units such as those of the Stratheden Group and Kinnesswood Formations (Figure 4). The palaeogeography of the Stratheden Group is broadly covered by the time zone described in Figure 3. The Stratheden Group and Kinnesswood Formation contain the most permeable zone of the Devonian-Carboniferous sequence. Other younger permeable horizons tend to be thin and hydraulically isolated.

GROUNDWATER FLOW MODEL

Groundwater flows from areas of high fluid potential to low fluid potential along pathways of greatest hydraulic conductivity. The configuration of the water-table (commonly a subdued version of the surface topography) or of the piezometric surface of a confined aquifer, defines lines of equal potential. A typical groundwater stream-path in a deep uniform and homogeneous aquifer arcs downwards from the area of recharge to a depth considerably below the elevation of the zone of discharge. It then arcs upwards to issue as springs or by seepage into streams or mine workings. The curved flowpath is due to the vertical to horizontal exaggeration of the theoretical homogeneous aquifer.

The north-western and south-eastern margins of the Midland Valley are elevated with respect to the lower lying Forth-Clyde axis. The fluid potential is thus greatest along these margins which provides a driving force for recharge and downward flow, with corresponding upward flow along the axis. In the western half of the Midland Valley the deep, upward flowing, warmer water induces an anomalously high zone of heat flow (Wheildon and Rollin 1986). This suggests that the magnitude of the flow may be greater in the west than in the east.

In reality the aquifers are neither homogeneous nor of infinite extent. They are laterally and vertically variable in lithology, intruded by or interbedded with relatively impermeable igneous rocks, fractured, faulted and generally complex. In a few cases the hydraulic conductivity is primary and dependent solely on the interconnected pore spaces within the rock, but in the majority of aquifers the conductivity has an additional and more important secondary component caused by the presence of cracks and joints.

The rocks of the Midland Valley can be divided into those which generally have a high hydraulic conductivity and those which commonly have low to very low conductivity. Generalised flow patterns can be assigned to represent shallow groundwater flow (Figure 5). The shallow flow is largely restricted to the upper 100m of aquifers which may be weathered and fractured. Some flow occurs at greater depths and Clark (1981) reported the greatest hydraulic conductivities in the depth range 100 to 150m. Nevertheless deeper flow probably represents less than 10% of the total (Robins in press).

Laboratory observations on available borehole specimens indicate that the intergranular porosity of the sandstones ranges from 11 to 25% and the coefficient of permeability ranges up to 2,500 mD. Near surface cracks and joints coupled with mineral leaching, which enhances void spaces, induce a three-fold increase in hydraulic conductivity at outcrop. For the most part, the overall aquifer permeability is of the order of 50mD, which given an aggregate aquifer thickness of 300m for the Knox Pulpit Formation (in the Stratheden Group) together with the more permeable parts of the adjacent Kinnesswood and Glenvale formations provide a transmissivity of 15Dm.

The model of the deep regional flow patterns in the coal basins can be derived by substituting for the real multi-aquifer system, a homogeneous aquifer of large dimensions but poor overall hydraulic conductivity. Upward and downward flow of groundwater follows the simple flow pattern described above, but refined in the light of geological constraints and the location of the coast (Figure 6). Downward flow predominates in elevated areas of recharge and upward flow occurs beneath lower lying areas. It is apparent that the groundwater recharge areas are limited in extent because of the extensive outcrop of impermeable rocks, and that upward flow is probable along a central zone that lies between the Forth and Clyde as well as in most coastal regions.

Proof of deep circulation within the coal basins is inconclusive. However, some support for the groundwater flow model is provided by hydrochemistry. In general the principal geochemical changes that occur along flow lines are (Downing and others, in press):-

1. mineral dissolution and the attainment of salination with various carbonate and silicate minerals.

2. various redox reactions, especially the complex reaction of oxygen derived from outcrop.

3. cation exchange reactions.

4. mixing with saline water.

