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A NOTE ON FAULTS, MOVEMENT SENSE AND IMPLICATIONS OF TERMINOLOGY

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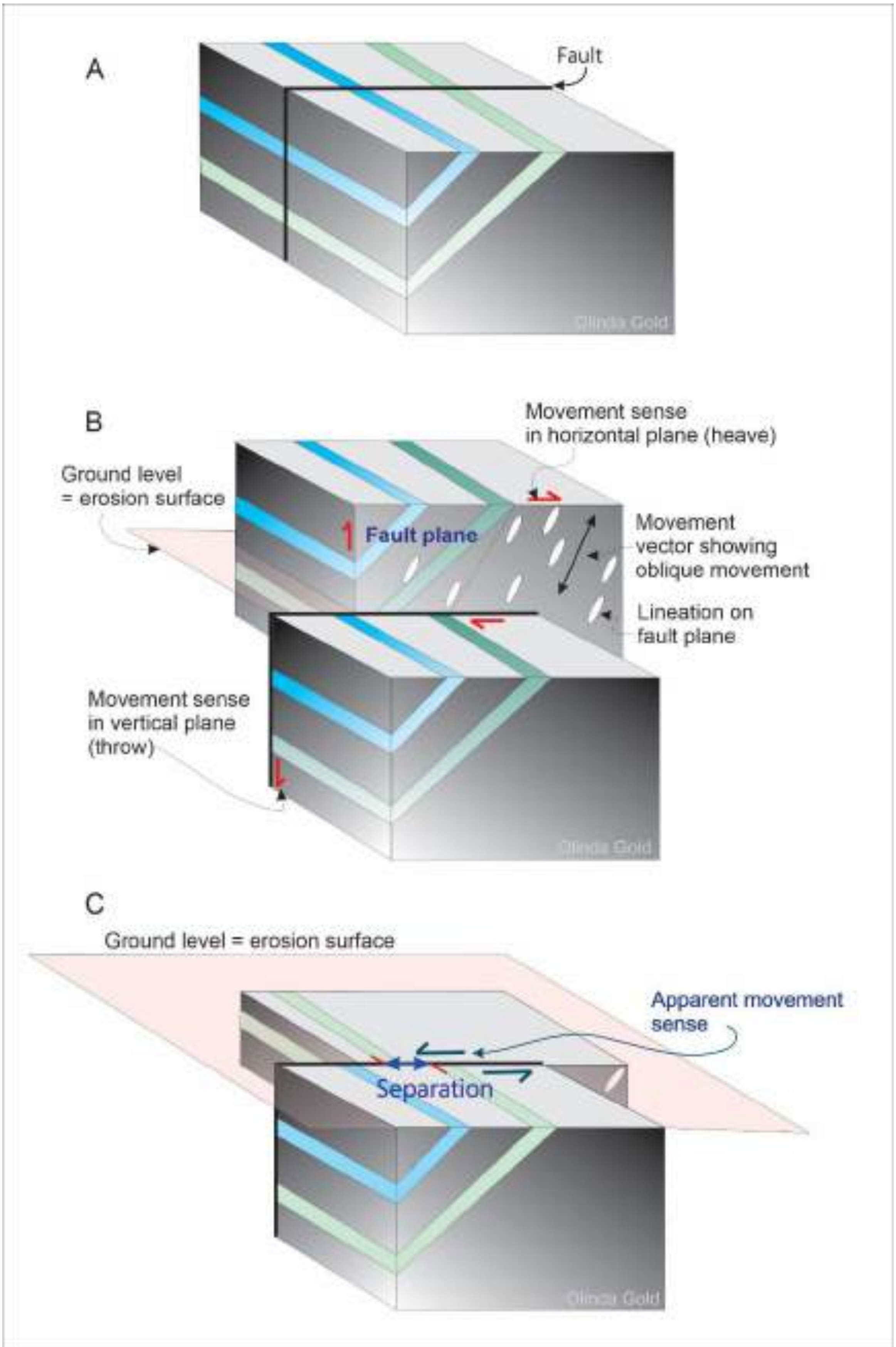
Introduction

This contribution has been sponsored by some of the posts I have seen in which faults are shown. Most of the comments here will already be common knowledge to many geologists. So, if you know all about faults and shear zones and associated terminology, please skip the post and save the rotten vegetables for someone else. However, I have seen enough posts to the contrary, and seen enough examples at mining and exploration projects globally, to make me think a discussion is needed.

We all know what a fault and a shear zone are. And we all know of the various kinematic indicators used to determine movement sense, even though there are common disagreements on the interpretation. But this post is not about movement sense per se. It is more to do with descriptions.

Firstly, there is the terminology that uses the word ‘shallow’ for a low dip. Shallow means depth. What if a fault has a dip of 10° and we intersect it hundreds of metres below the surface? Is it a shallow deep fault? We should use the terms *low, moderate* and *steep* for fault dip, and reserve the term shallow for depth in the crust (or for people incapable of serious thought, like some I’ve met in recent times, but I digress). I do note that low dips are sometimes referred to as gentle dips. This is acceptable (gentle is preferable to wild and unruly).

Next comes the ascription of movement sense to faults. More commonly than not, people will say ‘it is a sinistral fault’ or ‘it has a dextral sense of shear’. This is not a problem if it is a true displacement along the movement vector, which typically manifests as a lineation. Rarely, however, do people say it is an *apparent* sense of shear, even though they have no idea of the movement vector. However, the implications are obvious. Namely, the opposite sense of movement may exist such as in my diagram below. It shows the importance of knowing the movement vector. In this case the movement sense in plan is apparent, and the distance between the same unit on either side of the fault is called a separation, not a displacement. These are two totally different things (although, in marriage bust-ups we could possibly say that separation and displacement are the same, but I digress again).



Development of apparent movement relationships. Note that the distance between the same lithologies in plan is not a displacement, it is a separation.

