CORE ORIENTATION—1

Controlling errors minimizes risk and cost in core orientation

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Coring, the cutting of a representative cylinder of rock during drilling, is perhaps the most important technique available for gaining first-hand knowledge of the subsurface.

The goal of coring is to recover an undisturbed sample of the formation being penetrated. Cores can be used to supply orientation information for evaluating any directional characteristics of a formation.

Orientation of core with respect to geographic north is necessary to determine sediment transport directions, downhole stress fields, permeability or porosity directions, or fracture directions. Directional data can play a major role in evaluating field economics, often affecting decisions relating to well spacing, location, and number.

The decision to orient core cannot be made lightly. Historically, core orientation has not been a simple process and no data may result from a procedure that is both expensive and risky.

More typically, directional data are found to be significantly in error.

The authors have studied the problems associated with core orientation and believe the following discussion can assist in reducing the risk and cost of core orienting operations.

Techniques

Two different direct orientation procedures are used for most core orientation. Direct orientation of core generally utilizes either a multishot downhole camera system or a paleomagnetic plug sample technique.

Both make use of the earth's magnetic field but in quite different ways.

Multishot orientation. The multishot technique has been available for more than a decade and is generally accepted as the industry standard. It requires a downhole equipment package including a three-knife scribe shoe with a camera, automatic timer, and compass.[1]

The scribe shoe is located inside the mouth of the core barrel and the camera/timer/compass tool is located above the core barrel in a nonmagnetic Monel collar (Fig. 2).

A lug on the compass is aligned with the reference knife on the scribe shoe when the equipment is assembled on the rig floor, prior to tripping in the hole.

Inside the tool, the camera is trained on the compass and lug and the timer is preset to expose automatically individual frames of film at fixed time intervals ranging from 1-8 min. The film magazine generally contains sufficient film to allow exposures to be made for up to 48 hr at the maximum timer interval of 8 min.

Because the multishot tool is preset at the surface, there are no more adjustments that can be made after makeup on the rig floor.

The system operates throughout the trip in the hole.

After reaching bottom, normal coring continues, although sensitivity of the multishot tool to vibration requires some reduction of

Table 1

Sample reports from two types of core orientation

Multishot orientation report

Declination 13 East/west
Azimuth correction for declination
East Decl. ☒ add to azimuth
West Decl. ☐ sub. from azimuth

Reference groove correction:
From above, groove is 130 deg. R/L
of orientation lug.
☒ Right, add to lug azimuth
☐ Left, sub. from lug azimuth

Interval cored: 40 feet

Start: 8100
Finish: 8140

Time interval: 8 min.

Station				Drift			Orientation						
					Direction		Orienting lug, magnetic				Reference Groove		
No.	Time	Picture no.	Depth, ft	Angle,°	Magnetic	True	Direction	Azimuth	Declin. corr.	Or. Lug Az. true	Corr.	Az. true	Direction true
1	5:28	41	8101.3	3/4	S20W	S33W	N48W	312	+13	325	+130	455	S 85E
2	8:08	61	8106.0	1	S49W	S62W	S24E	156	+13	169	+130	299	N61W
3	9:12	69	8107.5	1	S49W	S62W	S24E	156	+13	169	+130	299	N61W
4	12:16	92	8112.5	1	S51W	S64W	S20E	160	+13	173	+130	303	N57W
5	13:44	103	8117.8	1	S49W	S62W	S22E	158	+13	171	+130	301	N59W
6	15:20	115	8122.4	1	S54W	S67W	S25E	155	+13	168	+130	298	N62W
7	17:20	130	8127.6	1	S46W	S59W	S25E	155	+13	168	+130	298	N62W
8	19:12	144	8132.3	1	S44W	S57W	S25E	155	+13	168	+130	298	N62W
9	21:12	159	8137.4	1	S43W	S56W	S26E	154	+13	167	+130	297	N63W
10	21:60	165	8139.1	1	S46W	S59W	S26E	154	+13	167	+130	297	N63W

