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

Presented to: Slope Stability 07

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Introduction

- 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.
- Commonly only the local area is generally assessed. This can lead to major features or deformation styles being missed.
- This presentation presents examples where structural geological analysis has delivered significant benefits to understanding the pit slope stability issues at two distinct sites

Benefits of Structural Geological Interpretation

- Identification of structural geological defects for use as primary inputs into the pit slope design process, thus helping the formation of geotechnical domains.
- Identification of potential critical major structures or major structural styles that may not be apparent from the limited exposures available, 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.
- 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.
- Reinterpretation of existing old geological models, which may reveal previously unrecognised structural conditions/styles that impinge on the geotechnical design.

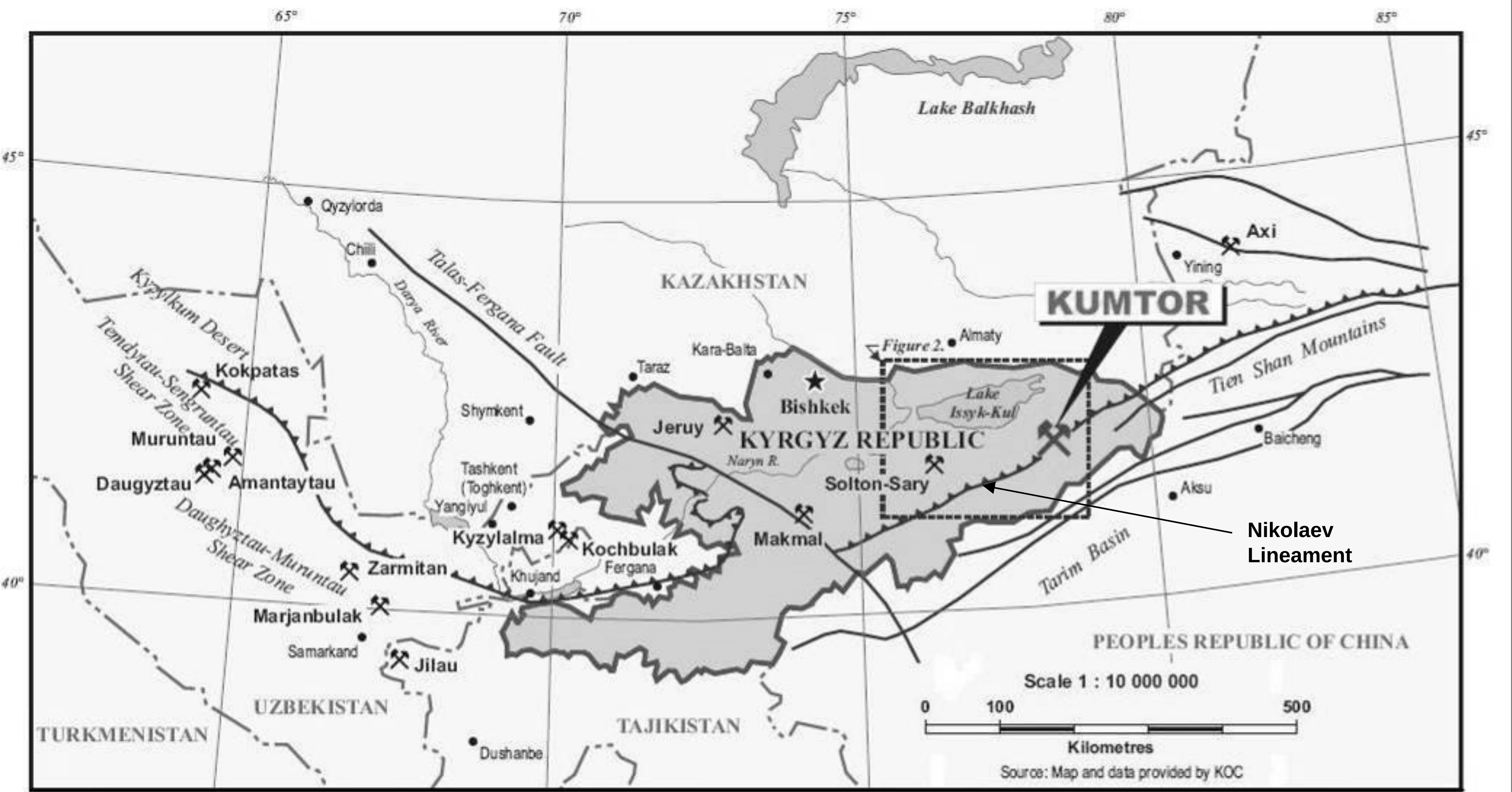
Kumtor Open Pit Structural Interpretation

- Kumtor is a large open pit gold mine, producing between 500,000 and 750,000 oz per year, situated at an altitude of 4000 m in the Middle Tien Shan mountain range of eastern Kyrgyzstan.
- The mine is operated by the Kumtor Operating Company (KOC), a subsidiary of Centerra Gold Inc.
- The NE pit wall is in excess of 500 m high and up to 4400m elevation.
- In recent years the mine has experienced problems with pit slope stability and in 2002 there was a significant rock slide in the high wall of the pit.
- As a result 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.

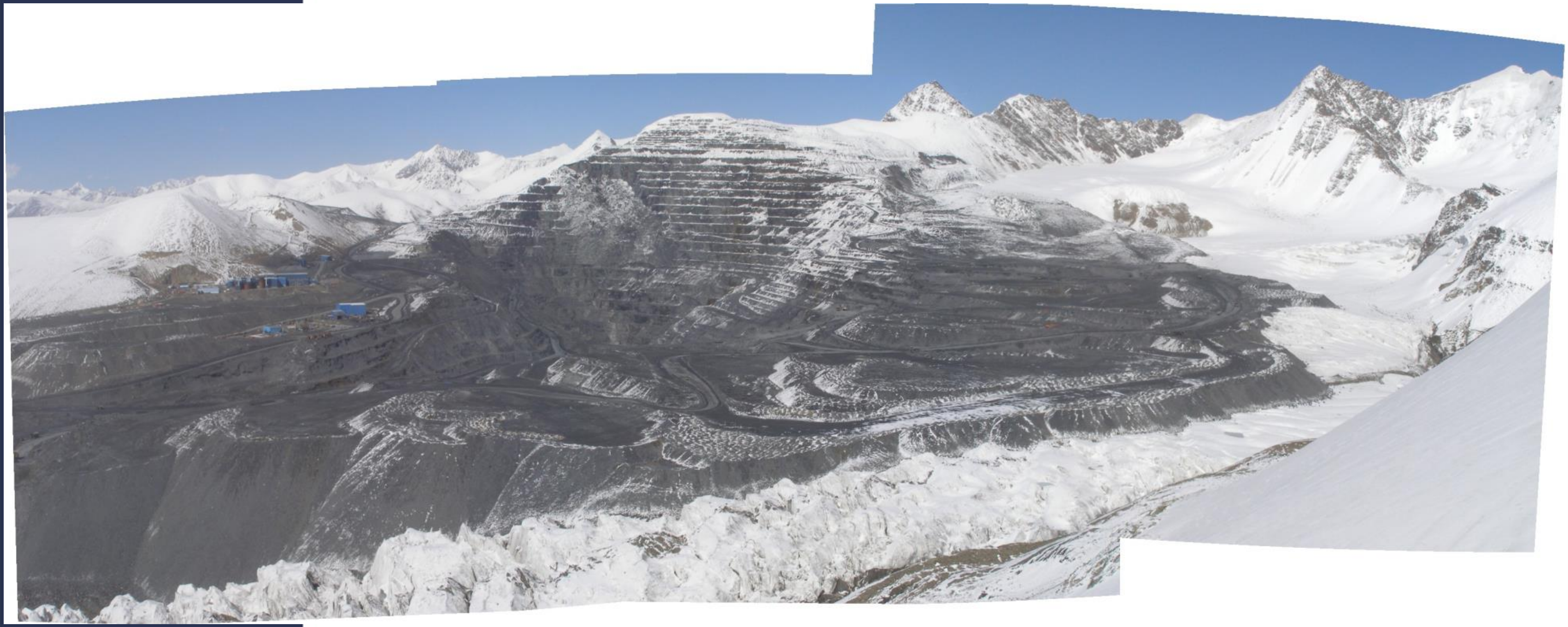
Approach

- Initial review and examination of all existing structural geology data and reports, as well as an assessment of the data gathering, analysis, presentation, storage systems and procedures.
- Result: proposed re-evaluation of structural model using detailed mapping, re-analysis of stored data sets and the construction of a new set of serial cross sections across the pit. Ongoing since 2004 and being continually updated.
- Previously, structural work had focussed on supplying data as a response to short-term geotechnical planning requirements. Result was that 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. More information and analysis were needed.
- Traditional methods of geological mapping and data processing introduced: 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, and mapping across benches as well as along them in traverse corridors.