The implications of changes in dip direction

My next concern pertains to dip-slip faults and the use of the terms ‘reverse’ and ‘normal’. If we go to Dr Google, we get the following definition – “Normal, or Dip-slip, faults are inclined fractures where the blocks have mostly shifted vertically. If the rock mass above an inclined fault moves down, the fault is termed normal, whereas if the rock above the fault moves up, the fault is termed a Reverse fault”. These are age-old definitions and are fit for purpose at the local scale, such as an outcrop in a creek or an exposure in a mining face underground. However, too often the term normal and reverse are ascribed to the whole fault, even though we can’t see it beyond our small field of observation. And that designation of normal and reverse assumes the fault will remain planar, such as in the images below.

So, what do we do with faults and shears that change their dip direction? This is super common, especially for steeply dipping faults and very low dipping (note – not shallowly dipping) faults. You only have to look through papers in the peer reviewed journals to see that faults are not straight entities – they can be sinuous or show marked abrupt changes in strike or dip direction. I show a couple of examples here of faults that are relatively planar at the scale of observation. I then show some others where the faults have more than one dip direction while retaining the same strike. The first example is the Bathurst Fault (Figure 1), which I photographed from a helicopter when working for Dundee Precious Metals in Nunavut, Canada. In this part of the world we were exploring for orogenic gold deposits. Believe it or not, this linear fault exposure is totally natural.

Figure 1: Bathurst Fault, Nunavut, Canada

In the example below we can see the Last Chance Shear, part of the early structural framework in the Kanowna area of the Kalgoorlie Terrane in Western Australia, and exposed in the Ballarat-Last Chance orogenic gold mine (Figure 2). The fault overall is fairly planar but does vary in morphology from a poorly veined ductile shear zone at the top of the exposure to one in which there are discrete structural zones in the lower exposure. The mid-part of the exposure shows the Last Chance Reef that was extracted by historical gold mining in the section just above the waterline. Note that the reef was not totally extracted. Rather it formed a veneer on the right-hand side of the mineralised shear that was preferentially mined. Note also, that the vein demarking the fault also changes in dip value, as shown in the photo following the one below (Figure 3).

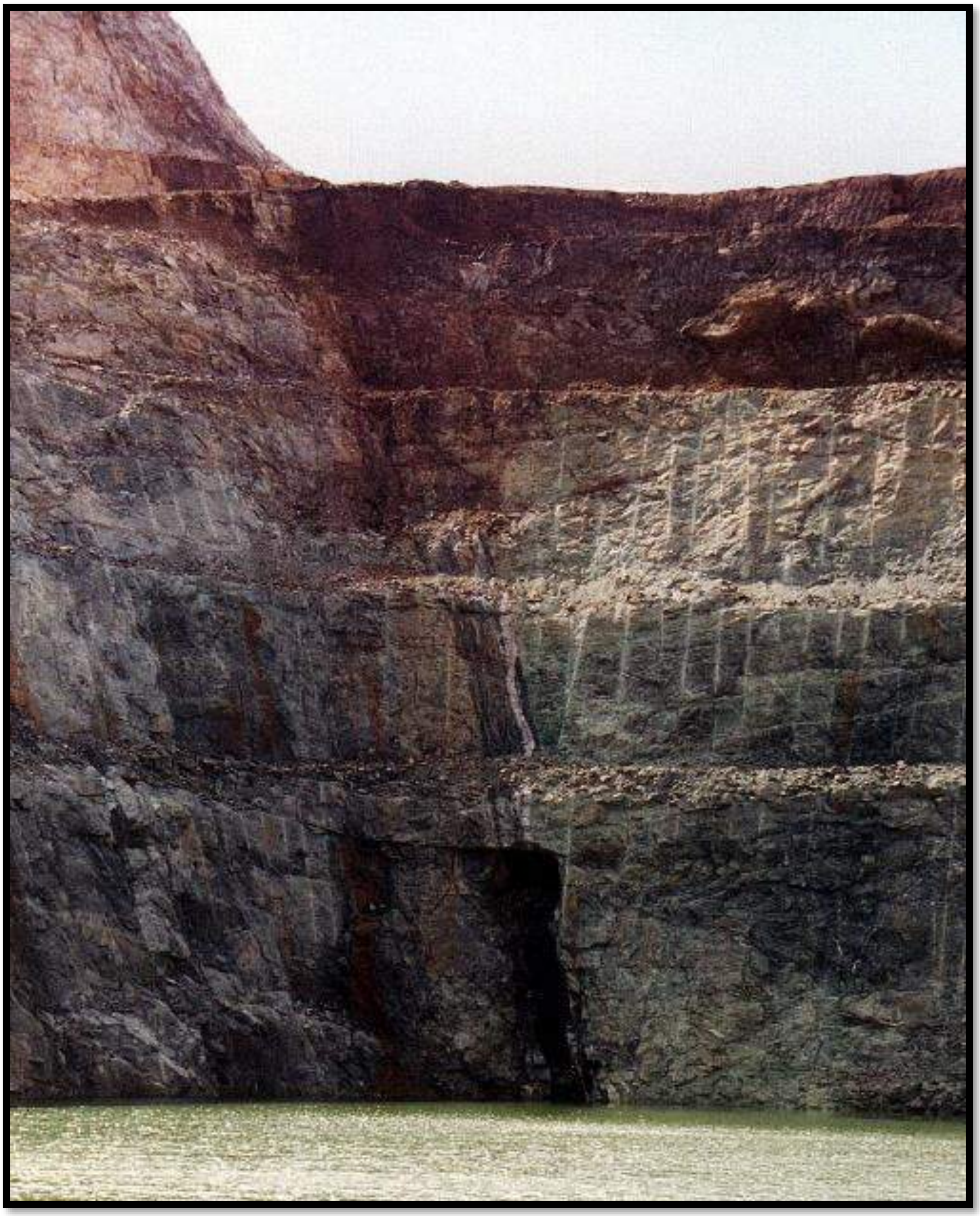


Figure 2: The Last Chance Shear in the Ballarat-Last Chance gold mine, Western Australia

