



## Best practice and new technology in core drilling, logging and fracture analysis

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**ABSTRACT:** Whilst drilling techniques are continually improving to obtain continuous, solid core from ever more difficult ground, logging systems remain largely manual with low auditability – such that much of the data used for mapping the sub-surface is entered on trust. Additionally matching core logs with downhole geophysics is often difficult, particularly comparing structures with those measured in televiwer scans, leading to significant uncertainties in modelling the ground sampled. As a result the full value of most drilling projects is seldom attained. In the main these shortcomings are due to inadequate monitoring of the drilling process to ensure the accuracy and reliability of three critical aspects, being: (i) depth registration of the core, to properly locate the position of every feature logged along the borehole path, (ii) core orientation, to precisely define the intersection of the geographic vertical plane with the core segments so that the dip and dip direction of structures intersected in the core can be reliably determined, and (iii) borehole surveying to correctly define the borehole path from collar to end-of-hole, enabling well-constructed models of the logged data to be built. Procedures are put forward to address these issues, following which an image based logging system is presented for optimizing the logging process. Digital photographs are used to create virtual 3-D models of the core on which contacts and structures are picked to record their depth, measure alpha/beta angles and enter full geotechnical and lithological descriptions, using templates customized to conform to the client's existing database codes. Thus the data is immediately available for audit, much of which can be done offsite using the annotated images. Depth registration is also adjustable, and at any stage, to facilitate alignment and meaningful comparison with downhole geophysics data, which can then also be used with confidence to augment gaps in the core logs as well as to correct sections of poor or non-existent core orientation. Such quality assured data is essential for reliable determination of fracture patterns and their distribution, and to match the joint sets with those mapped in outcrop to define their size and termination for realistic geomechanical simulation of the ground investigated.

### 1. INTRODUCTION

Whilst accurate modelling of the sub-surface is a prerequisite for any mining or civil engineering development, the stakes have been markedly raised by recent engineering advances that have made efficient bulk mining and mega construction projects possible, but carrying substantial long-term financial risks. Hence it is critical that all data used for predicting responses to the induced stresses calculated for any ground development are certifiably accurate, within well-defined limits.

Diamond drilling is the only sub-surface sampling method with the potential to timeously deliver such quality data. It has the added advantage that the required information is derived from two unrivaled independent sources, solid core and a smooth bore – the latter being ideal for downhole geophysical scans. Thus, given lithological and structural data from core that compares well with the downhole geophysical logs of the same geology, both data sets can be integrated and used to generate highly effective geological models.

In practice, however, correlating the two data sets is difficult. Sizeable depth shifts are frequently required in order to attempt a match between core and wireline logs. In addition the differences between the dip and dip directions measured for structures in drill core and televiwer scans are often unacceptably high.

Consequently there is a move to rely more on downhole geophysics for charting the sub-surface, largely because of the perception that the depth registration of wireline scans and the orientation of televiwer data is more accurate than can be achieved for core. This lack of confidence in drill core has grown even to the extent that drill rigs are increasingly being used simply to excavate expensive conduits for down-hole sondes [1].

Such a situation is obviously untenable; more so since core is the only source of vital descriptive information for characterizing the fractures intersected. Hence it is crucial to thoroughly investigate how accurately drill-core data can be coordinated in 3-D space, the three requirements for which are: reliable depth registration, verified core orientation and verified survey data of the borehole path.

Then given core for which the sub-surface location of all the logged data can be confidently plotted, the remaining requirement is for a drill core logging system that can quickly acquire statistically valid data that is consistently accurate and easily auditable.

### 2. THE DEPTH REGISTRATION OF CORE

All drillers have the means to accurately measure the depth of a borehole to the nearest centimeter, from the borehole collar, or ground-level, to the cutting face of the drill bit, every time the core barrel is extracted and

the core is emptied into trays (Figure 1). Each extraction is referred to as a *drill run* and, from an audit perspective, the requirement is to confirm the driller has adhered to this definition. Only then can the accuracy of every *end-of-run* depth be assured so that the core can therefore be correctly depth registered, or meter-marked in preparation for logging.



Figure 1: A core tray with depths written on core blocks separating the core recovered from each drill run.

Each depth measurement is recorded on a *core block* placed in the tray to separate the drill runs. The measurement is made by subtracting the rod length *sticking-up* above ground level from the known length of the *drill string*, comprising the core barrel plus drill rods of standard length (Figure 2). Hence in Southern Africa at least, the driller's depth log, which also records the *drill advance*, being the difference between this depth and that for the end of the previous drill run, and the length of *core recovered*, is referred to as the *Stick-up Log*.

