Basic Guide to Geosteering

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SECTION 1 – INTRODUCTION

Geosteering is the science, or art, of maintaining a near horizontal well bore within a pre-defined and often thin geological layer. The geosteerer must micro-adjust the well trajectory from the original plan, such that it is maintained within the pre-defined target for the greatest horizontal length possible. At the same time, the geosteerer must fulfil the client's specific trajectory requirements, which may have dogleg or inclination limitations, or hard ceilings / floors defined by fluid contacts.

Geosteering can be divided into three sections: 1) Planning stages; 2) the build-up and landing section; 3) the horizontal section. All are of equal importance for the success of a well. There are two basic methodologies in geosteering, one that can be applied where significant uncertainty exists and one, more scientifically, that can be applied when reasonable predictability exists.

SECTION 2 – PLANNING

2.1 FIELD PLANNING - HOW ARE YOU GOING TO GEOSTEER?

Gathering as much data as is possible about the target layer, overlaying strata and structure are essential to the success of a well. This is not to say that a well cannot be drilled in the absence of these data, but the probability of encountering issues, sidetracking and reduced target contact would be much enhanced. In some circumstances offset well data, geophysical data and computer models may be restricted for third parties, may not exist, or may be of limited quality. Even in the best scenarios the error margins for models are likely to be up to one order of magnitude greater than the target thickness.

When geosteering, one must be realistic about the target thickness. In flat or gently dipping and highly predictable structures it is possible to target very thin layers of the order of 3 ft in thickness (sometimes better, but 3 ft is realistic). In stronger dipping structures and where structural unpredictability increases a thicker target interval must be defined, which might be 10 ft, 20 ft or more. One can define an optimal layer, but in these circumstances it may not be possible to precisely follow it.

If there is no pre-existing familiarity with the strata, then a pilot study may be the way forward. The objective here is how to identify the different layers leading up to the landing point, such that the correct landing TVD within the target can be predicted sufficiently in advance to allow for plan adjustments. Secondly the layers within, above and below the defined target must be able to be differentiated from one another so that the correct stratigraphic position can be established, and the correct steering decisions made. Thirdly, the reliability and consistency of picks must be tested laterally.

In some areas differentiation of the various layers is simple, in other areas rocks may be cyclic or the rocks above and below the target may appear identical. The objective here is to find out how to differentiate the layers, as best as possible, and recognise them whilst geosteering.

Differentiation of the various layers might be achieved by various means:

1) Selecting the correct LWD suite. Maybe the layers are straightforward enough to use solely Gamma Ray, thus saving money. Maybe a full suite of Gamma Ray, Density, Porosity, Photoelectric Factor and Resistivity logs are required to differentiate the layers. One must also review the offset distances of the sensors and prioritise essential logs in the BHA or opt for near-bit sensors if available.
2) It is often the case, particularly when drilling horizontally, that the log response may look the same in layers above and below the target. The lithology may be the next line of attack. Subtle lithological variations may give clues as to the stratigraphic position.
3) Sometimes lithologies can appear identical, but micropalaeontological (calcareous micropalaeontology, nannopalaeontology and / or palynology) may differentiate rocks. Horizontal drilling is usually on a sub-evolutionary level and thus relies on variations in species or their abundances / ratios, which are in-turn palaeoenvironmentally related. This is usually referred to as biosteering.
4) Sometimes, you must conclude that the rocks above and below were deposited in the same environment and are, in fact, identical in every way – but not all is lost. Very simply, one is up, and one is down, on this basis image logs or directional LWD tools (up / down), put into context with trajectory data will enable you to steer.
5) Some technologies, for example Schlumberger PeriScope, even read into the formation and allow a picture to be built up of apparent structure and bedding dip. These are valuable tools. They can add a great deal of data where structural uncertainty exists, but in some circumstances may add little or even be misleading where there are fluid changes or lateral variations impacting resistivity values. The cost of running these tools must also be considered. Depending on the circumstances, a competent geologist with at least some offset well data may be able to do considerably better. The value herein lies where there is structural uncertainty, but lateral consistency in lithology and thickness exists. This tool does not read ahead, but like the geologists tries to understand the apparent bedding dip, to allow predictions to be made ahead.
6) An understanding of the strata will also enable the correct bit and steering solution. There are various steering methods from sliding to push-to-bit rotary steerable systems (RSS), to point-to-bit RSS and various hybrids. These will be variable aggressive in drilling a target. Some will give precise inclinations, others are cruder but may bounce against harder layers and thus keep the well bore in the target layer (or conversely prevent re-penetration of the target layer).

Every drilling location is unique and thus the tools / techniques, or combinations of tools / techniques must be tailored to the particular field or sub-field. Sometimes there is also a budgetary consideration, although often staying within the pay zone for a greater horizontal length will offset the cost of any required tool or technique. Often the cheapest and most effective tool in geosteering is to have the correct personnel whose attention to detail enables the correct steering decision to be made most of the time.

2.2 WELL PLANNING

At this stage, we assume that the field is up and running and that standardised procedures have been agreed and key decisions on BHA / LWD design have been made. For the most part these will remain unchanged unless new tools or technologies become available, or justification can be made for higher budget tools. The next critical stage is in planning for the individual well. Although the operations geologist will likely have made detailed plans many months ahead, the wellsite geologist's planning and data gathering will be done during the rig move (along with the write-up and assessment of the previous well). Some clients will save on cost by only having the geosteerers out at the last minute. This is often a compromise but will save money. It can work if the geosteerer is experienced in the field and the operations geologist has prepared the necessary offset data and ensured the plan is good. It can be false economy if the offset data has not been reviewed and the geosteerer is left without critical data or is working on the fly and hasn't predicted trouble that lies ahead because he / she hasn't yet reviewed the data.

This is a list of tasks carried out by the geosteerer as he / she plans the well. It is basically the same as any research project: 1) Gather data; 2) Research the data; 3) Execute the plan – in this case successfully drill the well!

1) Gather data. This includes (but might not be limited to):
    a. The geological well prognosis and drilling programme (including seismic, structural and porosity models).
    b. The most recent directional survey plan (this often changes last minute, so double check).
    c. Available data from relevant stratigraphic levels for ALL closely offset wells. Principally one is after a minimum of a TVD log, MD log and survey data. The final / end of well report and lithological / mud log may be of high value also.
2) Analyse the data.
    a. Identify any issues / problems in the prognosis.
    b. Is the directional survey plan acceptable? Is it a good, smooth profile? Is it achievable? Can you still land with the degree of uncertainty you have - i.e. in the worst-case scenario? Is the dogleg severity acceptable? Is the well path likely to stay within the predicted position of the target layer? Does it stay above / below any hard ceiling / floor or fluid contact? Is there a collision risk (maybe the directional company missed a nearby well from the anti-collision report) – not really your job, but you will be fired if you don't pick it up!
    c. Re-pick or check the layers / zones are consistent between wells. In most companies the picks are not consistent as different people worked on different wells at different times. Consistency to a high level is essential. Work out the thickness of all the different layers, based on your new picks, and the TVD distance of that layer to the top of your target layer. If you need more layers, just add distinct picks – it doesn't matter in drilling if it's A, B, C or X, Y, X, as you are just interested in your consistent stratigraphic position relative to the target. Is the data good? Was the data from a deviated well with dipping strata? – this may significantly affect the thicknesses. Work out averages or use only the most reliable well(s). If structural dip is reasonably well understood a correction factor can be applied to work out true stratigraphic thickness. Are thicknesses variable or consistent – is there a trend? Does thickness vary from the shoe to TD of the planned well? Deeper water sediments are typically less laterally variable and make things easier! Make a spreadsheet with these data and this is now the basis of your landing and horizontal drilling. Cross check data - do not blindly rely on a computer model which might be based on variable quality picks or linked to different horizons at different levels – you will quickly learn if you can rely on the computer model or not.
    d. If the computer / seismic model is bad or the well path has variable azimuth, then apparent dips can be calculated between wells and as azimuth changes. From these data you can manually construct your own sub-surface map.
    e. Review reports – identify problems in previous wells. Was there lateral variation? Was faulting encountered? Were any downhole mud losses encountered? Maybe there is a karstic

topography which is more variable in the drilling area? Maybe channelised deposits were encountered? Maybe the zonation (fossils or lithology) could be divided up further in this area or maybe it was less well defined? Where there any geology-related drilling issues such as slow ROP, tool failures due to temperature, problems steering due to lithology / RSS combination? [Make sure your reports include these kind of data as they will help you to do a better job in the future].