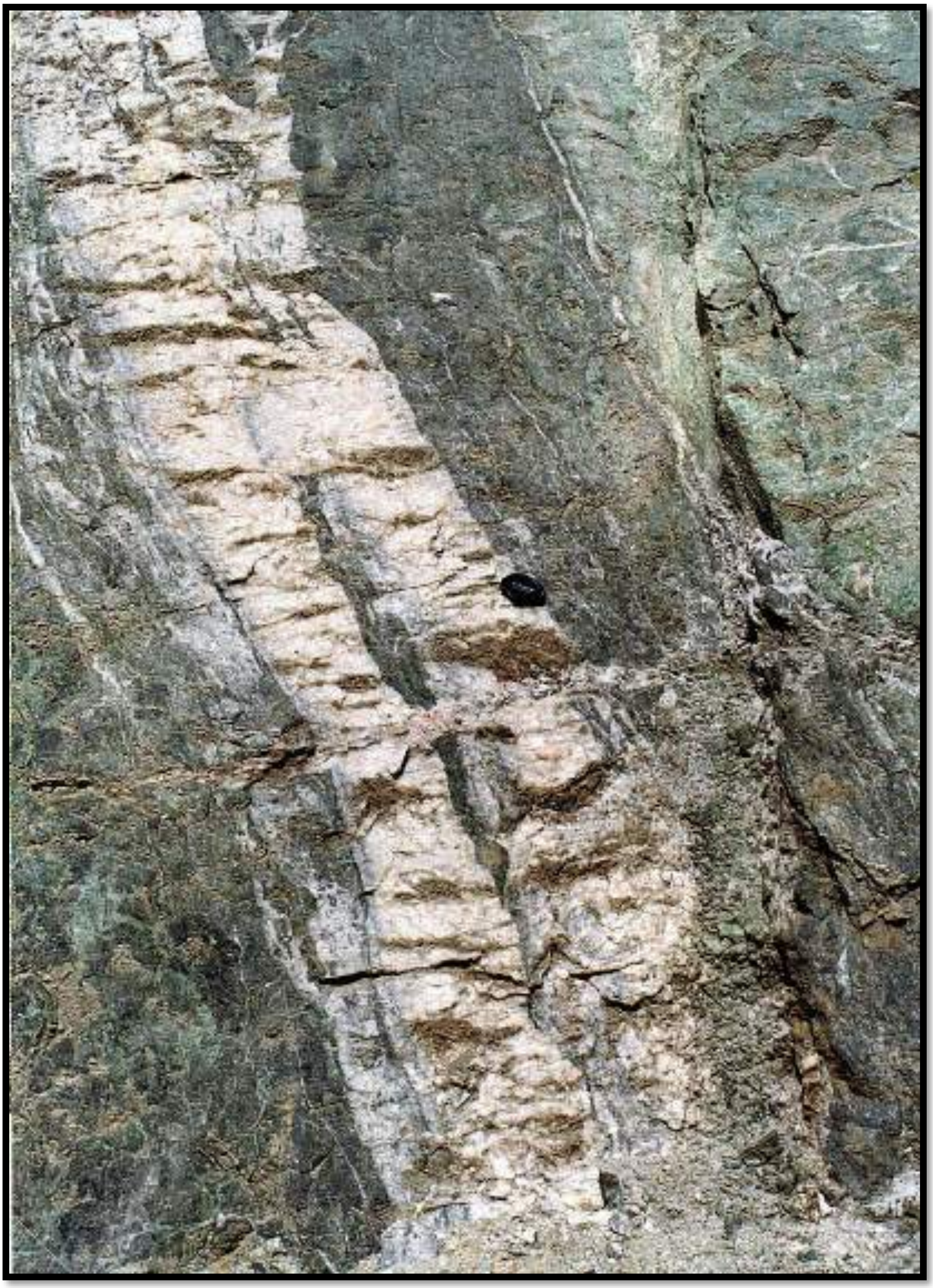


Figure 3: Detail of the Last Chance Reef in the Last Chance Shear

So, the figures above show how faults can be planar over large distances, to being variable in steep dip value but maintaining much the same dip direction. As faults steepen, however, they can have opposing dip directions, approximately 180° apart, at different portions of the faults. The first figure below shows the asymmetrically braided fault-vein network exposed in the Serajun open pit in the Mt Muro epithermal goldfield in Borneo (Figure 4).