Paleomagnetic core orientation

Formation age:
Magnetization age: late Cenozoic
Ref. paleomag. pole: 0°E, 90°N
Ref. paleomag. direction (D,I): 0°, +66°
Well deviation: None available*
Corr. ref. paleomag dir. (D,I): N/A

Continuous interval	Plug depths (min/max)	No. meas./ no. sel.	Paleomag azimuth	Polarity	True orientation Azimuth	True orientation Bearing	Remarks
5,824.0-5,831.2 (Core 1-1)	5,824.9 5,831.0	10/9	293°	N	67°	N 67° E	
5,831.3-5,836.4 (Core 1-2)	5,831.8- 5,836.0	8/7	341°	N	19°	N 19° E	
5,836.5-5,849.2 (Core 1-3)	5,837.2- 5,849.1	12/10	319°	N	41°	N 41° E	
5,852.8-5,857.0 (Core-1-4)	5,853.1 5,856.8	8/8	175°	N	185°	S 55° W	
5,865.0-5,875.0 (Core 1-5)	5,865.6- 5,872.9	8/7	135°	N	225°	S 45° W	

*Maximum orientation error per degree of well deviation: 2°

pump pressure and rotation rate. As the core is cut and enters the mouth of the bit, it is incised by the knives on the scribe shoe.

At specified depth intervals, rotation and pumps are shut down for a period of 2-4 min, long enough for a vibration-free image of the compass and lug to be recorded on the film strip. The procedure is repeated, typically at intervals of 2-5 ft, until the barrel is filled or jamming occurs.

Upon recovery of the tool at the surface, the film strip is developed and individual frames are related back to the surface-recorded depths corresponding to individual survey points. The azimuth of the lug is then determined in each frame. After making corrections for magnetic declination and the angular relationship between the lug and reference scribe, the actual azimuth of the reference groove at each depth is reported.

Table 1 shows an example of data taken from a standard report form.

Paleomagnetic orientation. The paleomagnetic core orientation technique does not require any specialized downhole equipment or procedures. It makes use of magnetic field directions recorded in the rock matrix.

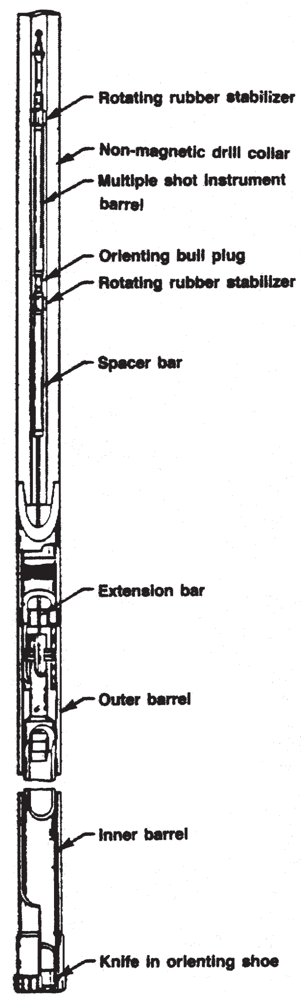
All rocks, including limestones and chalks, contain at least a small quantity of magnetic minerals, generally magnetite and hematite. These minerals act as miniature compasses, locking in the ambient magnetic field near the time of deposition and hence recording that field direction in the rock. This primary magnetization direction may be preserved in the rock for hundreds of millions of years.

Paleomagnetic core orientation uses both primary and any superimposed secondary directions which may have been reported in the rock's magnetic minerals. Early attempts to use paleomagnetism to orient core go back at least to the early 1960s.[2] It has only been since the mid to late 1970s that breakthroughs in technology, including high-sensitivity cryogenic magnetometers and better computer software and hardware, have permitted reliable measurements in a variety of sedimentary rock types.