3) Prior to commencing the well set up the necessary files and reports. These might include: Offset well thickness tables, well path spreadsheet or well path setup in geosteering software, morning reports, picks tables, mud losses graphs, gas ratio graphs, etc. Always get as much done as possible in advance / ahead of when it is needed. Drilling often presents surprises and you may find your time is taken up with another issue later. Communicate relevant information to third parties as required so that they can smoothly perform their job and within the data confidentiality agreements of the company.
4) Armed with the relevant data and necessary planning, you are ready to drill a successful well. A compromise in the client not giving the contractor confidential offset well data or in not allowing the geosteerer sufficient time to plan prior to drilling is just that – a compromise. One can mitigate against this by having correctly skilled staff in the operations role, feeding accurate and high quality (pointed if necessary) data as and when required.

SECTION 3 - DRILLING THE WELL

3.1 THE SETUP

Ideally a geosteerer will be a wellsite geologist with a specialization in geosteering. They therefore carry out all geological tasks on the rig. The geosteerer should have a natural ability, experience to suit the job, good organizational skills, awareness of the importance of consistency and have great attention to detail. In some instances, you may have a specialist geosteerer such as a biosteerer. This person is often a 'semi-academic' industrial micropalaeontologist specialised in geosteering and therefore an additional wellsite geologist is also required to handle the other routine geological tasks on the rig which fall outside the remit of 'geosteering'. Ideally, and is often the case, the geosteerer is tailored to the company's needs and will act as a wellsite geologist / geosteerer (and maybe even a biosteerer) thus reducing personnel and saving on cost. Overall, a geosteerer is cheap compared to the cost of drilling a well out of target or sidetracking. If the right person is in the job and the correct background research is done, money can be saved by using the correct combination of tools / techniques for that specific job. It is important to keep office-wellsite communication / feedback good and to review learning points for each well.

Typically, a landing and horizontal section will utilise a team of two geosteerers, each working 12-hour shifts. This shift pattern is the standard as a well requires constant monitoring and adjustment. If only one geosteerer is available, the likelihood of exiting the target is very greatly increased, if not inevitable in some cases. Additionally, two heads are often better than one in interpreting complex problems as ideas can be 'bounced' between individuals. A single geosteerer can be employed to work 18-hour days and be woken every 45 minutes to 2 hours during their sleep period (dependent on ROP and well position / confidence), but this is a compromise on safety and on the job quality, as decision making may be significantly impaired by fatigue. Ultimately the cost of employing 2 good quality geologists, who can work with and understand the data, is probably a better investment of money than trying to solve issues by running increasingly expensive LWD tools (which end up not being monitored 24 hours and therefore do not necessarily address the issue). A good geologist, attentive to lithology, may get more information than a very expensive new LWD tool, so in many cases it's better to ensure quality 24-hour coverage on lithology and data / log interpretation.

The rig setup will vary on the geological task involved and on available space. Ideally the geologist should have a dedicated office with two desk spaces, although it is entirely possible to work from a very small 'half-desk' space. Usually the sink, microscope and fluoroscope in the mudlogging unit are used, but if there is no mudlogging being carried out then provision for this equipment must be made. Typically, no highly specialist equipment is required, although certain micropalaeontological set-ups may require space for processing equipment.

Two computer monitors should display the drilling parameters from the mudlogging unit and the LWD data (ideally together with survey and tool face data) from the LWD unit. These are essential for geosteering. To not have these real-time feeds (which would be abnormal these days) will result in delayed reaction to problems, possibly resulting in reduced lateral section in the target. The monitors should be large displays and the software simple, interactive, reliable and cleanly presented. Often, multi-million-dollar tools are run in the hole, only to have their value massively reduced by low quality interfaces and a cheap $100 monitor. It is advised that any links to the provided monitors is made directly on the rig site (and can be repaired on rig site).

Increasingly data is being remotely communicated, meaning that it is transmitted by internet off-site and then relayed back to the site. This may result in down-time as rig internet connections and remote servers are highly subject to failure. Keeping things simple and on-site results in maybe 2-5% down-time, making things remote will often result in about 10% down-time, which is unacceptable when drilling.

The geosteerer will have 1 (or 2) laptops (ideally desktops on a semi-permanent location) to work on his / her reports and monitor the well trajectory. In remote locations it is recommended to always have a backup computer and to allow administrator rights as much as possible, as often problems cannot be solved remotely. A big failing is often that from a major city, one assumes perfect uninterrupted, trouble free, super-fast internet. This is often not the case at wellsite, even in optimal circumstances, and should never be assumed. If the internet connection is relied upon, then backup plans must be available if no connection is available.

3.2 THE LANDING

Landing a well in the correct stratigraphic position is not a complex task if the correct methodology is used. Communications between the geosteerer and directional driller should be good to ensure that final instructions are given at the correct time.

In my experience landing in the target is essential. To land slightly above or below the target may result in significant loss of section within target.

1) Know the thicknesses of the overlying units in offset wells. Know the distance from these picks to the top of your target formation. Know the variations in thicknesses – some picks may be better than others. Ensure your offset picks are consistent. Beware of deviated offset wells, unit thickness must be adjusted for dip (and even then, may be less reliable).
2) Armed with these picks and distances to top target, you simply make the same picks on your real-time logs. On the cross-section diagram you are drawing, utilizing the survey data, you project down to the top target. After several picks, you build up a clear picture of apparent bedding inclination. The same methodology is used, regardless of whether you use a pencil and graph paper, Microsoft Excel or specialist geosteering software – it is simply a matter of time savings and standardization of methodology.
3) Project this apparent bedding inclination forward. If the well is changing azimuth as it comes in to land, then this must be considered. You should have either an excellent, or at least some idea of apparent bedding inclination along two azimuths. This allows you to roughly calculate apparent bedding inclination along any azimuth, so you can project ahead how bedding inclination will change as azimuth changes to predict the landing point. This assumes no structural changes ahead, which is the only logical conclusion unless data exists (principally geophysical) to say otherwise.
4) Thicknesses sometimes vary, or apparent bedding inclination may change last minute. Aim to be at a good angle at the predicted top of the target formation. If the expected apparent bedding inclination is 90 degrees aim to be at say 85 to 87 degrees at the boundary. If the top does not come in as expected, then hold this angle and drill in rotary until the top is found and then raise the inclination. Never work on assumptions, work on facts, so confirm the target before raising angle (or you may need to drop angle again).
5) Aim slightly high – it is very easy to go deeper (at slight expense of vertical section) – you just hold angle and drill in rotary before continuing to raise inclination. If you are deeper and suddenly want to bring the landing point up TVD-wise there may be big issues and high doglegs. Try and avoid this scenario if possible.
6) If the bedding is dipping up, then land at the very top of the target unit. If bedding is dipping down, then land towards the base. Always try and land in the target. If you land deep you may place a sump in the well. If you land high you may lose considerable vertical section in the target (and

worse still, even become lost before reaching the target). Landing in the correct spot always pays off and is the seed of a good well!

