Structural and Stochastical Modelling of Possible Contaminant Pathways Below Nuclear Installations

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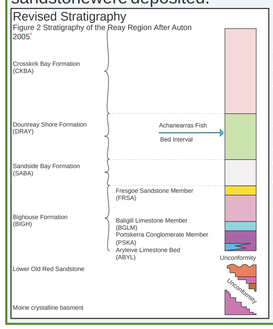
Section I - Introduction and Stratigraphy

Figure 1 Dounreay Nuclear Establishment looking west

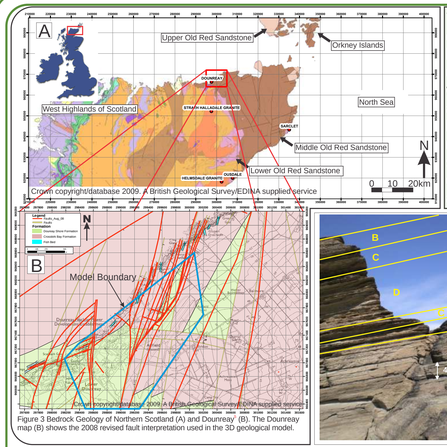
Dounreay Nuclear Establishment (Figure 1), northern Caithness, Scotland (Figure 3A and B) was established in the mid 1950's on a disused Second World War airfield[1] as the United Kingdom Government's Prototype Fast Reactor and experimental research laboratories. The Prototype Fast Reactor used Uranium to produce energy and in the process created Plutonium, which could be recycled and used to produce more energy.[2] Three reactors were built at Dounreay with the last ceasing operation in 1994.[2] By the late 1990's site decommissioning and clean-up had begun.[2] The Nuclear Decommissioning Authority (NDA) took ownership of Dounreay in 2007 with decommissioning to be completed by 2025[1] at an estimated cost of £2,228.6 million.[3] Due to the experimental nature of the Dounreay site and the variable nature of its geology, the decommissioning and clean-up is recognised internationally as one of the most complex in the world.[3]

The principal aim of this work is to gain an understanding of processes and controls on fluid flow pathways within such a complex geological terrains. The boundary between the bedrock and superficial deposits, and fracture networks within the bedrock can have a considerable impact on the rate and direction of transport of radionuclide particles. Consequently, an understanding of the bedrock-superficial boundary and the nature of how fractures and faults influence and control the transport of fluids is of key concern.

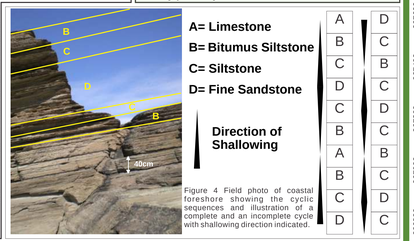
Dounreay is underlain by Moine crystalline basement, and Devonian sedimentary rock sequences (Figure 2) with the latter deposited within the Orcadian Basin. The Early Devonian Period was dominated by alluvial fans and deposition of breccia-conglomerates. In the Middle Devonian Period a lacustrine environment prevailed, in which rhythmical coarsening upwards sequences of siltstone to fine-grained sandstonewere deposited.



The Crosskirk Bay Formation and Dounreay Shore Formation are the principal bedrock units below the Dounreay site (Figure 3). These are underlain by the Sandside Bay and Bighouse formations. The Crosskirk Bay and Dounreay Shore formations were deposited when the lake was at its largest extent. The lacustrine sequenses of the Dounreay Shore and Crosskirk Bay formations are subdivided into four principal units; limestone (A), bituminous siltstone (B), siltstone (C) and fine-sandstone (D).



The 4 main units are deposited cyclicly e.g. A-B-C-D-C-B-A as lake levels varied with time (Figure 4). A units represent periods when the lake was at it largest extent, with seasonal algal blooms and finely laminated limestone was deposited. Units B to D represent a shallowing upwards succession as lake levels fell. Not all of the cycles are complete; A units are typically absent.



