Surveying the Path of Boreholes: A Review of Developments and Methods Since 1987

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INTRODUCTION

Numerous borehole surveying devices have been developed. Surveying a borehole is usually accomplished by moving a probe along the hole and sensing the movement of the probe relative to one or more frames of reference which may include the earth's gravitational field, magnetic field or other inertial reference, and/or by sensing the distortion or bending of the housing of the probe itself. Different methods have their own advantages and limitations. Some have the ability to operate inside steel casing, and others cannot. Some methods are time consuming and others are fast. Some are relatively simple to use and others are complex to operate. Other considerations are accuracy, cost, distance between measurements, ruggedness and reliability (Killeen *et al.*, 1995).

SURVEYING A BOREHOLE

A survey of a borehole should provide an accurate plot of the path of the hole in 3-dimensional space, i.e., the (x, y, z) coordinates (northing, easting, true depth) of every point along the path is known. In practice, the coordinates of a finite number of points are determined, and the path between these points is calculated by extrapolation. The greater the number of known data points, the less extrapolation required, and the more detailed the survey. The coordinates of points are computed from measurements of the dip, azimuth and length-along-the-hole (usually called 'depth'), as shown in Figure 1. These are the three components of the 'hole vector', The first data set is the dip, azimuth, and depth (which is zero) at the collar of the hole. Along the length of the hole the dip and azimuth will change from that at the collar. Measuring length along the hole is relatively easy, although not a trivial problem. Possible errors are associated with calibration of the pulley or sheave wheel and the depth encoder, cable stretch, cable and pulley icing in winter and pulley wear. The error in depth measurement may be larger than the error caused by the precision of dip and azimuth measurements. Here we will be concerned with the dip and azimuth measurements made by the borehole probe. The measurement of depth is a separate problem which will not be covered.

The earliest surveying devices only recorded the dip of the hole. However, the path of the hole could be in any direction on a cone of equal dip as shown in Figure 2, until the *azimuth* with respect to north is also measured.

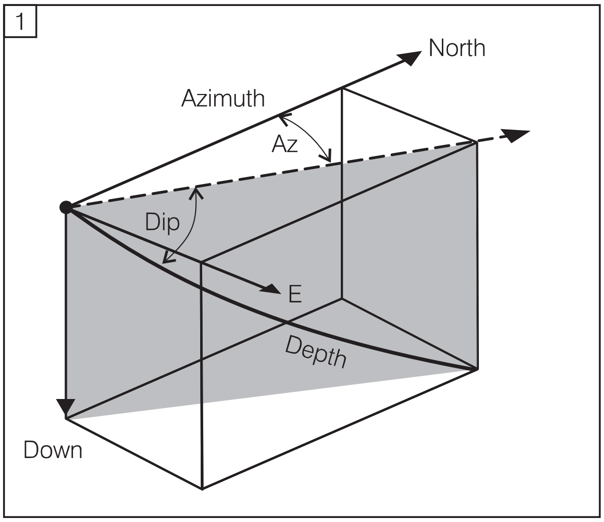
MAGNETIC-BASED METHODS

The Pajari (formerly Tropari) is a compass and clockwork mechanism mounted on gimbals to move freely in its housing (Figure 3). It is lowered into the hole to the measurement depth, and at a preset time the clock locks all the moving parts and the instrument is retrieved from the hole to read the dip and magnetic azimuth values.

Using basically the same principle as the Pajari, the Magnetic Single-shot replaced the clockwork locking mechanism with a camera that takes a photo (shot) of the dip and compass needle at the measurement depth. Sperry-Sun made a significant advance in the Magnetic Multi-shot system by installing in the probe an 8 mm film camera (Figure 4) that takes photos of the dip and azimuth readings at several measurement depths in one trip along the hole.

