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Understanding the Bigger Picture — Interpretation of Geological Structure in Open Pit Rock Slope Stability

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Abstract

Expert assessment of geological structure can significantly improve understanding of the open pit geotechnical framework. A good structural model of the pit and surroundings is essential to understand the potential for slope instability, though commonly only the local area is generally assessed. This can lead to major features or deformation styles being missed. This paper demonstrates how structural evaluation has been used to improve the geological and geotechnical understanding of the pit slope stability issues at two very different sites.

The Kumtor open pit gold mine is located in the tectonically complex Tien Shan Mountains in Kyrgyzstan. The structural geology is being reassessed, since it was proving difficult to understand styles of deformation and hence predict what potential failures could develop as the pit expanded. Careful assessment of in-pit and wider data has resulted in development of a comprehensive picture of the structural geology, from a regional to pit scale, including interpretation of the structure to be expected in the final slopes. Work is continuing to develop this interpretation, for long term mine planning purposes.

Taffs Well Quarry is located within Carboniferous Limestone of the South Wales syncline. A re-evaluation of the geological structure was carried out, as a failure indicated changes in structural style not previously expected. Structural mapping identified thrust faulting associated with major folding. These faults could potentially lead to significant failures as the quarry was expanded. The model was used to predict the structural scenario in the final quarry profile and allowed geotechnical design to be more confidently carried out.

1 Introduction

The purpose of the paper is to present examples where detailed, expert analysis of geological structure has resulted in significant benefits in terms of understanding the potential behaviour of pit slopes. In particular, the Kumtor Open Pit in Kyrgyzstan and Taffs Well Quarry in South Wales have been chosen to illustrate this approach. The two pits are very different in terms of scale and tectonic history: the former a large open pit gold mine located in Central Asia with four tectonic phases, including relatively recent Himalayan deformation, and the other a large limestone quarry with one phase of Variscan contractional deformation. However, both have complex structural settings, the styles of which were not immediately apparent, particularly when assessed at the pit wall scale. This has resulted in potential stability problems that have required resolution before a robust geotechnical model could be generated and appropriate analyses undertaken.

2 The benefits of structural geology in open pit rock slope stability

A model of geological structure within a pit and its environs is essential in order to understand the potential for slope instability and almost all rock slope stability studies should address the structural geology of the site (Wyllie and Mah, 2004). However, it is the authors' experience that the interpretation of geological structure often neglects the wider, regional context, which generally sets the structural context for the styles of deformation that can be anticipated. Often only the specific area of the excavation or a particular pit wall has been assessed and this can lead to major features or deformation styles being missed. Thus, important information on the potential structural setting may not be used when assessing slope stability. This can have a major impact on the estimated stability of the slopes, particularly if new structural styles or changes in the orientation of features are revealed as new areas of the pit are developed. The main areas where a specific interpretation of geological structure can add value to the geotechnical investigation or open pit operation appear to be:

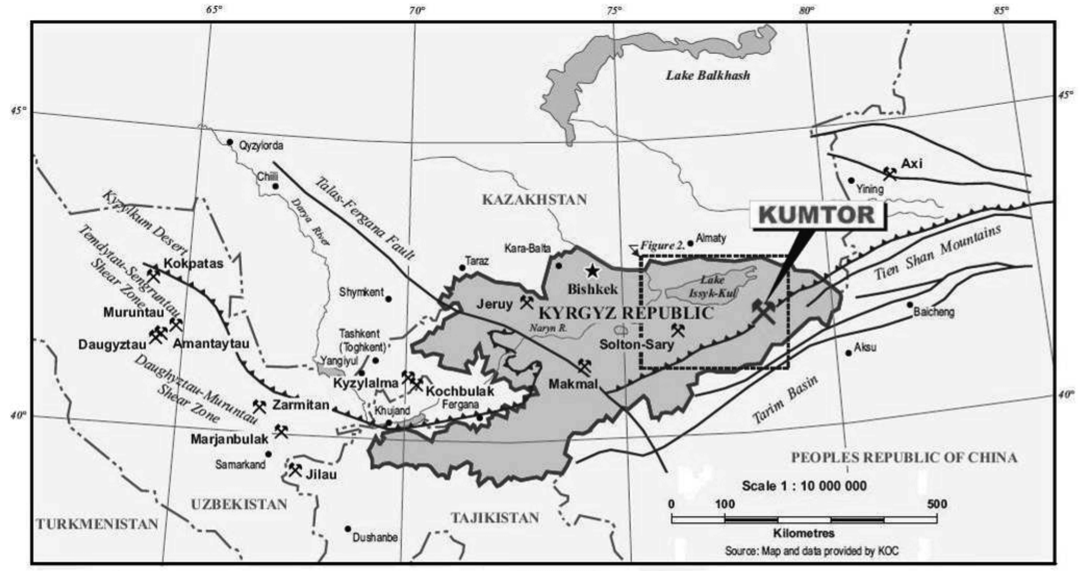
- Identification of the geometry and orientation of structural geological defects for use as primary inputs into the pit slope design process and thus helping the formation of geotechnical domains, so critical in the development of a robust pit geotechnical model.
- Identification of potential critical major structures or major structural styles that may not be apparent from the limited exposures available in the pit but may be inferred from regional tectonic features or interpretation.
- Understanding how and why the structural geology changes as the pit develops and using this knowledge as a predictive tool for day to day operational development, pit expansions and new projects.
- Interpretation of small-scale structures which can frequently be critical to understanding the bigger structural picture, even if they are not the immediate controlling factor in the stability of the slopes. Such structures can be indicators of regional tectonic processes.
- Reinterpretation of existing old geological models, which may reveal previously unrecognised structural conditions/styles that impinge on the geotechnical design.

Our experience is that in recent years more operations have recognised that a robust structural model is an important component of producing an adaptable geotechnical model that is required for the pit planning process. The structural assessment is therefore vital in helping to get the geotechnical model right, especially when creating large slopes at fast rates. The following case studies demonstrate where this approach has significantly improved the geotechnical assessment of the pit slopes.

3 Kumtor open pit structural geology assessment

3.1 Background to study

Kumtor is a large open pit gold mine, producing between 500,000 and 750,000 oz per year and is situated at an altitude of 4000 m in the Middle Tien Shan mountain range of eastern Kyrgyzstan (Figure 1). The climate is dry and continental with a mean annual temperature of minus 8°C. The mine is operated by the Kumtor Operating Company (KOC), which is a subsidiary of Centerra Gold Incorporated.



