STRUCTURAL MAPPING AND MODELLING OF DOLYHIR QUARRY, POWYS AS A BASIS FOR A REFINED RESERVE ASSESSMENT AND QUARRY DEVELOPMENT STRATEGY

***I.E.K. Brewer*[1], *N. Lykakis*[2] *and A.P. Wilkinson*[3]**

[1] *Previously Lafarge Tarmac, Stancombe Lane, Flax Bourton, Bristol, BS48 3QD.*

[2] *Midland Valley Exploration Ltd, 144 West George Street, Glasgow, G2 2HG.*

[3] *QuarryDesign Ltd, 1 Custom House Court, 80d Kenn Road, Clevedon, North Somerset, BS21 6EX.*

Abstract

Dolyhir Quarry is operated by Lafarge Tarmac and produces high PSV roadstone from Precambrian sandstones and greywackes of the Strinds and Yat Wood Formations, which are un-conformably overlain by Silurian limestones and shales. The geology has been subject to a high degree of deformation associated with the Church Stretton strike-slip fault system. Structural relationships are complex with strata tilted and extensively faulted by both pre and post-Silurian faults. Geological face mapping originally completed in 2008 revealed some structural features and this was used to develop conceptual structural models upon which a drilling program was designed and executed. Further detailed mapping was then undertaken at the quarry including areas with restricted access using laser scan imagery. Sub-surface structural geology was modelled using a 4D structural modelling package based upon face mapping, laser scan and borehole data. Modelled surfaces were exported for use in LSS Digital Terrain software to aid in the quantification of different material types. This refined the site reserve assessment based on product type, and informed the overall site development strategy as well as providing a better targeted exploration and pre-production drilling programme.

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e-mail: paul.joel@lafargetarmac.com (provided permission for the paper to be published).

Introduction

Dolyhir Quarry is located near Kington, c.33 kilometres northwest of Hereford in the Welsh Borderland and is one of 3 local quarries operated by Lafarge Tarmac (Figure 1). Quarrying has been undertaken at the site since at least the early 1900's, when limestone was originally targeted as a source of agricultural lime. Today the main production is for high PSV road stone with a secondary focus on agricultural lime and general purpose aggregate production.

The site has received limited geological study since the early 1990's when a number of academic and commercial studies were completed (Woodcock, 1988; Woodcock and Pauley, 1989; Walton, 1991). Since that time, the quarry has developed significantly and there is now much greater rock exposure which has revealed some new and previously unidentified structural features.

More recent geological work associated with mineralisation in the area (Cotterell et al., 2011) provided an update to the earlier geological mapping but lacked the detailed aggregate quality assessment and 3D interpretation required to manage the site operations. Accordingly, a new and comprehensive model of the site geology was required to form the basis for future quarry development and commercial strategy.

Aims of the new project were identified as:

- To develop a detailed knowledge of the individual geological units present on site with respect to their quality and performance as construction aggregates.
- To provide 3D surface models of the key structural and lithostratigraphic boundaries between the units to enable the site reserves to be refined based on product split.
- To provide a quantified development scheme for the on-going management of the non-premium materials in order to ensure a consistent long-term supply of high PSV stone.

To achieve these aims whilst maintaining cost efficiency a holistic approach was developed to make best use of the available data; with new technologies

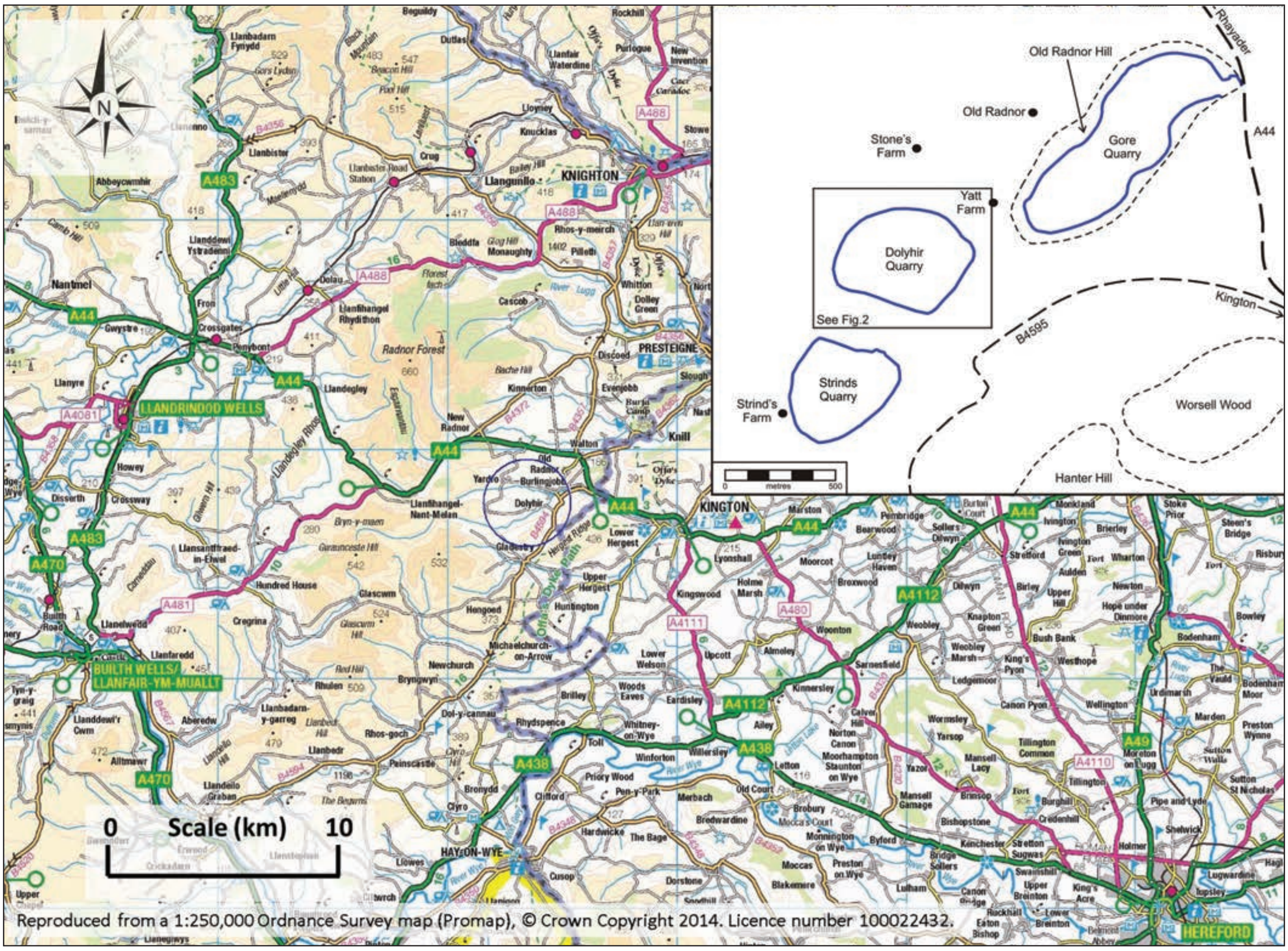

Figure 1. *Regional situation of Dolyhir Quarry with an inset map showing the local situation.*

applied where possible to reduce costs and minimise safety risk during site works. A phased approach of investigation was planned and implemented with an emphasis on accurate base mapping to thoroughly understand the exposed geology.