Using this improved technology, a paleomagnetic orientation technique[3] was developed between 1980 and

Fig. 1

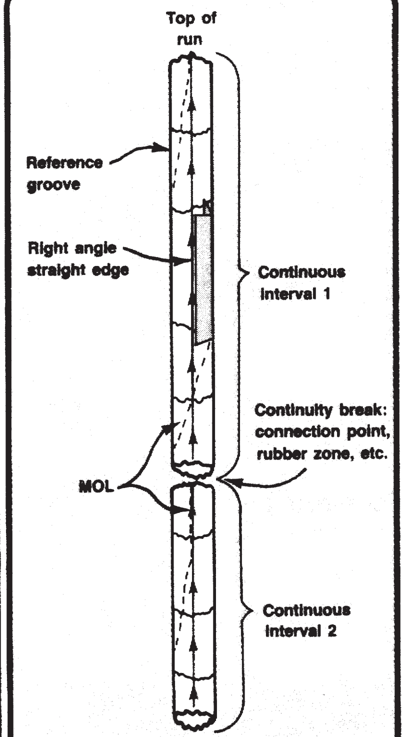
Multishot coring



Courtesy of Diamond Oil Well Drilling Co. OGJ

Fig. 2

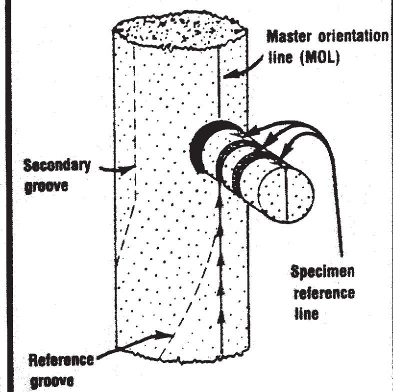
Master orientation line



Assembling continuous intervals within a core and marking the MOL OGJ

Fig. 3

Cutting plug



Procedure for collecting and marking oriented plug from drill core. A Teflon sleeve is used to transfer a reference line to each plug. This reference line is perpendicular to the core axis. The plugs are drilled on the MOL or along other lines which parallel the core axis. In the laboratory the plug is cut to yield a cylinder 0.9-in. long for measurement.

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1982 and has been commercially available since then.

To orient a core paleomagnetically, plug samples are taken from the core after it has been recovered from the hole. Since the core is visually inspected prior to orienting, paleomagnetics offer flexibility in selection of specific core intervals to be oriented. Plug samples of 1 in. diameter are cut at right angles to the core axis along the master orientation line (MOL). The MOL is a straight line marked parallel to the axis of the core (Fig. 2).

Each continuous interval of core, defined as the total length of one or more core segments that can be unequivocally fitted together, is sampled as a unit for statistical averaging of sample directions. Plug samples are cut into cylindrical specimens 0.9 in. long prior to measurement in a cryogenic magnetometer (Fig. 3).

The natural remanent magnetization (NRM) of a sample is first measured in the rock magnetometer. Through a series of thermal or alternating field demagnetizations, the primary and secondary components of magnetization are stripped off and separated. Interpretation of these components yields a representative direction which can be used to orient the core with respect to present-day geographic coordinates.

For paleomagnetic orientation, it is important to mark the core for up direction, although in most circumstances paleomagnetism also can be used for determining up direction.

The final result of the paleomagnetic analysis, generally supplied 1-4 weeks after collection of the plugs, is a data sheet reporting the present day geographic azimuth of the MOL for each continuous interval. Table 1 shows example data.

Other orientation techniques. In certain instances core orientations can be derived indirectly from other types of downhole tools. Where bedding planes dip uniformly it is possible to use a wireline dipmeter log to determine the azimuth of the dip. Accuracy of the technique depends on bedding characteristics, tool calibration, hole condition, and mud system.

Oil-based drilling muds are incompatible with dipmeter tools. Apparent bedding dips of less than 10° or more than 80°, as well as extensive cross-bedding, usually rule out the dipmeter as a core-orientation tool.

Borehole televiewer systems have recently proved useful for determining orientations of fractures in the sidewall. The technique works best on large scale features, since hairline or microfractures are smaller than a televiewer's resolution. Televiewers also cannot be used successfully in many of the more exotic mud systems.

Error analysis

Core orientation is a relatively expensive procedure and it is often difficult to evaluate the accuracy of the results immediately. Incorrect orientations can have major consequences for development of a field.

Fortunately there are quality control checks and procedures that can go far to assure an operator that valid orientation data are recovered.