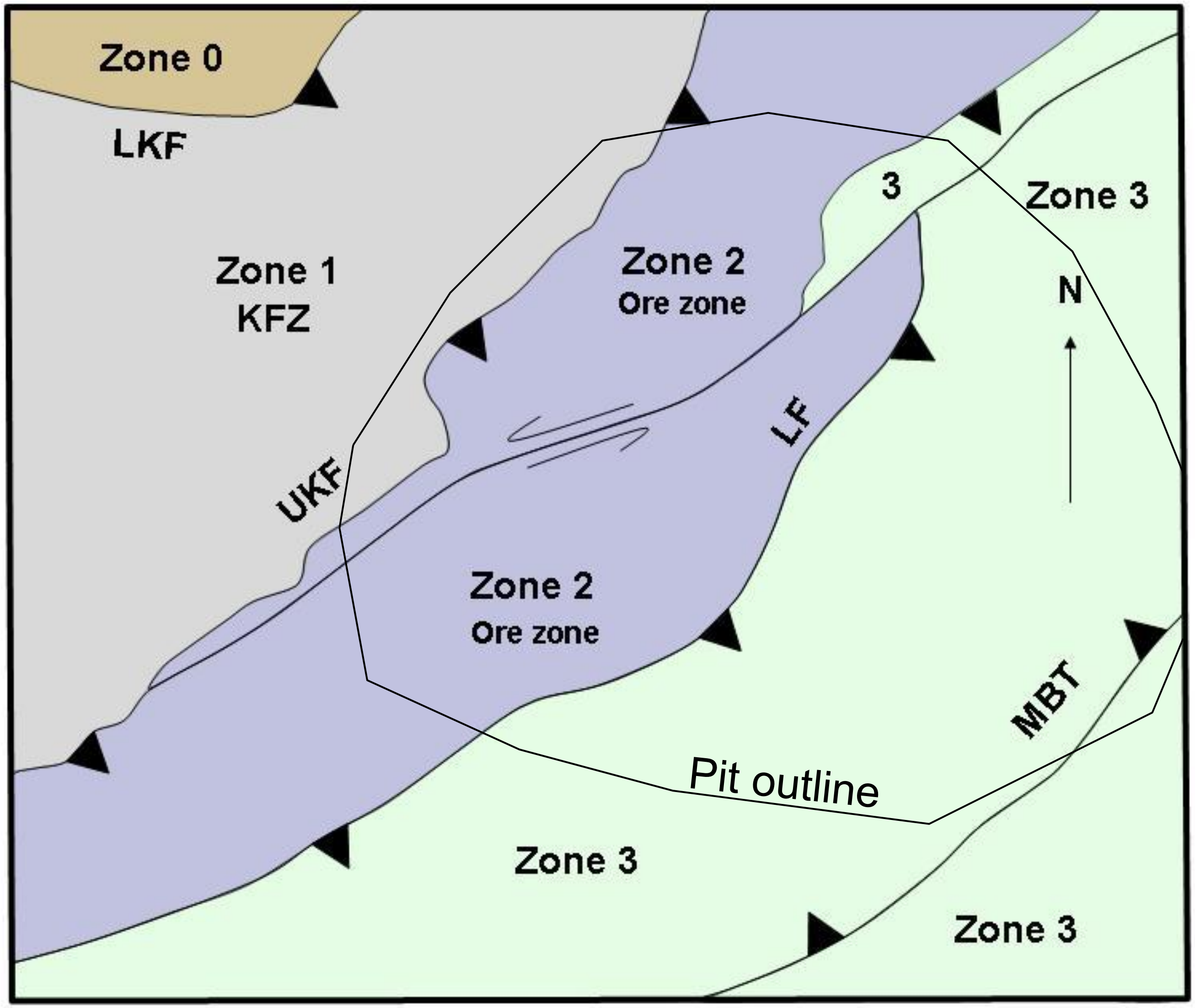
Location & Structural Setting of Kumtor Mine



Kumtor Central Pit

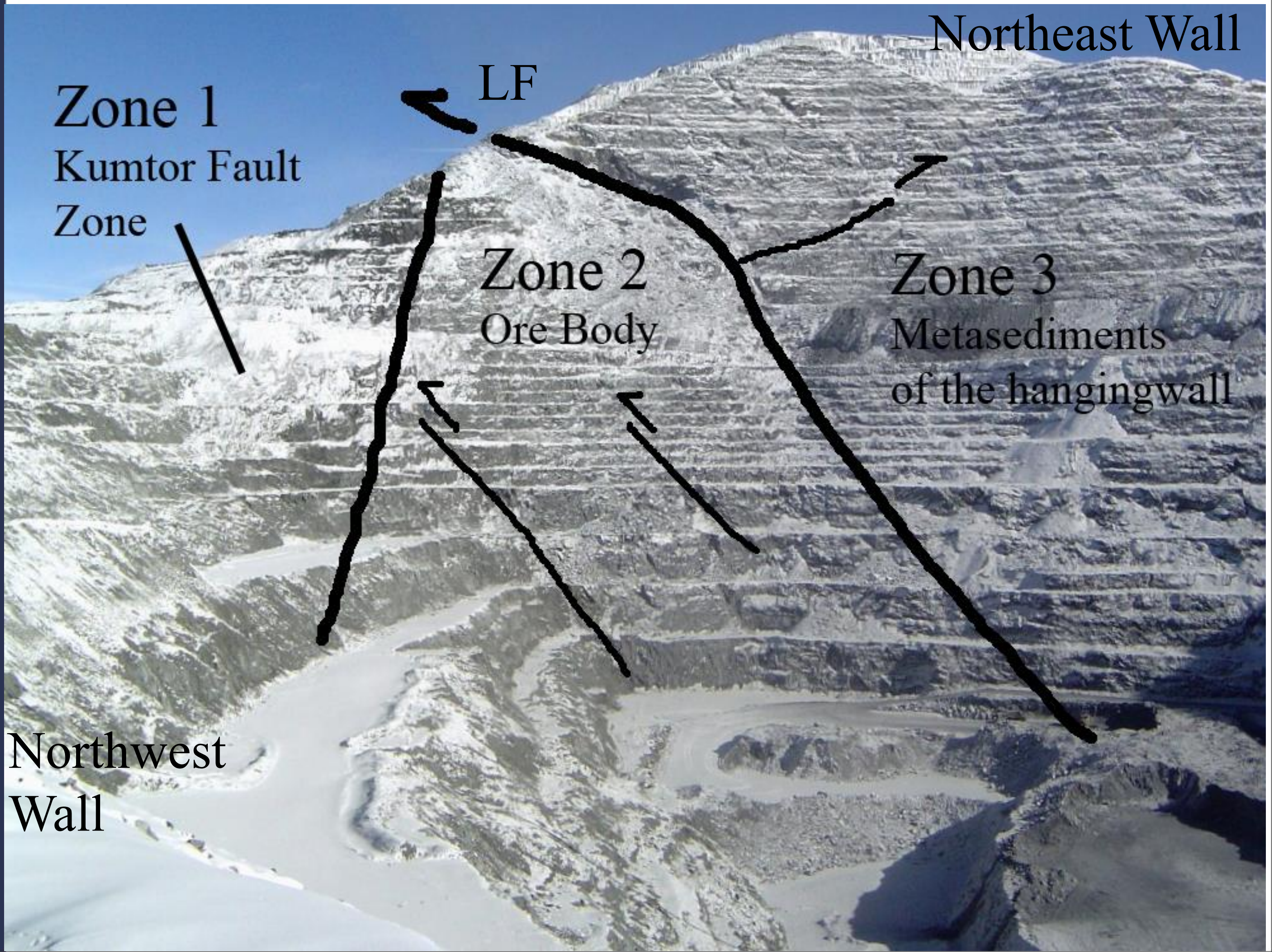


Revised Structural Model



Zones 2 & 3: Four phases of deformation (D1-D4). There is a corresponding suite of minor structures relating to each tectonic phase.