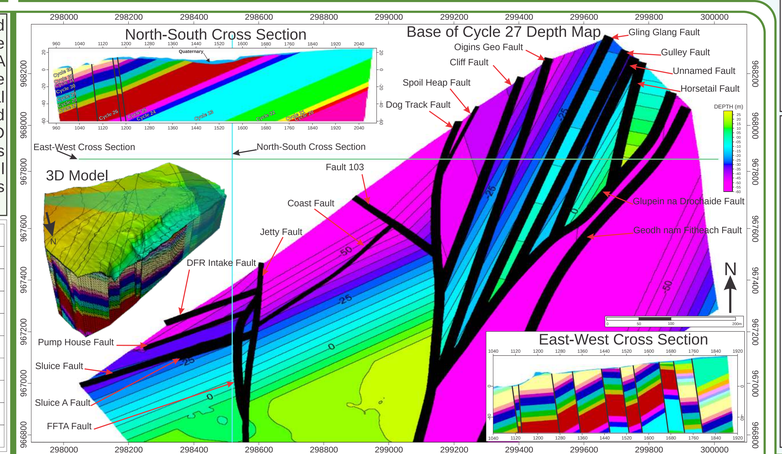
Section II - Geological Modelling of Rockhead and Bedrock

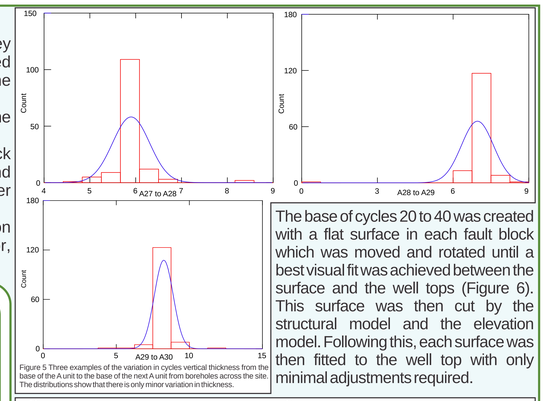
A land surface model was created by combining the site Digital Elevation Model (DEM), side-radar survey data, DGPS points and, for the sea floor, side-scan sonar bathymetry data. A rockhead horizon was created using a combination of well tops and DGPS measured points from excavations across the site and the interpolated depth of the superficial deposits.

The cyclicity of the bedrock enables a reference stratigraphy to be established, based on the presence of the distinctive A unit, with each cycle numbered sequentially, upwards from the base of the Bighouse Formation.

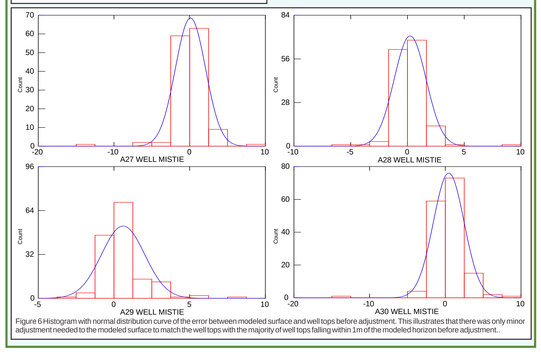
211 boreholes have been logged to this reference stratigraphy and are used in the creation of the bedrock model. The vertical thickness of each cycle shows minimal variation within the upper Dounreay Shore and lower Crosskirk Bay formations (Figure 5). There is more variation in the sandstone dominated lower Dounreay Shore and upper Crosskirk Bay formations.

The fault model was created using interpreted fault centre lines which were draped over the elevation model. These where then projected at a uniform dip and azimuth recorded from coastal exposures or, where no data were available, the average dips of similar exposed faults exposed on the coast were used.