Major sources of error or failure for both multishot and paleomagnetic core orientation techniques are summarized in Table 2. Not unexpectedly, human error is most prevalent for both orientation techniques. Much of the problem can be traced to the number of steps in each technique, requiring many different individuals and types of expertise.

Multishot technique. As a rule, multishot tools are serviced in a shop prior to being sent to a well site.

On site, the tool is checked as the barrel is being made up. The orienta-

Table 2

Sources of error in core orientation by technique

Error	Multishot: Correctable: At well site	Multishot: Correctable: At interpretation	Multishot: Amount of error	Paleomag: Correctable: At well site	Paleomag: Correctable: At interpretation	Paleomag: Amount of error
1. Downhole tool improperly aligned in shop or at rig site	Yes	Possible	180° (constant)	N/A		N/A
2. Secondary knife aligned with compass lug upon attachment to string	Yes	Possible	100 to 160° (constant)	N/A		N/A
3. Too few survey points specified for interval or too few samples taken	Not correctable		May result in usable data		Yes	Not predictable
4. Primary knife not carefully aligned with tool	Not correctable		10 to 30° (constant)	N/A		N/A
5. Downhole equipment failure: scribe knives; camera/timer/ batteries; connections between tool and barrel	Not correctable		Usually results in no usable data	N/A		N/A
6. Tightening or loosening of tool connections during drilling operations which affects lug/reference groove alignment	Yes	Possible	5 to 80° (usually cumulative with increasing depth)	N/A		N/A
7. Core depths and driller's depths not correlated correctly		Possible	10 to 100° (usually constant)	N/A		N/A
8. File inaccurately read (MS) or improper placement of sample (PM) during measurement		Yes	±5 to 10° or 180° (uncommon)		Yes	Generally 180° or inverted (uncommon)
9. Data inaccurately transcribed		Yes	Not predictable		Yes	Not predictable
10. Compass influenced by transient magnetic anomalies, or changes in penetration rate causing "errant" or anomalous survey points (MS) or rock magnetization affected by overprinting during drilling creating biased directions (PM)		Possible	Not predictable		Yes	Not predictable
11. Horizontol component of earth's magnetic field too small to stabilize compass or horizontal component of magnetization in core coordinates too small, a problem in high latitude locations	Not correctable		Not predictable	Not correctable		Not predictable
12. Scattered remanent magnetic field directions recorded by rock	N/A		N/A	Not correctable		Not predictable

tion engineer is responsible for measuring and recording the angular relationship between the reference knife and compass lug. The core engineer is responsible for the makeup of the barrel. Usually operator representatives, such as the drilling supervisor or site, geologist are responsible for specifying timer interval and depth penetrated between survey points.

After recovery of the core barrel, the site geologist is responsible for handling and marking the core while the orientation engineer develops and reads the film, ultimately providing the orientation data in tabular form.

Usually the tabular data are used to evaluate the core later. Individuals not present during the coring and handling operations may have primary responsibility for analysis and applying the orientation results.

Every person involved in the orienting process is a potential source of human error and miscommunicated conventions. Shop technicians can service the tool improperly. The on-site orienting engineer may miss the shop's error.

The measurement of the lug/reference groove offset angle introduces several potential sources of error. Particularly in adverse weather conditions, where the core barrel is subject to gusty winds, it may be difficult to measure the offset accurately.

As the length of the core barrel increases, the accuracy of the measurement decreases. By convention, the reference groove offset is measured in degrees right or left of the lug looking downhole. Depending on the orienting engineer's perspective, right/left corrections may be reversed and recorded incorrectly, leading to potentially large constant errors.

Also, a secondary knife may inadvertently be aligned with the lug, resulting in constant errors of 100-160°.

In a typical 30-ft core barrel, there are four or five threaded joints between the scribe shoe and the orientation lug. For each 30-ft section added to the core barrel, the number of threaded joints increases by one.

In making up the barrel and orienting collar it is important that all joints be fully tightened. Standard practice also calls for punch or chisel marks to be placed across each connection to identify any additional tightening which occurred downhole.