Source: Map and data provided by KOC

Figure 1 Location of Kumtor Gold Mine (after Centerra Gold Inc., 2006)

The pit wall, whose crest lies above 4400 m is in excess of 500 m in the NE portion of the pit and is proposed to be increased to approximately 600 m. In recent years the mine has experienced problems with pit slope stability and in 2002 there was a significant failure. Following on from this failure it was agreed that a more detailed structural geological assessment was necessary in order to further develop the geotechnical model as a predictive tool for future development of the open pit. In August 2004 a review of the structural geology of the current and future planned open pit was commenced.

3.2 Regional geological and tectonic setting

The region is characterised by Palaeozoic, intracontinental orogenic activity which has involved collision of the North and Middle Tien Shan. These two regions are separated by the Nikolaev Lineament, an important, regional scale, ENE trending suture which can be traced from Uzbekistan, through Kyrgyzstan to northern China (Figure 1). Juxtaposition of the Middle and North Tien Shan occurred during the Late Ordovician to Early Silurian (Caledonian Orogeny) and closure of the Palaeo-Asiatic Ocean (Zonenshain et al., 1990). The development of a new plate margin to the south and further subduction and closure of the Turkestan Ocean led to Hercynian deformation during the Late Carboniferous and Early Permian (Abeleira et al., 2000). Mineralisation occurred during the Hercynian orogenesis. Erosion and pene-planation occurred through the Mesozoic and the present topography is the result of the relatively recent deformation due to the Alpine collision between India and Asia during the Cenozoic (Abeleira et al., 2000). These major episodes of deformation have left their mark on the rocks observed in, and around, the Kumtor Open Pit and have created a complex structural geological framework.

3.3 Local geology of Kumtor

The Kumtor ore deposit occurs in the hangingwall of the Kumtor Fault Zone (KFZ) within a sequence of highly tectonised meta-sediments of Vendian age (Precambrian-Neoproterozoic). The KFZ is a possible splay fault off the Nikolaev Lineament and can be traced for more than 30 km along strike. The fault zone is approximately 600 m thick and is defined in places by a low angle structure with associated clay gouge at its base and a steep to sub-vertical, NE-SW trending, graphite filled fault at its top. It shows evidence of intense deformation and extreme shearing and consists of numerous closely spaced sub-parallel faults and complex folds incorporating and translating slivers of wall-rock and a number of footwall derived, exotic Cambro-Ordovician limestone blocks. The NW wall of the central pit is within the Kumtor Fault Zone and the SE Wall of the pit is in mainly unmineralised, but still highly deformed metasediments of Vendian age, again with a faulted contact to the ore zone below. The North and NE walls comprise all three main zones and are extremely structurally complex. Figure 2 shows the distribution of the main structural units in the north wall of the pit.

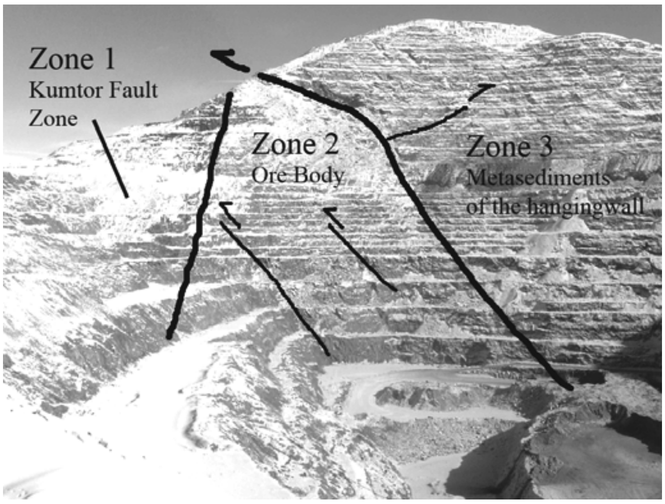


Figure 2 Photograph showing the main tectonic zones and the zone bounding faults in the North wall of the Kumtor central pit

3.4 Approach and methodology of structural re-assessment and analysis, 2004 to present

An initial review and examination of all the existing structural geology data and reports, as well as an assessment of the data gathering, analysis, presentation, storage systems and procedures in place within the Engineering and Geology Section of KOC was undertaken. As a result it was proposed that the model be re-evaluated using detailed mapping, re-analysis of stored data sets and the construction of a new set of serial cross sections across the pit. This work has been ongoing since 2004 and the resulting structural model is being continually updated, checked, confirmed and revised as more data becomes available.

Previously, structural work at Kumtor had focussed on supplying data as a response to short-term geotechnical planning requirements. As a consequence the broader structural geological setting of the pit was not evaluated. A large database existed but it was difficult to construct a model from this data alone and the resultant model was in need of additional information and analysis to allow it to be used most effectively for the pit slope designs.

Traditional methods of geological mapping and data processing were stressed for this type of work, including the use of field notebooks, careful analysis of structures accompanied by accurate field sketches and photographs, compilation of data maps at suitable scales down to 1:500, construction of hand-drawn cross sections, separation of data and interpreted cross sections (presented separately), and mapping across benches as well as along them in traverse corridors. The importance of this last point is demonstrated in Figure 3 where mapping across the benches can lead to a better understanding of the structural 'bigger picture'.