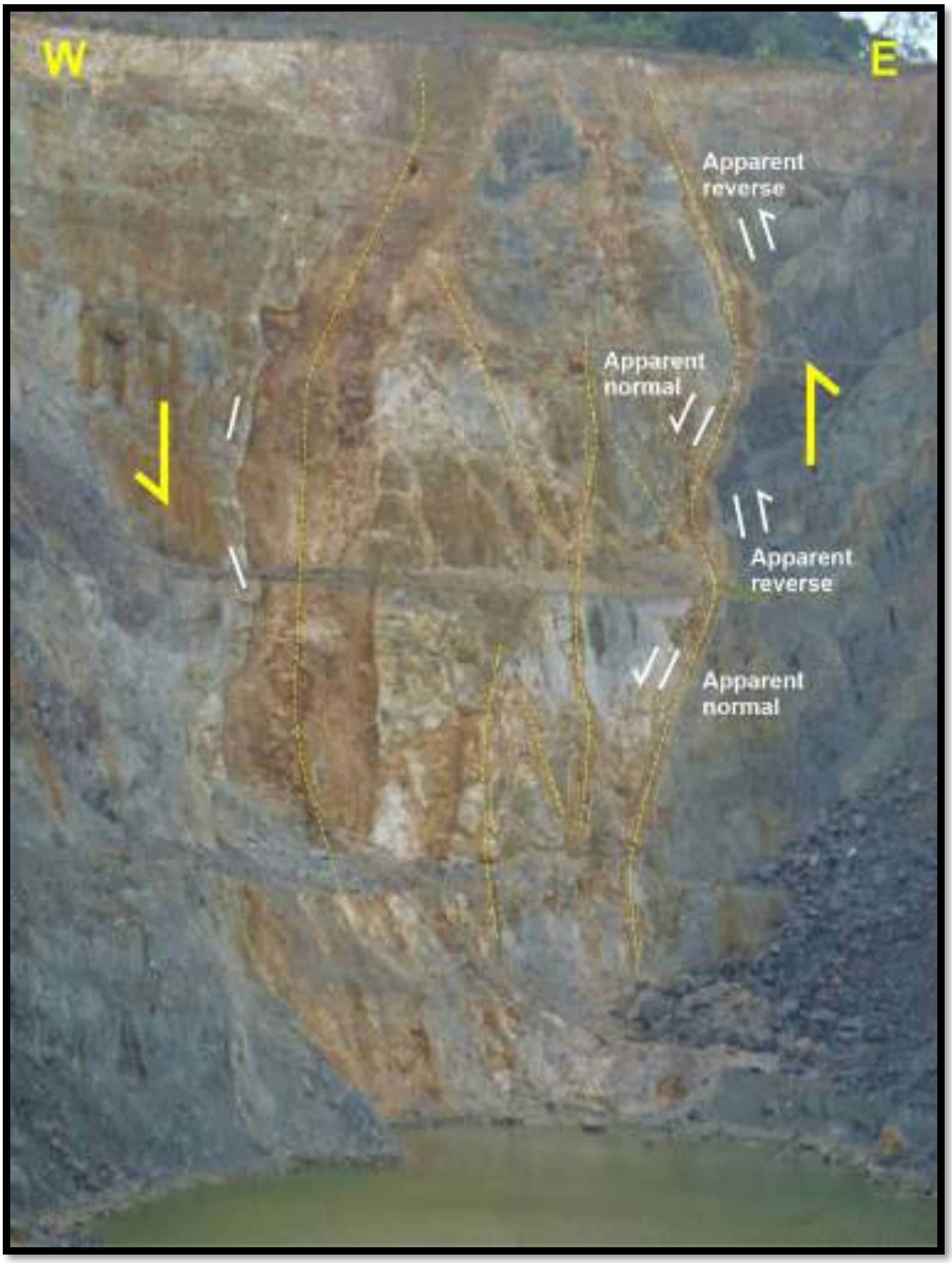


Figure 4: Serajun open pit, Mt Muro, Borneo

In the image above we are viewing along the strike of the overall structure and can see the anastomosing bounding structures with subordinate, moderately east-dipping extension veins. This indicates accommodation of an E-side-up sense of shear on the overall structure. However, if we look at the sinuous eastern bounding structure, we can see that it dips both to the east and to the west (shown with white lines), depending on the level in the pit. In the initial stages of pit development, the eastern structure could have been documented as a reverse fault. Further down, it could have been documented as a normal fault. Even the relatively thicker western structure shows local changes in dip direction. Obviously, this creates a few issues if viewed in isolation, which is commonly what happens at the current scale of mining.

The example below is from a major low- to intermediate-sulphidation epithermal gold deposit in the Western Cordillera of northern South America (Figure 5). The mauve-coloured features are major deposit-scale structures that link to a regional-scale fault network. The distribution of mineralisation is obviously spatially associated with the central steeply dipping structure, which has a sinuous geometry when viewed in section along its strike. It can also be seen that the dip direction of the structure (shown as heavy black lines) changes by 180° depending on RL.