In reality, the punch marks are commonly omitted or not checked after a run. The marks may appear on inspection to show no or a very small amount of additional tightening. However, even a small amount of tightening may be multiplied by five or six in a 60-ft barrel, leading to observed errors as great as 80°.

The penetrated interval between survey points is usually specified by the drilling engineer or site geologist. Closer spacing of survey points can improve orientation accuracy.

There is necessarily a trade off between the number of survey points desired and the time and risk involved in each shutdown of the coring operation. Reliable orientation requires surveys every 2-5 ft. Intervals greater than 5 ft can affect orientation accuracy, since the angular deviation of the scribe on the core must be tracked accurately by the multishot data.

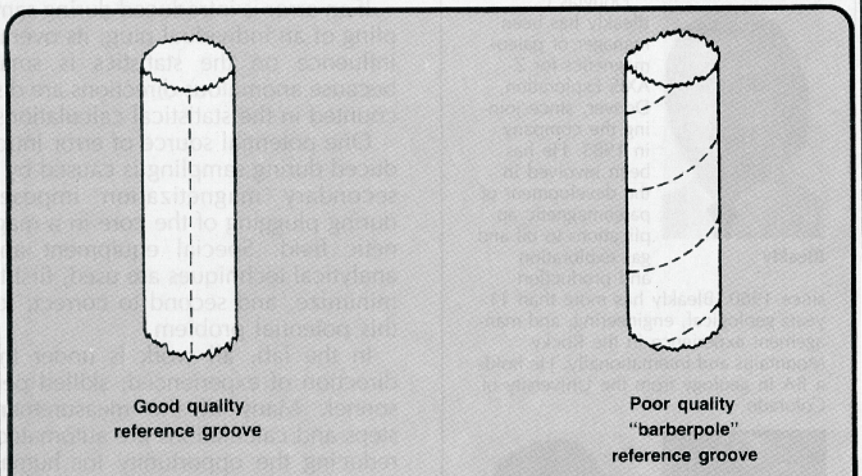
After retrieval, the site geologist is usually responsible for fitting the core together and marking up direction and depths. Accurate multishot orientation requires that depths marked on the core be in excellent agreement with surface-recorded depths.

The reference groove on the core is seldom parallel to the long-axis of the core. Angular deviation can vary over the length of a core from a few degrees to more than 360°/ft (Fig. 4).

Since survey points are referenced

Fig. 4

Groove quality



Straight grooves are the ideal and require that the inner barrel not rotate at all. Poor bearings, dull knives, or fractures will allow the inner barrel to spin excessively.

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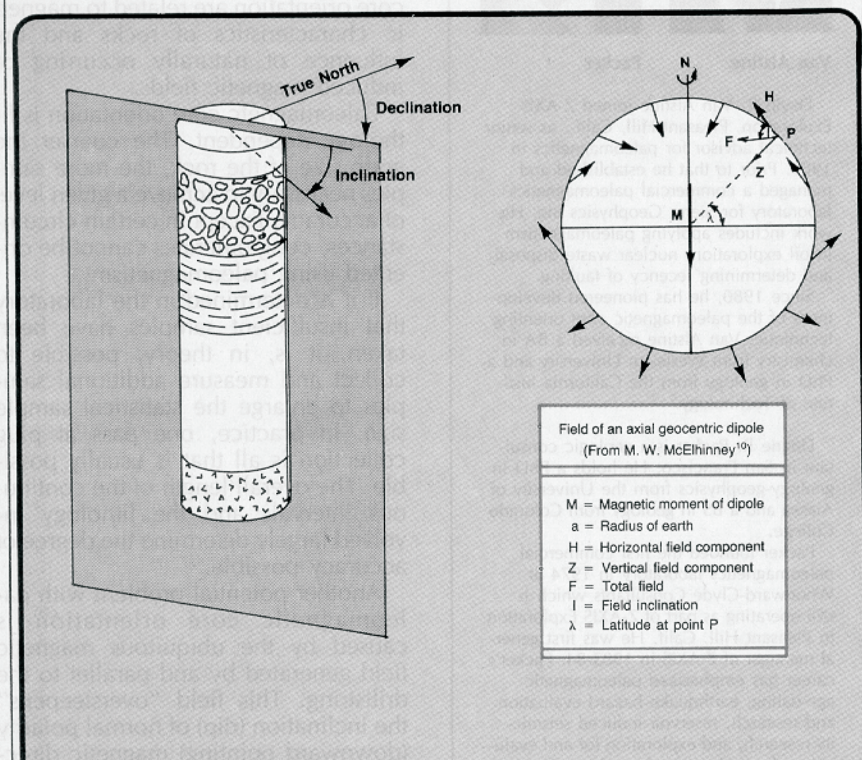
Fig. 5