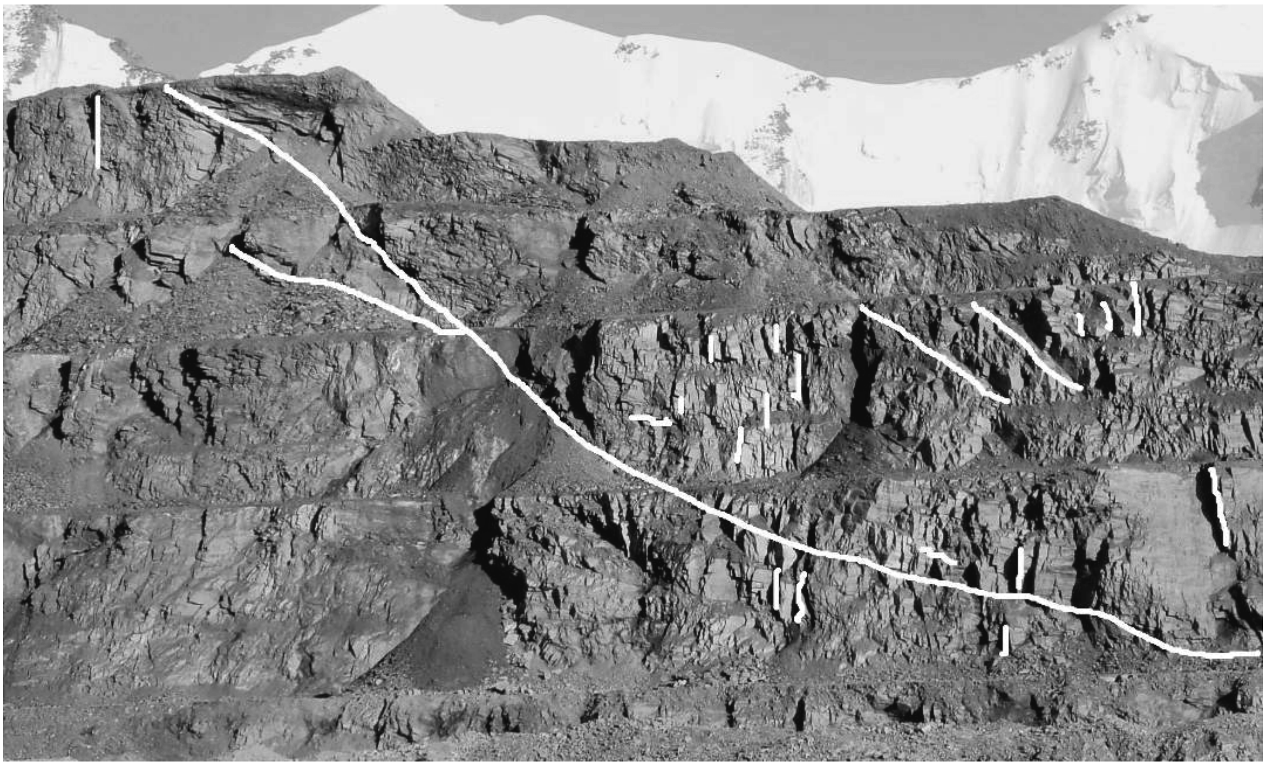


Figure 3 Photograph showing the importance of combining assessment of a major structure across multiple benches with mapping of minor pervasive features. Tectonic Domain 3 Kumtor Central Pit

For the structural re-evaluation plans and sections of both raw data and interpretation were compiled. It was also necessary to produce maps of both the foliation and faults, at appropriate scales (1:1000 and 1:2000), with areas of detailed interest at a scale of 1:500.

3.5 Revised structural model

The re-analysis of all the existing data, combined with that derived from new mapping, interpretation of new borehole drilling and preparation of maps and sections resulted in a revised and geologically viable structural model.

The pit area has been divided into a number of structural zones based on lithological character and spatial relationship to the ore zone (see below and Figure 4).

- Zone 0 - footwall to the Kumtor Fault Zone; thrust repeated rocks of Proterozoic and Palaeozoic age.
- Zone 1 - the Kumtor Fault Zone (KFZ); 600 m wide tectonic melange.
- Zone 2 - the Ore Bearing Zone; thrust slices of ore zone rocks and metasediments.
- Zone 3 - the hangingwall to the ore zone, comprising deformed Vendian metasediments.

The zones are fault bounded by long-lived faults (i.e. active during more than one deformation episode). Both the Ore Zone (Zone 2) and Zone 3 are subdivided into sub-zones defined by mineralogy and structural complexity respectively. The importance of the sub-division of Zone 3 is explained in Section 3.6.

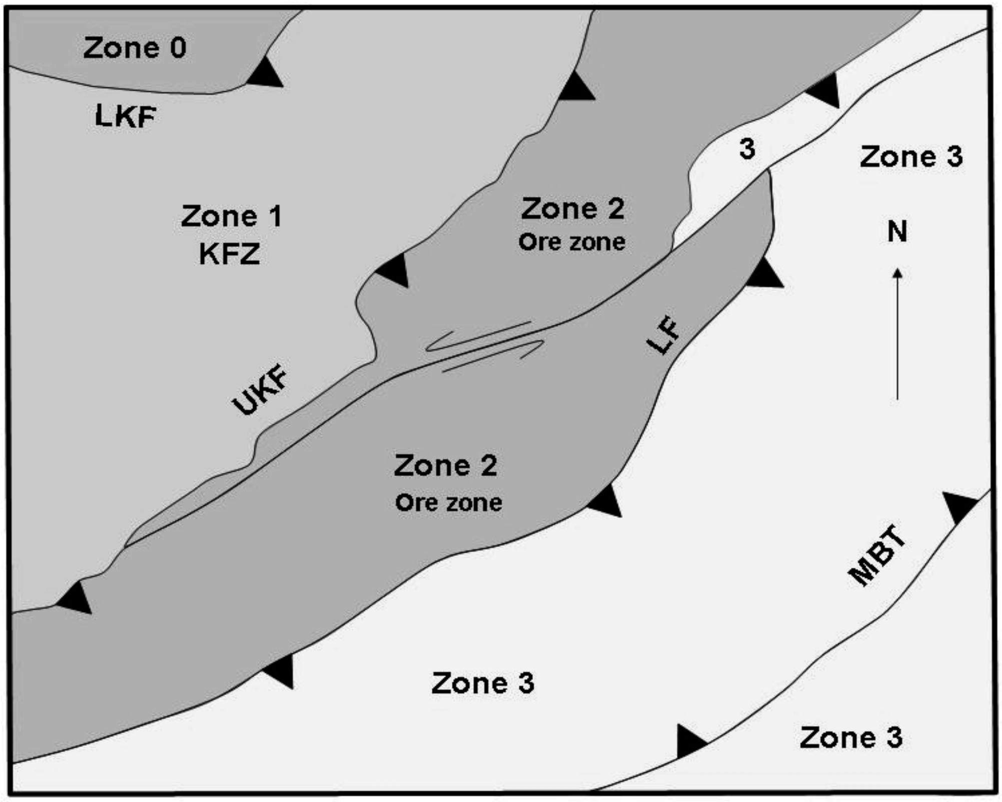


Figure 4 Sketch geological map of the Kumtor central pit area showing main tectonic zones and faults. LKF – Lower Kumtor Fault, UKF Upper Kumtor Fault, LF – Lysi Fault and MBT – Main Back Thrust. KFZ – Kumtor Fault Zone

Within the hanging wall rocks to the Kumtor Fault Zone (Zones 2 and 3), four phases of deformation (D1-D4) were initially identified with a corresponding suite of minor structures relating to each tectonic phase. A ubiquitous schistosity (S_1) resulted from the first phase of deformation (D1), axial planar to rarely preserved, isoclinally folded bedding and quartzose veins (Thomas, 1999). The S_1 orientation is variable but generally strikes NE-SW and dips to the SE. During the second phase of deformation (D2) the S_1 schistosity was folded by a series of open, asymmetric F_2 folds with an associated axial planar S_2 crenulation cleavage.

In general the S_2 cleavage dips shallowly to the west or south west and is perpendicular to the S_1 schistosity. F_2 folds verge NW and are commonly associated with thin-skinned, tectonic faults which on a small scale are represented by fore-thrusts, back-thrusts, pop-ups and side-wall ramps. The third phase of deformation resulted in both S_1 and S_2 being deformed by small-scale kink bands (F_3), D3 forethrusts and backthrusts and a series of NNE-SSW strike-slip faults. F_3 kink band folds plunge moderately to the east and axial plane surfaces dip steeply to the north. Extensional fractures are parallel to the E-W axial surfaces. D3 deformation is therefore related to N-S compression and is coincident with ore emplacement.

