The Characterization of Trough and Planar Cross-Bedding from Borehole Image Logs

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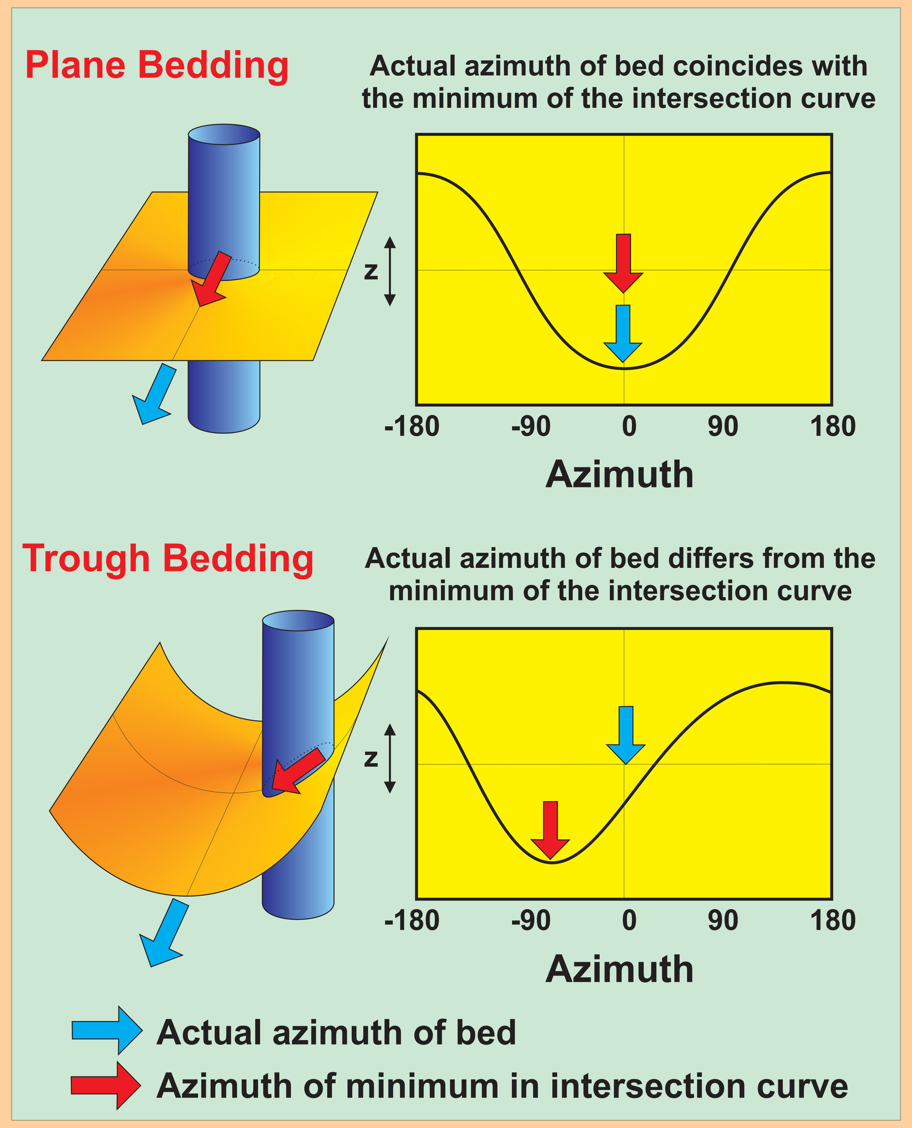
Abstract

Conventional analysis of FMI images for the determination of palaeoflow direction involves the fitting of sinusoidal curves to FMI homo-resistivity intersection curves. This analysis assumes that the sedimentary features are planar. However, if trough-bedding occurs in the section, the conventional technique can result in large errors in palaeoflow direction due to the unknown offset between the borehole axis and the trough axis. This effect is conventionally accounted for by taking the vector mean of a large set of azimuthal determinations from a depth interval of typically greater than 30 m, and assuming that the errors cancel themselves out. This results in low vertical depth resolutions.