Pit Geology – looking to NE



Structural Zonation of the Pit

- **The pit area has been divided into a number of structural zones based on lithological character and spatial relationship to the ore zone**
  - Zone 0 – footwall to the Kumtor Fault Zone – thrust repeated rocks of Proterozoic and Palaeozoic age
  - Zone 1 - the Kumtor Fault Zone (KFZ) – 600m wide tectonic melange
  - Zone 2 - the Ore Bearing Zone – thrust slices of ore zone rocks and metasediments
  - Zone 3 - 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.**

Structural Model & Geotechnical Implications

- **Zone 2 & 3 Structures:**

  D1 deformation results in ubiquitous schistosity (S1);

  D2 deformation folded S1 schistosity into a series of open, asymmetric F2 folds with an associated axial planar S2 crenulation cleavage; SE-NW tectonic transport direction

  D3 deformation resulted in both S1 and S2 being deformed by small-scale kink bands (F3), D3 forethrusts and backthrusts and a series of strike-slip faults (steep lateral ramps) S-N tectonic transport direction

  D4 deformation has re-activated many of the pre-existing structures and has imparted a NE-SW striking structural fabric, with an overall SE dip (locally dipping NW), 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. SE-NW tectonic transport direction

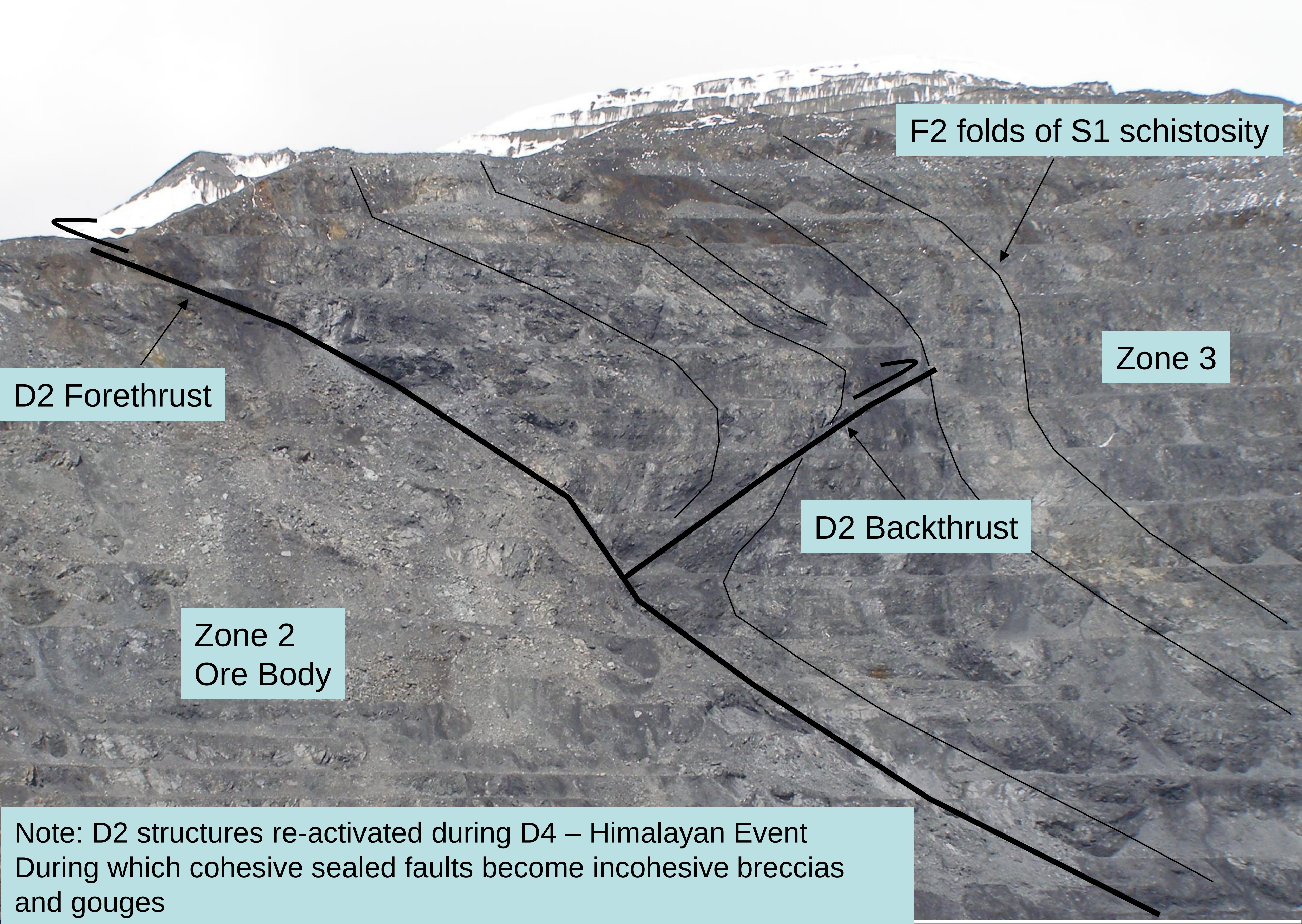
- **Most fault structures in the area are persistent, weak structures, with thick gouge or tectonic breccia and are therefore potential failure surfaces.**
- **A function of the formation of more recent brittle faults and the re-activation of older pre-existing structures from earlier deformation events.**
- **Important to distinguish these faults from older, sealed or cohesive faults which are stronger. Not always obvious which is why: needs careful logging of geotechnical boreholes.**

Main structural controls on pit slope stability

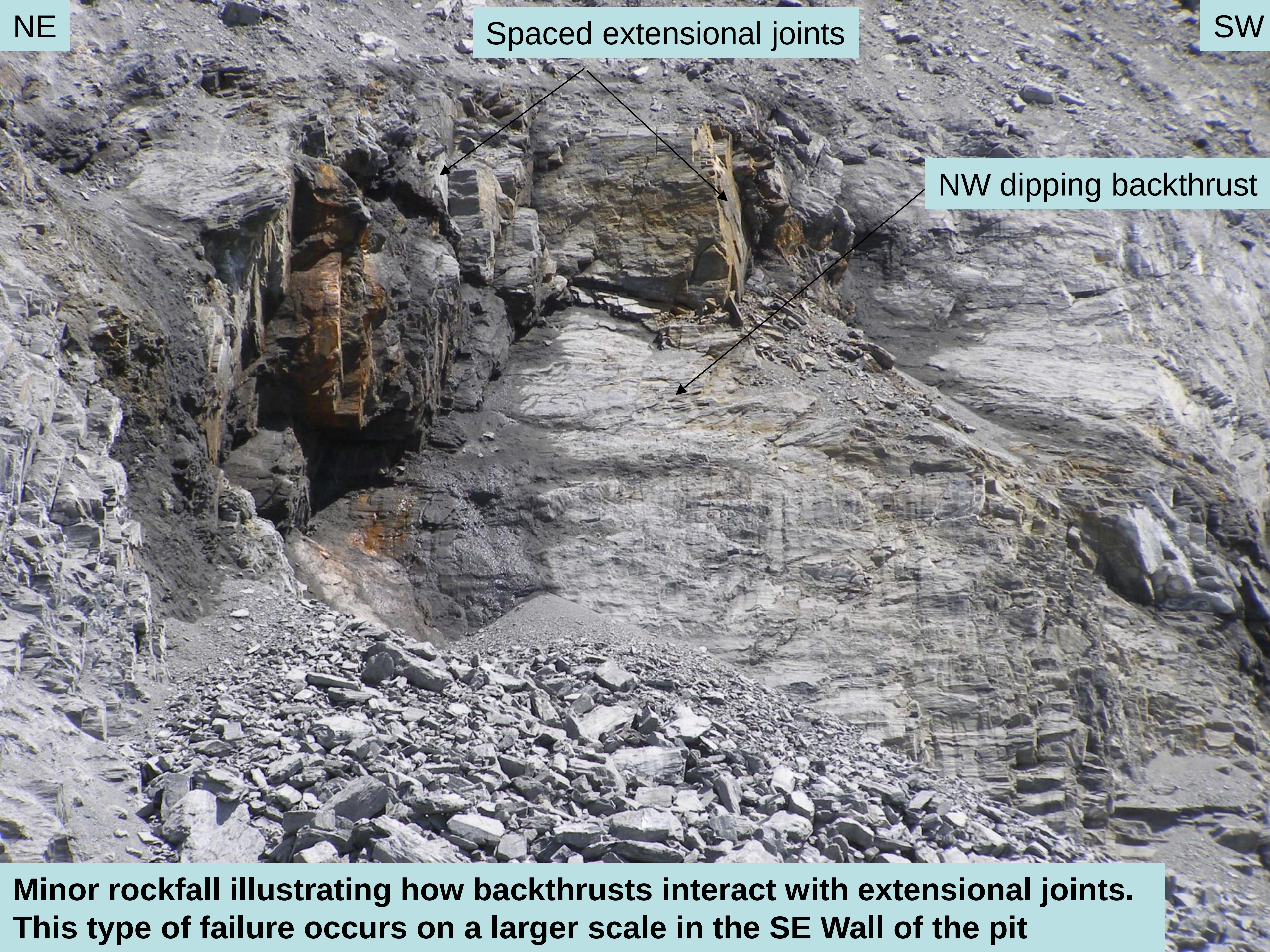
- **The major rock fabric in the hanging wall is the S1 schistosity. Major faults and folds of various ages (D2-D4) and orientations deform S1 creating structural features which play an important role in determining the location of present day slips.**
- **The SE Wall (Zone 3) of the pit was focussed on due to ongoing slope creep and the likelihood of potential failure. The area was divided, using the distribution of tectonic elements, into three sub-domains which had contrasting orientations in schistosity and faults.**
- **In all three zones there are structures which have a low westerly 'out of the wall' dip.**
  - S2 cleavage is only locally developed in areas of intense F2 folding and when adjacent to thrust faults and not a widespread feature.
  - S1 foliation orientation varies between structural domains and is critical where it dips out of the pit wall
  - Faults occur 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 dip out of the face and are the most likely cause of slope instability.
  - The NW dipping faults in the SE wall are of back thrust sense to the main D2 and D4 SE dipping fore-thrusts which are not critical to slope stability in this part of the pit.