A final stage of deformation (Himalayan/Alpine episode – D4) has re-activated many of the pre-existing structures and has imparted a NE-SW striking structural fabric, with an overall SE dip, upon the main faults and S1 foliation in the region. The D4 structures are a function of the latest movement along the Upper Kumtor Fault and movement within the Kumtor Fault Zone.

Most fault structures in the area are persistent, weak structures, with thick gouge or tectonic breccia and are therefore potential failure surfaces. This is a function of the formation of more recent brittle faults and the re-activation of older pre-existing structures from earlier deformation events. It is important to distinguish these faults from older, sealed or cohesive faults which present less risk in terms of failing. The separation of faults into those of incohesive and cohesive nature is not always obvious and errors can be avoided by careful logging of geotechnical boreholes.

Whilst this assessment of the different stages of deformation and their associated tectonics can appear complex and very detailed, it is precisely this type of chronological analysis of events and understanding of stress directions that is essential in developing a robust structural model which enables us to assess which are the most important structures, what are likely to be their main characteristics and how they might change around the pit.

3.6 Analysis and geotechnical assessment of the main controlling structural fabrics of Pit’s SE Wall

The major rock fabric in the hanging wall at Kumtor is the S1 schistosity. Major fault and fold structures of various ages (D2-D4) and orientations deform this schistosity creating structural features which play an important role in determining the location of present day slip planes.

At an early point in the investigation the SE Wall (Zone 3) of the pit was focussed on due to ongoing slope creep and the likelihood of potential failure. As part of the investigation, the area was divided using the distribution of tectonic elements, into three sub-domains which had contrasting orientations in schistosity and faults. Stereographic projections were utilised to display and analyse these data.

It was clear that within all three zones of the SE wall there were elements that were contenders for the movement occurring in the SE Wall. Structures were present which have a low westerly ‘out of the wall’ dip. S2 cleavage fell into this category and consistently showed this attitude but is only locally steep in areas of intense F2 folding and when adjacent to thrust faults and is not a widespread feature across the pit wall or particular to specific structural domains. It was therefore not considered to be the most likely cause of large scale slope movement. The orientation of the widespread S1 foliation varied between structural domains and was regarded as a critical element where it dipped out of the pit walls to the west and WNW but where it dips SE there was no such cause for concern regarding slope stability. Faults are found in all structural domains and those with a NW and WNW dip are of particular concern in the SE part of the pit. Here they dipped out of the face and were the most likely cause of slope movement. In terms of their structural age they were of back thrust sense to the D2 and D4 deformation events. Forethrusts of these ages dip SE and are not critical in this part of the pit.

Borehole data in one area also showed a set of low angle planar elements that dipped shallowly out of the slope, dipping to the NW. In mine records these elements are described as schistose zones and shear zones in the borehole notes and are likely to represent fault planes which cross-cut schistosity (back-thrusts), shears which have formed parallel to schistosity during D2 flexural slip folding or folded faults/thrusts which could have formed during D1 or syn-D2. These features were the subject of some debate prior to the structural re-evaluation, since they had only been observed in the boreholes and not the pit. However, these features are present in the pit but had not been recorded or previously understood and they are an important element in the newly devised structural model. The structural model then becomes a predictive tool for delineating structures at depth or behind pit walls.

3.7 Conclusions of the Kumtor structural geology study

The difficulties in predicting the pit wall failures, prior to commencing a detailed structural study, showed that existing structural ideas relied too much on interpretations made by the Soviet investigations of the late 1980s and that these had not been developed as mining had progressed and new data were being collected. It was also recognised that a change in approach to data gathering was required, along with assistance with interpretations. During the study it also became clear that important structural elements, vital to developing a model for the region were not being gathered.

A program of in-house training, revised working practices and assistance with analytical techniques and interpretation was implemented. A structural course was held at the mine site involving a series of tutorials, practical classes and field sessions. This new teaching programme has been closely maintained over the following three years.

3.8 Incorporation of results to geotechnical pit slope stability studies

The relationship between the geological structure and the slope stability is now firmly established at Kumtor. The geotechnical consultants, structural geologist, and the mine planning department meet regularly on site and discuss slope design issues and where best to concentrate on mapping and drilling efforts. The cross-sections and plans produced by the Engineering and Geology Group at the mine are now at the stage where they can be used as the main predictive tool for assessing the likelihood of certain structural conditions being exposed in the next set of pushbacks. An example section through the SE wall of the pit is shown in Figure 5, below.