We present an analytical model describing the intersection curves that result from the intersection of a vertical borehole with a mathematically generalized trough cross-bedded structure. Analysis of the new model shows deviations from sinusoidal behaviour that increases as the dip and the width of the trough decreases, and as the intersection offset between the borehole axis and the trough axis increases. The deviations imply that if a sinusoidal curve is blindly fitted to trough cross-bedded data, as currently commonly occurs, the dip can be overestimated by as much as 40^o, and the azimuth can be in error by $\pm 90^o$.

The conventional technique and the new model have been compared to 39 intersection curves from mixed plane cross-bedded and trough cross-bedded FMI data using non-linear fitting and a using range of statistical fitting tests. We have shown that the new technique provides an enhanced analytical capability characterized by (i) greatly improved accuracy in dip and azimuthal determinations, (ii) additional information concerning the width of the trough and the offset of the borehole axis from the trough axis, and (iii) enhanced vertical resolution arising because accurate directional data can be obtained from individual intersection curves. This information enables each trough bedded structure to be accurately and uniquely mapped in three dimensions in the sub-surface.



Conventional FMI Analysis

- FMI is an electrical technique used in boreholes to image bedding and fractures around the perimeter of the borehole
- FMI images of planar bedforms cut the borehole with sinusoidal intersection curves
- The amplitude of the curves indicate the dip of the bedding
- The position of the minimum indicates the azimuth of the maximum dip (palaeoflow direction)

Problems with Conventional FMI Analysis

- In many cases the bedding is **NOT PLANAR**
- Trough cross-bedded structures produce intersection curves that look similar to true sinusoids, but are significantly different
- This gives **large errors in dip and azimuth**
- The problem is recognised and conventionally accounted for by averaging the results from many intersection curves
- Then hoping the errors cancel out!!!

Conventional Model

- Based on equations for the intersection of a circular borehole with a plane
- Parameters provided by the model are:
  - Azimuth, ϕ
  - Dip, θ
- Blindly applied to all data leads to errors in non-plane bedded systems

New Model

- Based on equations for the intersection of a circular borehole with a hemi-circular trough
- Parameters provided by the model are:
  - Azimuth, ϕ
  - Dip, θ
  - Ratio of trough radius to borehole radius, d
  - Ratio of offset distance to borehole radius, b
- Blindly applied to all data does not lead to errors in plane or non-plane bedded systems

Errors in Conventional FMI Analysis

There is no *a priori* knowledge of where the borehole intersects the trough

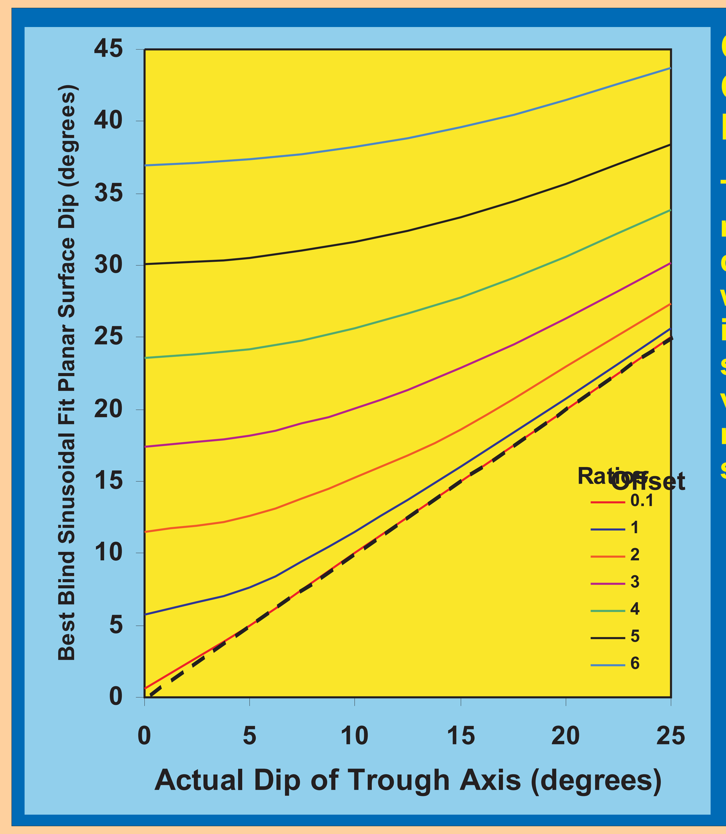
- If the borehole intersects the axis of the trough, the curve is similar to the plane case
- If the borehole does not intersect the axis of the trough, the side walls have the following effects:
  - The dip will be overestimated by as much as $+40^o$
  - The azimuth will be in error by as much as $\pm 90^o$