Geological Setting

The quarries (Figure 1) are developed in rocks of the Old Radnor Inlier, a kilometre scale fault bounded block of Precambrian rocks within the strike slip Church Stretton Fault Zone. This fault system is the eastern-most component of the Welsh Borderland Fault System (Woodcock, 1988). There are two main inliers within the Silurian strata that dominate the area. The Old Radnor Inlier comprises Precambrian sedimentary rocks and the Stanner-Hanter Inlier consists of Precambrian basic igneous rocks. Both are interpreted as being faulted slithers or flower structures of basement rock which have popped up as a result as transpressional stresses along the fault zone (Coster et al., 1997).

The quarries work Precambrian clastic sediments of the Yat Wood and Strinds Formations (of the Old Radnor Inlier). These are viewed as comparable to the sediments of the Longmynd plateau of Shropshire (Garwood and Goodyear, 1918). The sequence includes a wide range of lithologies including medium grained massively bedded sandstones which form the bulk of the premium high PSV production and finer grained mudrocks which are suitable only for general purpose fills. The Precambrian was tilted, faulted, intruded by dykes and eroded prior to deposition of the overlying, unconformable Silurian (Wenlock) Dolyhir Limestone. The limestone passes up into the overlying mudrocks of the Coalbrookdale Formation, as shown on Figures 2 and 3. Within the Old Radnor inlier the rock mass has been subject to extensive deformation and there are a large number of faults with a wide range of activation ages. These faults both pre and post-date the deposition of the Dolyhir Limestone and show both dip and strike slip displacement.

The significance of the geology of the site is such that the site has been designated a geological SSSI and has been listed in four separate volumes of the Geological Conservation Review Series due to its Caledonian structure, Silurian and Precambrian stratigraphy and mineralogical interest (Aldridge et al., 2000; Bevins et al., 2010; Woodcock, 1992, 2000).

Face Mapping

Face mapping was undertaken over 5 days and involved the visual inspection of faces, and recording the location of salient features with a handheld GPS used in conjunction with a recent quarry topographic survey.

Mapping established the detailed stratigraphy of the

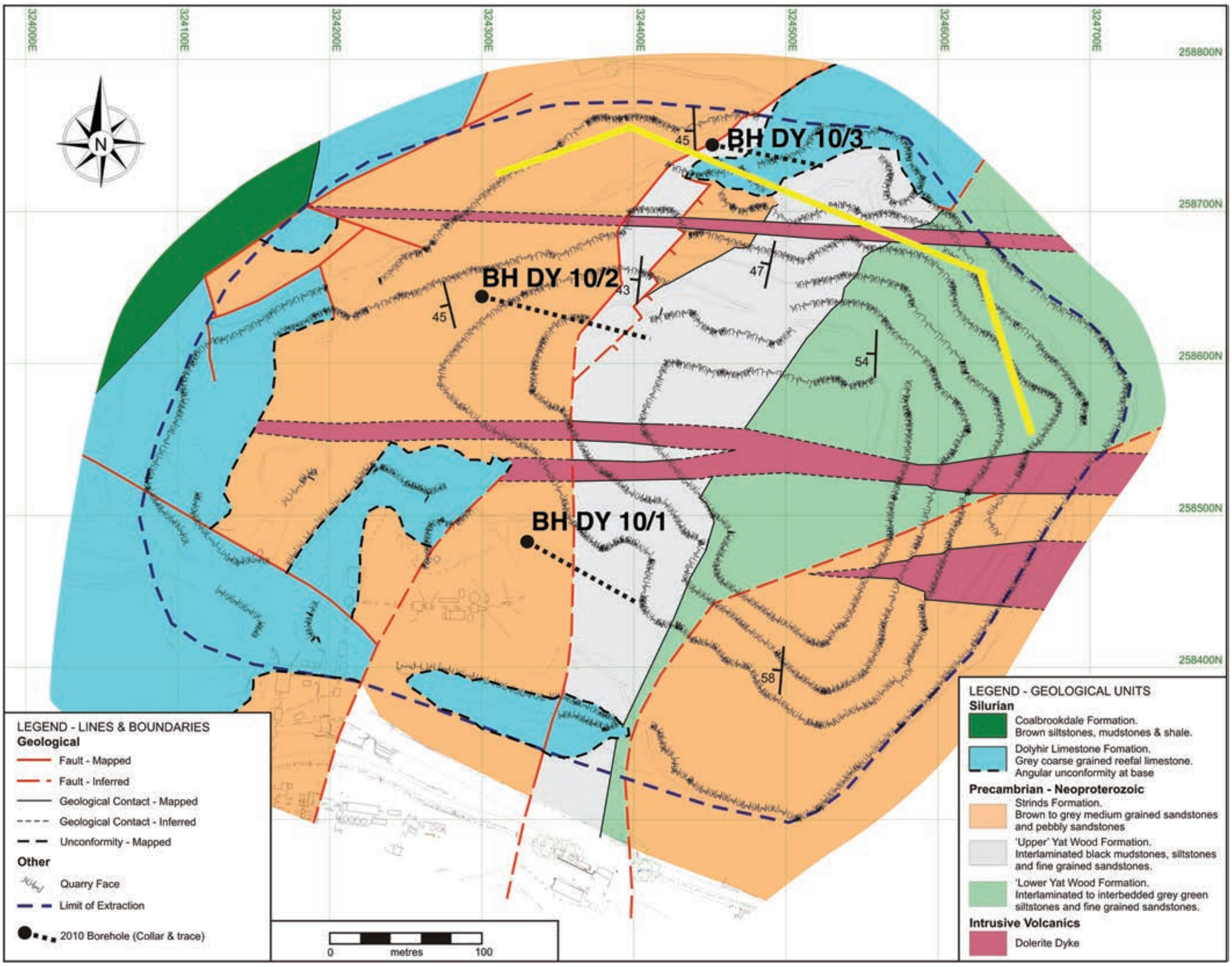

Figure 2. *Geological map of Dolyhir Quarry; prepared using mapping data produced as part of this study. Borehole BH DY 10/4 is not shown here, its position is north of the limit of the figure. The yellow line shows the approximate position of the Figure 4 section.*