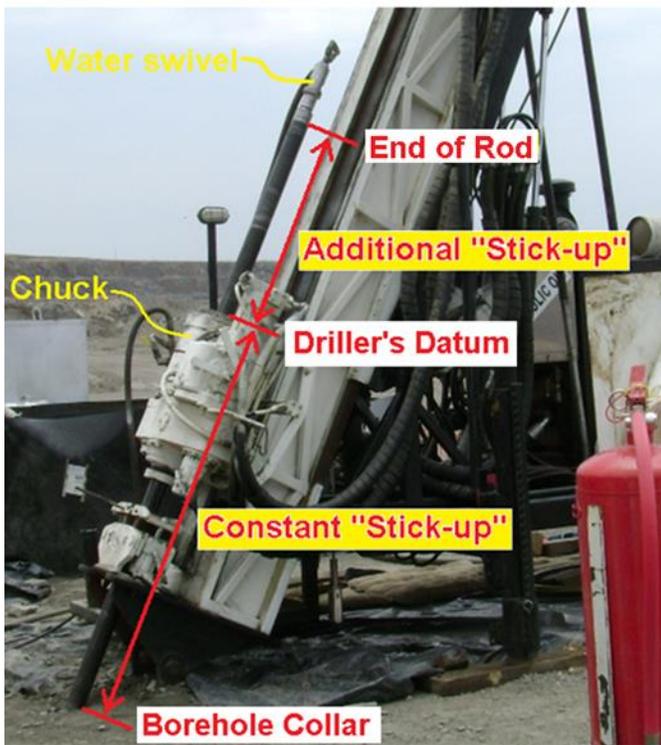


Figure 2: Determining the driller's datum against which to measure the stick-up for borehole depth calculation. (Photo courtesy De Beers)

Even though depth can be measured accurately to the cutting face of the drill bit, most core loggers soon realize there is a problem with depth registration. It is quite usual to find long sections of core that easily lock together across several runs, showing there cannot have been any *core loss* due to grinding, or natural cavities etc., yet the stick-up log nearly always records a loss and occasional core gains, some of which are substantial.

The culprit is the *core-spring* or *core-lifter mechanism* that is used to break the core when the barrel is pulled and extracted to surface. This mechanism sits a short distance behind the drill bit so that a stub of core is always left in hole. (Figure 3).

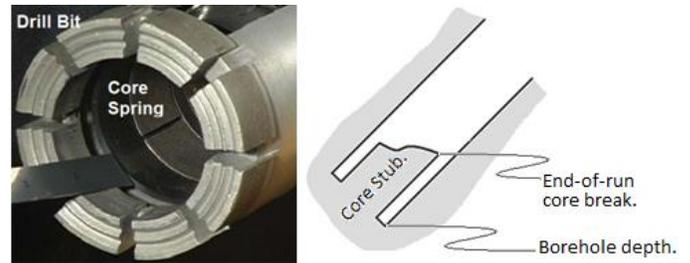


Figure 3: The core spring mechanism used to grip and break the core and the resultant stub always left in-hole.

Hypothetically, if the core could always be broken flush with the bottom of the bore at the end of each drill run so that there was never a stub, then the depths written on the core blocks would always be accurate for every end-of-run core break. Any difference between the advance and core recovery could only be due to *actual core loss in that run*, which could then be confidently distributed to breaks caused by cavities or core grinding etc., to relocate the core segments as close as possible to their in-situ positions along the borehole path. If this were the case the depth registration accuracy of the core would not be in doubt and it would be used with confidence to depth adjust any downhole geophysics logs.

The problem however is the stub. This results in an *apparent core loss* for each run, the amount of which can be significant, especially if the core spring slips. When this happens the driller normally recovers the long stub in the next run by reducing the advance to avoid overfilling the core barrel and hence a *core gain* occurs.

Thus for accurate core depth registration the amount of apparent and actual core loss in each drill run should be distinguished, so that only the actual is used for any spacing of the of the recovered core segments. In practice this is impossible to do when measuring down from each core block to meter mark the core or find the depth of any feature logged.