7) Always monitor bedding inclination and ensure the well is landed at a good bit inclination relative to the bedding inclination. Remember that around 0.5 degrees is commonly lost when drilling out of the casing shoe. It should only be in exceptional circumstances that the well is landed at a bad angle, e.g. 83 degrees with 90 degrees bedding. This might occur if a fault was encountered and a decision was made that it will be easier to steer with the BHA planned in the next section due to availability of different LWD data, therefore optimizing chances of success. Generally, the build BHA will deliver higher doglegs so, where possible, it is best to complete any build and turn in the build-up section. There is usually little excuse not to land in the target (or very close) with a decent angle. Failure to land in target is usually a result of lack of planning or poor methodology and rarely due to exceptional circumstances with regards engineering or geological issues.
8) Beware of drilling breaks. Ensure you are monitoring Surface RPM (i.e. whether they are drilling in rotary or sliding) also monitor weight on bit (WOB) whilst viewing ROP. Keep an eye on simple things like temperature or gas values that may indicate target penetration. Flow check if necessary, particularly on drilling breaks (even if a flow check was already performed at the top of the target).
9) Always closely study the samples returned to surface. Always examine a bottom-up (BU) sample at TD. Never assume you are in the target, always check samples and then make sure you remain in the target, on samples, to section TD.
10) In all drilling, be very aware of mud additives and LCM which are, or may later be, in the system. An influx of $CaCO_3$ / ground marble additive, for instance, may cause confusion. If on a new rig always take additive samples, wash them and see what they look like in advance. Ensure the Mud Engineer feeds you information during drilling.

So, how do you land a well if you have no, or limited offset data, either due to unavailability or restricted access? It can be done, but it comes at a price, both monetary and in terms of vertical section. As uncertainty increases, so will your tangent sections. The precise details and angles will be dependent on the degree of uncertainty and on the precision required for the landing. Simply you will hold tangent sections (a fixed angle) until you hit certain markers. For instance, you may want to be at 70° bit inclination until you hit the formation above the one you intend to land in. You might then build-up your inclination to 85° and hold until you hit your target formation, at which point you continue to build up angle to land in your desired layer. Without a good understanding of layer thicknesses, any estimates of bedding dip will be educated guesses. Utilisation of directional LWD tools such as image logs or Schlumberger PeriScope can assist in understanding the apparent bedding dip and reducing uncertainty. In this scenario one must always tailor a landing that considers the worst structural and / or stratigraphic thickness variations with an angle that allows adjustments to be made to land within the specified target layer. This technique may result in the well landing earlier or significantly later than anticipated, so can be problematic if the well is required to land at a precise geographic position. Often a hybrid well plan between certainty and uncertainty can be adopted if reasonable guestimates can be made.

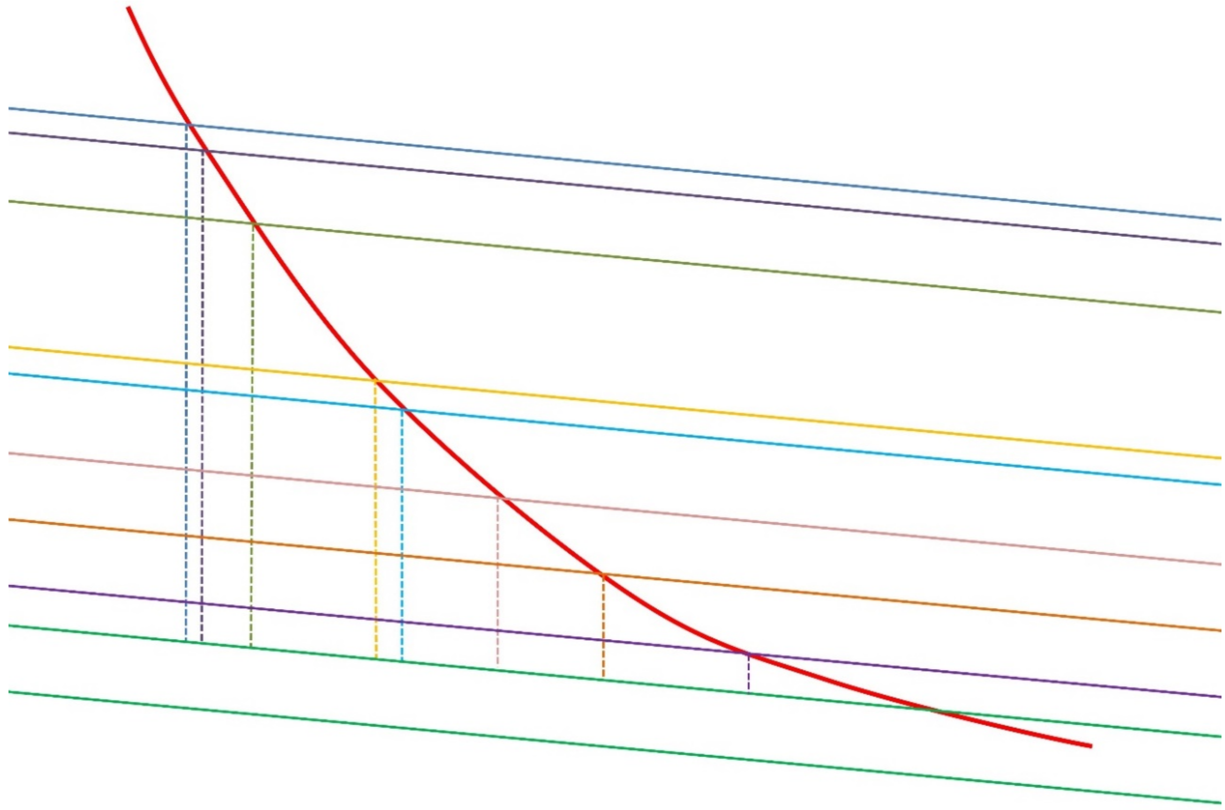

FIGURE 1: In the build-up section a projection should be made at each formation top or log pick down to the top of the target. Distance to the top of the target is calculated from offset well data.