New Model Equation

In its most general form the intersection equation is:

$$z = \frac{1}{\cos\theta}\left[\sin\theta\cos(\alpha-\varphi) + \sqrt{d^2 - (\sin(\alpha-\varphi) - b)^2}\right]$$

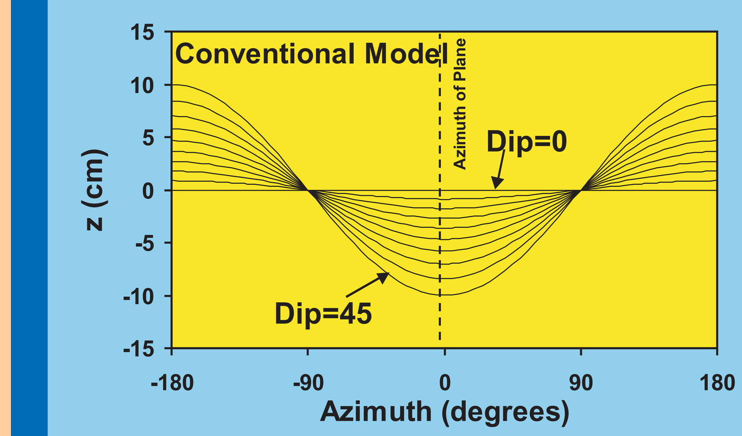
θ = *Dip*
d = Ratio of trough radius to borehole radius
b = Ratio of offset distance to borehole radius
Azimuth, ϕ is derived from φ and α *by symmetry*



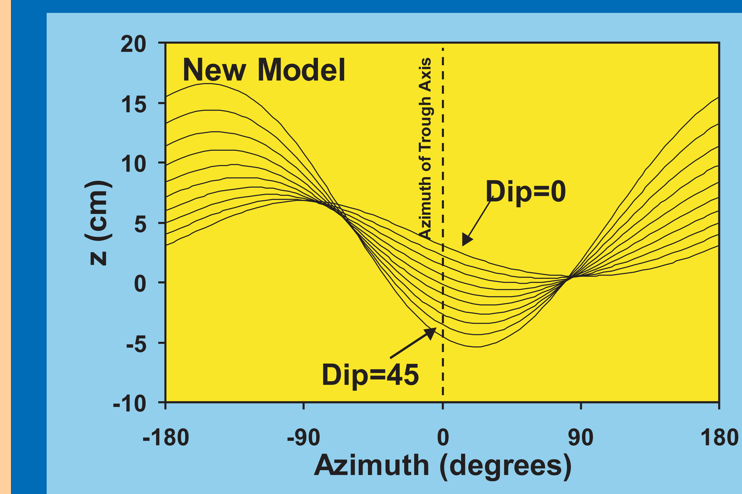
Conventional Overestimation of Dip

The conventional model overestimates dip badly, becoming worse if the borehole intersects the trough structure at large values of offset ratio, i.e., up the sides of the trough