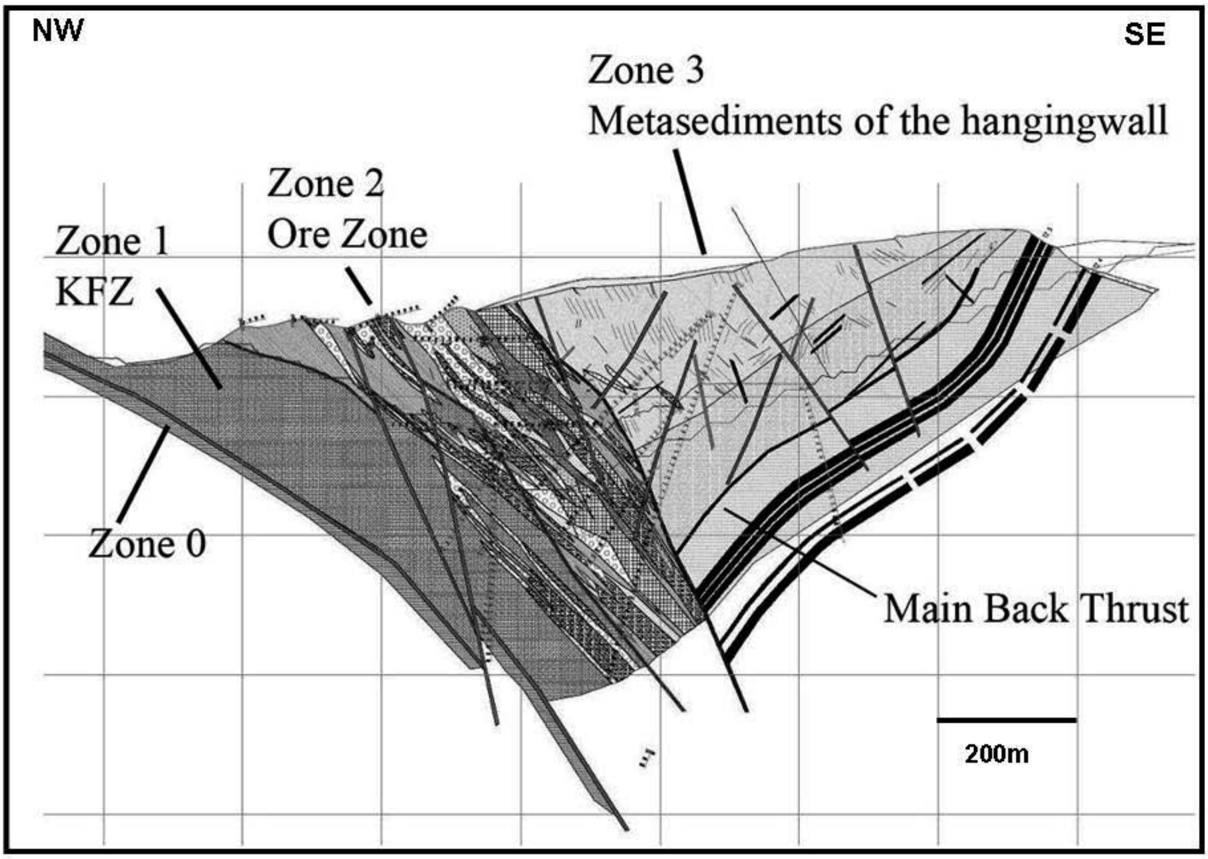


Figure 5 Typical structural section across the central pit illustrating the nature of the main faults. KFZ – Kumtor Fault Zone

The cross sections can now be used by the mine to target more detailed areas for mapping and drilling campaigns, to increase the amount of data available for the geotechnical model and improve the accuracy of the slope design. In particular, W and NW dipping structures predicted by the structural model and proved by detailed pit mapping have been confirmed to exist behind the SE Wall of the pit in follow-up geotechnical drilling programmes. Results from a targeted drilling campaign, based on the structural assessment, show numerous WNW dipping fault horizons and the presence of a major thrust zone running roughly parallel to the slope (Main Back Thrust). The drilling, having confirmed its position at depth, can now be accurately plotted, as shown in section in Figure 5 above. Three other tectonic zones have also been recognised behind the pit wall which can be traced over significant distances in the eastern part of the Central Pit. These faults consist of incohesive fault breccias and gouges and sometimes amalgamate to form fault zones that can be up to 10 m thick. These incohesive faults have in some places reworked older sealed faults and may provide potential unstable horizons in the rock mass.

The structural analysis has not predicted all the unfavourably oriented structures, nor has it prevented some unexpected failures occurring in the slopes, which may in some instances be difficult to avoid, considering the complex nature of the structure and the prevalence of major, weak structures that dip out of the slope. However, the approach (construction of detailed structural cross sections and the formulation of a structural model) has significantly improved the confidence of geotechnical prediction and allows the slopes to be managed more effectively and the instances of unplanned failures to be significantly reduced.

4 Taffs Well Quarry structural geology assessment

4.1 Background

Taffs Well Quarry is a large Carboniferous Limestone aggregate quarry located at the southern edge of the Variscan-age South Wales syncline, near the city of Cardiff, UK. It is owned and operated by Cemex (UK) Limited and produces approximately 1.5 Mtonnes of limestone from an excavation which reaches up to 100 m depth. In 2005 some interesting new thrust fault structures were observed in the recently quarried NW corner, in an area that had not been previously well exposed. Soon after a significant fault structure was exposed dipping out of the face in the topmost bench, with thick, slickensided gouge infill. Further along the strike of the strata, both the bedding and faults had been observed to be dipping gently northwards into the North Wall and thus the new structure was somewhat unexpected, indicating that a significant structural change was occurring in the excavation.

At roughly the same time a small failure occurred in the same area, thus bringing the discovery of the new, south dipping fault into focus. The failure surface was shown to be a weak, clay filled layer parallel to bedding and dipping gently to the north out of an active quarry face. The failure displaced approximately 1 m only and had little impact on safety or production, but the quarry owners wanted such features to be identified prior to expansion in this area to reduce the risk of a potentially consequential failure occurring.

4.2 Regional geology

Taffs Well Quarry is situated on the southern limb of a regional scale syncline that contains the South Wales Coalfield in its core (Figure 6). The region was folded in late Carboniferous times during the Variscan Orogeny which deformed southern Britain. In general fold axes trend E-W and major thrust horizons dip south.

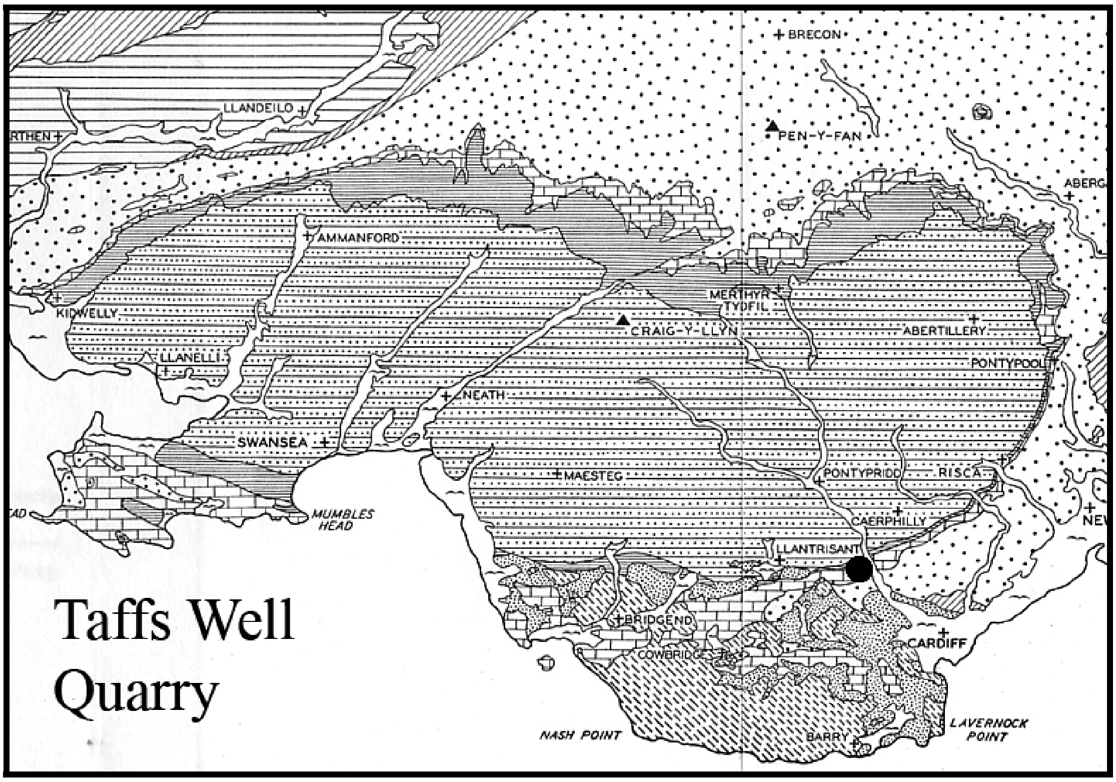


Figure 6 Geological map of the South Wales Coalfield and the location of Taffs Well Quarry (after Pringle and George, 1948)