Such *top-down* depth registration, however, is the preferred method, despite many irregularities, such as anomalous gaps between segments on either side of run breaks, even though they lock together well, and overlapping sections. (Figure 4 - see runs 3, 4 and 5. Note:

Adv. = advance; CR = Core Recovery; L\G = Core Loss\Gain).

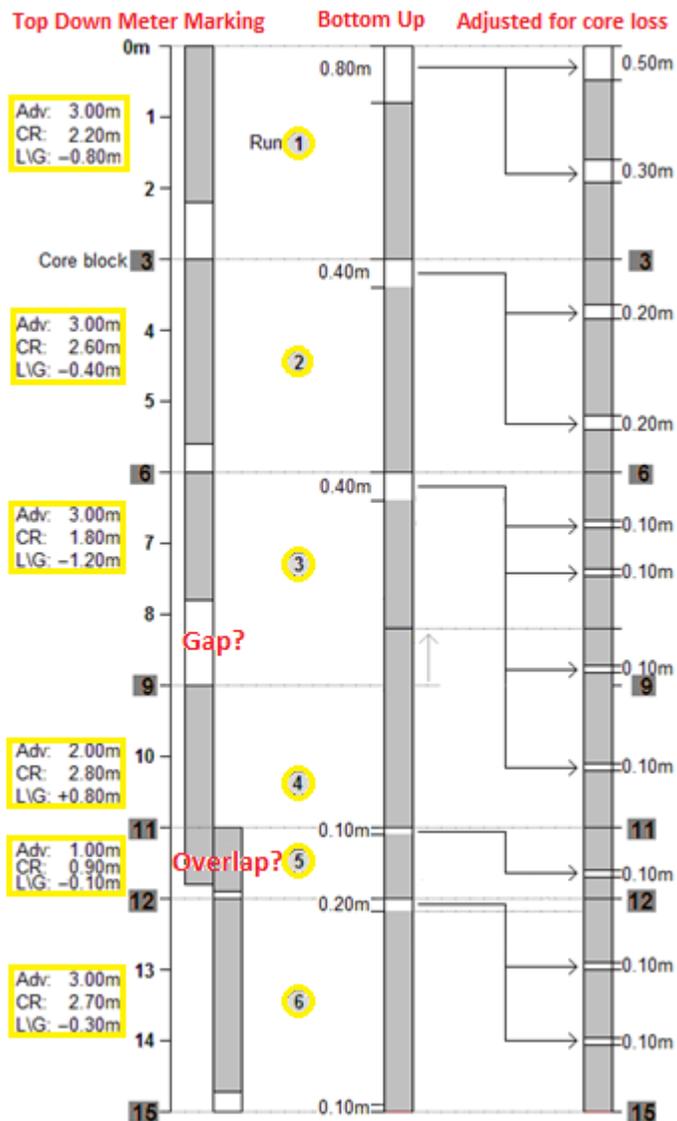


Figure 4: Top-down versus Bottom-up core depth registration.

Unfortunately these anomalies are more often than not incorrectly blamed on the driller, who is accused of incompetence and the ‘mistakes’ are rectified by moving the core blocks, which just makes the situation worse.

The correct depth registration method, to avoid these problems, is to measure from the *bottom-up* effectively ‘stacking’ the core from the base of the borehole. Apparent core losses are now automatically eliminated as any core gain correctly extends into the run above and therefore any gaps can only be attributed to actual core loss, which can be apportioned to breaks from grinding or natural cavities to adjust the location of the core segments and properly map their position along the borehole path (Figure 4).

Regardless of the measurement method though, the success of drill core depth registration depends on how carefully the driller has measured each end-of-run depth, as per the definition given previously, viz: A drill run

occurs each and every time the core barrel inner tube is pulled and emptied, after which the bore depth and core recovery must be measured and the stick-up log completed, however short the advance.

The main reason why this definition must be adhered to is that it is otherwise very easy to lose track of the number of drill rods in the drill string – and hence the true core loss – explaining why depth discrepancies up to several meters are not unusual between features found in the core and wireline logs – such as a density change over a dolerite/sandstone contact for example.

These depth differences result when runs are assembled using core from two or more core barrel extractions to achieve a near constant advance. This modus operandi has two advantages for the driller – it avoids insults of incompetence and ensures compliance with the standard contractual requirement of  $\pm 95\%$  minimum overall core recovery.

Such drilling practice is easy to detect. Core recoveries often exceed the core barrel inner tube capacity, which also results in a succession of runs with core gain, and another dead give-away are tapered core segments within a run. The latter occur when drilling over core that was dropped from the barrel on extraction – indicating the end of a drill run that should have been recorded as such (Figure 5).