Structural Features

Main Structures of the High Wall – Central Pit



Note: D2 structures re-activated during D4 – Himalayan Event
During which cohesive sealed faults become incohesive breccias
and gouges



Minor rockfall illustrating how backthrusts interact with extensional joints. This type of failure occurs on a larger scale in the SE Wall of the pit

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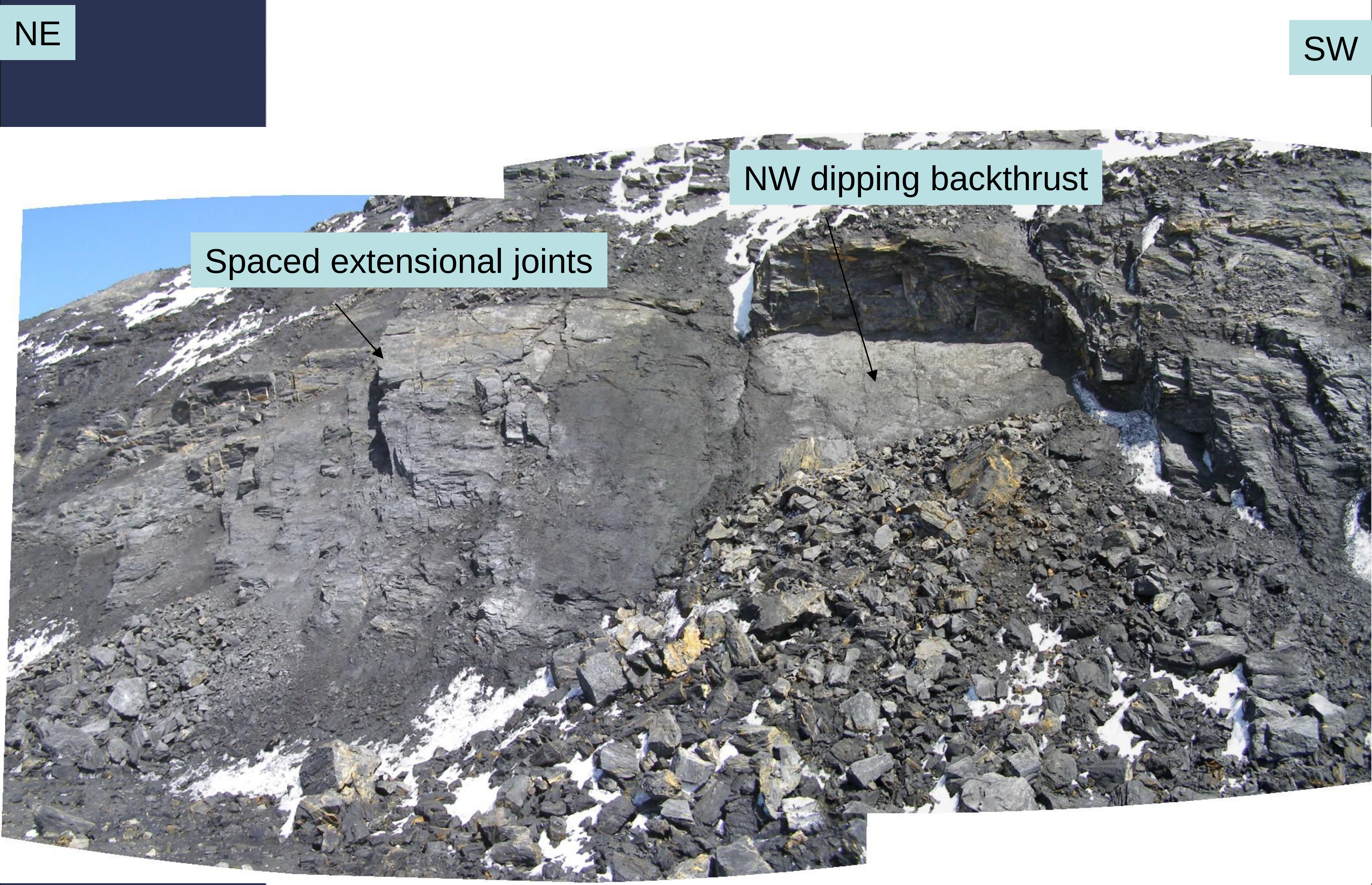
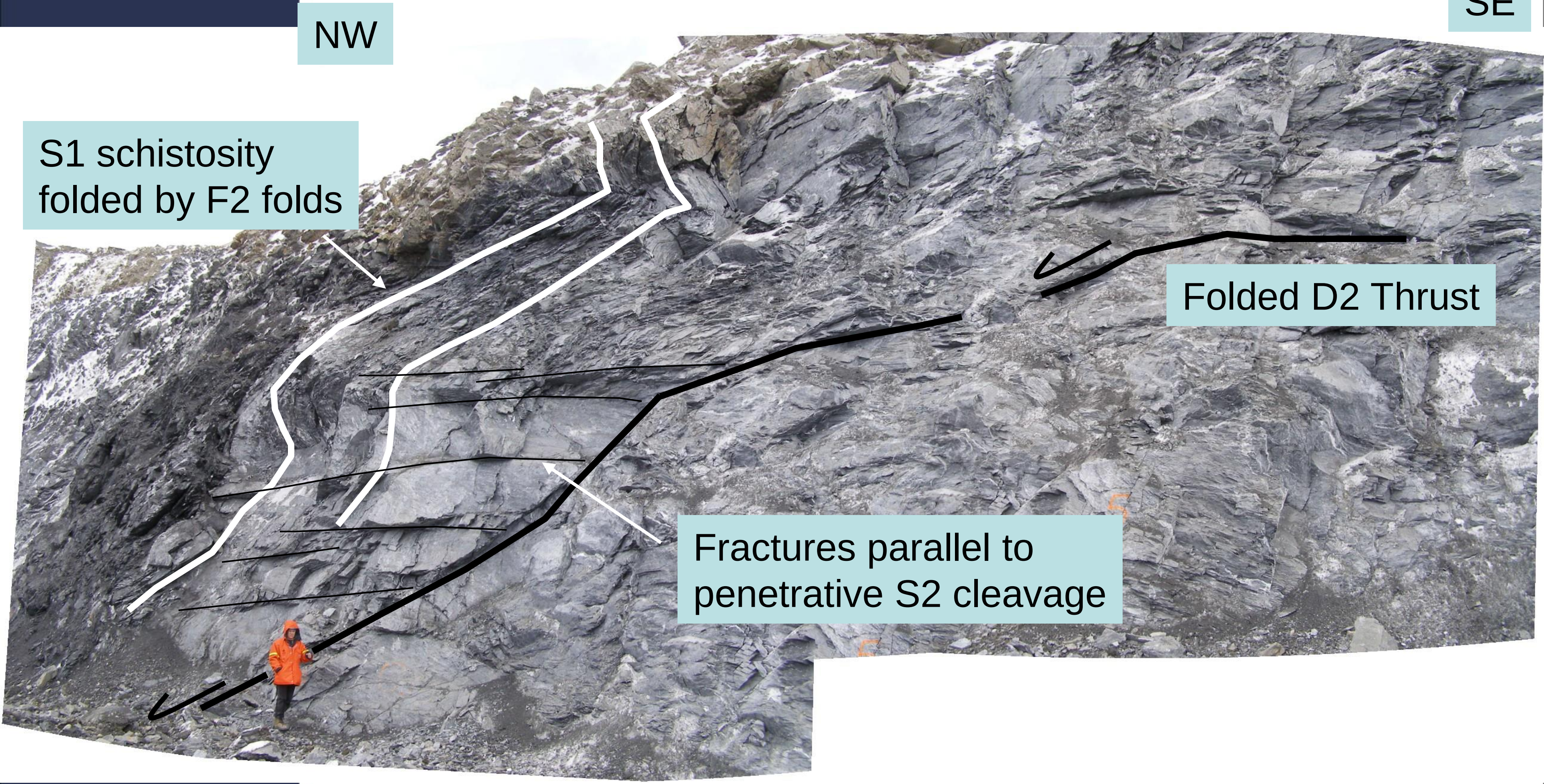