Precambrian succession and the main structural relationships present within the exposed faces are shown on Figures 2 and 3. The Yat Wood Formation comprises to the east of the quarry the 'Lower Yat Wood' formation; of well bedded, fine to medium grained greywackes which pass up into a c.50m thick sequence of finer grained, interlaminated siltstones and mudstones that is termed the 'Upper Yat Wood' within this study. The uppermost part of the Yat Wood Formation becomes progressively coarser and then passes into the overlying Strinds Formation, comprising much more massively bedded, medium grained, locally pebbly sandstones which commonly show a marked tectonic brecciation. No evidence for way up was identified during the study so the whole sequence may in fact be overturned and the terms 'upper' and 'lower' are applied here purely in turns of their relationship on site.

Previous work (Woodcock, 1988; Woodcock and Pauley, 1989; Walton, 1991) has always regarded the relationship between the Strinds and Yat Wood Formation to be wholly faulted but evidence from the current study suggests that there is in part a stratigraphic contact between the units. Mapping also established the presence of a number of major sub-vertical basic dykes up to 20m thick that are intruded into the Precambrian sediments and trend mainly east to west.

In terms of production, the Strinds Formation, the basic intrusions and much of the Yat Wood Formation are of premium quality and produce a 65 PSV road stone whilst a thinly laminated zone within the Upper Yat Wood Formation is of lower quality and produces second grade fills. Limestone is now mostly worked out from Dolyhir but where present is produced as a concreting aggregate.

To minimise the safety risk associated with rock fall from the quarry faces, structural measurements of bedding, faults and joints were sighted except where safe access to the face was possible. Mapping identified that bedding within the Precambrian is generally consistent, dipping at 50° to the west (Figure 2). A northeast to south trending, fault-bounded 'wedge' of the Yat Wood Formation is present, sandwiched between the Strinds Formation. That outcrop of the Yat Wood is complicated in the northern faces by a shallowly eastward dipping fault that shows normal displacement (Figure 4). Faults are generally orientated sub-parallel to the main trend of the Church Stretton Fault System (i.e. NNE to SSW), although additional features trending W to E, to WNW to ESE are also present.

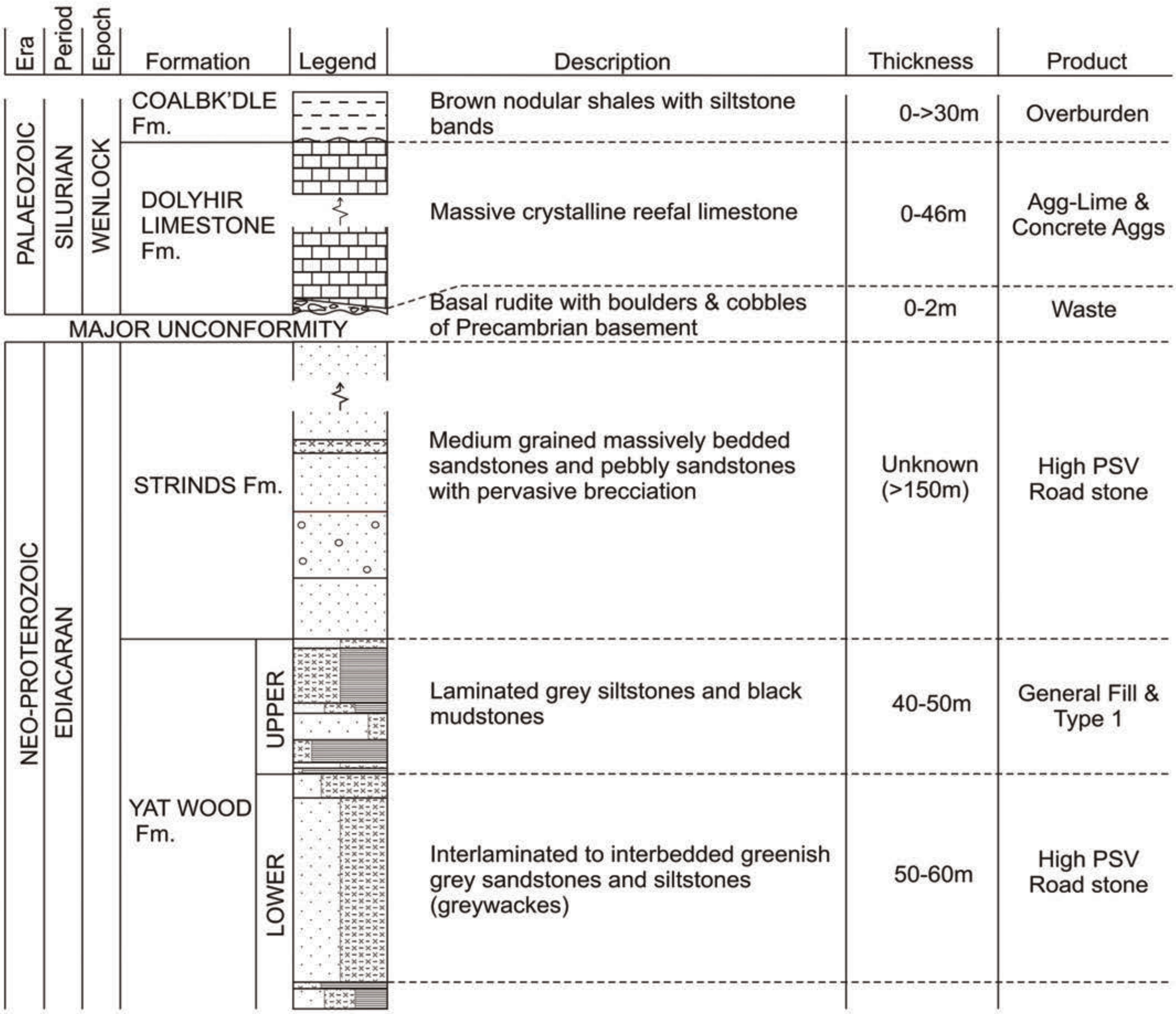

Figure 3. *Stratigraphic table of the geology of Dolyhir Quarry (after Woodcock and Pauley, 1989; updated based on site-based observations).*

Drilling

On completion of the mapping work, preliminary geological models were prepared using the surface mapping information and existing borehole records. Construction of preliminary models was undertaken using LSS Digital Terrain Modelling software. The software was also used to report results back to operational management by way of a 3D fly through as well as informing the drilling programme. The models showed that the existing boreholes on site, which were all vertical, were insufficient to accurately define the structural boundary of the wedge of Yat Wood Formation and the poorer quality materials at depth within the future quarry workings. Given the dip of bedding and the location of structural features it was considered that angled boreholes should be drilled to intersect the Yat Wood Formation, perpendicular to bedding. This would enable the structural features to be proven at depth and the full sequence of strata to be core drilled, allowing a detailed quality assessment to be made whilst minimising the drilling depth.