Figure 5: Tapered core segments indicating runs were made-up to achieve a near constant advance. (Photo courtesy Debswana)

It is therefore essential to count the rods as often as possible and at least on every bit change, to confirm the borehole depth. A discrepancy means the overall core loss is greater than that recorded in the driller’s log and, since this additional loss is impossible to locate along the borehole path, the value of the lithology and structural logs is severely compromised.

### 3. ORIENTING DRILL CORE

The cylindrical geometry of core is ideal for structural measurements. The outline of any plane intersected in the core is an ellipse, the long axis of which lies in the dip direction so that all that is needed to find the structure’s true dip and dip direction is to:

- i. Measure the alpha angle, being the inclination of the long axis relative to the core axis (Figure 6).
- ii. Measure the beta angle, as subtended between the *geographical vertical plane* and the plane containing both the core axis and the long axis of the ellipse (Figure 6).

- iii. Interpolate the plunge and trend of the core at the depth of the structure from the borehole survey, and use these angles to rotate the alpha/beta angles (stereographically) and find the plane's dip and dip direction.

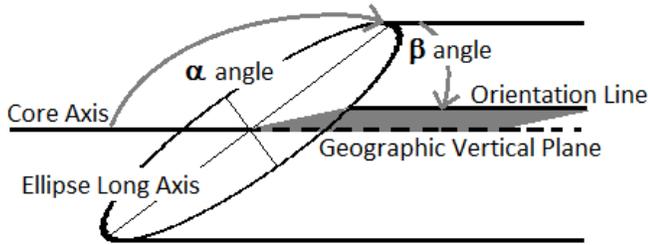


Figure 6: Measuring a geological structure in oriented core.

Thus drill core is the preeminent source of structural data, particularly since each plane can also be identified as a joint, bedding surface, etc., and fully described – information that cannot be obtained from televiewer scans. Hence orienting core should be the norm for all drilling contracts – why then is this not the case [2]?

A range of instruments have been invented to draw a line that marks the intersection of the geographic vertical plane to orient core. Success however depends not only on tool design but also the skill of the operator. Hence orientation accuracies should be evaluated: firstly by ensuring every run is independently marked and then measuring the offsets to plot the *cumulative orientation offsets*. This is done by joining the segments on either side of each run break and continuing the line from the upper run a short distance down onto the lower run. The angular difference between the two marks is then measured and, using the convention that offsets to the right are positive and those to the left are negative, the cumulative offsets are calculated and plotted (Figure 7).



Figure 7: A graph of cumulative orientation angle offsets. (Photo courtesy Debswana)

Well oriented core has small, evenly distributed offsets, unlike BH074 (Figure 7) which was failed because of large offsets caused by different drill shifts marking the core either bottom-side or high-side! In addition the skewed spread indicated a faulty instrument.

Orientation efficiency should also be assessed on the amount of core that is oriented (Figure 8). If this length is low due to long sections of rubble then it is vital to also obtain televiewer data for geotechnical analysis.

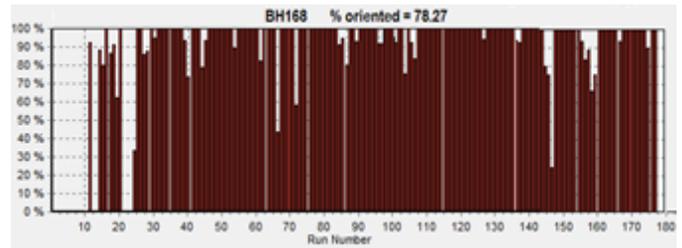


Figure 8: Histogram plot of the % core oriented per run. (Courtesy De Beers)

If however a low percentage orientation is due to mechanical damage such as core grinding (Figure 9), the driller should be persuaded to perform better.



Figure 9: Core grinding from incipient through to a full grind. (Photo courtesy Debswana)

Thus, with care a high standard of core orientation can be achieved. In addition drill core orientation success can also be verified through comparison of the structures logged with televiewer scans of the borehole, although such comparisons can be frustratingly difficult.

In the main the problems are due to spurious televiewer picks, the number of which depends on how well the tool is calibrated and centralized, as well as the acoustic or optic ‘visibility’ of the borehole wall, which can be masked by drilling-mud and grease, etc. The skill of the scan interpreter is also a factor and to overcome these issues and filter the noise a proprietary method has been devised using *tadpole plots* of the data (Figure 10).