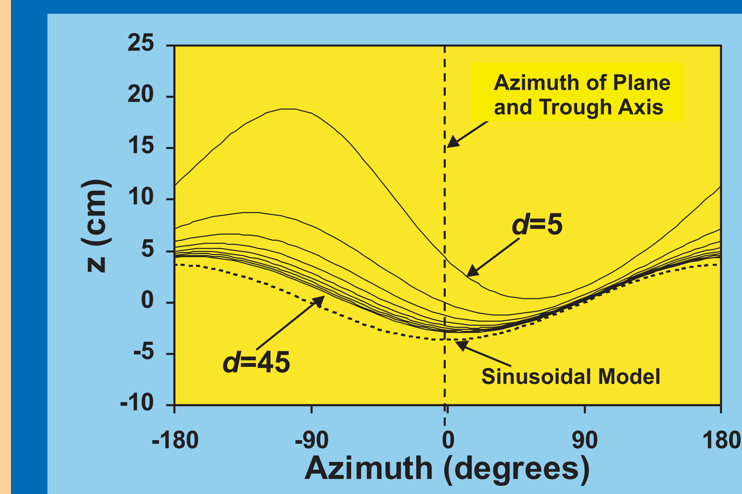
Properties of the New Model



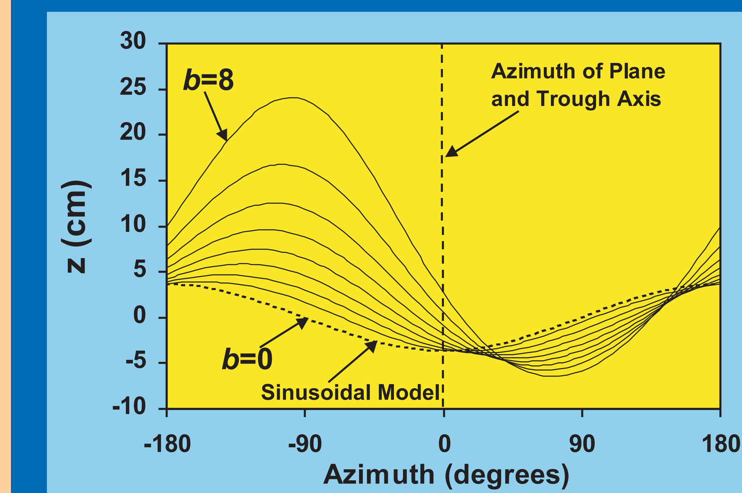
The conventional model is sinusoidal for all values of structural dip



The new model is not sinusoidal. Here, for d=10 and b=3 the model gets more sinusoidal and the minimum moves towards the true azimuth of the structure at larger dips as the dip compensates to some extent for the effect of the trough sides.



The new model becomes less sinusoidal and the minimum moves away from the structure azimuth as the diameter ratio decreases (d gets smaller) as the trough becomes more acute.



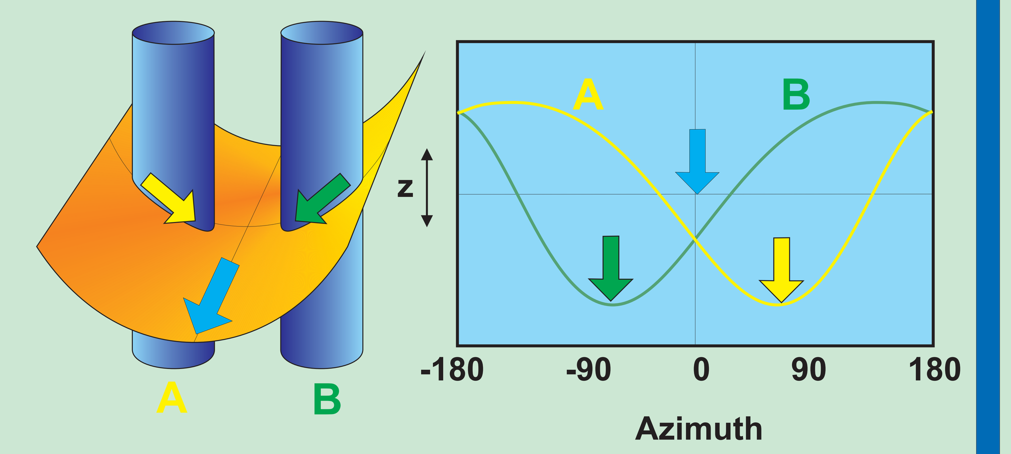
The curves become less sinusoidal and the minimum moves away from the true azimuth of the structure as the offset ratio (b) increases. (b=0 indicates that the borehole axis intersects the trough axis.)