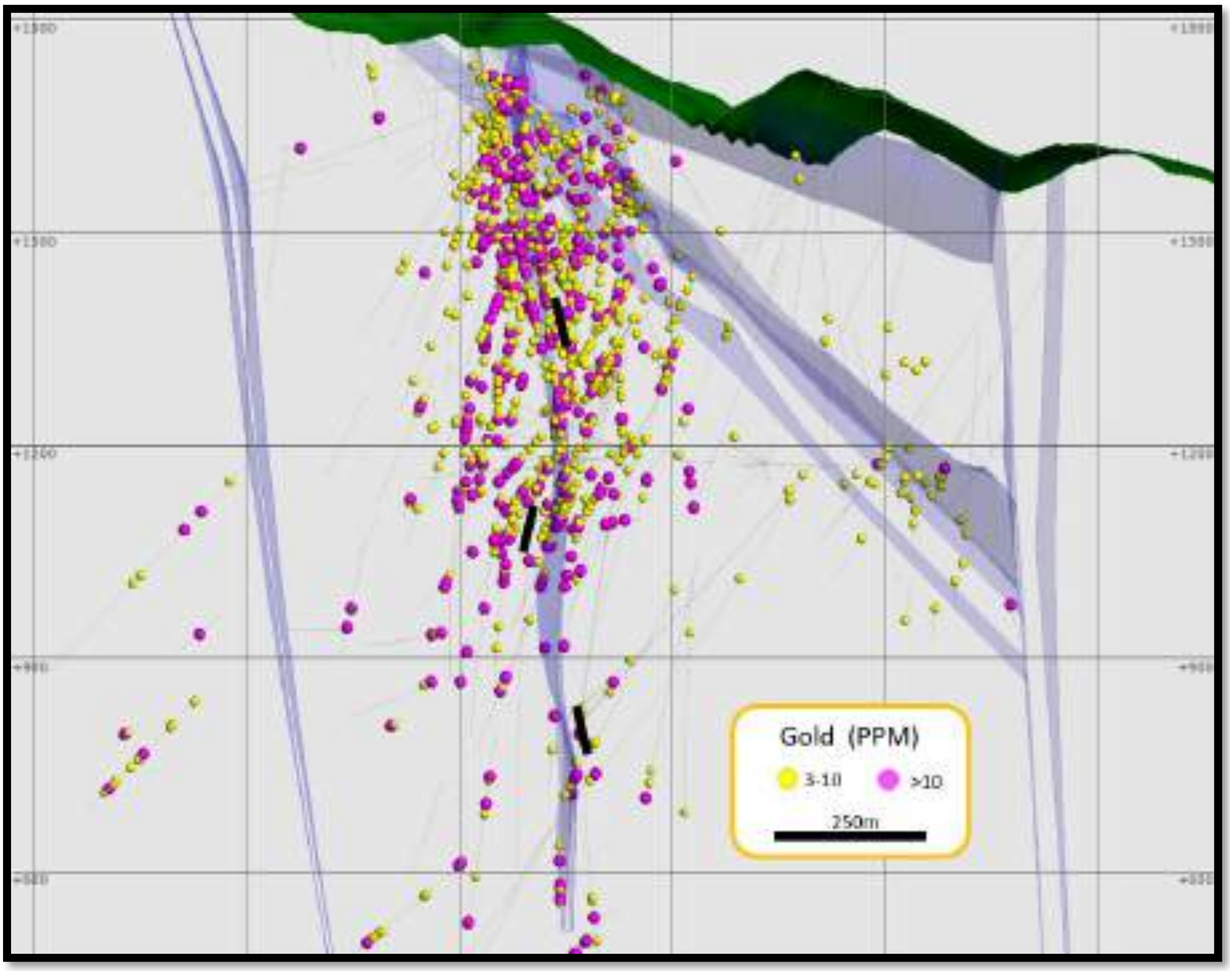


Figure 5: Fault network with gold grades. Deposit ID not disclosed due to confidentiality.

In underground mining scenarios, and especially in cases where there is development of a fault permeability network rather than a single structure, the interpretive linkage of faults will come down to an assessment of their defining characteristics. We all know of the uninformed 3D models that are created when structures aren't correctly interpolated, due to factors that include not enough data or the incorrect interpretation of data/observations. In the former case, this is commonly because the model producers are removed from the volume being modelled, either due to inability to travel (e.g. COVID) to site, corporate policy (you're a modeller – you stay here in head office and model), or because they are too lazy to go to site to understand the structures that are important. In the latter case, I can't think of anything worse than spending one's life in an office or basement, producing 3D models, and only taking time out to sniff your armpits (but, once again, I digress). The smart, world-class modellers, such as Jun Cowan, Brett Gossage etc, will go to site, will collect the data, and will only incorporate quality information. Anyway, digressions aside, the incorrect terminology will hinder the correlation of structures. Faults are less likely to be linked if one is called a reverse fault and one is called a normal fault. I have tried to show this diagrammatically in Figure 6 below, where two people have braved the ladderways to different levels and encountered the same fault, only to describe it differently.

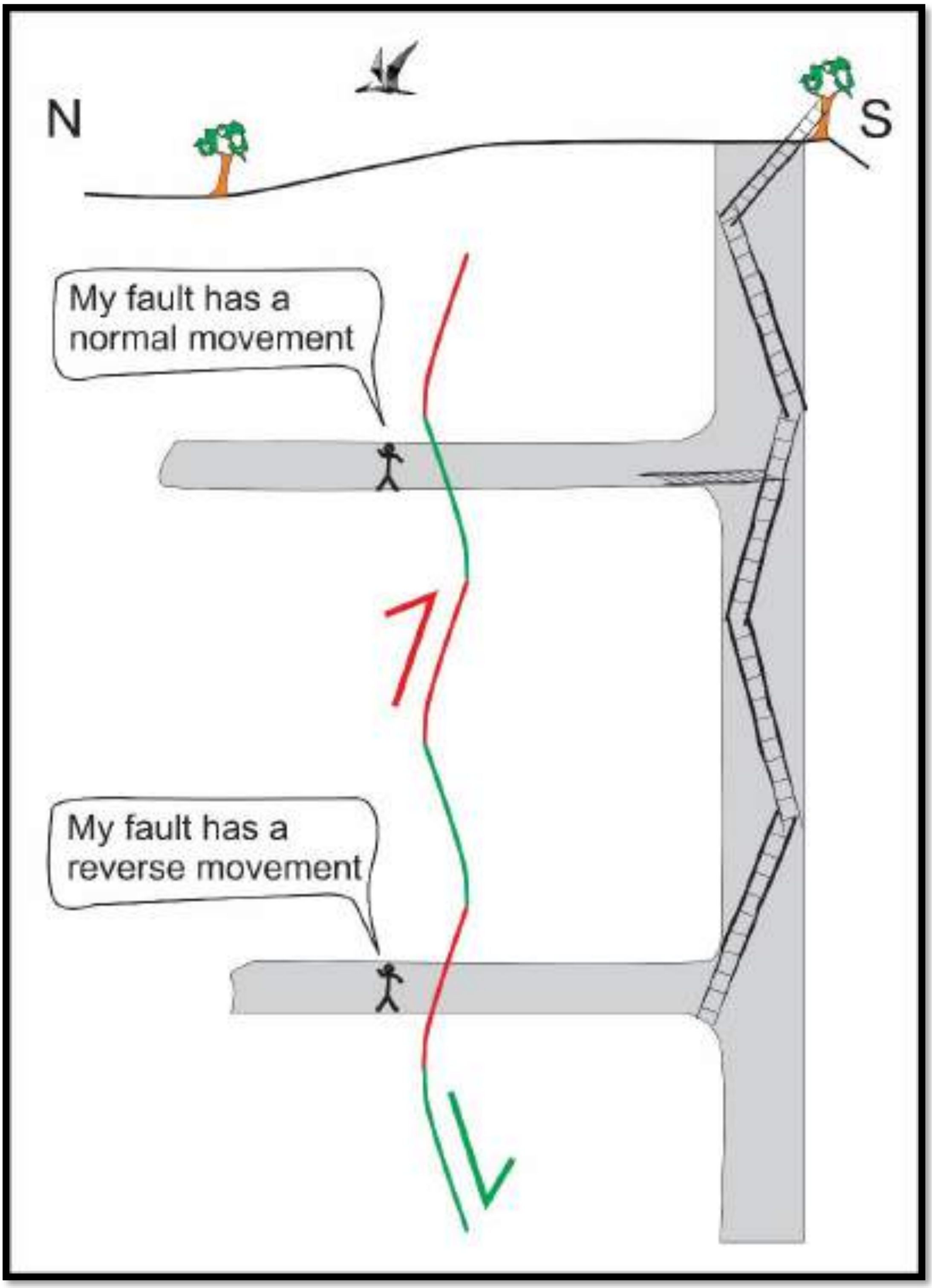


Figure 6: Faults are never straight. Use of 'normal' and 'reverse' terminology is not good practice when dealing with steep structures that change dip direction. Note that pterodactyls are compulsory figure embellishments.