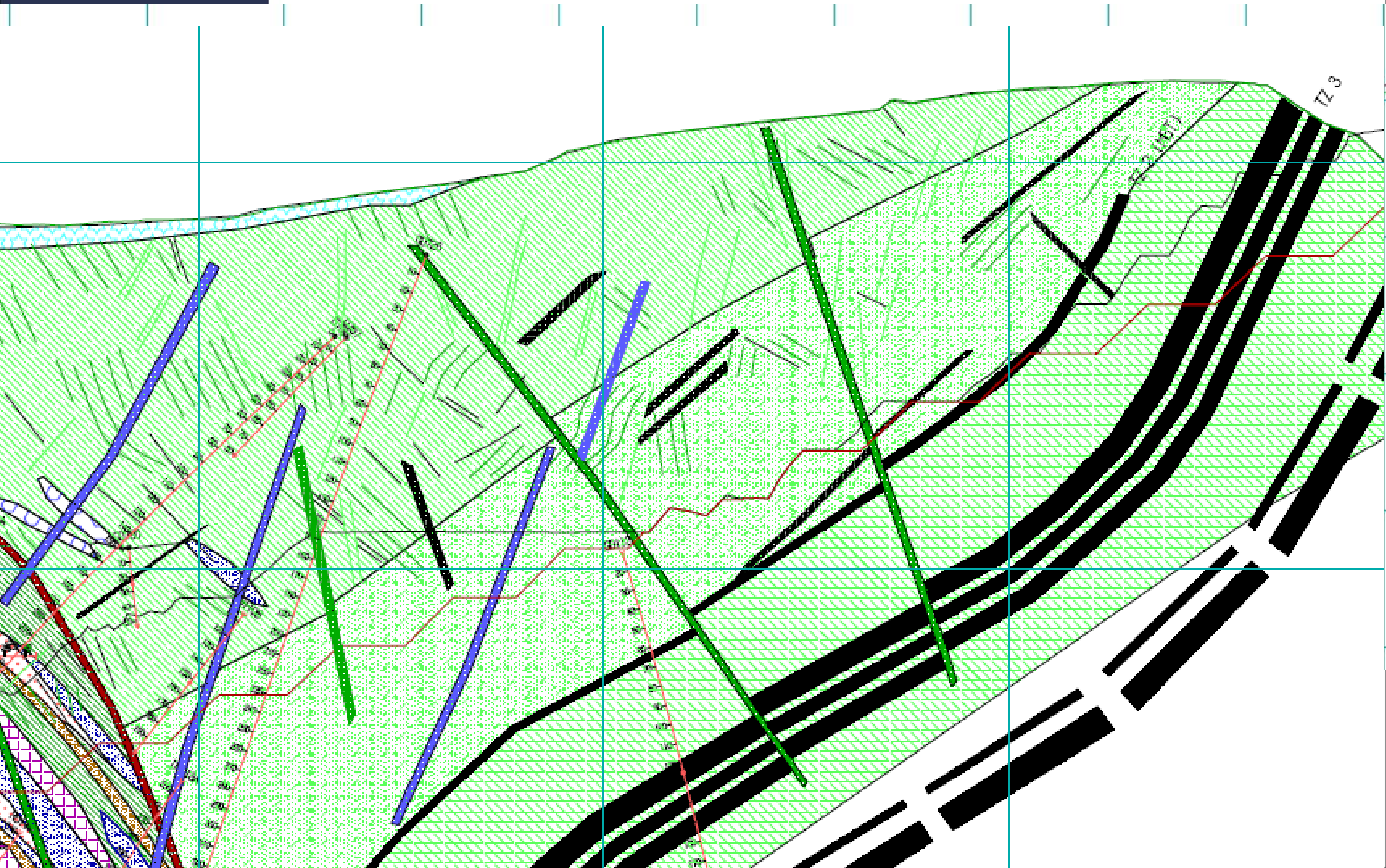
Out-of-the wall dipping structural elements which have a direct impact on slope stability



Main structural controls on pit slope stability, continued

- Borehole data in one area showed low angle planar elements dipping shallowly out of the slope, to the NW.
- Mine records describe them as “schistose zones” and “shear zones”
- Actually 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.
- The subject of some debate prior to the structural re-evaluation, since they had only been observed in the boreholes and not the pit.
- These features are in fact present in the pit but had not been recorded or previously understood.
- They are an important element in the newly devised structural model which can now be used as a predictive tool for delineating structures at depth or behind pit walls.
- Subsequent geotechnical drilling programmes with oriented core has confirmed the presence of numerous out of the wall NW dipping faults.

Interpretative Cross-section



Results and Conclusions

- The difficulties in predicting the pit wall failures, prior to the detailed structural study, showed that existing structural ideas relied on 1980’s interpretations.
- These had not been developed as mining had progressed and new data were collected. Important structural elements, vital to developing a model, were not being gathered.
- A change in approach to data gathering, plus assistance with interpretations was required. A program of in-house training including a structural geology course, revised working practices, plus analytical and interpretational assistance was implemented,. The teaching programme ongoing.
- 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 mapping and drilling efforts.
- The cross-sections and plans produced can be used as the main predictive tool for assessing the likelihood of certain structural conditions being exposed in the next set of pushbacks.

Conclusions & the Way Forward

- Cross-sections now used 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.
- West 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.
- Three other fault/shear zones have also been recognised behind the SE wall which can be traced over significant distances in the pit. These faults contain incohesive fault breccias and gouges and sometimes amalgamate to form fault zones that can be up to 10m 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 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.