Testing the New Model

Procedure

- 50 m of FMI log with 55% FMI coverage
- 39 intersection curves of mixed trough/plane bedding
- Curves fitted to conventional and new models
- Dip and azimuth derived from the conventional model
- Dip, azimuth, diameter and offset ratios derived from the new model
- Statistical tests carried out to determine goodness of fit

Derivation of Corrected Azimuth



The azimuth is not explicit in the new model equation. It is derived by plotting the intersection curves from mirror images, with the azimuth (blue arrow) occuring at their intersection closest to the minima (green and yellow arrows).

Statistical Tests

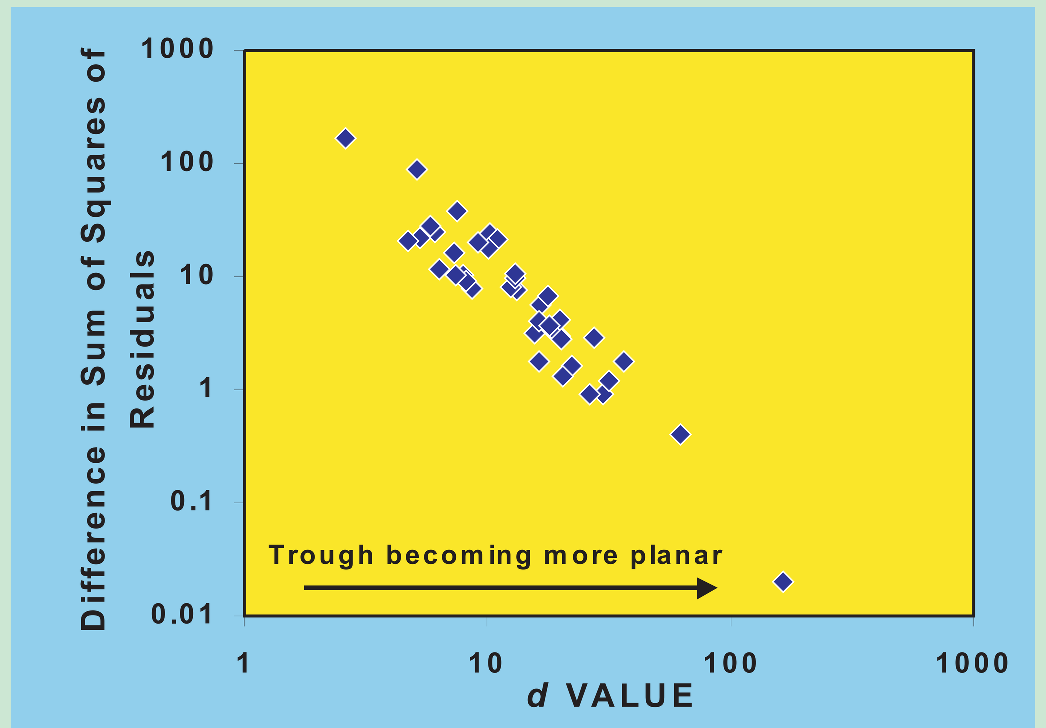
- The new model fitted the data better than the conventional model in the majority of cases

Test	Conventional	New
Sum of Squares	35.4	19.81
Absolute Deviation	0.021	0.015
Adjusted R^2	96.4%	97.9%
Durbin-Watson (<0.8)	0.6631	1.050