Magnetic components related to earth's field



In the earth's magnetic field, declination is the horizontal component; inclination dips into the earth's surface. Inclination is related to latitude by the equation: tangent of the inclination is equal to 2 times the tangent of the latitude.
($\tan I = 2 \tan \lambda$)

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to drilling depths, orientation data can be inaccurate in varying amounts over the entire length of the core if careful attention is not given to correlating core and driller's depths.

Where core recovery is close to 100% and angular deviation of the reference groove is small, depth correlation error is generally small. As the angular deviation increases, accuracy decreases, and depth correlation becomes increasingly critical.

Accurate depth correlations can be very difficult to achieve in cases where core recovery is 90% or less. By convention, lost core is placed at the bottom of a run. This assumption is usually not appropriate when working with multishot orientation. As core loss increases, orientation data eventually become meaningless since no reasonable correlation is possible between core depths and surface-recorded depth.[1]

At the well site, the orientation engineer retrieves the film magazine from the tool, develops the film, reads and records the lug azimuths for each survey point. The quality of the developed film can have an effect on the reported azimuths. Film quality may be poor enough that significantly different readings could be made by different individuals. Preliminary data sheets are presented to the client on location. Final sheets are supplied later after a review of the film.

Most sources of multishot error are related to procedural and quality control problems occurring throughout the course of an operation. Data are recovered but accuracy is compromised to a greater or lesser degree. There are cases, however, where an obvious mechanical failure prevents the recovery of any usable data.

Perhaps the most common failures involve the scribe shoe. If the knives are not sharp, no grooves may be cut or, since the knives play an important role in keeping the inner barrel stationary, excessively wide, spiralling grooves may occur.[4] Total failure of the shoe or knives also occurs, resulting in no grooves on the core. Worn bearing assemblies can seize, obliterating the grooves.[4] Naturally fractured reservoirs may cause excessive spiralling of the grooves as well.[5]

The camera/timer/flash system can fail due to high downhole temperatures. Tools without special heat shields cannot be used at temperatures above 200° F. Even with shielding, downhole operation time is usually limited to 12 hr or less.

Excessive vibration and jarring can cause camera failure or, in some tool configurations, separation of the tool from the barrel. In cases where tandem cameras are run, failure of one camera does not prevent data recovery, but excessive vibration is likely to cause failure of both units.

Multishot orientation is not possible in situations where the top of the barrel and tool are inside a casing string. The magnetic effects associated with the casing prevent the proper functioning of the multishot compass.

In more typical coring situations there are occassionally errant, or anomalous, survey points recorded. Possibilities include the presence of nearby magnetic anomalies or momentary compass sticking.

At very high latitudes all magnetic instruments, including multishot tools, can be affected by magnetic storms and proximity to the magnetic pole. There are also greater constant errors at higher latitudes, similar to those experienced with magnetic borehole deviation surveys.[6,7]

Paleomagnetic technique. Paleomagnetic core orientation is compatible with all core barrel assemblies. Therefore the optimum equipment configuration can be matched to anticipated hole conditions.

Although the use of a three-blade scribe shoe is recommended to assist in assembly of the core at the surface, the shoe is not critical to the orienting operation. After the core is retrieved at the surface, it must be assembled and marked for up direction and depth.

Descriptions of core handling procedures invariably stress the importance of careful assembly and marking of cores at the time of recovery,[8,9] and this step is even more important for paleomagnetic core orientation.