Boreholes were drilled during winter 2010-2011 using wireline coring in NQ size with a Diamec 250 diamond drill rig. The maximum downhole length was c.160m at a target angle (for all holes) of 45° to intersect bedding. Given the length of holes and the angled nature of the drilling, hole wander was considered a potential issue and to counter this (to ensure accuracy in determining geological intersections), down-hole directional surveying was undertaken. A Reflex Ez-Trac directional logging tool was utilised and a multi-shot survey was undertaken on completion of each borehole during retrieval of the drilling rods. Given the total cost of the drilling, the additional cost to hire the directional logging tool for duration of the work was considered insignificant and ensured the accuracy demanded by the study's approach. The results of the directional logging show that there was up to 2° variation in dip down-hole and up to 4° variation in azimuth which, given the depth of the boreholes, could have caused significant error and led to unsatisfactory inaccuracies in the resultant geological models and volumetric calculations.

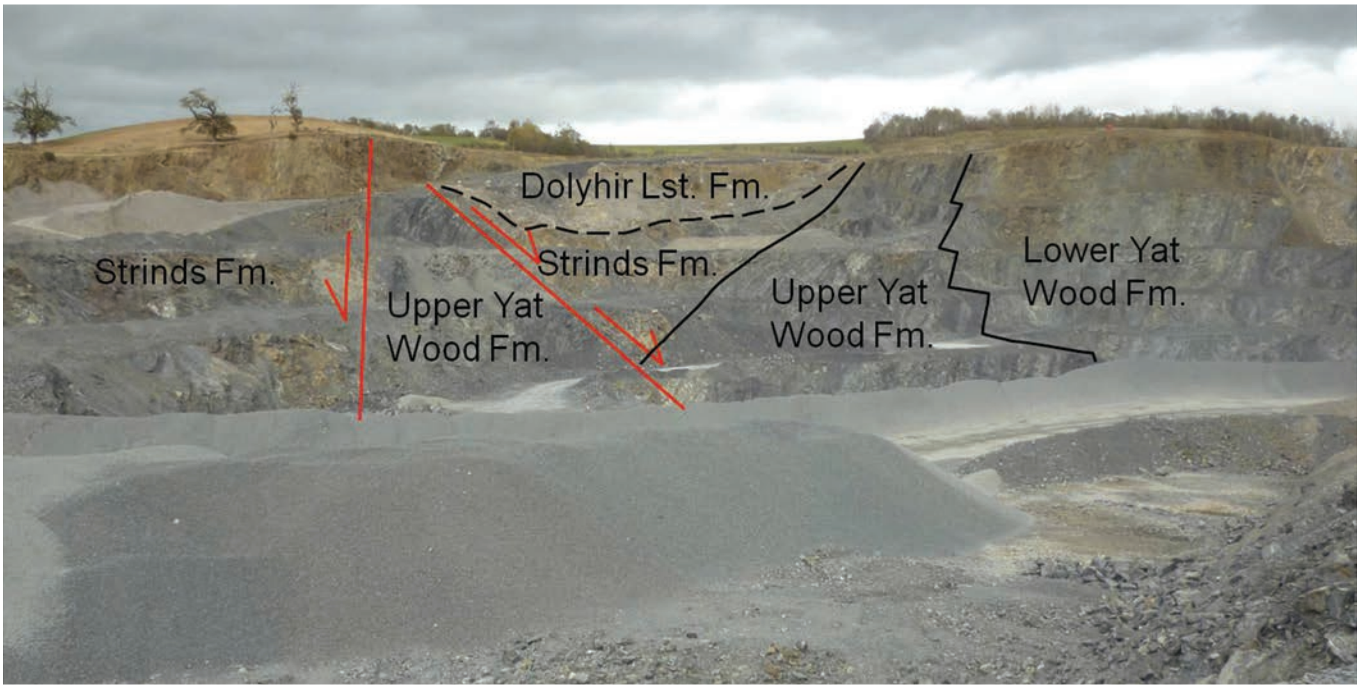

Figure 4. *Photograph of northern faces in Dolyhir Quarry. This image shows progressively from right to left: Lower Yat Wood Formation, passing into Upper Yat Wood Formation, overlain by the Strinds Formation, a shallow angle normal fault causing repetition of the Upper Yat Wood sequence and then a major steeply dipping fault back into the Strinds Formation with the Silurian Dolyhir Limestone Formation resting unconformably on top. The approximate line of this photographic section is shown on Figure 2.*

On completion of the drilling, the core was logged in detail. The face mapping had identified key intraformational marker bands and the aspiration was to correlate these with down-hole observations drawn from the logging. The correlation is shown in Figure 5. Three boreholes intersected the contact between the Strinds and Yat Wood Formations which is faulted in this area, and a representative full section of the Yat Wood Formation was cored. Borehole logs were input along with directional logging data into the gINT Geoenvironmental Data Management and Reporting software package. This was used to produce presentation borehole logs and to export XYZ co-ordinate intersections of key lithostratigraphic boundaries into modelling software.