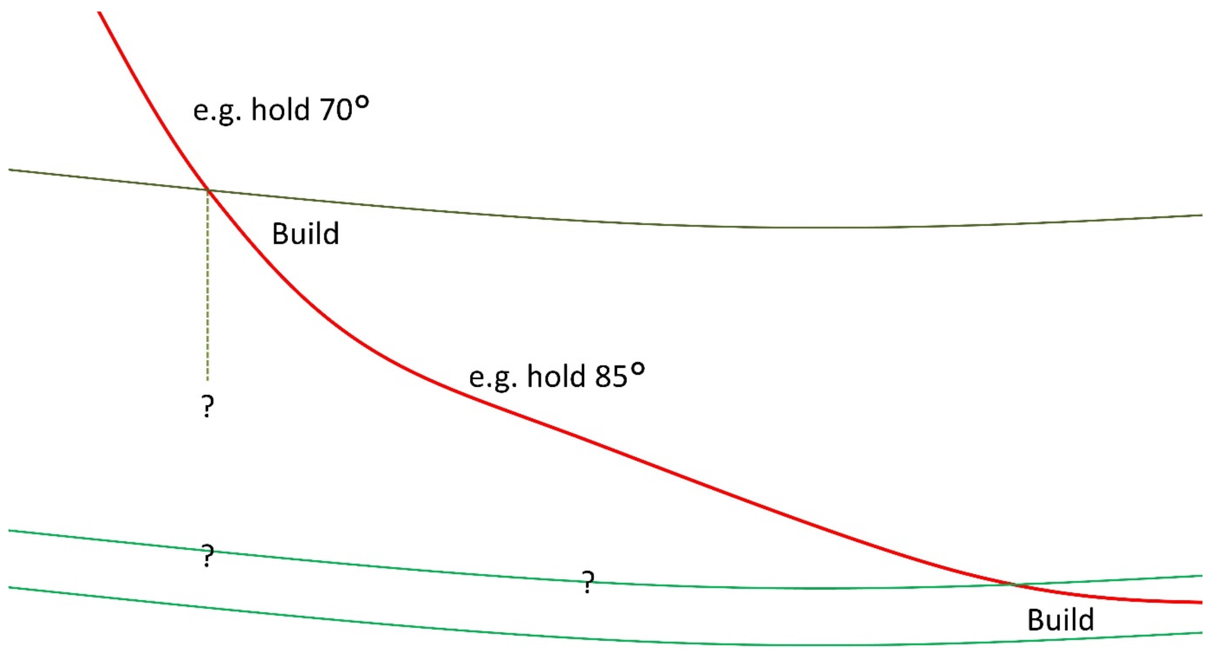

FIGURE 2: In the event that the bedding thicknesses are not known (or are highly variable) and / or the structure is highly unpredictable then tangent sections can be held until 'goal' layers are observed and then reacted upon by building. This may result in increased loss of vertical section.

3.3 THE HORIZONTAL SECTION

Amongst geosteerers, there is often a dichotomy of techniques, neither of which is entirely ideal. By adopting both methodologies, often the best results may be achieved. The first methodology involves little skill and is adopted primarily due to a lack of understanding on how to draw a cross-section and calculate apparent bedding inclination. It is either employed by an unskilled geosteerer or by a skilled geosteerer in the absence of offset data or high lateral and / or structural variability. This technique simply involves aggressively geosteering and always maintaining the bit inclination significantly above or below what you reasonably believe the apparent bedding inclination might be. This creates a zig-zag profile, potentially results in more time out of target and increases dogleg severity. You are, however, constantly reassured of the stratigraphic position without having to think a great deal or make more than a crude guestimate of dip.

The second methodology, detailed below, is utilised by skilled geosteerers. A cross-section is built up. Current stratigraphic position and apparent bedding inclination is very well understood, and a forward projection is made based on the historic data and the modelled / geophysical data. The aim here is less to keep hitting control points and more to place the well in the optimal porosity and then adjust the bedding inclination to parallel the apparent bedding inclination. This is obviously the ideal, the reality being that there is almost always a degree of uncertainty.

In truth, a hybrid version of the two methodologies seems to work best. The second, skilled and scientific methodology should be aspired to. However, if you find yourself moving out of target this often represents an uncertainty, often an unpredicted change in apparent bedding inclination. This therefore reduces your ability to accurately project ahead. To maximise section spent in the target, aggressive steering more than the likely apparent bedding inclination can therefore produce favourable results. This can be followed by calculations and then re-adjustments of the well path to again target the optimum porosity, rather than blindly hitting the top or bottom of the target again. Gentle, non-aggressive, controlled geosteering is the ideal but as uncertainty increases then more aggressive geosteering is desirable. The operations geologist should ascertain that the uncertainty is due to geological factors and not lack of skill or understanding on the part of the wellsite geologist, and this is achieved by the operations geologist requiring thrice daily cross-section reports. Now, the cross-section is based on calculations and logic, and a good geosteerer should be happy to modify based on the incoming of further data. The cross-section is a working model, showing logical thought process on available data.

The fundamentals of geosteering are to be in control of the well. To do this you must know your current stratigraphic position and be able to project this ahead and plan where you need to be heading. In a horizontal well, to know your current stratigraphic position, usually necessitates knowing your earlier stratigraphic positions from a distinct control point or the landing point. A horizontal well can be likened to holding a wild snake – if you don’t do it right and stay in control, it’s going to be everywhere and you’re going to get bitten.

The well cross-section plot: When drawing a well cross-section diagram the scale must be adjusted to suit the field. In relatively flat fields (87-93 degrees apparent bedding inclination) a scale of 1:10 for TVD:VS is recommended. In fields where very strongly dipping strata is encountered (say 20 degrees off horizontal plus) a 1:1 scale would be recommended. Always be sure to point out the exaggerated scale to the client, otherwise they may be horrified at the appearance of the well path which is, in reality, practically flat! If drilling a well in which azimuth is constantly changing or changes significantly then it is recommended to plot TVD against Horizontal Length (HL) and not Vertical Section (VS). It is also recommended in this case to also make a plot of the plan view (Easting - Northing). Cross-sections can be made by hand on graph paper, in an Excel spreadsheet or by use of specialist geosteering software. It is unimportant which method is employed, it is merely a case of saving time, automating and standardising processes. It can be good to double up on methods so that an error on one chart will be highlighted by another. One should also be careful in the process of automation that one does not ignore the data. An example might be surveys being automatically imported into the software rather than manually plotted. Subtle azimuthal variations or dogleg issues might easily be missed.

The plan view plot: This is of variable importance. In many drilling operations, it is fine to view the well from a two-dimensional perspective, just bearing in the back of your mind the three-dimensional structure. If time is a consideration, the plan view plot can be done away with in 'straight wells' so long as the left / right offset from the plan is monitored closely. In other cases, failure to visualise the well from a three-dimensional perspective will lead to disaster! This is particularly the case where the well changes azimuth during the landing or part way through the horizontal section. In coiled tube drilling, due to the lack of rotation of the string, the well path necessarily 'snakes'. Azimuthal changes therefore become important in predicting the change in apparent dip. In stronger geological structures, azimuthal changes become increasingly important. In a perfectly flat structure, azimuth changes are not important. Once again, the plan view plot can be plotted manually or automatically; however, be sure to maintain awareness of the data. Maybe the change in apparent bedding dip that is being experienced is due to a subtle change in azimuth, or maybe the azimuthal deflection just indicated whether you were scraping the top or the bottom of the layer. In manually reviewing data these subtleties are not lost: More care must be taken when the processes are automated.

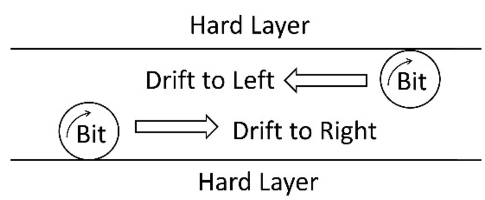

FIGURE 3: If the well is drilling in a 'soft' target it may drift to the left if there is a hard layer above, or to the right if the hard layer is below. If uncertain if you are at the top or bottom it is worth discussing drift tendency with the directional driller as it is another possible line of evidence.