In recent years new hardware was adapted from satellite and guided missile technology for use in logging tools. The magnetic compass was replaced by a ring-core fluxgate magnetometer (Figure 5) and the dip measurement was made by solid state tilt-meters or accelerometers with no moving parts (Figure 6). The solid state tiltmeters are oriented orthogonal to each other in the probe to measure dip, and at the same time compensate for roll of the probe as it moves in the hole. Dip and azimuth data are transmitted to the surface in real time for recording and display. Typical sensitivities quoted by various manufacturers are ±0.1° dip and ±1.0° azimuth. The magnetic azimuth measurements are converted to geographic azimuth using the declination of the local field. Although these magnetic-based methods are adequate for most holes, surveys based on magnetic azimuth cannot be done inside steel casing, or where there are anomalous magnetic fields. These considerations led to the development of non-magnetic systems.

In "Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration" *edited by* A.G. Gubins, 1997, p. 709–712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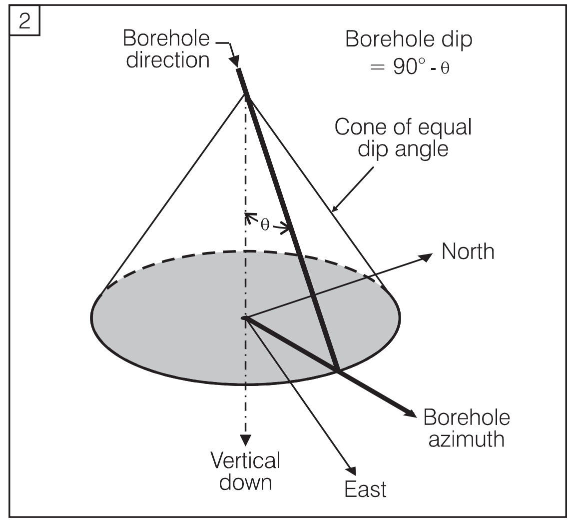
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Borehole dip = 90° - θ
Cone of equal dip angle
θ
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Borehole azimuth
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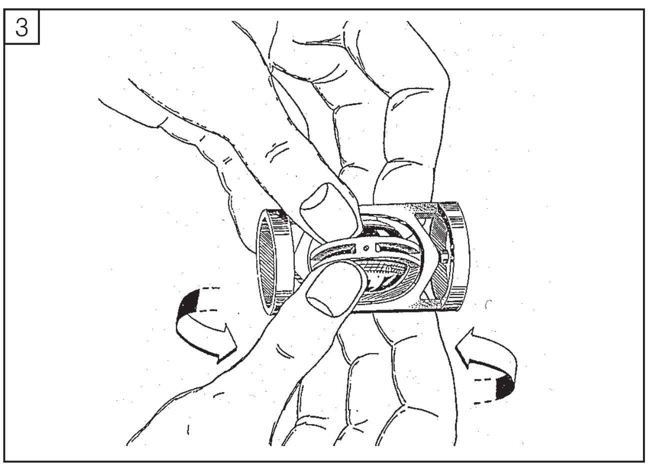
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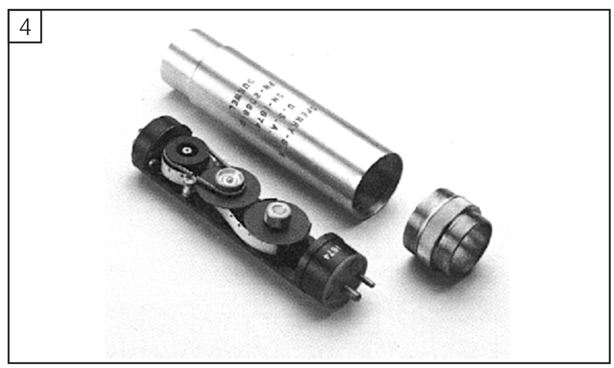
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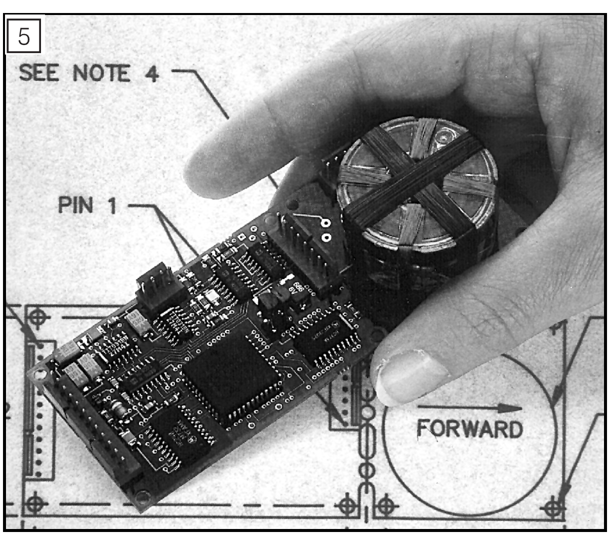
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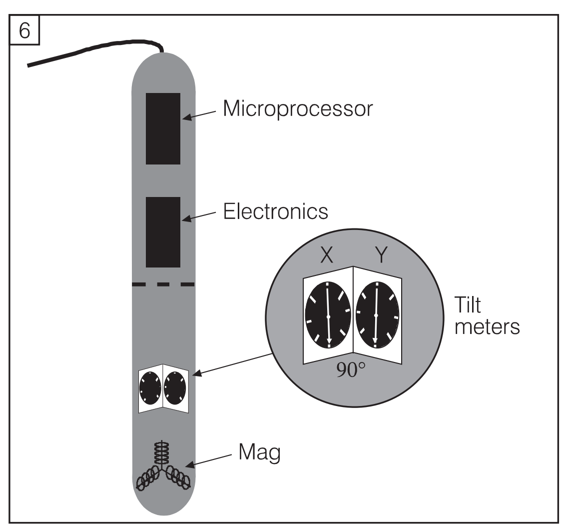
6
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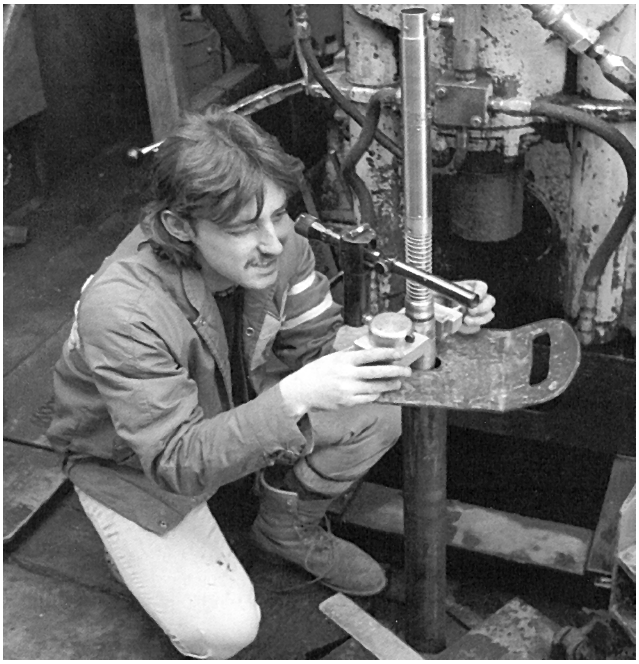