Sources of mineralised and reducing water, or anomalously warm water are few at surface. They may occur along the coast or emanate from the coal bearing strata in which case they could be concealed by the complex chemistry of those strata. However, one source does prove the existence of deep older water. At Bridge of Earn, near Perth, highly saline water discharges at a rate of 1 ls^{-1}. The water is not marine in origin but rather a Ca-Cl type, an old water drawn up from deep slow moving/low volume circulation in cracks and joints. The tritium (^3H) concentration is 9TU indicating that a component of the water is greater than 33 years of age. The spring water temperature is 12°C compared to 8-10°C for shallow groundwater. Clearly mixing and cooling with young, shallow and less mineralised water has occurred near the spring source. However, it does indicate the existence of deep slow circulation of groundwater as postulated in the hydrogeological model.

Deep drilling (up to 2.5km) may continue in the Midland Valley of Scotland because of current oil prospects. The new information derived from these boreholes and associated geophysical work will enable a more detailed groundwater flow model to be constructed. In the meantime, the simple model of groundwater flow is retained with shallow and some deep water circulation down to 4km in depth.

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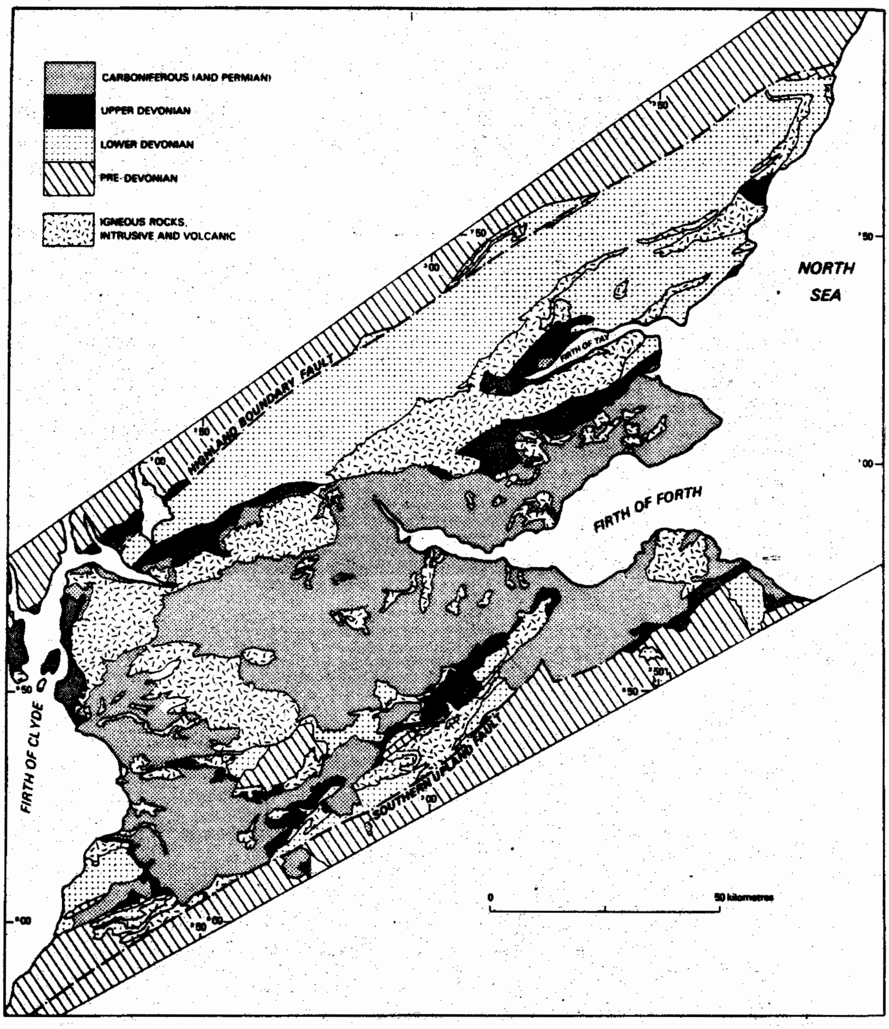