The well cross-section plot (and plan view, if required) is the focal point on which all data is assimilated and viewed in context with. A geosteerer who does not produce a well cross-section diagram might be acting as a general wellsite geologist or supervisor but is not geosteering *per se*. The cross-section must be produced, but the means of producing it are open. From a personal point of view, I find the most effective use of this tool is by hand plotting the section on graph paper. This is because in doing so, you are forced to think about the data and view it survey by survey. One can generate an identical cross-section in an Excel sheet or on geosteering software and this enables one to make very rapid calculations. Time considerations, however, can often lead to a dropping of the manual methodology. Specialist software is available, and it is up to the individual or company if it is used. Geosteering software improves presentation of data, improves consistency in methodology between geosteerers and can lead to a significant time savings by automating processes. One must be careful, however, not to lose the subtle indicators that can really make a difference to the job. Maybe the software allows you to log match three log traces from one offset well on your screen. You might be losing data from another offset well, or maybe you miss the slight increase in gas values, a small azimuthal deflection, the presence of rare gastropods in a grainstone that occurs at the bottom of a layer or a rise in temperature. The software should be used to free up time to focus on all the data. It should not be used to be take a lazy approach and discard 75% of the 'less useful' data.

Geosteering software is principally log matching software. Log matching is a significant part of geosteering and has traditionally been done manually. Log matching software can be a valuable tool but is one of many tools employed by the geosteerer. It utilises offset wells to predict the log pattern at various angles and it is then a case of matching the two log patterns. This can be reproduced manually by the geologist holding two logs and comparing them or change the scale of one log and then compare them! This type of software flounders in laterally variable shallow water sediments, where you must think laterally as well as vertically. Issues may be encountered when utilising older data or data from another company. Absolute values should be avoided, relative values between peaks and troughs should be employed. Problems are also often encountered when a fault is crossed – the operators focus on the logs, when the answers are in the sample under the microscope. This type of software is highly dependent on the operator – if the operator is a poor geosteerer then garbage in, garbage out. In the past I have seen this kind of geosteering software effectively marketed as artificial intelligence. Following, unqualified or inexperienced geosteerers are employed and it then simply does not work, and this is before you throw a fault in! Bottom line is a piece of graph paper and experienced geosteerer works better than any software alone, although a good geosteerer and good software can be a very good pairing so long as the geosteerer has attention to detail, reviews all data and avoids ‘tunnel vision’ on a small amount of the available data. Ultimately, the adoption of geosteering software enhances the job, so long as all other aspects of the job are maintained. If the geosteerer’s computer fails at a remote wellsite location, he should be of a competence level whereby it is an inconvenience rather than a catastrophe.

So, you use your cross-section diagram to assimilate all your data, which includes:

a) All your LWD data.
b) Detailed lithological data (the geosteerer MUST personally examine and describe samples, keeping detailed records. Attention to subtle details is essential).
c) Oil show data.
d) Gas data.
e) Downhole mud losses data.
f) ROP data.
g) Micropalaeontological data if available.
h) Notes such as a general trend to drift right / left up / down (may indicate harder / softer layer above / below), points where stopped drilling / POOH (as log values may change in this section), thoughts, etc.
i) Anything else available – even a temperature change may help you to see if you’ve entered a new formation / layer. Weight on bit and surface RPM with reference to ROP often give clues to rock properties.

These data are not necessarily plotted on the cross-section diagram itself but are always referenced to it. An LWD log, for instance, is meaningless on its own – it could be from a vertical, deviated or horizontal well. The LWD log must be put into context with the survey / trajectory data. It can then be interpreted. All other data also follows this rule. When all available data is merged a clear (or sometimes cloudy) picture emerges. Definite or possible bedding can then be drawn onto the cross-section. In this way a record is kept of where the well has drilled. Often in a horizontal section, if you know where you were then you know where you are now (and you know where you’re going), without this record it is easy to become lost. The cross-section then makes the final well write-up a breeze!

3.4 CALCULATING BEDDING INCLINATION

A geologist uses dip, whereas a directional driller uses inclination. In order that the geologist can communicate effectively with the directional driller the geologist should refrain from using dip and instead adopt bedding inclination (apparent bedding inclination or true bedding inclination).

1° apparent up-dip becomes 91° apparent bedding inclination.

2.4° apparent down-dip becomes 87.6° apparent bedding inclination.

Apparent bedding inclination can be calculated or estimated in several ways.

1) Seeing the same log feature repeated – a mirror image. This is a very reliable method of calculating dip. Simply use a basic trigonometry function: Tan (Angle) = Change in TVD / Change in VS. On a Casio calculator: Change in TVD / Change in VS = SHIFT TAN =. On a Canon calculator 2nd TAN (Change in TVD / Change in VS) =. A margin of error of say 0.3 degrees + / - might be observed if repeat points are relatively close. Bedding may have gentle undulations on top of a more regional dip.
2) If you know the thickness of your bedding you can calculate bedding inclination in the same way as above, subtracting the thickness of the bed. Tan (Angle) = (Change in TVD - bed thickness X) / Change in VS. On a Casio calculator: (Change in TVD – bed thickness X) / Change in VS = SHIFT TAN =. On a Canon calculator 2nd TAN ((Change in TVD – bed thickness X) / Change in VS) =. Note that bed thickness should strictly be perpendicular to bedding but projecting directly up makes very little difference when bedding is dipping at just a few degrees, as in most oil fields. If bedding is very steep you can make a guess of the dip, apply a correction factor and project up. This is a bit of a circular argument but allows a quick calculation and is better than nothing.

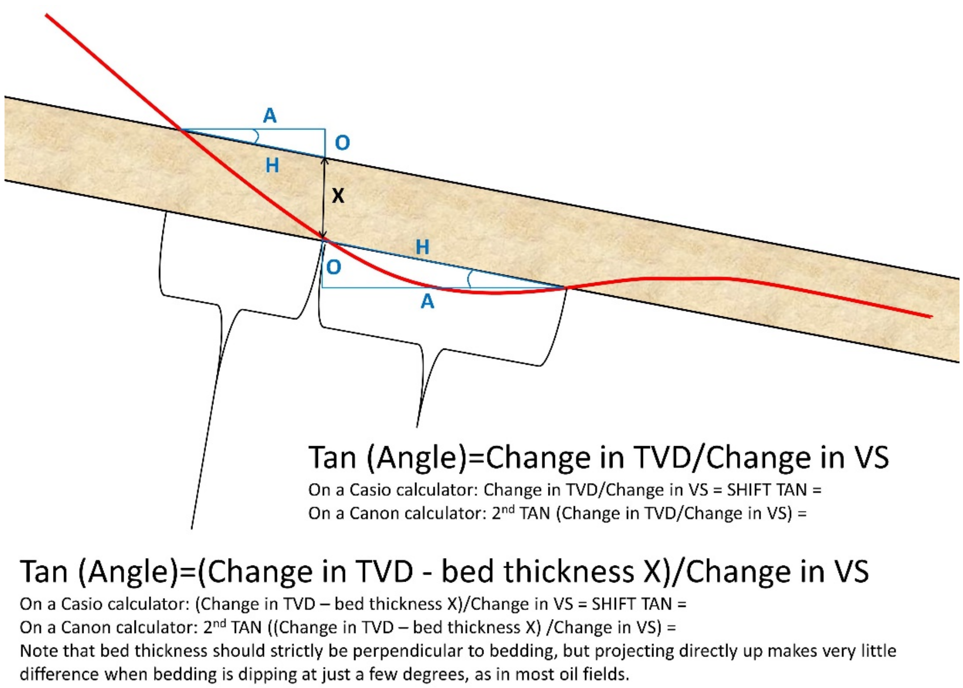

FIGURE 4: Two methods of calculating apparent bedding inclination from assumed bed thickness and by repeat crossing of the same boundary.