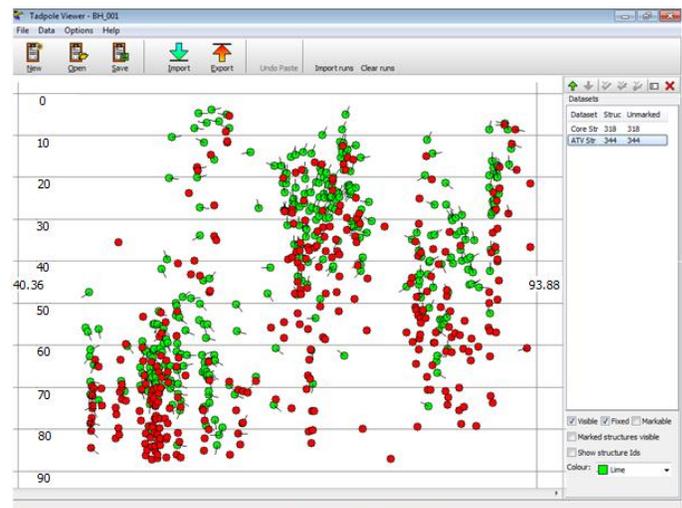


Figure 10: A tadpole plot comparison of structures logged from core (red) with those interpreted from a televiewer scan of the borehole, and filtered for noise (green).

This graph plots the alpha, or dip angle for each structure against depth, as the tadpole ‘head’, whilst the direction of the tadpole ‘tail’ around the head points in the structure’s beta angle or dip direction.

The strength of the graph lies in the fact that the alpha/dip angles for structures seen in the core and their associated televiewer picks are very close. Hence their tadpole heads plot close together with a similar distribution pattern (if not the televiewer navigation data should be compared with the borehole survey) and televiewer tadpoles with no matches can be filtered out as noise. The tails of the televiewer tadpoles remaining can then be compared with those logged in the core and used to adjust their beta/dip direction angles, or orient the core structures for which only an alpha has been measured.

In the example shown (Figure10), the core tadpoles are largely unoriented, whereas the ATV tadpoles all have beta angle tails. Since the distribution pattern of both data sets compares well the ATV beta angles could then be copied to properly orient the core structures.

Note most televiewers use an on-board magnetic survey to rotate the *structure pick* angles and derive dip and dip direction. It is recommended the sonde be set to scan to *high-side* and a gyroscopic survey used instead to avoid issues with magnetic interference.

#### 4. BOREHOLE SURVEY VALIDATION

Authenticating a borehole survey is difficult [3, 4] and obviously impossible if only one survey is available. All that can then be done is to calculate the borehole path to check for unrealistic bends that would otherwise cause the drill rods to break. Thus such single surveys are failed either due to tool malfunction or, in the case of a magnetic instrument, ground interference.

The minimum requirement for validation of a borehole path is an IN/OUT survey, using the closest station spacing that the tool can provide. Before starting though the correct tool calibration should be confirmed with an in-date certification and, for multi-hole projects, the drill rods should be left in an early bore for periodic field calibration checks.

Given an IN/OUT survey the usual quality assessment is to calculate the *closure error* in a loop, i.e. the end coordinates of the IN survey are used as the start point of the OUT. By arbitrary convention the data is passed if the difference between the end of the OUT and the start of the IN is within five meters, normalized to 1000 meters.

If more than one IN/OUT survey is available then their *separation errors*, again extrapolated to 1000m, are calculated by reconstructing the borehole paths in 3 dimensions, each starting at the collar. Any number of path surveys can be compared by this technique and the

maximum used as a rough and ready statistic to gauge final accuracy.

For example, the closure errors for the three IN/OUT surveys of BH015 carried out at 293m, 406m and 505m, were each less than 3.5m. However the separation errors showed a 21m divergence at 1000m (Table 1).