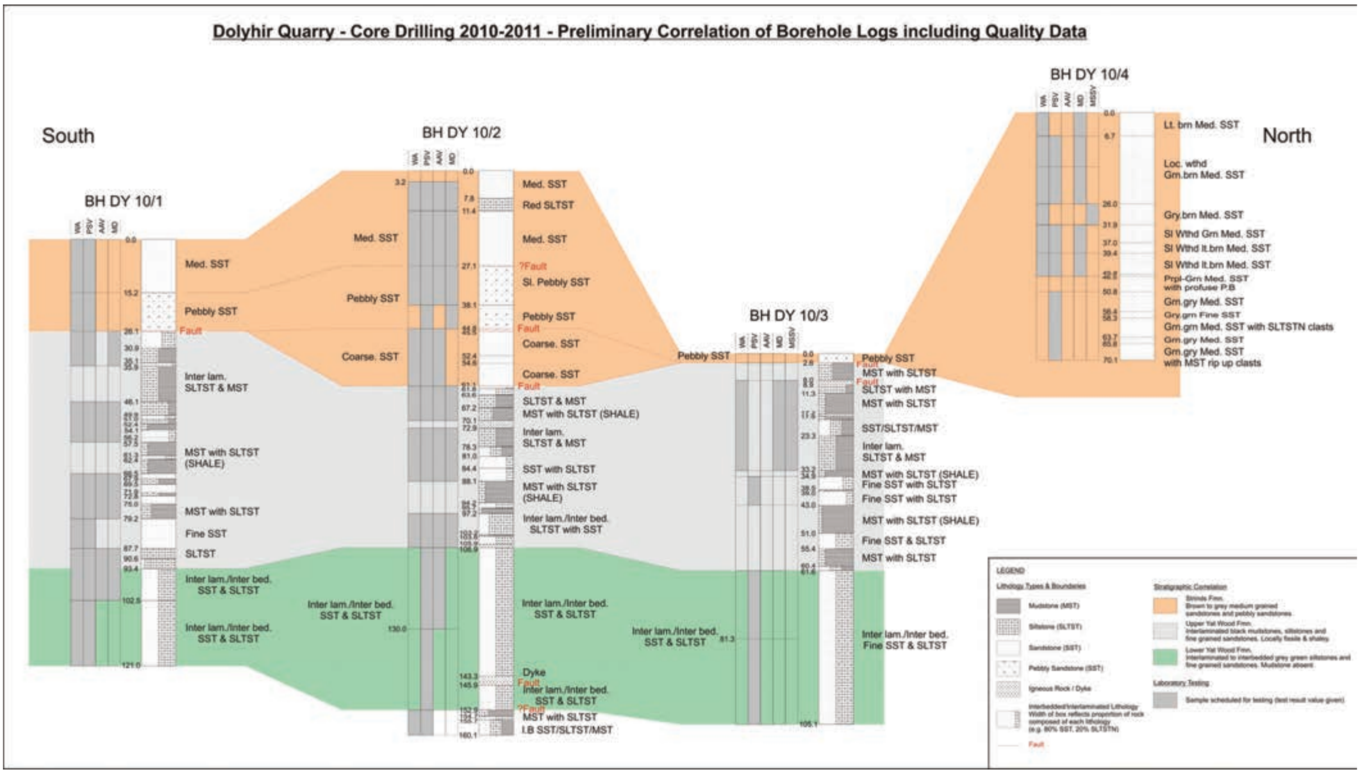

Figure 5. *Stratigraphic correlation of the 2010-2011 borehole data (borehole positions and traces shown on Figures 2 and 10).*

Laser Scanning

Prior to modelling the site geology it was recognised that more mapping data needed to be collected and should include data from some inaccessible areas of the quarry. On review, it was decided that a full laser scan of the quarry faces would be the most appropriate technique and the objectives for this work were as follows:

- To enable accurate mapping of structural features from all areas of the quarry including inaccessible benches and areas beyond the reach of staff undertaking face mapping,
- To provide accurate measurements of bedding and fault planes; to enable subsurface projection of the structure,
- To provide discontinuity data for use in future Geotechnical Assessments,
- To provide a permanent record of the site geology to assist future geological mapping and any study work (considered important given the SSSI status of the location).

A 3D model of the quarry was produced by QuarryDesign in March 2012 using an Optech ILRIS-3D-ER LiDAR (Light Detection And Ranging) laser scanner. Figure 6 shows the scanner making a scan of the northern benches including the complex zone with the shallow angled east-dipping fault. A detailed explanation of the general principle of LiDAR scanning technology is dealt with by Petrie and Toth (2008) and Liadsky (2007) and will not be discussed further here except to illuminate the methodology used for the Dolyhir scanning work.

A detailed scan plan was produced in advance of the site work using the recent quarry topographic survey to enable the key areas of interest to be scanned at the required resolution with minimal set ups. LiDAR scanners work by generating an optical pulse of a given wavelength (in this instance 1535nm in the infra-red spectrum) which is then reflected off an object and returns to the system receiver where a high-speed counter measures the time of flight from the start pulse to the return pulse along with a 'local' bearing of the pulse. The 'flight-time' is converted to a distance and the acquired bearing and distance data is then downloaded and 'parsed' (processed) in to local XYZ co-ordinates. For the Dolyhir survey work, inclusion of control points within the scan allowed the resultant point cloud to be orientated to the quarry grid. The point clouds analysed at Dolyhir were produced by scanning from an average 500m distance from the face with a 35mm contact spacing which was considered sufficient given the scale of the structure present. The resultant point clouds were processed as RGB (Red Green Blue) colour images using a calibrated digital camera and as a greyscale Reflectance Intensity image (where white points represent a highly reflective material and dark grey points represent a low reflectance material).

Figure 6. *Photograph showing the laser scanner scanning the northern faces of Dolyhir Quarry.*

After the data had been converted into XYZ format, multiple scans were stitched together to produce a composite quarry model. Composite point cloud sets for the quarry were analysed in both RGB and Reflectance Intensity, with geological boundaries and faults being digitised in Polyworks IMSurvey software. All main structural features and boundaries were digitised from the laser scan and exported for use in the modelling package.

Figure 7 shows a pair of point-cloud images obtained from scanning of the northern faces at Dolyhir. The image on the left shows a point-cloud processed in Reflectance Intensity values and the image on the right shows the same image processed in RGB values. The shallow, normal fault is more clearly depicted (and hence is more easily digitised and its location mapped) in the processed reflectance point-cloud than in the processed RGB point-cloud. Conversely, the two dolerite dykes exposed in the eastern faces were far more readily identified in the RGB point-cloud than in the corresponding Reflectance Intensity point-cloud.

Figure 8 shows a scanned section of the eastern faces in which the RGB point-cloud clearly highlights red coloration caused by oxidation of iron in the two dolerite dykes, allowing these features to be accurately and remotely mapped. Conversely, at the face these features were much more difficult to define.

As well as the stratigraphic contacts and major structural features obtained from the bulk mapping, discontinuities were also traced and measured from the laser scan data using Split Engineering's Split-FX software. This discontinuity data was analysed directly within SplitFX by plotting a stereographic projection using the relevant bedding and joint measurements. The information was then grouped and exported with XYZ data to the chosen geological modelling software. Discontinuity and fault data was used separately to improve the data set used for Geotechnical Assessment work. Figure 9 shows the Reflectance Intensity point-cloud the eastern faces as viewed in Split-FX. Digitised discontinuities with similar orientations have been grouped together and coloured as sets of discontinuities. The coloured sets shown on the inset stereonet being the same as the coloured sets shown on the point-cloud.