Figure 7: *Gyroscope orientation is determined with respect to geographic north by sighting on known points.*

NON-MAGNETIC METHODS

The inertia of a spinning mass can also be used as a stable reference for a series of azimuthal measurements in a borehole. The gyroscope mechanism replaces the magnetic compass, and its orientation with respect to geographic north is determined at the collar of the hole (Figure 7). Surveys can be carried out inside metal pipe and in the presence of magnetic anomalies. Early versions were combined with a camera, such as in the 'Single-shot' device. Recent versions, called 'surface recording gyros', transmit the data to the surface digitally in real time. New optical gyros (e.g., ring-laser gyros) with almost no moving parts to wear out, may replace the mechanical gyroscopes which are more prone to drift.

A completely different borehole surveying technique is based on a light source in one end of a long rigid tube, with the lightbeam focused on a target in the other end of the tube. Bending of the tube as it moves in the borehole causes deflections of the light on the target, and this information is converted into borehole orientation survey data. The technique is not affected by magnetic fields and can be used inside metal pipe or drill rod. In the first version, the 'Fotobor', designed in Sweden by Reflex Instruments AB (Hood, 1975), the illuminated target was a set of concentric rings and a level bubble, used as the vertical reference. A camera recorded the data on film for processing and correlation with the time and depth data recorded at the surface. Another optical system made by Gyro-log Ltd., Canada, uses the position of the lightbeam 'spot' on a target (instead of rings) for measuring the bending of their 'Light-Log' instrument. The most recent Swedish version, the 'Maxibor', shown in Figure 8, detects the position of the rings with optical sensors and the data are recorded in a solid state memory in the probe.

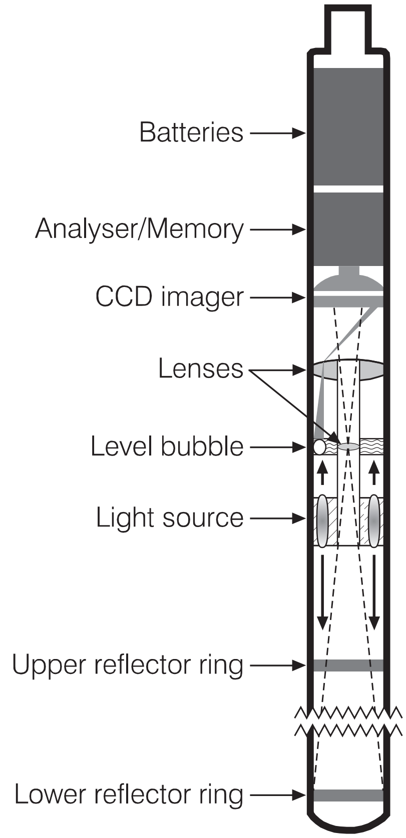

Figure 8: *The Maxibor detects the position of rings with optical sensors and records data in solid state memory in the probe.*

Figure 1: *The three components of the 'hole vector'; the dip, azimuth and depth.*

Figure 2: *The hole path may be in any direction on a cone of equal dip until the azimuth is also measured.*

Figure 3: *The Pajari gimbal-mounted compass and clockwork mechanism locks all moving parts at a preset time.*

Figure 4: *An 8mm film camera in the Magnetic Multi-shot probe photographs dip and azimuth readings at several depths.*

Figure 5: *Advanced technology replaces the magnetic compass with a three component ring-core fluxgate magnetometer.*

Figure 6: *A magnetic-based survey system with fluxgate magnetometers and solid state tilt-meters transmits data to the surface while logging.*

DESURVEYING

The raw dip, azimuth and depth data must be converted into a plot of the path of the hole in three-dimensional space by interpolating between measurement points as shown in Figure 9. A number of different 'desurveying' (Howson and Sides, 1986) algorithms can be used for the interpolation. After desurveying, the output is a display of the path of the hole projected on planes in an east-west or north-south direction, or in plan view, one scheme of which is illustrated in Figure 10. Reviews of the various methods of computing borehole position, and their possible errors have been presented by several authors including Wolff and deWardt (1981), Balch and Blohm (1991) and Killeen *et al.* (1996).