Figure 1 Simplified geological map of the Midland Valley of Scotland

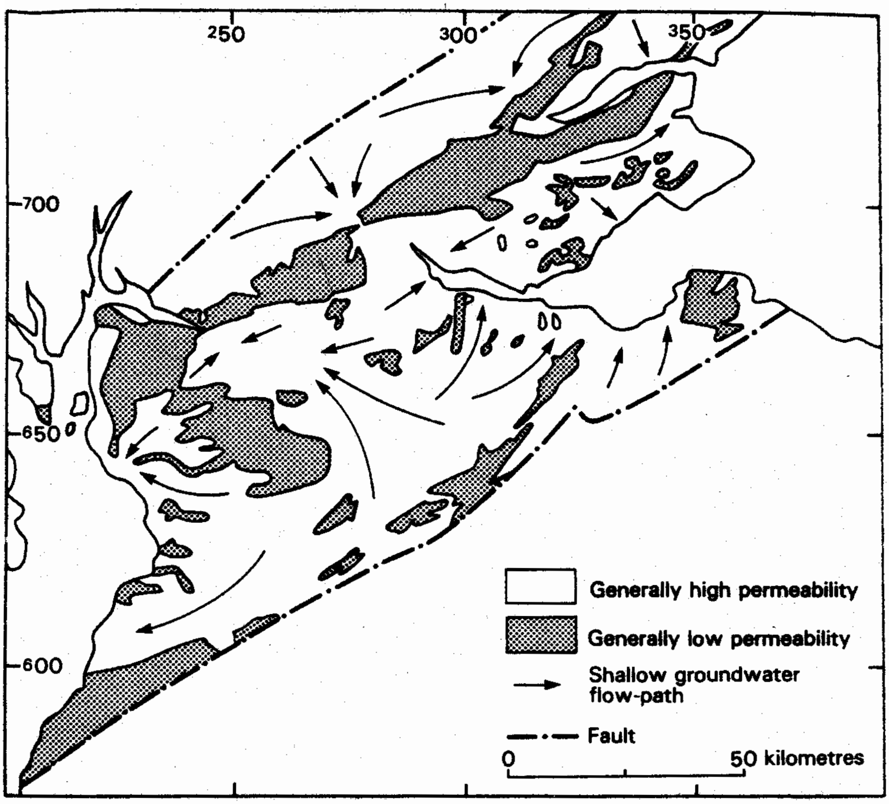

Figure 5 Shallow groundwater flow pattern

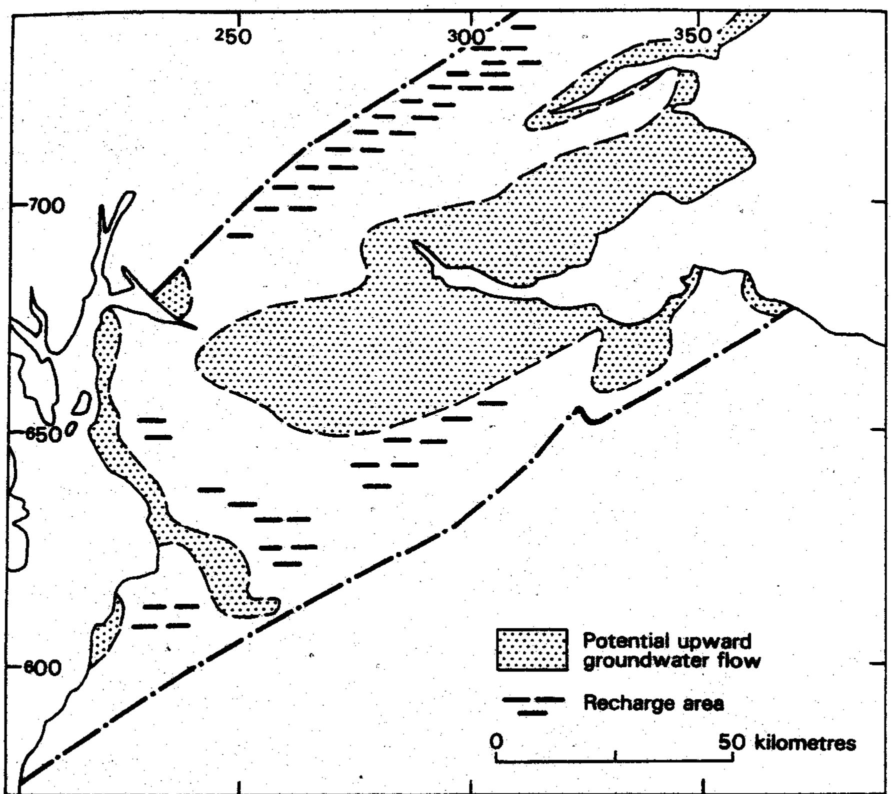

Figure 6 Areas of potential upward groundwater flow due to heat flow and position of coast-lines