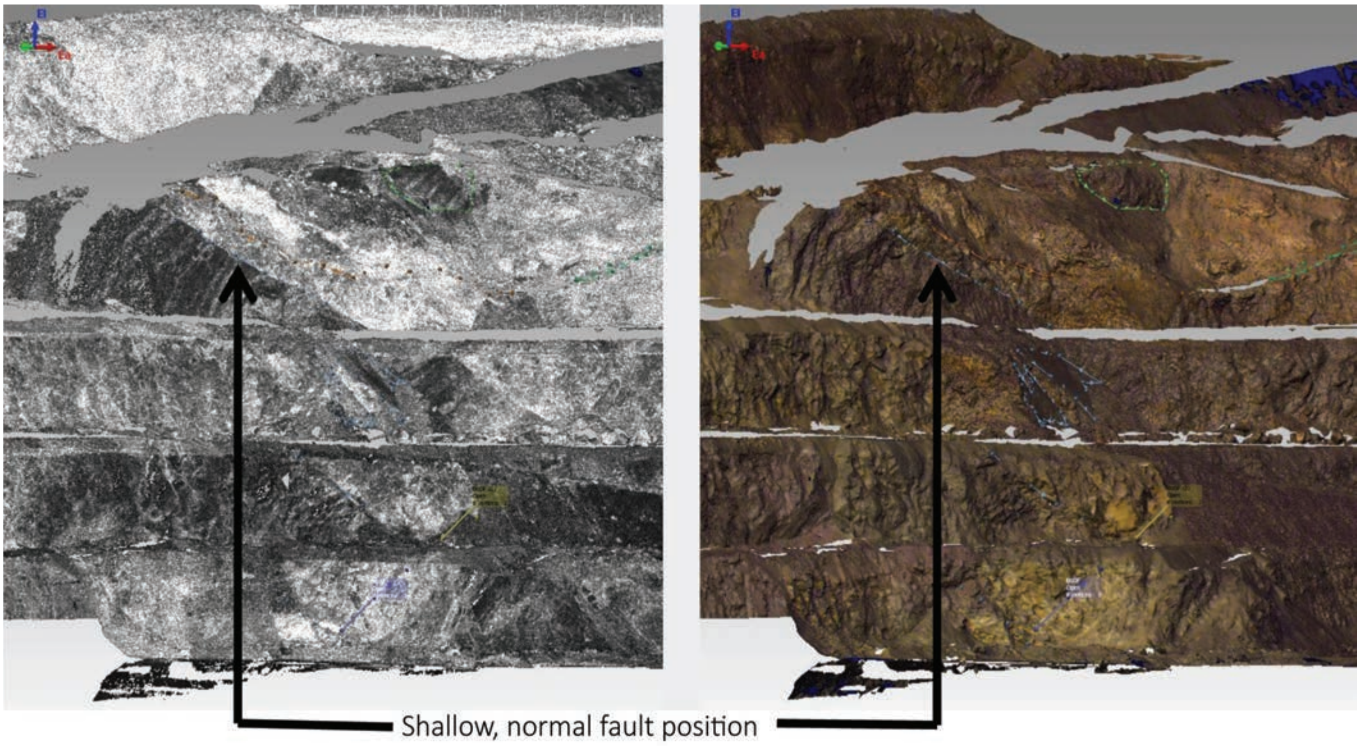

Figure 7. *Laser scan images of northern face. The image on the left was processed in Reflectance Intensity values and the image on the right in RGB values. The shallow, normal fault, more clearly identified in the left image is highlighted.*