Separation Data - BH015					
Depth (M)	Base Survey	Compared Survey	Separation	1000m Separation	Max 1000m Separation
292	1 OUT	1 IN	1.014	3.474	21.963
292	1 OUT	2 OUT	6.389	21.881	
292	1 OUT	2 IN	6.386	21.869	
292	1 OUT	EOH OUT	1.037	3.551	
292	1 OUT	EOH IN	1.051	3.599	
293	1 IN	2 OUT	6.435	21.963	
293	1 IN	2 IN	6.424	21.926	
293	1 IN	EOH OUT	1.204	4.110	
293	1 IN	EOH IN	1.039	3.546	
406	2 OUT	2 IN	1.298	3.197	
406	2 OUT	EOH OUT	6.490	14.110	
406	2 OUT	EOH IN	6.572	14.286	
407	2 IN	EOH OUT	6.535	14.175	
407	2 IN	EOH IN	6.627	14.375	
505	EOH OUT	EOH IN	1.255	2.485	

Table 1: Three IN/OUT survey separation error combinations.

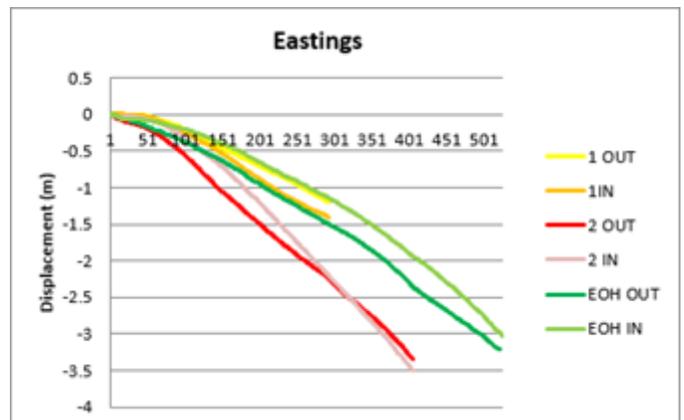


Figure 11: The three IN/OUT survey pair paths for BH015.

Instead of failing all the surveys though, the second was found to have been done using a different gyroscope, as shown clearly in the Eastings plot (Figure 11), and that surveys one and E.O.H could be passed.

Paths calculated from the survey data can be displayed in an Eastings/Northings plot to give a visual sense of how well the borehole has been surveyed (Figure 12).

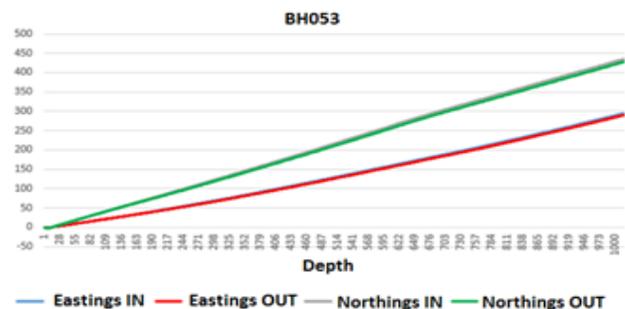


Figure 12: A typical IN/OUT survey coordinate graph.

However such graphs reveal little about the behaviour of the survey tool as it traverses the borehole; for this a tadpole plot is used (Figure 13).

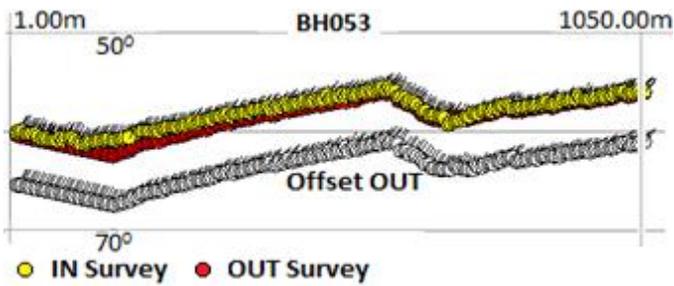


Figure 13: A ‘millipede’ borehole survey plot. Note the OUT survey has been copied and offset for easier comparison.

The data plotted in Figure 13 is for the same borehole as that shown in Figure 12. Each survey station is plotted as a tadpole and the graph shows at a glance that the OUT survey deviates significantly until near surface, where it tracks in a suspiciously straight line back to the collar, to reduce the closure error.

Thus the more repeat surveys there are for a borehole the greater the confidence in using the final OUT survey to define the borehole path – so long as the separation errors are less than five meters and given reasonable tool behaviour.

## 5. IMAGE BASED CORE LOGGING

Clipboard core logging is still widely used since it is simple to operate under harsh conditions. It is also just as fast as most digital systems and is just as auditable. Consequently few geologists stay long in the core shed as there is little opportunity to develop new skills when only recording routine, prescribed observations as well as spending much time making tedious depth and angle measurements.