How do we avoid ambiguity when documenting fault movement?

So, what to do? The simplest solution that avoids ambiguity, is to describe the direction of motion of one fault block relative to the other. The people in the image above obviously know the movement sense. So, the next step is for both of them to simply state that the fault is a north-side-up feature. This is a unique attribute to the fault and will typically be consistent to the scale of the deposit (forgetting about the complications of structures such as scissor faults). Similarly, in the example of Serajun previously, an east-side-up movement is consistent at all exposed levels.

So, can we have mismatch of interpretations in other fault environments? I'm glad you asked because we can, and this applies to volumes of rock where low-dipping (note – not shallow-dipping) faults are encountered.

The first example (Figure 7) is from a calcareous sequence hosting a base metal deposit in Bosnia. We can see several dislocations against which portions of the sequence are excised and where dip values of the bedding change, locally markedly. Volume problems during deformation have produced voids that were unable to be filled by veining associated with the hydrothermal system (for more info on this, check out the veining document I have made freely available via GeoHUG). We can also see that the dip direction (shown as yellow lines) changes between westward dips and eastward dips. For arguments' sake, let's accept that a movement sense is as shown.

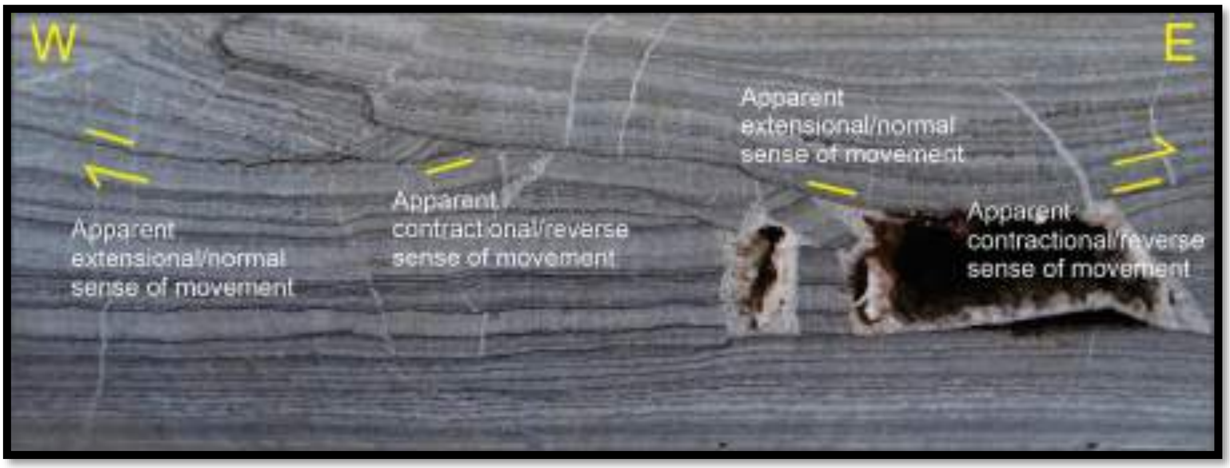


Figure 7: Apparent normal and apparent reverse movement on the same low-dipping structure, Vares, Bosnia.

It is very very common for people to see the low-dipping portions of the fault with an apparent reverse movement and call it a thrust fault. If we go to the USGS website we find the definition of a thrust fault as follows – "a dip-slip fault in which the upper block, above the fault plane, moves up and over the lower block. This type of faulting is common in areas of compression, such as regions where one plate is being subducted under another as in Japan. When the dip angle is shallow, a reverse fault is often described as a thrust fault".

Similarly, if we go to one of the great structural geology texts, Structural Geology by Robert J. Twiss and Eldridge M. Moores (1992), we get the following definition – "Thrust faults and reverse faults are dip-slip faults on which the hanging wall block has moved up relative to the footwall black. Generally, older rocks are emplaced over younger rocks, and in a vertical section through the fault, stratigraphic section is duplicated. These faults accommodate shortening of the Earth's crust. Reverse faults have dips greater than 45°, whereas thrust faults dip less than 45°."

Ok, my pedantic aversion to the word 'shallow', as used in the USGS definition, to describe a low-angle fault aside, we can see that at least two locations on the structure above fit the definition of a thrust. However, these portions of the fault are continuous with segments where the dip direction reverses and the fault would fit the description of an extensional fault, not one associated with compression. Commonly we cannot see stratal repetition and shortening-related structures, such as fault propagation folds, at the scale of observation in the open pits or underground development we are working with. So, inferring a structure is a thrust based on local dip and movement can cause issues. As another digression, there is an excellent text called Thrust Fault-Related Folding by McClay et al. (2011).

The arguments above apply to the situation below, which shows a low-dipping fault that has accommodated hydrothermal fluid movement in a sedimentary sequence from a road cutting in Tigray Province, Ethiopia (Figure 8). As yet another digression, this photo was taken before the protracted recent unrest in the region.