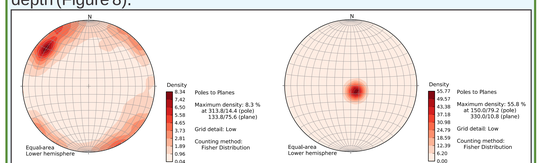


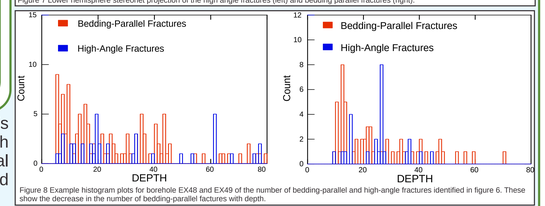
The base of cycles 20 to 40 was created with a flat surface in each fault block which was moved and rotated until a best visual fit was achieved between the surface and the well tops (Figure 6). This surface was then cut by the structural model and the elevation model. Following this, each surface was then fitted to the well top with only minimal adjustments required.



Section III - Fracture Networks and Bedrock Hydraulic Conductivity

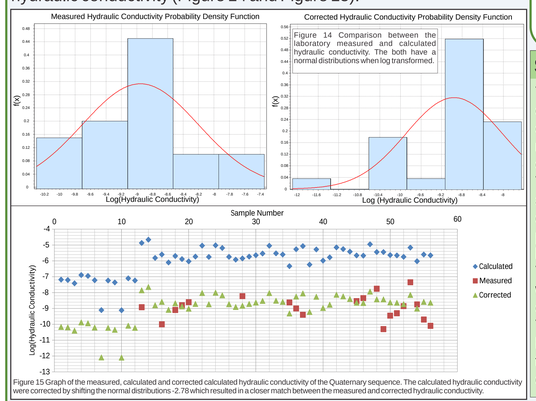
Three fracture sets have been identified (Figure 7). The first two sets of fractures are approximately orthogonal, trending northwest and northeast respectively; they represent the regional fracture set. The third fracture set is shallowly dipping and bedding parallel; a result of unloading. The frequency of bedding-parallel fractures decreases with depth whereas the frequency of high-angle fractures varies less with depth (Figure 8).

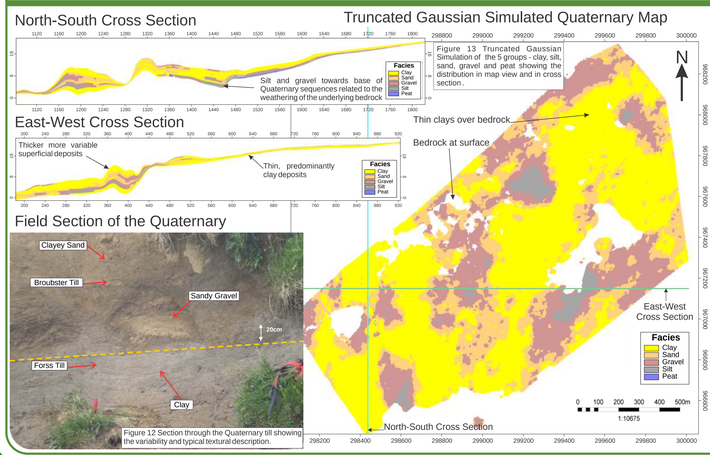




Section IV - Quaternary Classification

The Quaternary of Dounreay area comprise tills, glaciofluvial sands and gravels, wind-blown sand and peat. Three tills are recognised: the Dunbeath Till Formation, the Forss Till Member of the Reisgill Burn Formation, and the Broubster Till Member of the Reay Burn Till Formation. Within the limits of the model the primary Quaternary deposits are the Forss Till Member and the Broubster Till Member (Figure 12) . Additionally, there are extensive man-made deposits directly below the nuclear site. Numerous site investigations have been carried out and the sediments logged geotechnically, with textural descriptions of their bulk compositions; for example clayey, gravely, SAND (Figure 12). Based on these descriptions the Quaternary is divided into five types - Clay, Silt, Sand, Gravel and Peat - which are geostatistically simulated through the modelled volume using the Truncated Gaussian Simulation (Figure 13). Using sieved grain size distributions, the permeability for a range of Quaternary samples were determined using Krumbein and Monk's' equation. This was converted to hydraulic conductivity and compared with laboratory measured hydraulic conductivity values. The calculated values were corrected to the measured value by adjusting the mean value of the calculated hydraulic conductivity (Figure 14 and Figure 15).





