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The characterization of trough and planar cross-bedding from borehole image logs

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Abstract

Conventional analysis of borehole images involves fitting sinusoidal curves to borehole/structure intersection curves, and assumes that the sedimentary features are planar. If trough cross-bedding occurs the conventional technique can result in large errors in the direction of the trough axis (up to +35° in dip and ±90° in azimuth) due to the unknown offset between the borehole axis and the trough axis. We present an analytical model describing the curves from the intersection of a vertical borehole with a mathematically generalized trough cross-bedded structure. The new model shows deviations of the trough axis from sinusoidal behavior that increase as the dip and the width of the trough decreases, and as the offset increases. The conventional and new techniques have been compared by using both of them to analyze blindly a set of mixed plane and trough cross-bedded electrical or acoustic image data. This analysis shows that the new technique provides (i) improved accuracy in dip and azimuth determinations, (ii) additional information concerning the width of the trough and the offset, and (iii) enhanced vertical resolution arising because accurate directional data can be obtained for individual structures, enabling each structure to be accurately and uniquely mapped in three dimensions in the sub-surface. The new model may be modified to provide intersection curves between elliptical boreholes with hemi-cylindrical or elliptical sub-surface structures. The limitations of the new model are that its useful applicability is controlled by the resolution of image log data, the size and quality of the borehole, and the use of a centralized tool.

Keywords: Image logs; Paleoflow direction; Trough cross-bedding; Azimuth; Dip; FMI; BHTV

1. Introduction

This paper sets out to analyze intersection curves from image logs that are likely to contain trough-bedded structures with two methods. The first method is that which is followed conventionally by the logging industry and major exploration companies. It involves fitting sinusoidal curves to the image log data and assumes that all structures that intersect the borehole are planar, and provides the apparent dip and azimuth of the plane (Rider, 1996). The second method is developed within this paper. It involves fitting the intersection curves with an equation that has been generated from the analysis of the intersection of a cylindrical borehole with a generalized hemi-cylindrical structure. It assumes that the tool is centralized in the borehole. In principal the mathematical model developed in this paper can be extended to take account of an elliptical borehole, any hemi-elliptical subsurface structure, and non-verticality of the borehole. These extensions will be the subject of further publication.

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This method is equally applicable to planar or trough-like structures and provides the dip, azimuth, size and offset position of the structure with respect to the borehole. These data are fundamental to the analysis of paleocurrents, which can provide detailed information concerning the lateral distribution of oil and gas reservoirs by allowing the reconstruction of paleogeographic maps (e.g., Glennie, 1972; Hurley et al., 1994).

The basic assumption in paleocurrent analysis is that bedforms migrate down-current, and hence produce a sequence of inclined foreset laminae that plunge in the direction of flow. The mean direction of transport can be found by measuring the direction of the plunge (azimuth), plotting the azimuth values as rose diagrams, and then calculating their eigenvalues (Curray, 1956) and vector means (Scheidegger, 1965).

As bedforms migrate, they fill local hollows in the morphology of the depositional system, such as a river channel, or they aggregate laterally on a point bar surface (Pettijohn et al., 1987). During this process of net deposition the cross-beds form. Several types of cross-bedding occur, which can be broadly classified as (i) planar/tabular, (ii) trough, (iii) hummocky, and (iv) mixed, and can develop a significant complexity (Lofts et al., 1997).

For planar and tabular cross-bedding the foresets are near parallel and dip in the direction of the paleoflow between 10° to 35°, while the bounding surfaces have a much lower dip (0°–10°).

Trough cross-beds form where higher flow intensities are present (Rubin, 1987) which cause erosional scours at the base of the slip slope of transverse bedforms (Pettijohn et al., 1987). The trough cross-bedding comprises a scoop-shaped or cylindrical scour filled by curved foreset laminae, with the axis of the scoured trough and the crescentic fill laminae oriented parallel to the local principal flow direction (Trexler and Cashman, 1990). The trough-shaped basal scour surfaces form the bounding surfaces of the sedimentary packages, and have a low dip (0° to 15°) that increases in the direction of sediment transport (Cameron et al., 1993; Rider, 1996). The foreset laminae are also trough-shaped, and have dips ranging between 10° and 35° in the direction of paleoflow (Trexler and Cashman, 1990). The foreset surfaces can, in most cases, be described as cylindrical (Singerland and Williams, 1979; DeCelles et al., 1983), but channel trough-beds are also known to occur with elliptical cross-section with half-width to thickness ratios of 4.25 and 5.2, and also with non-axisymmetric cross-sections (Robinson and McCabe, 1997). It should also be noted that it is rare that a full hemi-cylindrical cross-section is found as subsequent erosion normally removes much of the original trough deposit, leaving just the lowermost parts of the hemi-cylinder.

A range of cross-bedding styles can be observed using electrical or acoustic image techniques (e.g., Borehole Televiewer (BHTV)). Conventionally, such imaging data are analyzed by fitting blindly sinusoidal curves to layers of the same resistivity on the unwrapped borehole image. This procedure works well for plane cross-bedded structures such as foresets and set bounding surfaces in planar/tabular cross-bedding. It also works approximately for set bounding surfaces and foreset surfaces in trough cross-bedding if the borehole intersects the axis of the trough by chance.

However, the common case is that the borehole axis intersects the trough at some unknown offset from the trough axis. In this case it is clear that the planar assumption will lead to overestimations in dip and inaccuracies in azimuth of the axis of both the basal trough-bounding surface and its foreset layers that are caused by the steeper trough flanks. The errors in azimuth are a recognized problem that result in broader, more variable azimuth rose diagrams, and azimuth histograms where the trough foresets cannot be distinguished from the set-bounding surfaces. This variability is corrected for approximately by obtaining the vector mean azimuth from a depth interval, and assuming that the errors in azimuth caused by the trough sides cancel out evenly (Rider, 1996). Such a procedure requires a set of azimuthal data for a depth interval commonly greater than 30 m, in which the lithology and structural style of the sediment does not vary. The vector means therefore have a low depth resolution.

2. Intersection curves

Only perfectly planar bedding surfaces produce a true sinusoidal signature in image logs. All other non-planar surfaces produce curves which represent smooth oscillations, and may even appear similar to sinusoidal curves, but they are not sinusoidal. The deviation of these curves from the true sinusoid is a direct function of the deviation of the bedding surface from a perfect plane (Fig. 1).

If a vertical borehole intersects a plane structure of dip $\theta=10°$ and azimuth $\alpha=0°$ (Fig. 1a), the intersection curve on the electric or acoustic image data appears as a sinusoidal curve with its minimum in the direction of the maximum dip (i.e., the azimuth of the plane), and its amplitude being related to the size of the dip (Fig. 1b). The z values span $z=0$, which is the depth at which the borehole axis intersects the plane.

If the same vertical borehole intersects a trough with a trough axis dip $\theta=10°$, azimuth $\alpha=0°$, and at some