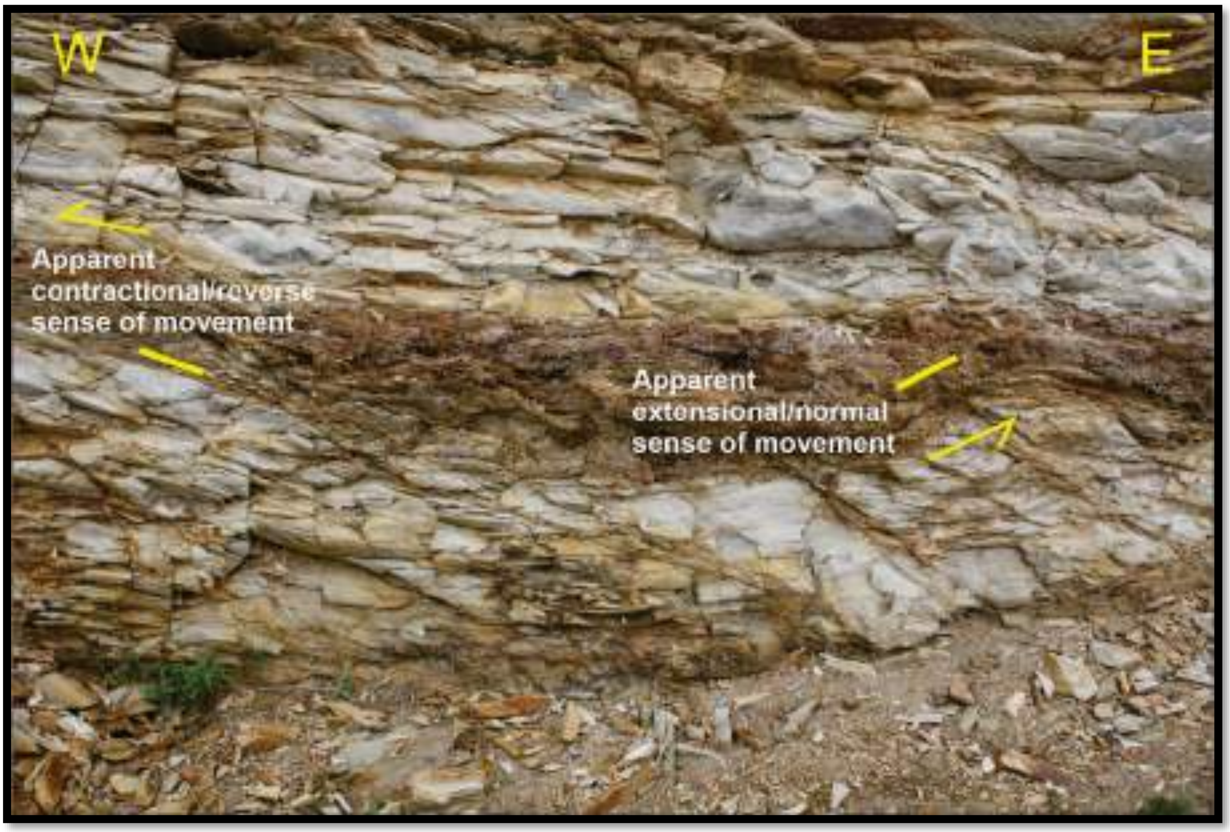


Figure 8: Apparent normal and apparent reverse movement on the same low-dipping structure, Tigray Province, Ethiopia.

Clearly there is a problem with terminology and interpreted context of the faults if we are calling the same structure both a thrust and an extensional fault (Figure 9). This has implications for the tectonic context of the host environment e.g. are we in a region of compression or are we in a region of extension?

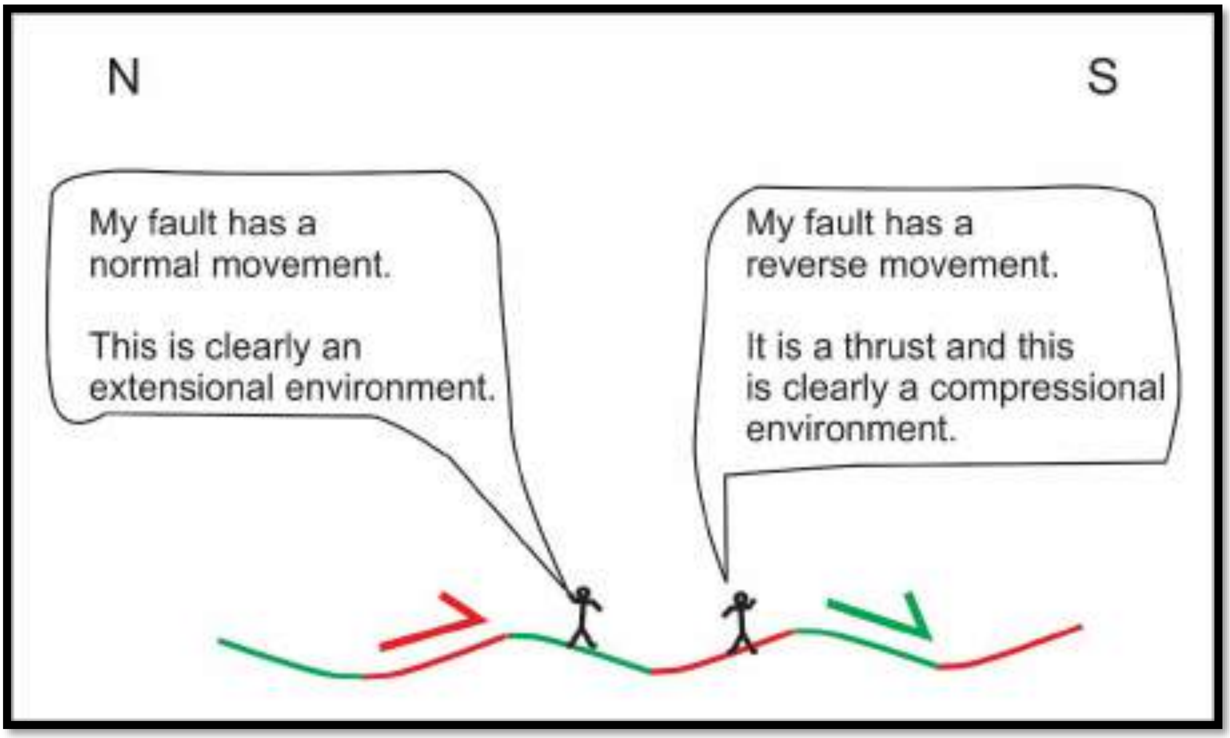


Figure 9: The use of terminology that doesn't include a unique movement sense (e.g. top-side-south) can complicate understanding models, tectonic understanding etc