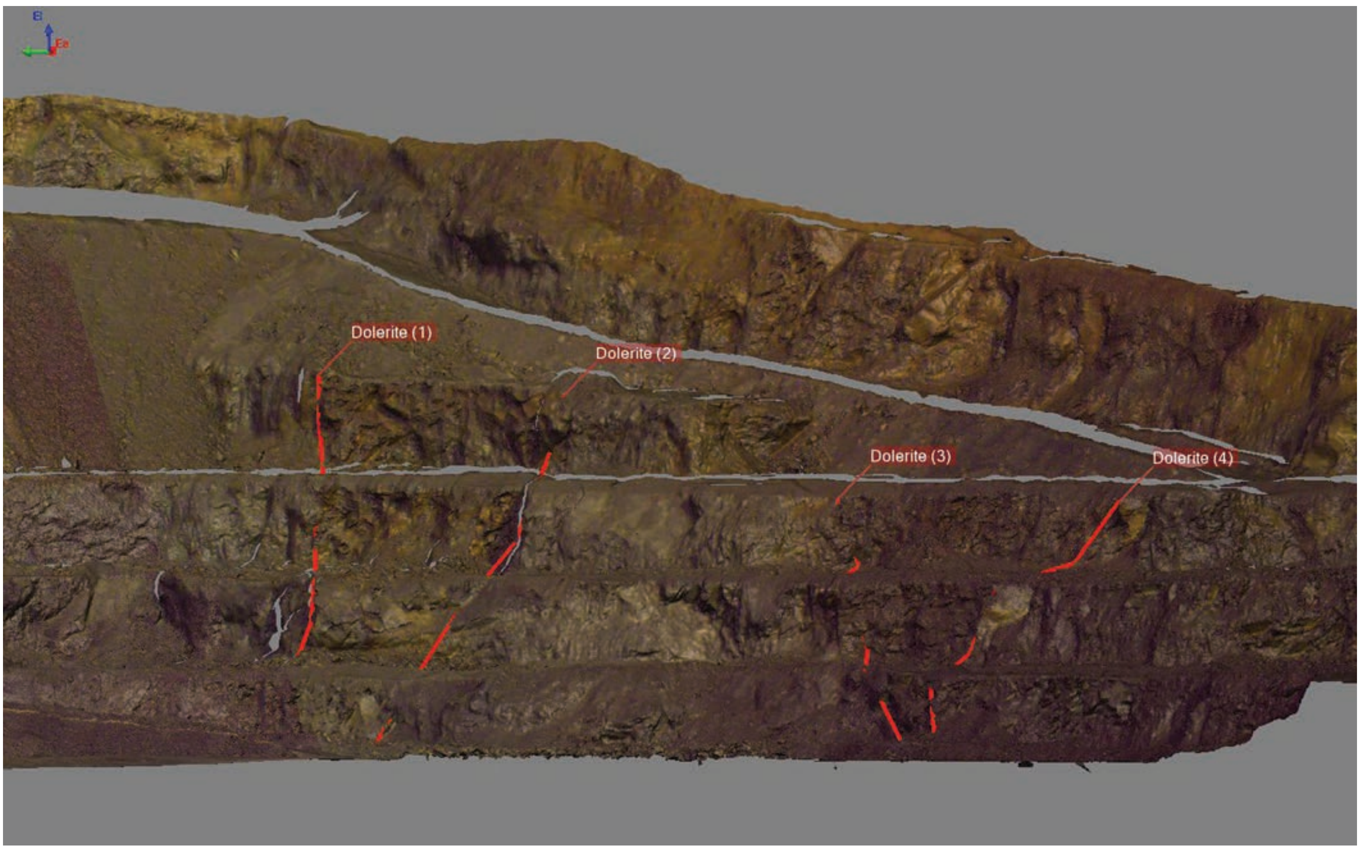

Figure 8. *Laser scan images of eastern faces showing RGB values. Red colouration has allowed the positions of two dolerite dykes to be defined. The outer limits of one dyke are highlighted by 'dolerite (1)' and 'dolerite (2)', and the outer limits of the second dyke by 'dolerite (3)' and 'dolerite (4)'. The dykes are shown in plan view on Figure 2.*

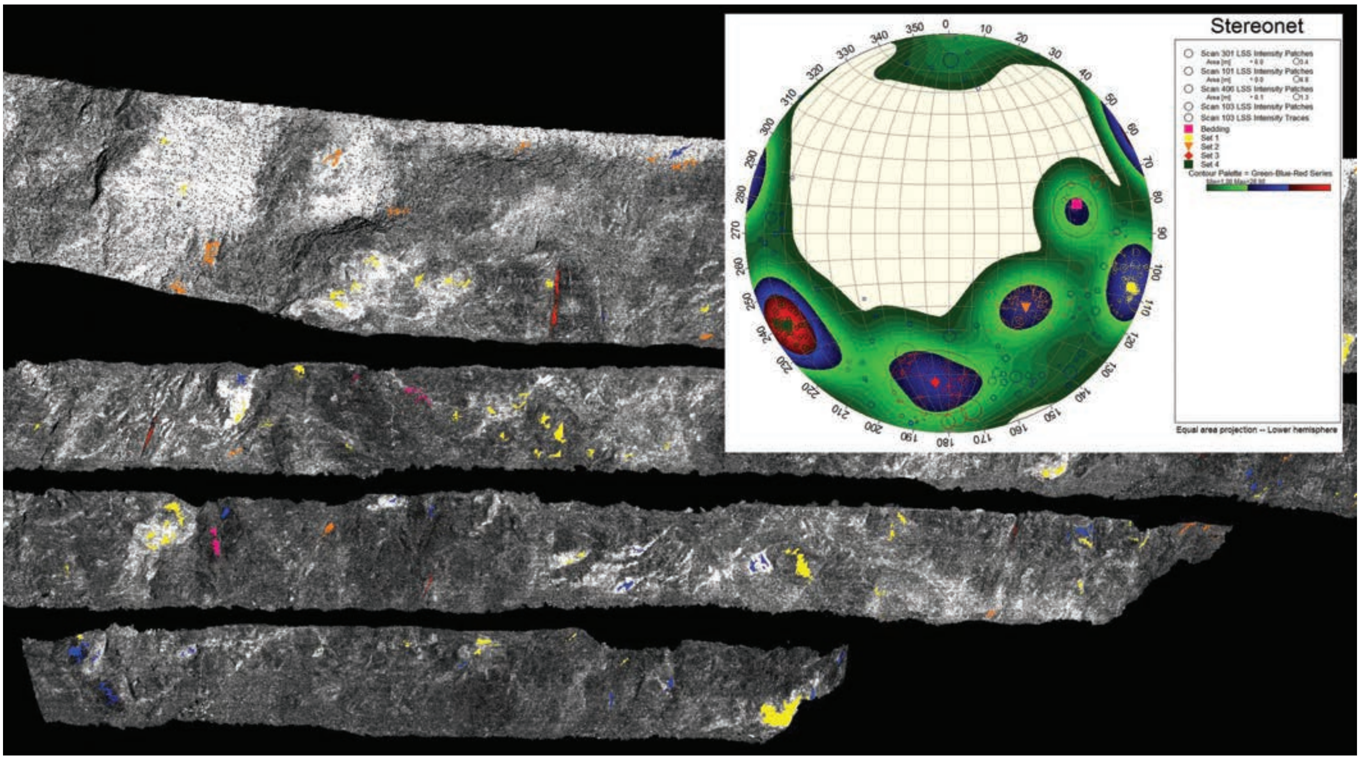

Figure 9. *Laser scan image of the eastern faces showing Reflective Intensity values. Coloured areas identify sets of similarly orientated discontinuities that have been traced and measured within the Split-FX programme. The inset image shows those same (coloured) discontinuity sets plotted on a stereographic projection.*

MODEL BUILDING

The integration of all available data for use in 3D model production, taking into account the complexity of the site and the various data types was a significant challenge. A review of available specialist software packages was undertaken to evaluate how the challenge could be best approached. The use of 4D structural modelling within the non-petroleum extractive industry has previously been promoted (Kloppenburg et al., 2008), but until recently has had relatively little uptake by the UK quarrying industry. Geological model construction was undertaken using Midland Valley Exploration's 'Move' software. This package, originally developed for the petroleum geology sector allows structural modelling with significant functionality to work with and visualise a wide range of 3D data types for use in model construction. In addition it enables the use of structural restoration to test the validity of the models. Given the strike-slip nature of the faulting at Dolyhir together with the regional scale displacement (Woodcock, 1988), it was considered that structural restoration would add little to the resultant validity of the model. The primary objective was to manage the wide variety of data and to produce a 3D model using established structural principles. In order to facilitate this, an external structural geologist was engaged from Midland Valley Exploration to work alongside the Lafarge Tarmac geological team and to undertake the modelling. The rationale for this being two-fold:

1) Time constraints; It was considered that given the specialist nature of the software package, the length of time required to up-skill to a sufficient level needed to undertake the complex model construction would have been unsatisfactory given the time demands for the project completion.
2) The knowledge of a structural geologist would enable areas of inferred structure to be predicted using his/her expertise and with reference to established structural principles and so would add value to the interpretation.