Accurate paleomagnetic orientation requires sufficient samples from each continuous interval to provide statistically valid calculations. If the core is mishandled and improperly fit together, the lengths of the continuous intervals will be reduced and there may be insufficient core material in some intervals to provide adequate samples to ensure accuracy.

If the core is mishandled to the extent that some segments are turned upside down, this error can be discovered at the time of paleomagnetic measurement. Although the up/down inversion can then be rectified, it may prove difficult to orient that portion of the core accurately.

Aside from the conventional red-black parallel lines marked along the length of the core, it is also necessary to designate an MOL over those portions of the core to be oriented. If straight, one of the previously marked parallel lines may be designated the MOL, or a separate line may be located at some other point around the circumference of the core.

It is important that special care be taken to ensure the MOL is straight (± 1 to 2°) relative to the long-axis of the core. A poorly marked MOL will decrease the accuracy of the resulting orientations since the samples over that interval will show a greater spread in paleomagnetic declinations.

Top and bottom depths of continuous intervals must be recorded accurately at the time the core is fitted together and marked. Inadvertently incorporating core segments in the wrong continuous intervals can decrease the accuracy of the results. Field marking of the core is usually handled by operator representatives rather than orientation-service-company personnel. Initial handling affects every other phase of the orientation procedure and special care must be exercised during this first step.

Sampling is carried out by service companies using specially designed nonmagnetic equipment. Care must be taken in cutting and marking each plug sample to avoid introduction of errors. Some errors which may occur at this stage are relatively simple to detect at the laboratory measurement stage, including mismarked depths, up/down inversion of samples, etc. Standard sampling procedures incorporate color coding and written records to minimize problems.

If an error is introduced during sampling of an individual plug, its overall influence on the statistics is small because anomalous directions are discounted in the statistical calculations.

One potential source of error introduced during sampling is caused by a secondary magnetization imposed during plugging of the core in a magnetic field. Special equipment and analytical techniques are used, first to minimize, and second to correct, for this potential problem.

In the lab, all work is under the direction of experienced, skilled personnel. Many of the measurement steps and calculations are automated, reducing the opportunity for human error. Random errors can be introduced but such problems can be traced back to handling or marking errors which can then be corrected.

The more serious sources of error which can arise in paleomagnetic core orientation are related to magnetic characteristics of rocks and the influence of naturally occurring or induced magnetic fields.

Paleomagnetc core orientation is lithology dependent. The coarser the grain size of the rock, the more samples necessary to achieve a given level of accuracy. Except in certain circumstances, conglomerates cannot be oriented using paleomagnetism.

If it is determined in the laboratory that insufficient samples have been taken, it is, in theory, possible to collect and measure additional samples to enlarge the statistical sample size. In practice, one pass at plug collection is all that is usually possible. The overall length of the continuous intervals and the lithology involved largely determine the degree of accuracy possible.

Another potential problem with paleomagnetic core orientation is caused by the ubiquitous magnetic field generated by and parallel to the drillstring. This field "oversteepens" the inclination (dip) of normal polarity (downward pointing) magnetic directions in the core (Fig. 5).

If the inclination is parallel to the long axis of the drillstring the core cannot be oriented paleomagnetically. The amount of oversteepening is dependent on such variables as lithology, core bit and barrel composition, rotation rate and penetration rate, bottom-hole temperature, well-site latitude, and hole deviation angle.

The effect cannot be totally removed by laboratory or mathematical procedures. At latitudes below 60-70°, the oversteepening does not appreciably affect orientation accuracy,

The authors. . .

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Since 1980, he has pioneered development of the paleomagnetic core orienting technique. Van Alstine received a BA in chemistry from Wesleyan University and a PhD in geology from the California Institute of Technology.

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Packer founded the first commercial paleomagnetics laboratory in 1974 at Woodward-Clyde Consultants which is still operating as part of Z-AXIS Exploration in Pleasant Hill, Calif. He was first general manager of Z-AXIS in 1983-84. Packer's career has emphasized paleomagnetic age-dating, earthquake hazard evaluation and research, reservoir-induced seismicity research, and exploration for and evaluation of petroleum and geothermal resources using paleomagnetics and magnetotellurics.

unless wells are deviated more than 10° north.