4.3 Local geology

Taffs Well Quarry exposes dolomites forming part of the Carboniferous Limestone Series and is structurally positioned on the northern limb of the regional Usk Anticline (Figure 7). To the north of the quarry is the northerly dipping and younger Lower Millstone Grit Series and to the south the older, Devonian Old Red Sandstone, which also dips to the north. The large-scale structure is therefore relatively simple. However, smaller and more complicated parasitic structures, related to the regional folding, outcrop within the quarry. The main structures that occur within the quarry, from north to south, are the Pen-y-Garn Thrust, the Castell Coch Anticline and the Tongwynlais Syncline, as shown in Figure 7 (Squirrel and Downing, 1968). These elements define the overall structural setting of the quarry. The Pen-y-Garn Thrust has a general trend of ENE-WSW whilst the folds swing from an E-W trend in the east of the quarry to a NE-SW trend in the west. The folds plunge westwards. Faults (thrusts) with relatively minor displacements occur throughout the quarry and follow this regional trend, as does the bedding. The dip of the strata tends to be shallow but is sometimes locally moderate or steep in the immediate vicinity of thrust faults.

4.4 Structural review methodology

Since quarrying at Taffs Well is relatively low volume in comparison to a large open pit (e.g. Kumtor) it was possible to complete a detailed mapping exercise of the entire operation, which will only require infrequent updates. The detailed mapping was completed in one week followed by a period of time during which data maps and cross sections across the pit were completed. The interpretative structural maps and cross sections were then passed to the geotechnical team for the purposes of assessing the stability of the planned development of the NW corner of the pit.

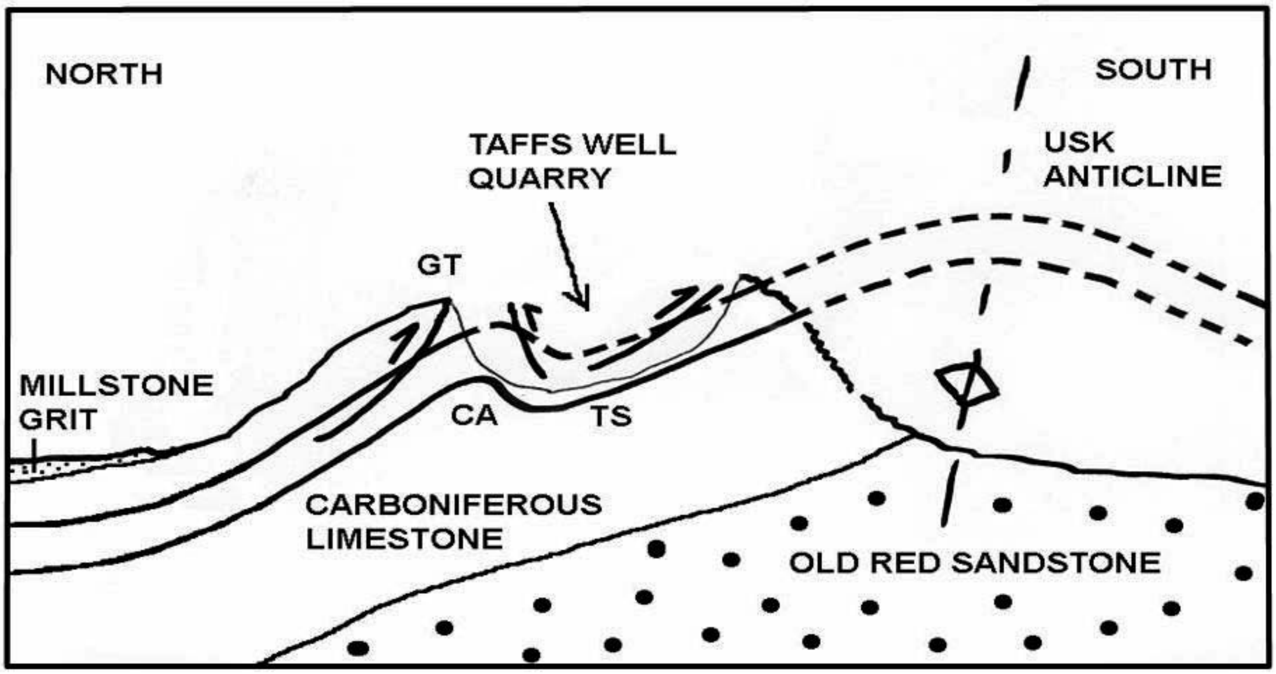


Figure 7 The geology of the Taffs Well area showing its structural position within the regional cross section. CA – Castell Coch Anticline, TS – Tongwynlais Syncline and GT – Pen-y-Garn Thrust (NB - section is not to scale)

4.5 Structural review results

Two main quarry-scale folds are present, forming an anticline-syncline (Z-fold) pair (see Figure 7) with related thrust structures on each fold limb, which correlate to the Castell Coch Anticline and the Tongwynlais Syncline (Squirrel and Downing, 1968) and which are clearly visible within the quarry. Minor thin-skinned thrust faulting occurs on the larger scale fold limbs, having formed in response to strain accommodation during flexural slip folding (Figure 8). The thrusts dip to both the north and south with a specific orientation/attitude dependant on the host fold limb. Many of these contractional faults become bed parallel with depth and tip-out within the syncline (out-of-the-syncline thrusts).