To extrapolate the implications further, the style of deposits we are exploring for will change depending on the perceived tectonic setting. In reality, most of the problems I have mentioned will be encountered at the mining- and prospect exploration-scale. It is necessary to incorporate information at all scales to see if low-dipping structures have attributes beyond the local scale of observation that will justify their designation as thrusts (e.g. an older formation placed on top of a younger one, macroscale fault propagation folds etc) or extensional faults (e.g. exposure of relatively higher metamorphic grade rocks below the structure, such as in core complexes).

In both of the examples above, the sense of movement is best described in terms of the relative motions of the blocks, without inference of compressional or extensional environments. That is, in the first case, a designation of top-block-to-the-east correctly describes the fault without the necessity of calling it a thrust or an extensional fault. In the second case, a designation of top-block-to-the-west correctly describes the fault without the necessity of calling it a thrust or an extensional fault. Once we gather more information on the overall context of the fault, we can think about calling it a thrust or an extensional feature.

Now, please bear with me as I mention one more example where there may be confusion. As noted above in the quote from Twiss and Moore (1992), thrusts commonly manifest where, in a vertical section through the fault, stratigraphic section is duplicated (Figure 10). However, there is commonly no need to invoke a thrust. Consider the same volumes of rock as shown in the first image in this post, and the moderately dipping strata in the fault blocks. We can see that a drillhole can intersect the same strata twice across a vertical fault with oblique movement without any necessity for thrusting. I know that most people who have persisted reading this post to this point will think this is obvious. However, this is exactly the scenario I encountered on one consultancy job where the client had inferred a thrust based on a fault separating intersections of the same sequence either side of the fault.

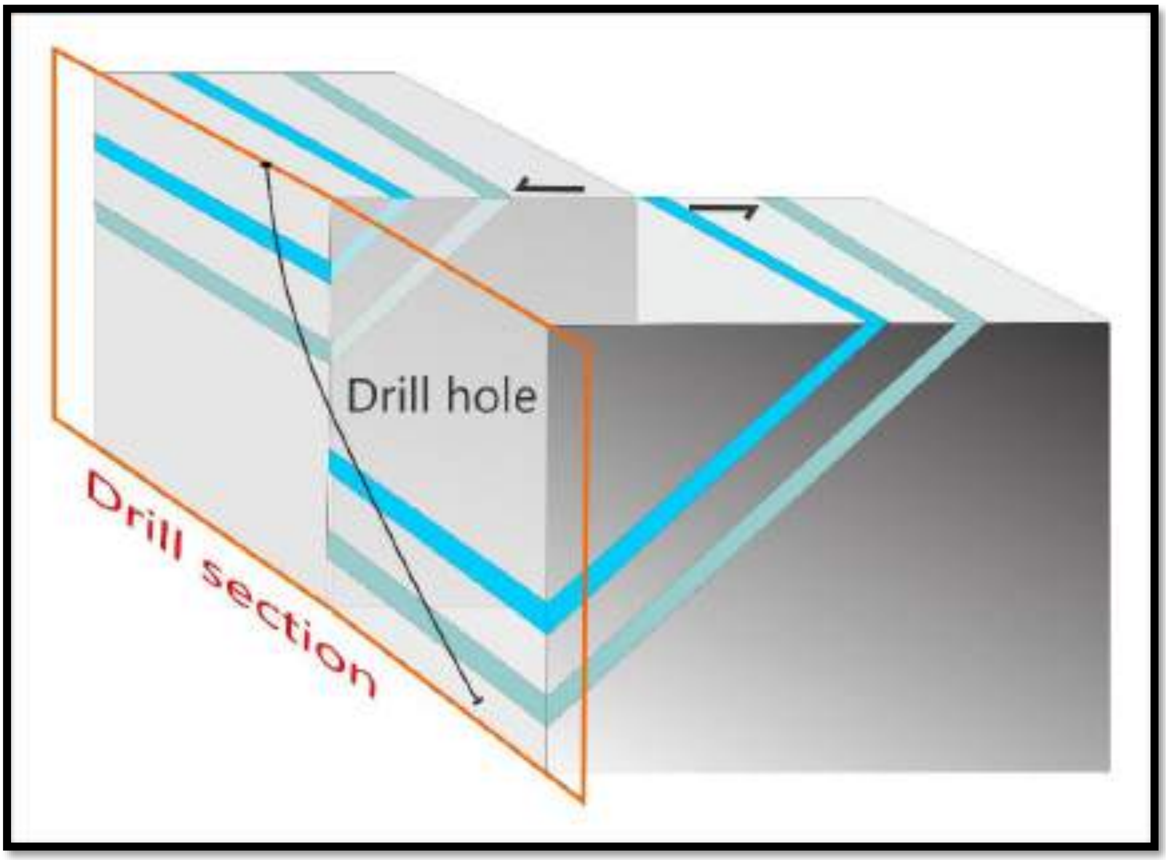


Figure 10: An example where sequence repetition in a drill hole need no imply large vertical fault movements.

Ok, that's it. Many people will say 'ho-hum, we knew all that – why make a post about it?'. The reason I made the post is that I have encountered all the scenarios described in this post, some more than once. These scenarios can dramatically affect the 3D structural analysis and models of mineral deposits, and can impact exploration programs, especially in terms of potential to waste money.

The end.