3) If you are drilling ahead at a fixed angle and nothing is changing, then this might be a sign that you are drilling horizontally. Obviously, this depends on specific circumstances, but it is a good sign that you are following the apparent bedding inclination. If in the reservoir it's best not to make any inclination adjustments in these circumstances as gaining a control point will probably mean exiting the target.
4) Image logs. One can calculate the dip of the strata using the image log, considering the angle of the hole. This may be variably reliable for horizontal drilling in my experience unless you have a very well-defined image feature. The margin of error is in the range of ± 1 to 2 degrees, which is not useful when changes of 0.3 degrees might be critical. I often calculate the dip from image and look for other methods to calculate or estimate dip to evaluate whether the value obtained is ± correct. Image logs are, however, extremely valuable in giving an impression as to whether you are cutting up or down through bedding and whether you are doing this rapidly or gradually. Image logs are simple to interpret. Adjust the scale to optimise the image (this is essential) and then a 'smiley face' means you're going up and a 'sad face' means you're going down.

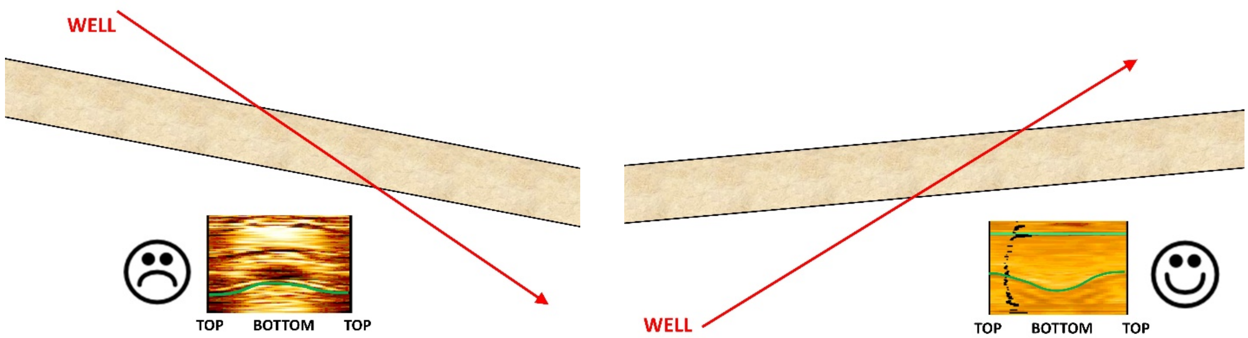

FIGURE 5: Using image logs to determine whether the well is drilling up or down stratigraphy. The centre of the image log is the bottom of the hole and the sides are the top of the hole. A sad face indicates the well is cutting down through the stratigraphy whilst a smiley face indicates the well is drilling up through the stratigraphy. Apparent bedding inclination can be calculated from the image logs but is sometimes not accurate enough for precision geosteering in a horizontal section.

To calculate the relative angle on an image log (ensure you use the same units throughout, e.g. inches or cm):

A. Relative Angle = $\tan^{-1}$ ((Caliper hole diameter + (2 x effective penetration length of the tool)) / (distance taken to cross layer))
B. Apparent bedding inclination if moving up-stratigraphy = Angle of the hole - Relative angle. Apparent bedding inclination if moving down-stratigraphy = Angle of the hole + Relative angle.

5) Hinge points on logs or image logs, where one sees a mirror image. If one takes this point and looks at the near-bit inclination at this point a rough idea of apparent bedding inclination can be ascertained.
6) If you are changing azimuth, then if you have two apparent bedding inclinations on two different azimuths you can calculate the true bedding inclination and apparent bedding inclination for any azimuth. This assumes no change in true dip, so you must assess if this is likely or not.

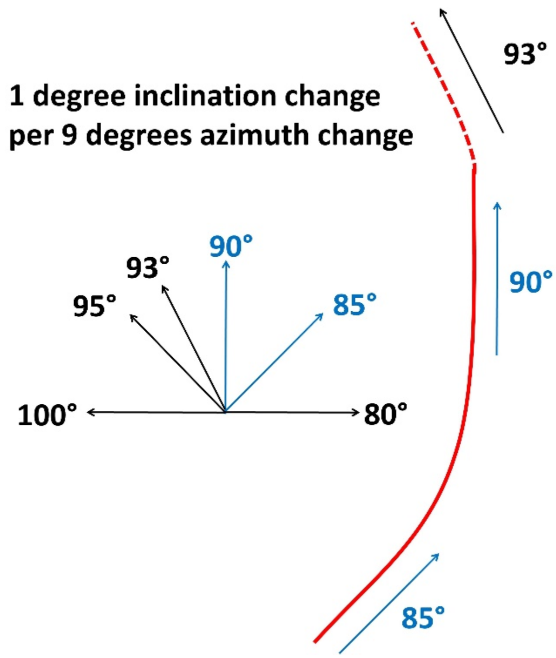

FIGURE 6: If the apparent bedding inclination is known on two azimuths (blue), then the apparent bedding inclination can be calculated for any azimuth (black), assuming no change in true bedding inclination.

7) You will likely have a seismic model and Petrel or structural model. You should use this to anticipate changes in bedding inclination. After a few wells it will become apparent as to how reliable the field model is. The model should be viewed in context with all available real-time data and then a decision made, in consultation with the operations geologist, as to whether to follow the plan or deviate from it. Often, if the well being drilled has closely offset wells the data will be more reliable. If the well is deep with isolated offset wells the data will be less reliable.
8) Schlumberger PeriScope (or similar tools) can read resistivity values up to 21 ft into the formation. It does not read ahead, but like the geologists plots the bedding as it is drilled. This allows the structure and the apparent bedding inclination to be calculated allowing projections to be made ahead increasing the likelihood of the well being landed or drilled horizontally within the target layer. Being a resistivity tool, the PeriScope is influenced by fluid changes and by lateral variation in lithology. In my experience it works well in some reservoirs, not so well in others and it may push other useful tools further from the bit. It is ideal if you have little structural control and your strata is laterally consistent and predictable in character (however, this being the case, once you have minimal offset data the value of this tool would be reduced significantly).

3.5 FAULTING

A horizontal well should be designed to avoid known faults where possible, unless the objective is to drill through the fault into a 'new' block or the fault is unavoidable. Faulting should be planned for – seismic data should be reviewed and likely throw direction and magnitude should be assessed.

There may be several clues as to whether a fault is crossed. Often samples offer the first indications. Clear crystalline calcite may (or may not) be present in a carbonate target (Note: do not confuse with $CaCO_3$ additive). Sometimes an increase in iron pyrite is noted to be associated with faults. Often you will observe a sudden and unexpected change in lithology, although this is dependent on how distinct the different geological layers are. Once LWD sensors are over the interval a sharp break may be seen on logs. Image logs will be marked by a sharp line. Resistivity values will often show a peak or trough centred on the fault (Note: always check that it's not a single bad data point). Down-hole mud losses may or may not be observed – if a fault is suspected then check on losses.