Taffs Well Quarry Structural Reassessment

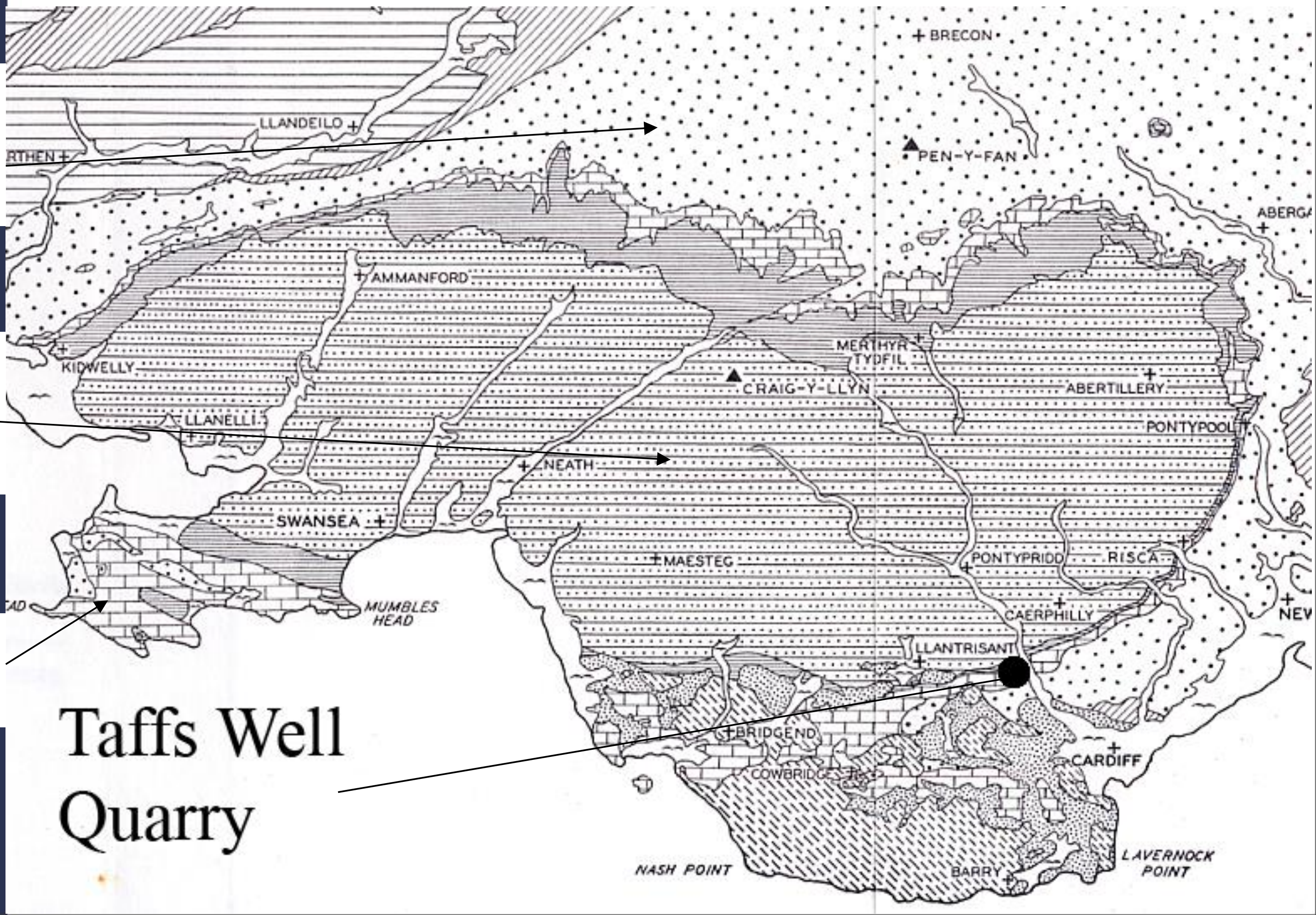
- A large Carboniferous Limestone aggregate quarry located at the southern edge of the Variscan-age South Wales syncline, near the city of Cardiff, UK.
- Operated by Cemex (UK) Limited, producing approx. 1.5 Mtonnes limestone from a maximum 100m deep excavation.
- In 2005 new thrust fault structures were observed in the recently quarried NW corner, in an area that had not been previously well exposed.
- A significant fault structure was exposed dipping out of the face in the top bench, with thick, slickensided gouge infill. Further along strike, both the bedding and faults had been observed to be dipping gently N into the North Wall.
- The new structure was unexpected and indicated that a significant structural change was occurring in the excavation.
- A small failure occurred in the same area at roughly the same time, focussing attention on the new, south dipping fault.
- 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.
- Cemex wanted such features to be identified prior to expansion in this area to reduce the risk of a potentially consequential failure.