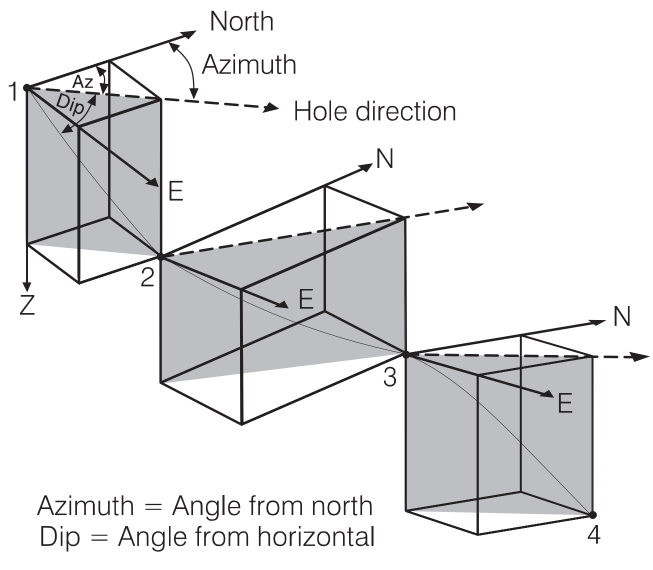

Figure 9: *Desurveying interpolates between measurement points of depth, dip and azimuth data.*

Most modern orientation probes make measurements continuously, and these are sampled as often as every half-second. Measurements of dip, azimuth, and depth can be made every 5 cm along the path of the hole.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the material used in the illustrations of the borehole surveying equipment. In particular, we thank Reflex Instruments AB, Pajari Instruments Ltd., and Sperry-Sun Drilling Services of Canada. We also thank Sue Davis (GSC) for production of the line drawings.

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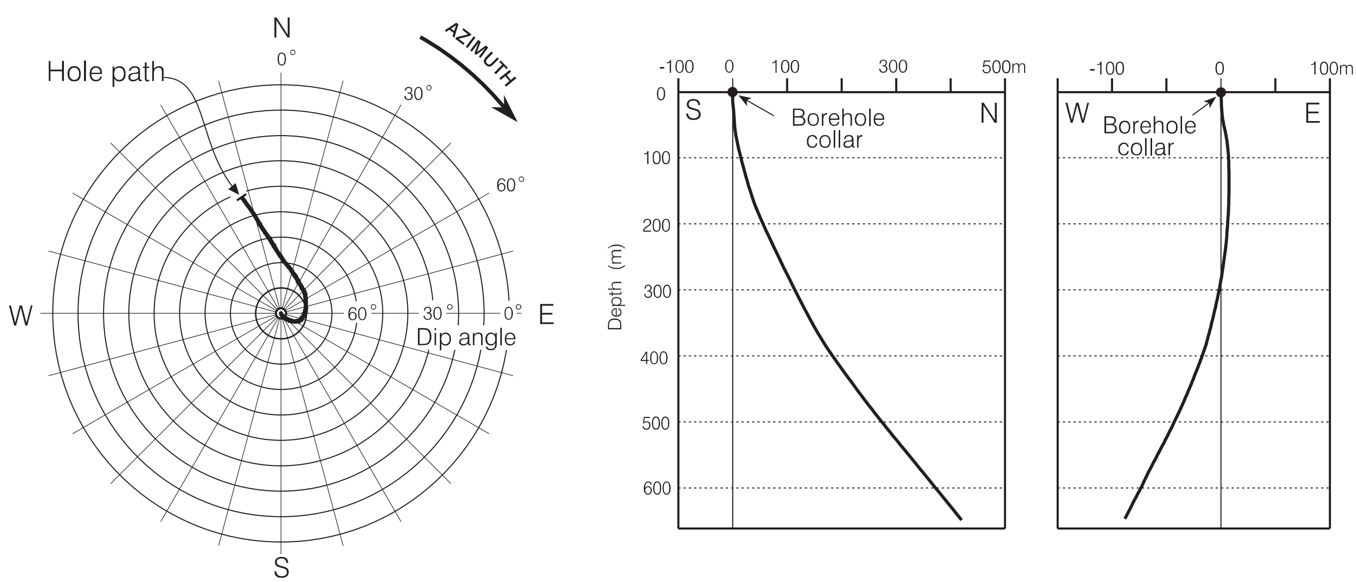

Figure 10: *Survey results are displayed on planes in an east-west or north-south direction, or in plan view.*