Image based logging [5], StereoCore™ PhotoLog, uses hand-held digital photographs of the core trays placed within in a simple reference frame used to undistort and accurately calibrate the images to convert the photos into virtual 3-D models of the core (Figure 14).

Segment lines can then be drawn to scale along the core and colour coded yellow if unoriented or red for bottom-side and purple for top-side oriented lines. Each core block is assigned its depth, to depth register the core using the bottom-up, or stacking method recommended above. Thus the advance and true core loss per run is automatically calculated and can be used to insert *spacers* at appropriate breaks in the core to relocate the segments as closely as possible in their in-situ depths along the borehole path (Figure 14). Such depth adjustment can be made at any stage to align the core as closely as possible with the downhole geophysics.

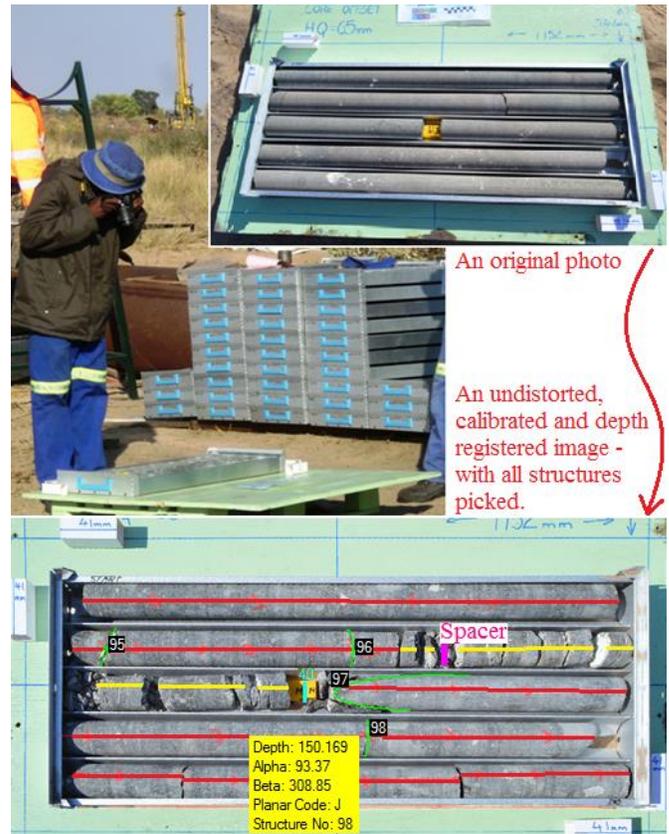


Figure 14: StereoCore™ PhotoLog in operation.

Once the virtual core is depth registered, elliptical traces are drawn to match the structures intersected in the core. The geometry of each trace is then automatically computed to log its alpha/beta angles (Figure 14), avoiding a common mistake – since alpha is measured from 0° to 90° using a goniometer and unless the correct end of the segment used to measure is noted, as either top or bottom of core-stick, the dip direction calculated for the plane will be out by 180° (Figure 15).

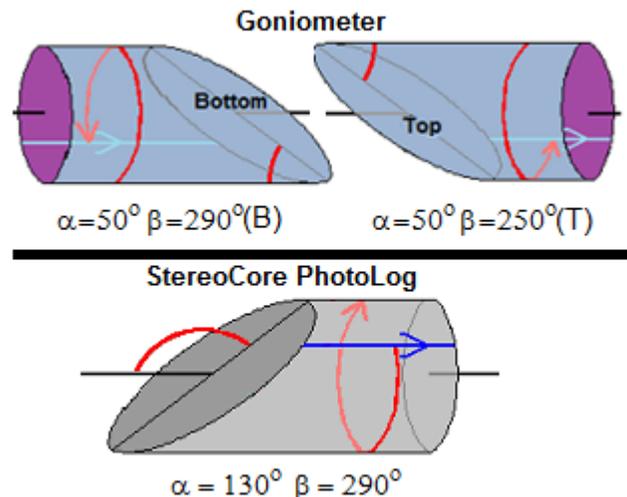


Figure 15: Comparing manual and StereoCore goniometry.