Location of Taffs Well Quarry & Geological Setting

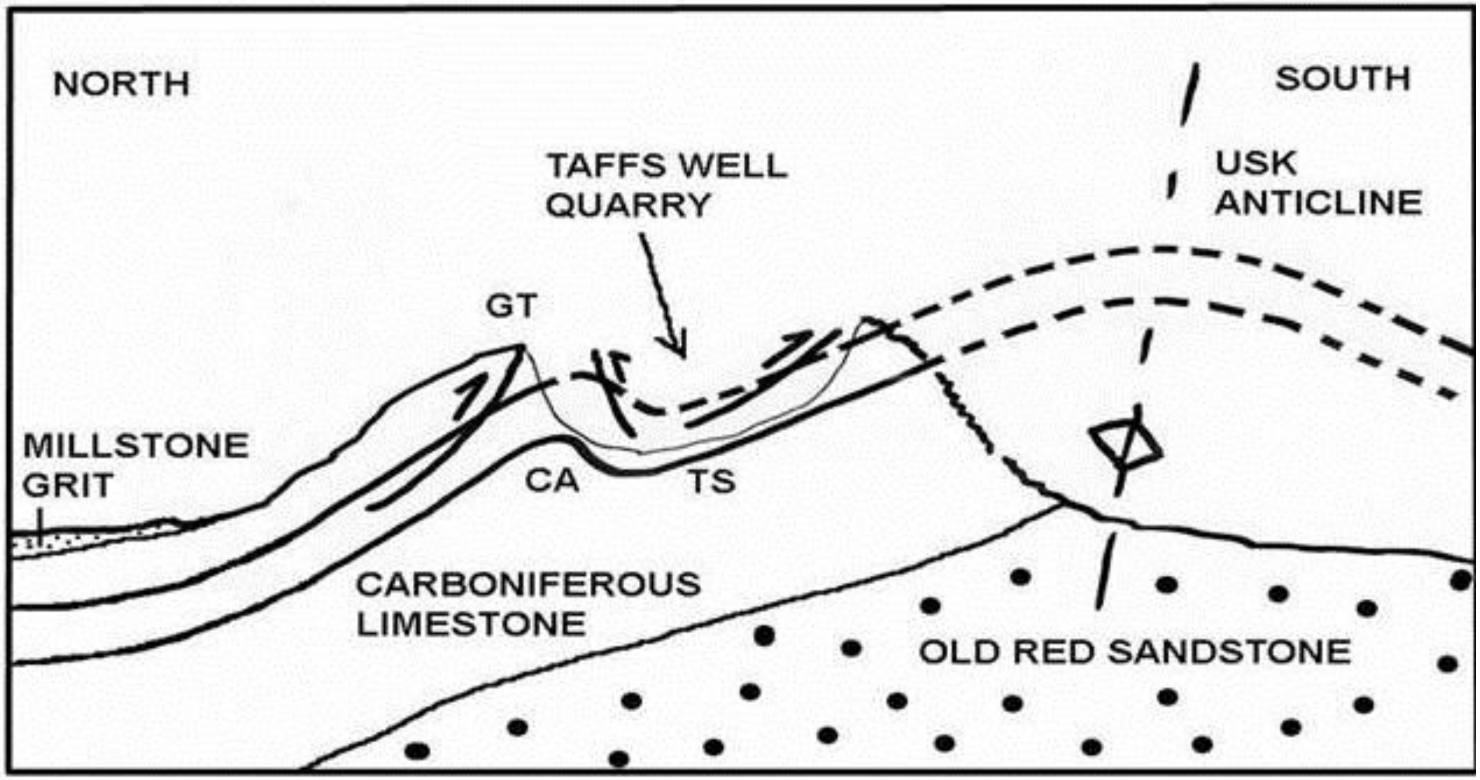
Devonian Old Red Sandstone

Carboniferous Coal Measures

Carboniferous Limestone



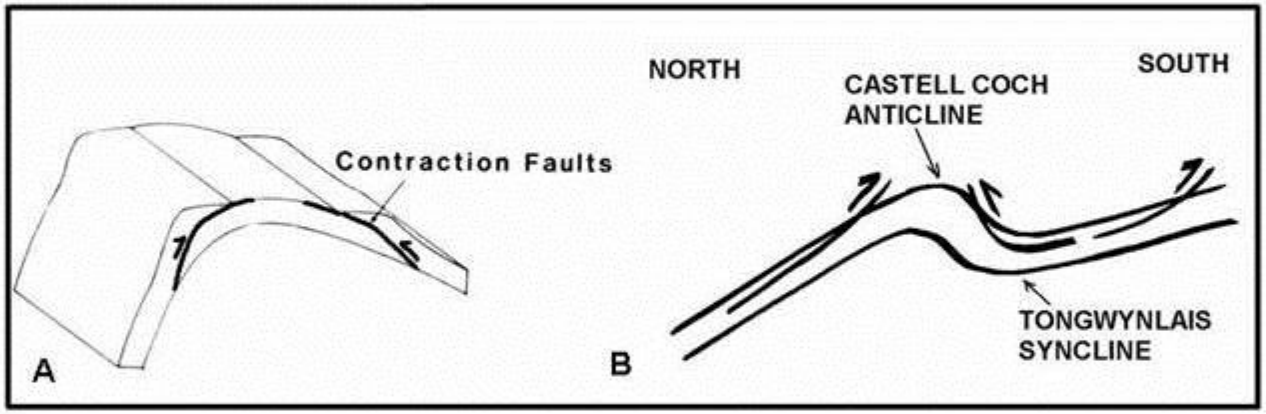
Structural Setting – Cross Section

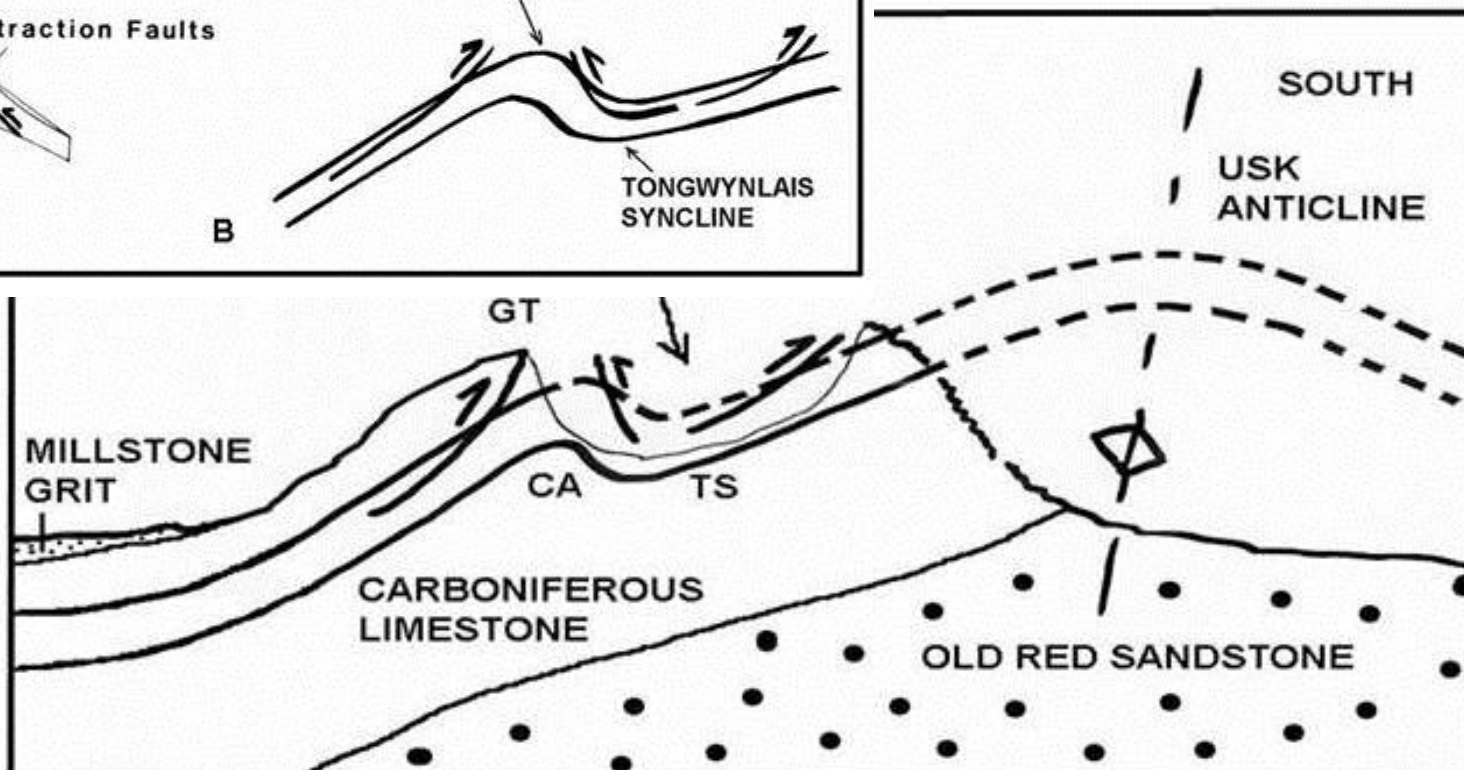


Structural Model

- **Two main quarry-scale folds are present, forming an anticline-syncline (Z-fold) pair with related thrust structures on each fold limb, 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**
- **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).**
- **Flexural slip on bedding planes also occurs with displacement/movement directed towards the fold axis.**

Structural Setting – Cross Section

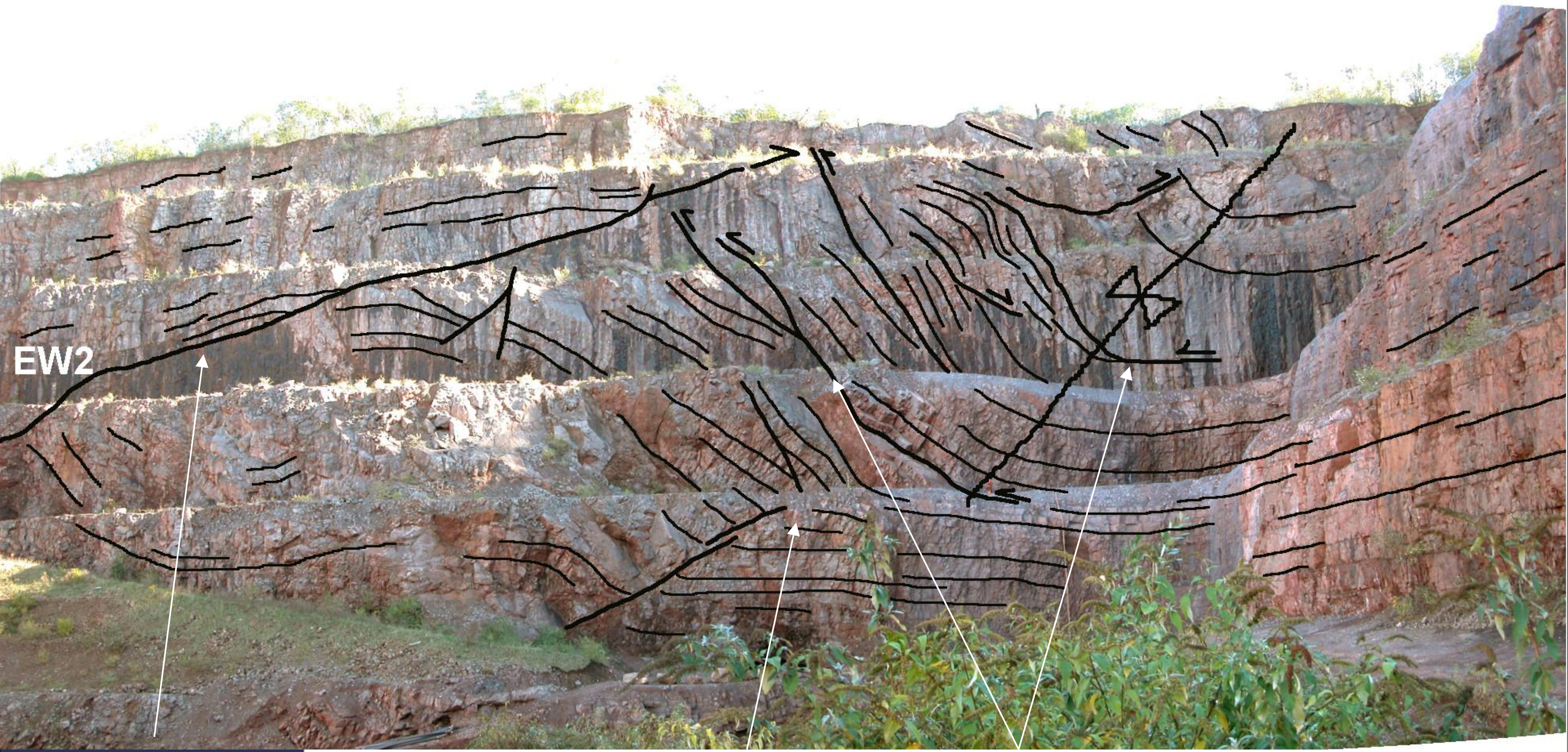




Structural Model

- Orientation and location of these thrusts is one of the critical features for quarry planning:
- They are the most likely planes of weakness.
- As new 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.
- Main quarry fault is 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.