Mean values for all 39 curves

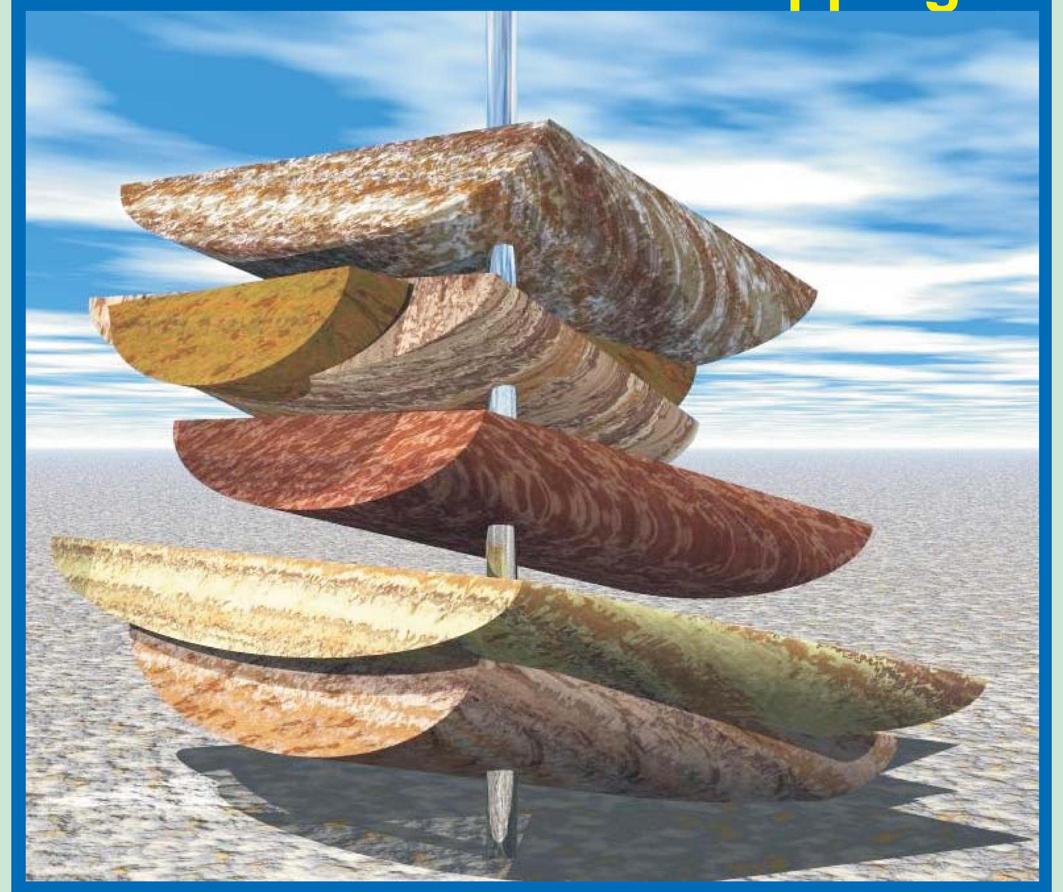
A Durbin-Watson value of less than 0.8 indicates that the curve fit is inappropriate, and above 0.8 indicate the fitted curve is appropriate.

WARNING: Closeness of conventional R^2 value to 100% indicates that conventional curve may seem to be a good fit, but actually the fitted curve is the wrong one!



As the diameter of the trough becomes larger, the difference in the residuals from the conventional and new models approaches zero: The trough has become a plane.
However at small trough diameter, the residuals from the conventional fit can be up to 200 times those from the new model.

Subsurface Structure Mapping



The new model gives accurate values of dip, azimuth, diameter ratio and offset ratio when applied blindly to trough or plane bedded data. This allows the structures in the subsurface to be mapped individually with high resolution.

Summary I

- The conventional method for analysing FMI intersection curves often leads to large errors and low vertical resolutions in trough-bedded systems
- We have produced a new method for analysing FMI intersection curves that can be used to analyse plane and trough-bedded systems accurately with high resolution

Summary II

- The conventional method provides data on mean dip and mean azimuth for sets of curves spanning a significant vertical interval
- The new method provides highly accurate values of dip, azimuth, trough radius and offset for individual structures
- This allows them to be mapped uniquely in the sub-surface