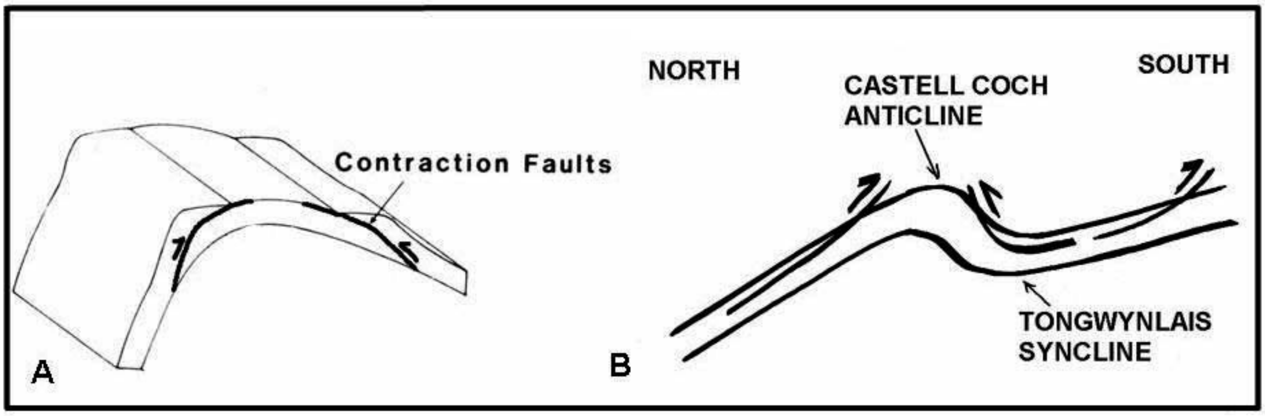


Figure 8 (A) Illustration showing the position of contractional faults (e.g. thrusts) during flexural slip folding on an anticlinal structure. (B) Location and attitude of thrust faults in relation to folds seen at Taffs Well Quarry

Flexural slip on bedding planes also occurs with displacement/movement directed towards the fold axis. The orientation and location of these thrust faults is one of the critical features in terms of quarry planning in that they are the most likely planes of weakness leading to slope failure, especially if the faults are not sealed or contain incohesive fault gouges or breccias. The presence of the thrusts means that, as the faces are developed, new structures that dip more steeply than the bedding may be encountered abruptly, as they splay off the bedding planes, and result in planar slab failures at either a bench or multi-bench scale.

The main fault at the quarry is the Pen-y-Garn Thrust, which cuts the northern limb of the Castell Coch Anticline and can be traced through part of the north wall of the quarry. All other thrust faults can be considered minor in terms of structural displacement of strata but can still have a significant impact on the pit wall stability, depending on their location relative to the existing and planned slopes, and also depending on their specific geotechnical characteristics. Other structures consistent with the folding and the low angle thrust tectonic model were observed around the quarry. Low angle listric shaped faults, which become bed parallel with depth are common and tip-folds, lateral ramps and pop-ups are present, as shown in Figures 9 and 10 below.

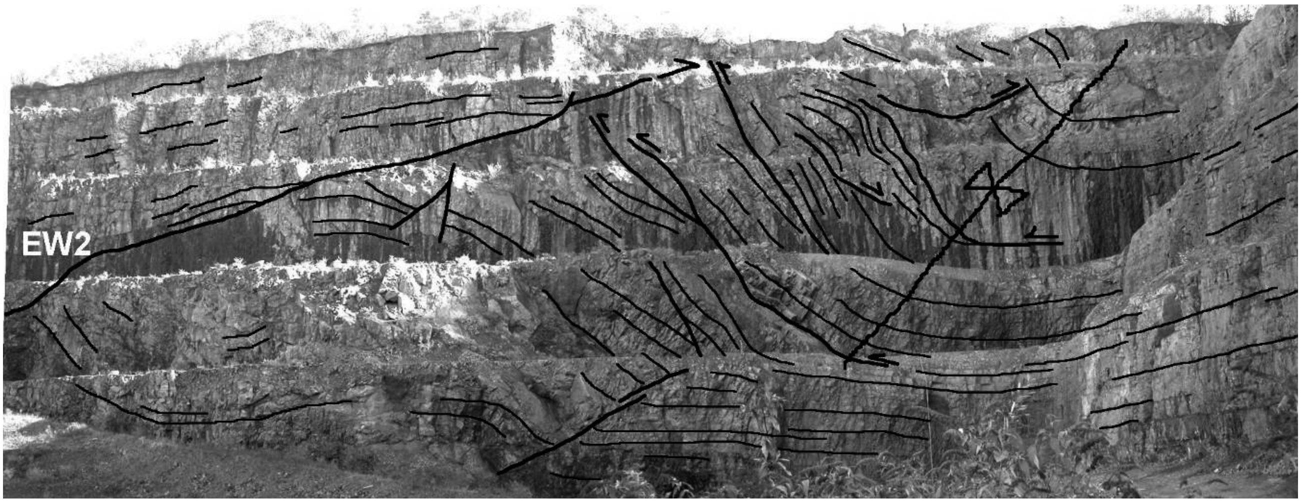


Figure 9 Tip-fold in the south-east corner of the quarry

Figure 10 Close-up of lateral ramp in South Wall of quarry. Movement is to the south and into the face. Thrust dips out of the face and is parallel to bedding on the left side of the image

Because many of the thrust faults are either bedding parallel where they are exposed, or cut the bedding at very low angles, these structures are difficult to identify and the other, more obvious structures, such as the back-thrusts, pop-ups and tip folds give good supporting evidence for the style of deformation. The structures shown in Figures 9 and 10 helped define the structural model for the pit, even though they were located in a different part of the quarry that was not being developed. Figure 11 shows a situation where a thrust truncates bedding at a very low angle, its actual morphologoly not being immediately apparent, especially when thrusts merge into bedding and when there are zones of zero displacement further back into the limbs of the folds.

Figure 11 Thrust showing low angle truncation of bedding

4.6 Geotechnical implications

The thrust faults related to the main anticline-syncline structure of the quarry, as identified by the structural review, were of great significance to quarry planning, especially during a phase of quarry expansion and with the experience of a previous failure along the quarry wall. The structure of the quarry was oversimplified in existing models and local pit wall scale faults were not understood in sufficient detail, such as the fault shown in Figure 11.

The strike of the bedding and the plunge of the syncline-anticline pair relative to the existing and planned pit slopes also complicated the quarry planning process. The variable fold axial trends and the constraints imposed on the pit development by extraction boundaries meant that as the pit developed from east to west, the structure relative to the pit wall changed. From a situation where the bedding was generally dipping into the pit slope (north limb of Castell Coch Anticline), the bedding began to dip out of the face as the excavation encountered the south limb of the anticline. Whilst bedding dipping out of the face at a shallow angle was considered manageable, the possible presence of more steeply dipping thrusts was considered to be a significant risk. Thus it was critical to understand whether there was a large thrust structure that was sitting within the pit slope in the pit expansion area, which could potentially cause a major slope failure if it were exposed.

Geotechnically, the most important feature of the structural geology in the north wall is the interaction of structures in the immediate footwall to the Pen-y-Garn Thrust, where faults dip into, and out of, the proposed quarry faces. The structural review suggested that a south dipping fault daylights mid-way down the north wall and has an associated north dipping, thrust splay which also daylights on the north wall. This complex type of thrust arrangement is not readily observed in the faces, as shown in Figure 12 but is implied by the structural model and can be traced through detailed mapping of the exposure in more than one plane. These structures were of critical importance in understanding what is likely to occur during the next phase of development. If this structure exists in the planned development area, and depending on its orientation and geotechnical characteristics, it could affect the north wall by a planar sliding mechanism parallel to the thrust.