Structural Geometry in SE Corner

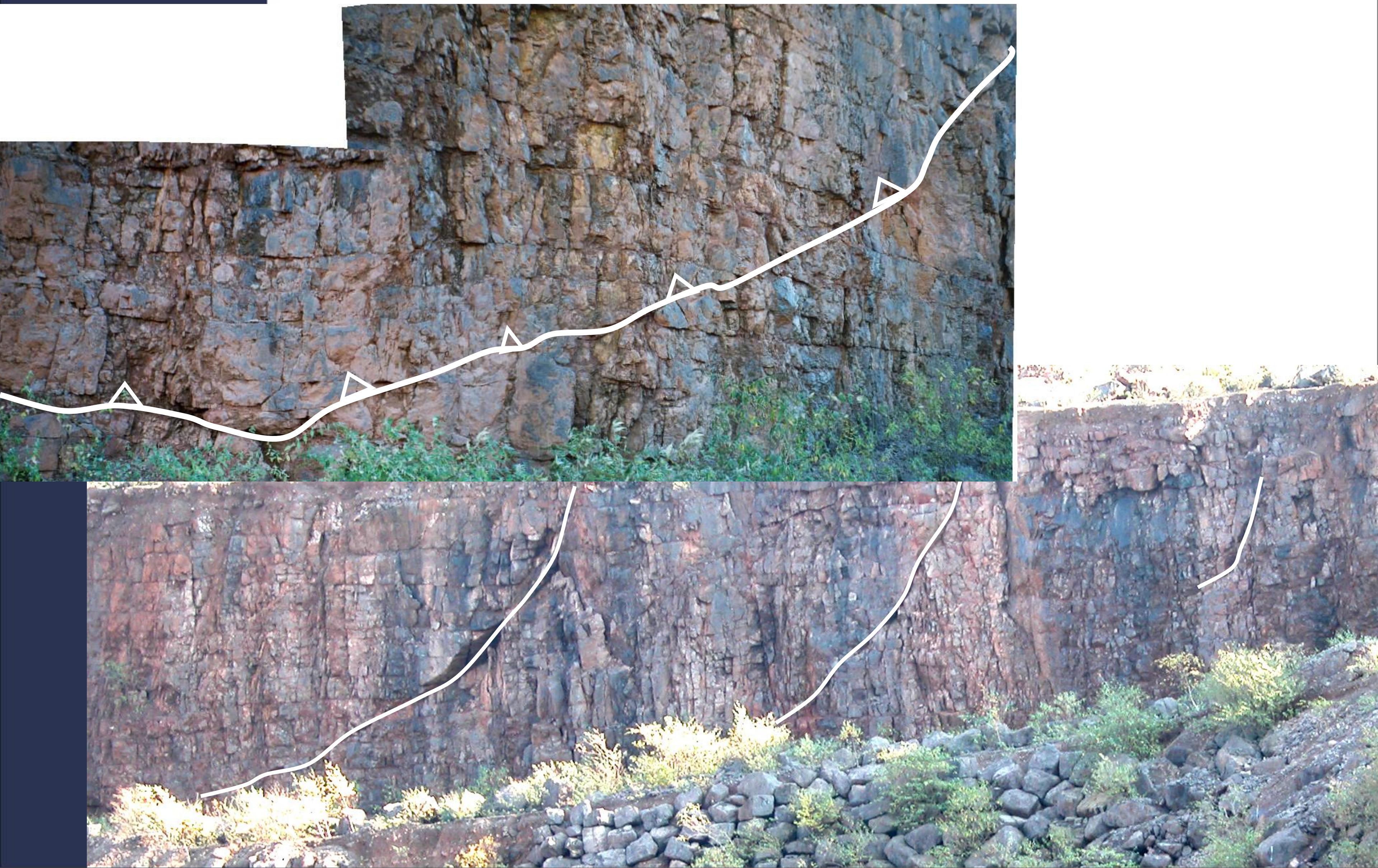


N-dipping thrust

Thrust tip dies out into syncline

Minor faults accommodate strain in folds

Lateral Ramps of Thrusts

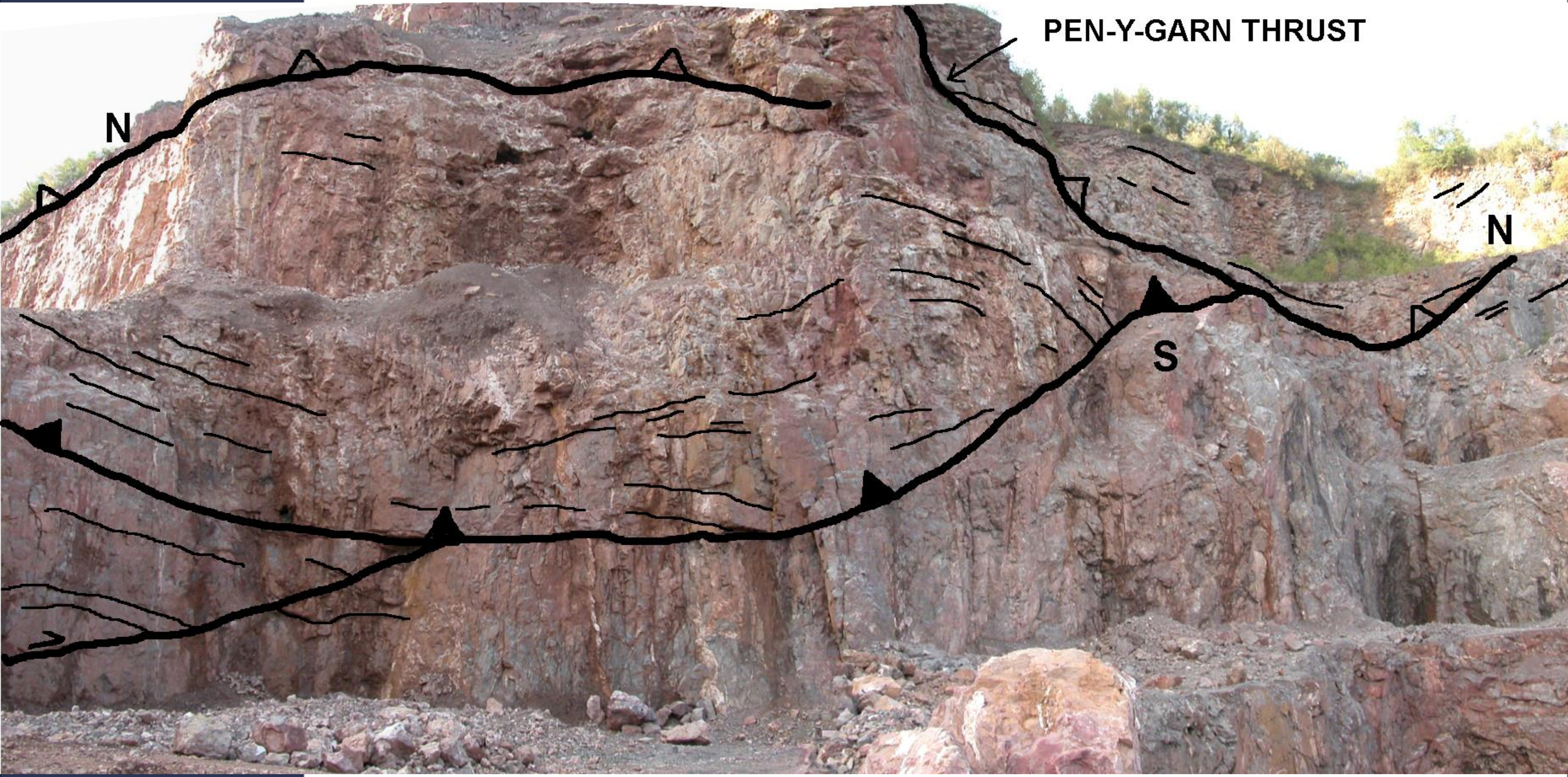


Thrust showing low angle truncation of bedding

Geotechnical Implications

- The thrust faults related to the main anticline-syncline structure of the quarry were of great significance to quarry planning.
- The structure of the quarry was oversimplified in existing models and local pit wall scale faults were not understood in sufficient detail.
- 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.
- 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 major S-dipping fault daylights mid-way down the North wall and has an associated N-dipping, thrust splay which also daylights on the North wall.

Main structural features in North Wall



N = N-dipping thrust

S = S-dipping thrust

Development in West Wall

South

North

Overall structure is a syncline which passes northwards into an anticline. Note south dipping thrusts on the south dipping limb of the syncline and north dipping thrusts on the north-dipping limb. Arrows show the movement directions of the thrusts.

Conclusions

- 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.