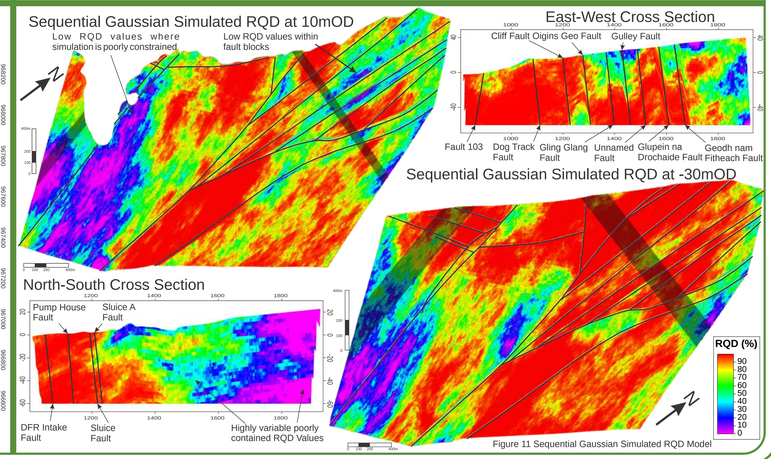
Section V - Conclusions

The Dounreay site with its intense and continuing site investigations have offered an invaluable opportunity to create a 3D model of its near surface geology and gain a greater understanding of the complexities of the weathered zone. The cyclic bedrock geology and the establishment of a detailed reference stratigraphy have enabled the construction of a well constrained structural model with 20 cycles with true vertical thicknesses between 2 and 40m.

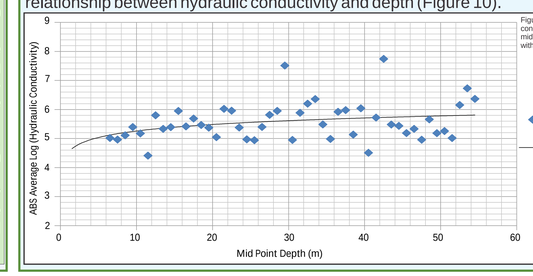
The bedrock is highly fractured, with 3 principal fracture sets identified, two high-angle sets, which are approximately orthogonal to each other, and a shallow dipping set parallel to bedding. The fracturing decreases in intensity with depth. This is principally the result of a decrease in the number of bedding-parallel fractures. This trend is also reflected in the geotechnical RQD and to a lesser degree the hydraulic conductivity.

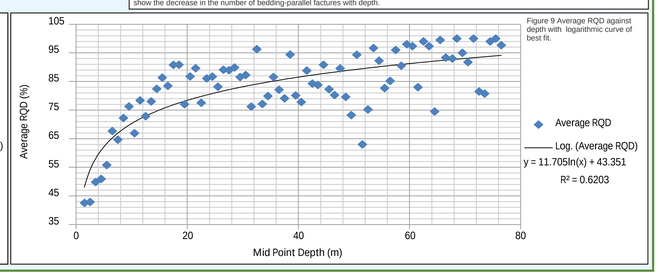
The Quaternary deposits, complicated by the presence of man-made deposits, are heterogeneous, with sands and gravels and low permeable clay. The base of the Quaternary/top of bedrock is often composed of sands, silts and gravel resulting from weathering of the Devonian bedrock.

This understanding of the near surface geology gives a conceptual model of fluid flow, principally between the more competent deeper bedrock and the clay, and over the ground surface with recharge to the shallow groundwater system predominantly through the more permeable sands and gravel deposits within the Quaternary.



Rock Quality Designation (RQD) is the percentage of intact core greater the 10cm per core run. It is routinely logged during cored drilling. There is a strong logarithmic trend between RQD and depth (Figure 9). RQD values were simulated through the geocellular volume of the model, using sequential Gaussian simulation algorithms (Figure 11). There is a similar but less pronounced and constrained relationship between hydraulic conductivity and depth (Figure 10).





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