When it is established that a fault has been crossed it can be worth stopping drilling and circulating a sample up. Circulating a sample up is generally only worthwhile if your geo-layers are very readily distinguishable on samples. More usually you must drill ahead to gain data, usually holding the angle you had prior to the fault, or adopting a 'neutral' angle. After 100 ft or 200 ft, sometimes more, you may gain sufficient information to allow you to decisively geosteer back up or down to the target. It is best not to have a knee-jerk reaction. Take your time, gain confidence in the stratigraphic position and make the correct steering decision first time. If the decision is taken prematurely you may steer up, only to find you must steer down. This eats up more vertical section than if a 'neutral' angle had been held longer and then the correct decision made first time.

Faulting often necessitates a re-think of the well plan. Maybe a side-track option is the way forward but ensure that you know what is happening at the fault before sidetracking. You may also wish to consider an alternate target layer if the fault is large or calling TD if the target is unattainable within a reasonable distance.

3.6 COMMUNICATIONS

A big part of the geosteering task is communication. Steering decisions are usually jointly made between the wellsite geologist (geosteerer) and operations geologist, although the degree of involvement of the operations geologist varies between companies. Typically, the geosteerer will automatically make minor adjustments to stay within the target (informing the operations geologist as per his / her requirement). Significant plan adjustments, target exits of significant structural changes / faulting always involve the operations geologist. Major changes such as side-track options / premature TD will usually go to head of department (via the operations geologist) and be discussed with the drilling department. If in doubt the operations geologist should always be involved (day or night) and company man informed (day or night).

When any changes are made at wellsite they must obviously be communicated to the directional driller (who will carry out the adjustment), but should also be communicated to the company man, drilling engineer if relevant, and to your back-to-back. The most effective way to communicate changes is in writing. It is good practice to fill in a form with well name, date, time, current MD, geosteering instructions given, observations / reasoning for change and whether discussed with operations geologist / rig personnel, geosteerers signature (if necessary the directional drillers and company man's signature – although avoid this if possible as it wastes time). A copy of this form is then distributed to the directional driller, company man and a copy kept by the geosteerer. The advantage of this system is that everyone is informed, and a record is kept if there are subsequent problems. A sequence of events can be established if there are major problems such as loss of a tool. Also, the directional driller cannot fail to perform and then blame the geologist (or visa-versa). The directional driller should receive the document of change and it should be discussed in person. Discussions by phone or pager can cause confusion when dealing with crew of different nationalities: Face to face discussion is essential. I would recommend that this procedure be followed, but at a minimum then diary notes of changes should be made to ensure there is no confusion at shift change-over and a record is kept if problems occur. A diary, does not, however, prevent the 'he said, she said' scenario as a single copy diary can be falsified. An alternative is to verbally inform the directional driller of a change then follow up with an email or a real-time chat window cc'd or including other relevant personnel. This methodology works fine and in fact can reduce workload as the same comments can go directly into report and evaluation formats, but extreme care should be taken in a busy work environment that the DD is personally instructed on the change. The DD may not immediately see an email or chat message and it should never be assumed that they will view it in a timely manner.

On the rig, daily meetings and meetings to discuss major changes in plan should be held. In terms of reporting to the operations geologist, this is dependent on his / her requirements. I would recommend thrice daily reporting and telephone conversation, with a main morning report and two updates. The main report should include a geological report, a cross-section, survey data, LWD data (LAS and PDF, MD and TVD (TVD not required when horizontal), 1:200 and 1:1000 scale is normal, but vary as necessary), mud log, gas data and mud loss data. This report should be delivered immediately prior to office hours. Updates should include LWD and survey data and cross-section as necessary. If the operations geologist has a real-time rig-link then the updates may not be required, but it is good to discuss drilling progress to keep communications thorough.

All data should be logically labelled, filed, and in good order on the company mainframe. It should be the wellsite geologists' and the operation geologists' responsibility to ensure all data is updated on the system daily or at convenient points (and certainly at the end of the well). There is zero excuse to go back to a well a few months after drilling and discover no survey data or missing log data.

The wellsite geologist / geosteerer should always keep a hard copy of key data in a well-organised file. This allows the geosteerer to rapidly access past reports, interpretations, surveys, LWD data and past steering decisions made. If something happens during drilling, you need the data at your fingertips to solve the problem rapidly and answer questions. The hard copy also ensures good handover with your back-to-back. The hard copy is a great backup in case you accidently lose soft copy data. At the end of drilling the well folder should be kept to hand on the rig as it allows for rapid cross reference of notes, thus aiding future drilling. Increasingly we move towards the paperless office, whilst this should be encouraged on many fronts, I would still maintain a hard copy. There is a value in being able to find what you are looking for in seconds rather than minutes opening a dozen files.

SECTION 4 - CONCLUSIONS

To geosteer a well you must first land the well at the correct stratigraphic level and at the correct angle. This is usually a straight-forward task with the correct planning. In the horizontal section you must always understand (as best as possible with available data) the structure / target position where you have been drilling, where you are now and the most probable structure ahead in the undrilled section. The most powerful tool for assimilating data and assessing the structure is the cross-section diagram. Every piece of available data should be utilised, and very close attention paid to samples. To project the target ahead one can simply project ahead on the cross-section or combine these data with the predicted structure from offset wells and / or seismic data. The success of geosteering is usually directly related to the quality of the geosteerer. By adoption of good standardised geosteering techniques and methodologies any geosteering job can be optimised.

SECTION 5 – GEOSTEERING SOFTWARE, REMOTE GEOSTEERING AND ARTIFICIAL INTELLIGENCE

Several specialist geosteering software products are available on the market. These essentially automate a lot of the processes. This results in standardization of the product the geosteerer delivers, saves time on calculations and reduces the risk of error. Typically, the centrepiece of geosteering software is a form of log matching. One takes one or more offset wells, and from these data predictions of the expected log trace in the horizontal section can be made. The actual LWD values in the horizontal section can be matched to the expected values and stratigraphic position accurately determined. With this information to hand the structure and apparent bedding inclination is understood. This is often marketed as something that traditional geosteerers do not do. This could not be further from the truth. Log matching is, in fact, the bread and butter, of the job. Geosteering software, however, makes the task somewhat less manual and is certainly of value if used correctly. The downfalls are 1) lateral variation: Logs don't match. 2) Absolute values should not be used as they may differ depending on age of the well and 3rd party who did the logging. 3) This software is often mistaken for automating the whole process (i.e. an artificial intelligence) and I've seen non-geologists given a geosteering role. This software simply does not do the job, it is an extra tool to enable a skilled geosteerer to make accurate picks. One wrong pick and the subsequent picks are often all wrong too! 4) The use of this software can lead to tunnel vision with the user focusing on a few selected logs. Neglection of other log data, of lithology, gas values, etc. can lead to incorrect decisions. Correct decisions are made by incorporating as much data as possible, of which log matching software is just one part.

Specialist geosteering software should be embraced as a tool to enhance and facilitate interpretations, to standardise methodologies, to save time, and to improve presentation and communication. It should be used to replace manual log interpretation and manual / Excel construction of cross-sections. It does not replace other aspects of the job: Lithological description and quality control, reviewing oil shows, reviewing drilling parameters, reviewing gas data, reviewing mud loss data, reviewing survey data in detail, troubleshooting issues on the rig, supervisory roles on the rig, etc. It does not replace the need for a highly skilled geosteerer, it merely helps to facilitate part of their job.