A recent development in StereoCore™ PhotoLog is the use of *tags* to mark features on the photos and capture descriptors in a table – without first requiring the images

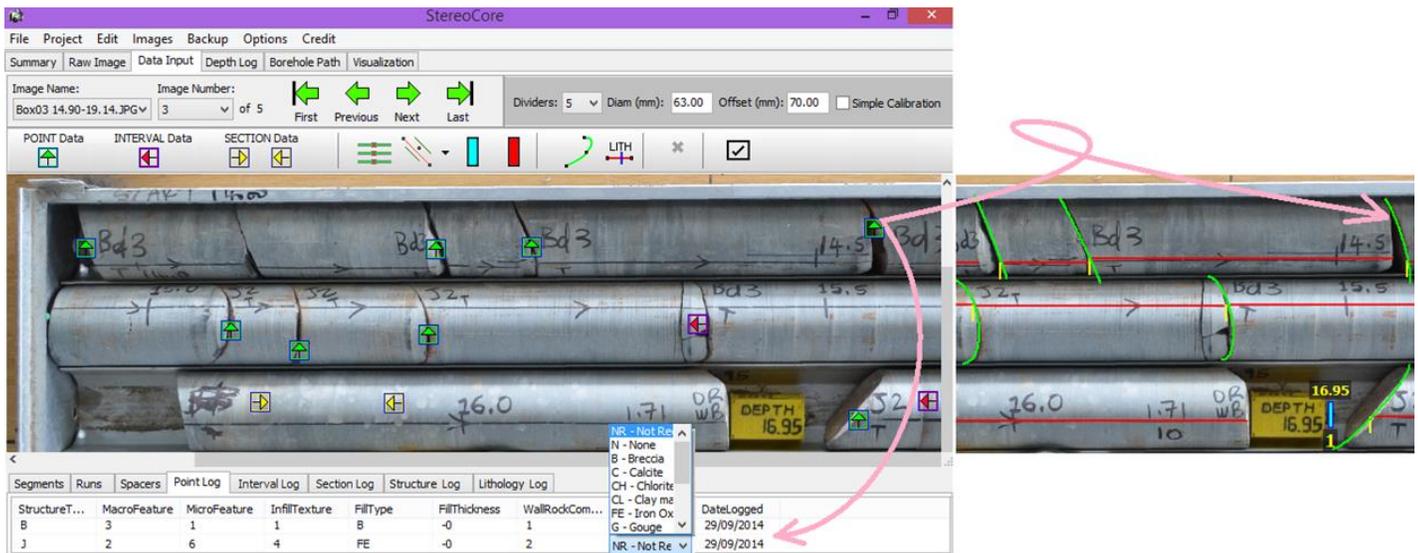


Figure 16: Data transfer from tagged image to depth registered and picked image.

to be depth registered and the structures picked. This can be done later, by an assistant, to automatically record the depths and angles of the features as well as transfer their data to the relevant structure or lithology log simply by dragging and dropping each tag onto its associated pick (Figure 16), thus optimizing the geologist's time.

Manually logged data can also be imported to display the structure traces at their logged depths. This feature has been used extensively to audit and correct logs and more recently to import and correlate ATV data.

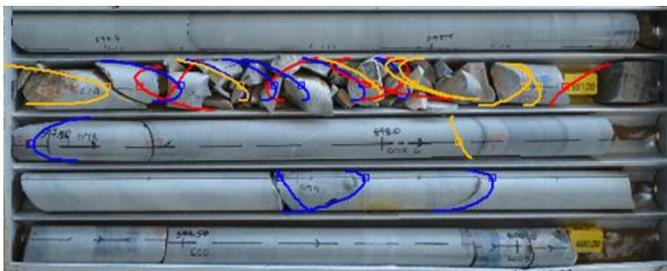


Figure 17: ATV data compared with structures seen in the core. (Photo courtesy Debswana)

In the example (Figure 17) the blue ATV traces have good expression on the borehole scan and correlate very well with fractures in the core. The orange to red traces less so, but their intensity increases markedly over the rubble zone giving valuable structural information for these sections of unoriented core that otherwise would have been largely ignored.

## 6. CONCLUSION

The foregoing makes the case that provided a diamond drilling project has: (i) well-informed supervision of the drilling process; (ii) skilled and cooperative drill operators; (iii) sound, professional service from wireline borehole survey contractors; and (iv) a well designed digital tool for both rapid data logging and straightforward correlation with downhole geophysics,

then it is difficult to imagine that the standard of information delivered will ever be surpassed by any other sub-surface exploration technique. Thus given such high quality data its predictive power lies entirely in the skills and interpretative abilities of the modeller.

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