The sequence of works associated with the model construction is outlined below and the final geological model for the site is shown in Figure 10:

1) Importation and geo-referencing of all data into Move including: topographical surveys, quarry designs, borehole data, dip data of bedding and faults, geological boundaries and structural features from laser scan data, scanned geological maps.
2) Site visit to review the existing mapping and ensure mapping is up to date with inclusion of any new areas of development using FieldMove (field version of Move which is loaded onto a ruggedized tablet PC with a built in GPS).
3) Analysis of all dip data by utilising the stereonet plot within Move to identify the dip and dip azimuth of the bedding planes.
4) Construction of cross sections through the site and projection of relevant data including bedding orientation, dip and strike data, mapped surface intersections and borehole data onto those sections, and 2D model construction. (Numerous iterations were undertaken to provide adequate structural control).
5) Creation of 3D surfaces for each key structural feature or main stratigraphic boundary using the 2D section traces and other relevant data.
6) Review of the model to confirm validity.

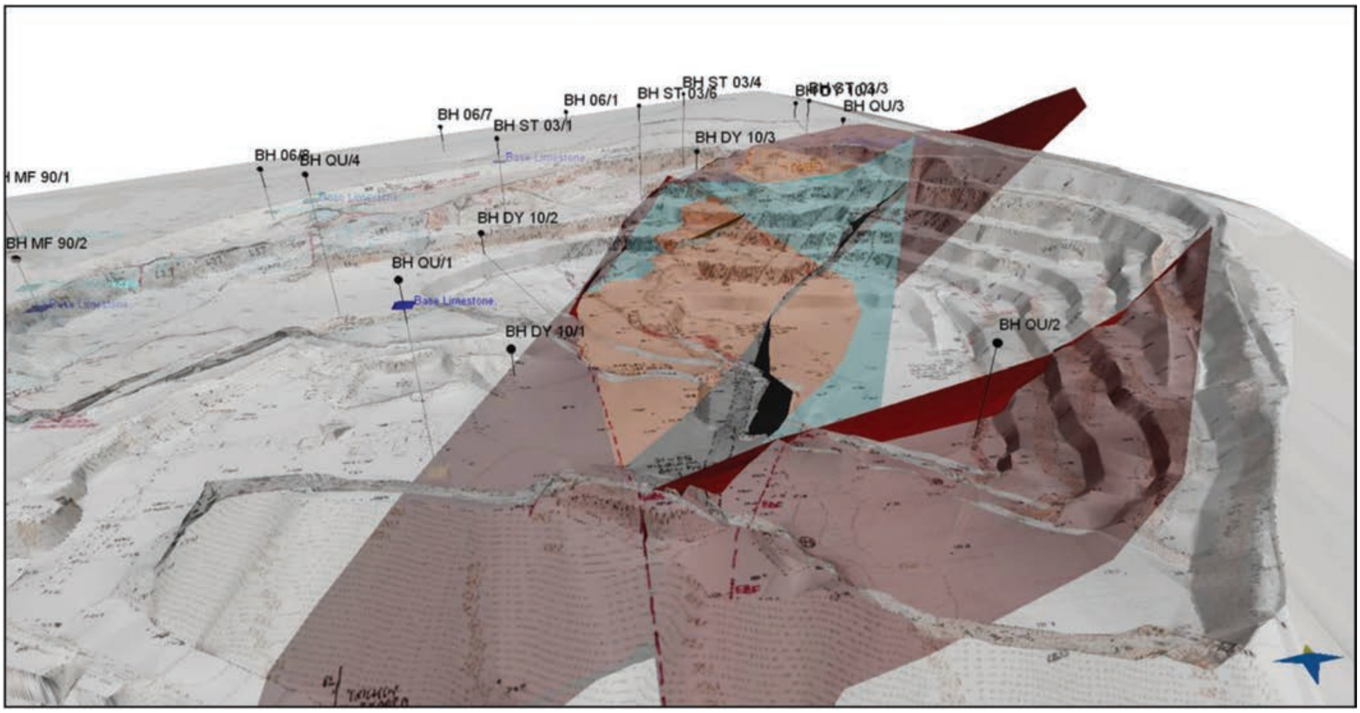

Figure 10. *Final 3D geological model of the bulk Precambrian structure of Dolyhir Quarry within the 'Move' programme. Field mapping results are shown as a drape.*

Results

The main outcome of the project was a series of 3D surface models that constrained the various material types present within the remaining extraction area. The surface models were exported into industry standard DTM software (LSS) for use in onward design, 3D visualisation and volumetric calculation. In addition, the detailed characteristics of the various geological units present in terms of both their lithology and mineral quality have been better established enabling an assessment of aggregate product type to be made. The information has been used to plan the future development of the quarry by providing an accurate estimate of the volumes of lower quality materials which need to be managed to ensure a continued supply of premium high PSV stone. In practice, the key boundaries between the various product types are plotted directly onto the quarry development plan. They have been used to direct the short-term operations and to provide the commercial team with quantified targets for second grade materials sales. In the longer term, a more realistic view can now be taken on potential marketability of the lower grade materials and where necessary, appropriate tipping plans developed in order to manage surplus materials.

In addition, the detailed 3D model enables the location (within the final faces) of important structural features such as faults, key boundaries and the unconformity between the Precambrian and Silurian to be predicted with a degree of confidence. This may have benefits in terms of the important geodiversity and SSSI status of the site, and it enables the design of the restoration scheme to be influenced by these features of interest, so as to provide access and enhance the potential for after use.

A detailed understanding of the geology of the final faces is also essential to enable the stability of the final faces to be properly assessed and the final quarry design optimised to maximise reserves.

Conclusions

The use of high technology and advanced computing has significantly improved the geological interpretation and subsequent operation of this complex quarry. The project has resulted in the appreciation of numerous observations that will be useful to many quarry geologists. These are:

- The use of appropriately detailed and accurate face mapping is an essential precursor to major exploration expenditure and can significantly reduce costs by enabling borehole programmes to be designed appropriately.
- The logging of core to an appropriate level of detail pays huge dividends in the ability to interpret and correlate lithologies and features across site.
- The 3D location of boreholes should be accurately known.
- The use of the now established laser scanning technique enables accurate, safe and efficient mapping to be undertaken as well as providing a record of the site geology for future reference.
- New software technology provides significant advantages in terms of storing, visualising and modelling data and should be integrated at early stages of a major structural project for maximum benefit.
- Recent technological advances across the extractive industries provide a variety of new techniques that when combined, enables complex structural mapping and modelling to be undertaken and recorded with accuracy and efficiency.

- The challenge for the industry is to better integrate these systems with conventional quarry design and volumetric calculation processes.

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