As this software is combined with improving telecommunication networks, remote geosteering becomes feasible. Remote geosteering simply replaces the wellsite geosteerer with a remote geosteerer, both skilled positions. When moving down this path careful evaluation is necessary. If the remote geosteering centre is handling a sufficient number of rigs (the precise value being dependent on several factors such as staffing level and remoteness) it will eventually become cheaper to run than having individual wellsite geosteerers. One must also factor in that the remote geosteerer will not have the same level of information as the wellsite geosteerer on which to base decisions. A concerted effort should therefore be made to minimise loss of any potentially valuable data. The principle data loss is focused around lithological data – an often exceedingly valuable, effectively near-bit, data source. Losses can be mitigated by using microscope videography (although this is far from the same as properly analysing a sample), improving the quality of mudlogging crew from an entry level to a more skilled geological position, or by increasing input from the LWD source. In all these cases, money saved may be spent on costly alternatives, exemplified by having to run additional expensive LWD tools to replace the loss of virtually free lithological data.

One must also recognise that replacing the geosteerer is not the same as replacing the wellsite geologist. A wellsite geologist may still be required on location, albeit with potentially a lower skill set required (or the job dropped after careful safety and technological evaluation). Remote geosteering is fully workable, but more reliant on log data (with potentially higher associated cost). A decision on whether to adopt remote geosteering must factor in cost savings (potentially fewer highly skilled personnel and transportation / accommodation costs) vs additional expenses (e.g. communication costs, additional LWD data, 24 hr computer support) and must focus on the requirements needed to geosteer. For instance, if a subtle increase in pyrite is a clue that an overpressured shale is being approached (and penetration may result in loss of a million-dollar tools and radioactive source) then it would be wise not to rely upon an entry level mud logger to be the only thing between success and disaster. If you are running only 2 rigs it will be more expensive and less successful to use remote geosteering. If you are running 20 rigs and they are drilling thick targets easily differentiated on LWD data, then utilising remote geosteering will be a no brainer!

In the future we visualise artificial intelligence (AI) being able to replace geosteerers. It would not simply take databases and analyse the data: It would make the databases. It would be more consistent, more accurate and more logical than any human being. A good geosteerer always makes logical and justifiable decisions, based on pre-determined criteria, correlations and experience. The decisions made are not always correct but can always be justified as a logical decision based on the information at the time. This lends itself very neatly to AI, with AI having a distinct advantage in potentially having knowledge of tens of thousands of wells as oppose to the few hundred an experienced geosteerer might have notched up. AI will not be designed specifically for geosteering, a field rather too specialised to make economic sense. AI will simply be a more generic intelligence, capable of applying itself to many different applications, of which geosteering will be one of many.

Again, as with remote geosteering, probably the main losses would be in terms of lithological data and direct communication with experienced personnel such as the directional driller. With AI, however, the material gain of tens of thousands of wells in experience level would probably largely mitigate against the loss of a small amount of additional data. It may be that the mudlogging process itself needs to become more automated to produce binary results. Lithological analyses could be automated to process samples: Colour descriptions could be automated, as could hardness, chemistry could be analysed (this is a key area, with perhaps x-ray fluorescence, near-infrared spectrometry or atomic absorption spectroscopy being used to define target lithologies), grains like ooids or certain fossils might be recognizable to a trained computer, shows could be evolved. It might be that data could even be gained, rather than lost. AI may be a double-edged sword though: I would envisage that once AI can make, learn from and act upon large databases, it would not be long before quantum leaps are made in physics, fundamentally changing the need for oil as a commodity.

MEASUREMENTS AND ABBREVIATIONS USED:

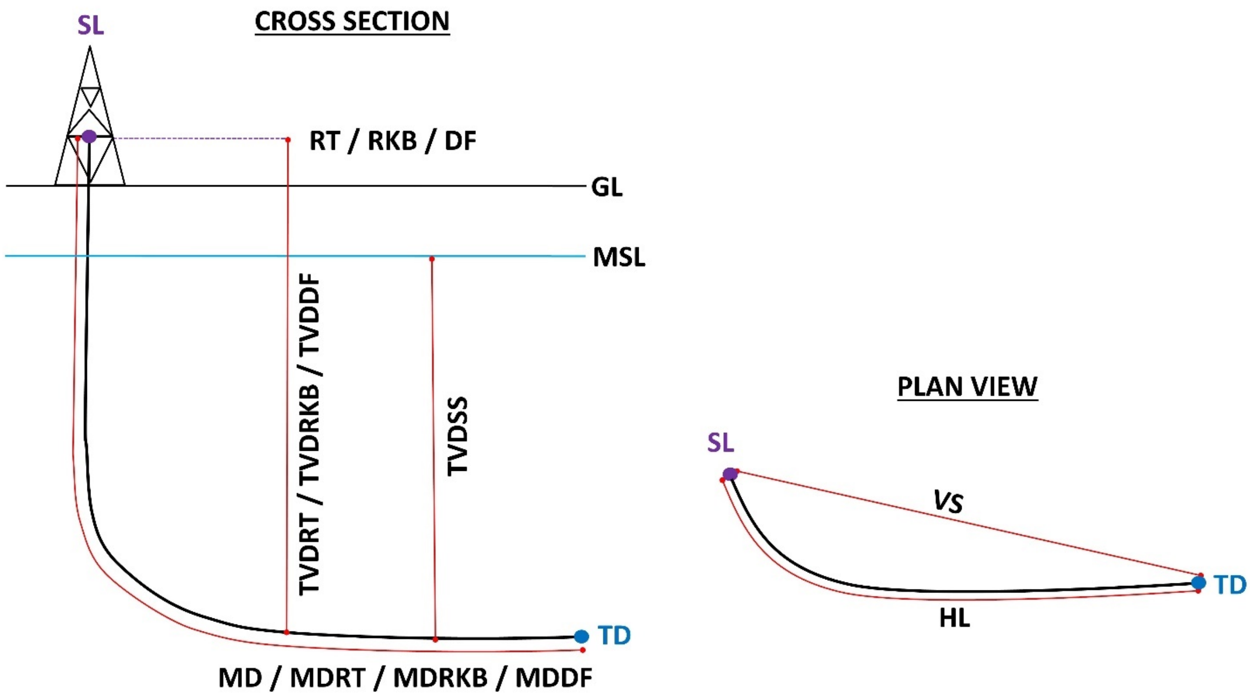

FIGURE 7: Some of the basic measurements used in drilling. Abbreviations can be found below.

ABBREVIATIONS:

BU = Bottoms-up.
BUS = Build-Up Section.
CTD = Coiled Tube Drilling.
DD = Directional Driller.
DF = Drill Floor.
DFE = Drill Floor Elevation.
DLS = Dog Leg Severity.
GL = Ground Level.
HL = Horizontal Length.
LCM = Lost Circulation Material.
LWD = Log Whilst Drilling.
MD = Measured Depth.
MSL = Mean Sea Level.
MWD = Measure Whilst Drilling.
PWD = Pressure Whilst Drilling.
RKB = Rotary Kelly Bushing.
ROP = Rate Of Penetration.
RPM = Revolutions Per Minute.
SL = Surface Location.
TD = Total Depth.
TVD = True Vertical Depth.
TVDDF = True Vertical Depth from the Drill Floor (use on top-drive rigs)
TVDRKB = True Vertical Depth from the Rotary Kelly Bushing.
TVDRT = True Vertical Depth from the Rotary Table.
TVDSS = True Vertical Depth from mean Sea Level (Geologists must always use TVDSS to compare with offset wells).
VS = Vertical Section.
WOB = Weight On Bit.