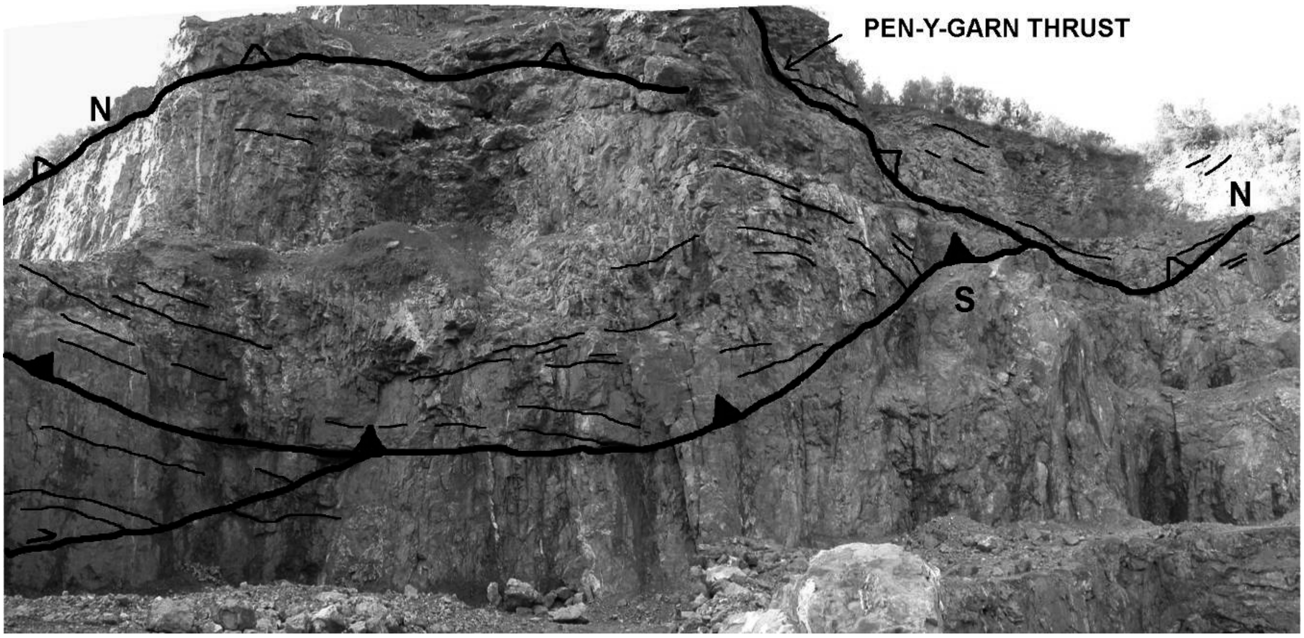


Figure 12 Looking north at structures in the footwall of the Pen-y-Garn Thrust (top). Note how the north dipping thrusts cut the south dipping thrusts along the north wall of the quarry. N – North dipping thrust, S – South dipping thrust

Also observed in the southern limb of the Tongwynlais Syncline are numerous north dipping thrusts, which emerge from the syncline (see Figure 13). This was also extremely important for quarry planning, since development of the northwest corner of the excavation would result in north facing slopes as well as the south facing slopes in the north wall. North facing cuts would potentially expose multiple thrust faults dipping out of the slope. The configuration of these faults in this wall was the main structural control in the 2005 failure.

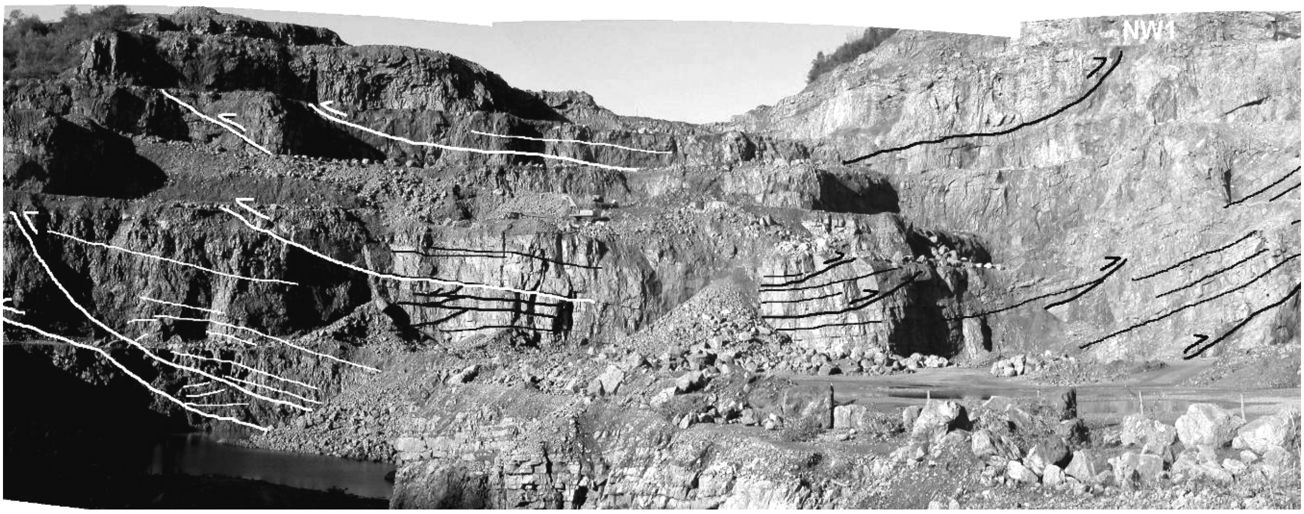


Figure 13 Looking west at the syncline in the NW corner of the excavation, showing the presence of south dipping thrusts on the south-dipping limb and north dipping thrusts on the north-dipping limb. Arrows show the movement directions of the thrusts

Following the structural interpretation, the revised structural geological map and interpretative cross sections which detailed the complex thrust fault configuration, were combined with the proposed quarry plans to help in predicting the likely position and orientation of the main north wall thrusts relative to the planned pit slopes. These sections were then analysed using slope stability software. Geotechnical parameters for each of the main structural sets were defined from the mapping data and previous geotechnical studies at the quarry.

Using the new structural model and the predicted locations of the structures in the final quarry wall the slope stability analysis allowed the quarry planners to adjust the development plan without compromising safety, loss of reserves or needing to seek additional consents to quarry beyond the allowable extraction limits.

5 Concluding remarks

The examples described clearly show that in many instances a detailed structural geological interpretation is needed to develop a robust geotechnical model that can be used to base future geotechnical decisions in the mine planning process. It is of great benefit to geotechnical engineers and engineering geologists that they recognise the value that detailed structural geological analysis can add to pit slope design.

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