At higher latitudes, accuracy has been reduced in some cases, but unaffected in others since the oversteepening effect can be enhanced or offset by angle and direction of well deviation and structural attitude.

Even in the absence of drillstring overprint, cores cut at very high latitudes may not be oriented paleomagnetically because of the very small horizontal component of magnetization recorded by the rock. All magnetic tools, including multishot, encounter similar problems at high latitudes. (However, paleomagnetism is unaffected by magnetic storms.)

An apparent correlation has been observed between the amount of oil staining present in a core and the intensity and directional accuracy of the magnetization of the rock. Possible explanations of this phenomenon might involve geochemical or bacterial destruction of the magnetic minerals in the rock due to the presence of the petroleum. In either case the end result is decreased orientation accuracy in heavily oil stained rock.

High bottom hole temperatures generally improve the accuracy of paleomagnetic core orientation. The technique has a theoretical maximum working temperature of 1,324° F. (680° C), the Curie point of hematite, and has been shown to yield good results in granites at 450° F. and in conglomerates at 275° F.

Next week's conclusion discusses data evaluation and quality control.

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Mapping technology: a key to EOR control

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Success of an enhanced oil recovery (EOR) process is often dependent upon determining the extent of reduction in residual oil saturation and early discovery of detrimental flow paths of injected fluids; therefore, increasing emphasis is placed upon controlled application.

Control depends on knowledge of what is happening in the pay zone; thus, the ability to measure processes in situ becomes very important. But the field engineer needs to know what techniques are currently available and which are most suitable to his oil field.

The purpose of this article is to provide an overview of the technology being developed for mapping EOR processes, and to indicate the strengths and limitations of each.

The numerous EOR processes currently in use or development make the scope of an all inclusive article too broad. Attention will be restricted to the more conventional techniques.

Depending upon the reservoir, one would be interested in either a very broad knowledge (i.e., three-dimensional) or, perhaps where the vertical development is not important, to the areal expansion of processes. Communication between specific wells suggests pressure transient and tracer techniques.

If one has good knowledge of the field geometry and its temporal development, this may provide information needed to optimize production. However, if there are problems with a field, one may wish to know the three-dimensional development of an EOR process, e.g., a bypass to an underlying strata. But in the more normal case, one should want to know how to make a specific project perform more effectively.

Seismic. The basic assumption for mapping EOR processes by the seismic method is that changes in wave velocities and amplitudes occur as a result of the process application.

There are laboratory measurements that suggest detectable changes should occur for steamfloods.[1] The effects of in situ combustion or gas drive have not been as thoroughly investigated in the laboratory.

The field application involves a seismic array of receivers and transmitters on the surface over the area of the EOR operation. From the measured travel times and amplitudes, an inversion would give the distribution of velocities and dissipation factors within the reservoir.

By comparison to laboratory data and by mathematical modeling, one could infer the location of the EOR process.

A recent test of seismic mapping of a steam front indicates good agreement with post pilot core data.[2] The formation at 1,500 ft (460 m) depth had about 50 ft (16 m) of pay with steam being injected into an upper zone of about 26 ft (8 m).

The pilot was shut in for 3 days to allow for seismic surveying. Four seismic survey lines were run. These lines were through the center injection well and at 45° to each other. The signature was a change in wavelet shape.[2]

If additional data had been obtained, the authors felt they would have been able to more accurately map the thickness of the steam zone as well as its areal extent.

Microseismic. The microseismic technique is an adaptation of a method used in the mining industry for monitoring highly stressed regions.

Making the assumption that a fire flood will generate microseismic activity, the thermal front is monitored by hydrophone and geophones.[3 4] The signals appear to be from a shear failure event.

Normally the hydrophones and geophones are lowered into wells and cross-linked for accurate timing. The wall-locking geophones give the most useful information. The authors feel they can locate an event to within 10 m if enclosed within the area bounded by the observation wells.