‘X-ray Plunge Projection’— Understanding Structural Geology from Grade Data[1]

E J Cowan[23]

ABSTRACT

This paper introduces a new down-plunge projection method that allows geologists to rapidly determine the first-order structural geometries of mineral deposits. The method assumes that the mineralised bodies under analysis resulted when hydrothermal fluids flowed through highly permeable zones that were formed from deformation. Therefore, the grade patterns should mimic the significant structures that controlled the fluid flow. Once these structural geometries are determined, the patterns can be used to simplify, speed up, and substantially increase the accuracy of the geological modelling processes of both explicit and implicit methods of modelling.

Down-plunge projection, or down-structure method, is a way to examine structures on a geological map by orientating the map so as to look down into, and along, the direction of the plunging structural features, such as folds and fault intersections. This method of deriving true sectional geological structural geometries from an oblique viewing angle has been known to geologists for more than 100 years. However, this practical technique has not been extensively used in the field of economic geology, even though the application is very broad and relevant to the interpretation of grade distribution in mineral deposits. This century-old graphical methodology is reintroduced in this paper by combining it with a computer rendering technique called Maximum Intensity Projection (MIP). MIP is a 2D projection method that displays the highest value point of a point cloud along a line-of-sight orthogonal to the computer screen. This allows the geologist to ‘see through’ a dense 3D grade point cloud on a computer monitor and aids structural interpretation of the details of the high-grade core that is surrounded by low-grade values. Because the rendering method appears to allow the skeletal core of a grade dataset to be visualised through a low-grade surrounding, it is informally termed the ‘X-ray’ method of grade data visualisation.

Originally developed for the medical industry in 1989, MIP is highly relevant for interpreting drill hole sampled grade data. A geologist with structural geological analytical experience can rapidly identify the structural controls of mineral deposits, often within minutes of viewing the data, by simply applying the X-ray view, and also viewing parallel to the down-plunge direction. Such rapid and accurate geological interpretations using ‘X-ray plunge projection’ are not possible with full 3D modelling methods (including implicit modelling), which are relatively more complex and expensive than MIP. However, when combined with either explicit or implicit modelling, the X-ray plunge projection technique can result in very accurate geological models for resource evaluation purposes.

While the geologist requires no experience in 3D modelling, relevant structural geological theoretical knowledge and field experience is essential for the accurate use of X-ray plunge projection. Without appropriate structural experience, it is difficult to interpret the range of possible structural scenarios that could be controlling the grade distribution in a mineral deposit.

A structural geological framework determined from X-ray plunge projection is an essential requirement for accurate geological modelling using implicit modelling software. Without this framework, the geological modelling is left entirely to algorithmic methods of modelling, which are often devoid of geological logic and are unlikely to yield geologically sensible results. These ‘black box’ methods are becoming the primary workflows implemented in the design of implicit modelling software products, but if left unchecked such modelling practices are likely to greatly increase the chance of geological misinterpretation of data, which in turn will adversely affect the resource evaluation of mineral deposits.

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INTRODUCTION

Mining and exploration companies would benefit if the structural context of any mineral deposit—at the scale of the deposit—could be obtained rapidly with little effort. Not only would this fast-track resource evaluation, as it would highlight a geometric and structural framework to guide modelling and grade estimation, but it would also benefit near-mine exploration. This paper reintroduces a century-old mapping projection method and combines it with a 20-year-old computer rendering method that together achieves this task quickly and effortlessly. This new technique described in this paper has been used by the author in the past decade on more than five hundred mineral deposits, and it has been very effective for rapidly determining structural geological controls and assisting in the interpretation and modelling of mineral deposits of various commodities.

Geologists who interpret drill hole data and construct geological models for the purposes of resource evaluation often ask how structural geological data could be incorporated into their 3D geological models. As virtually all deposits are structurally controlled, it would seem sensible to obtain guidance from structural data, but a method to accomplish this task easily and efficiently has eluded researchers of structural geology of ore deposits.

The deceptively simple approach introduced in this paper addresses this issue.

The solution is to use the assayed grade data obtained from the deposit's drill holes as the primary structural data for interpretation[4]. This is an 80:20 approach that provides a rapid structural geological framework for the grade distributions of mineral deposits and, in turn, allows sensible strategies to be implemented for geological modelling and resource estimation.

Grade is an unconventional dataset for structural analysis, but if the assumption is correct that virtually all deposits are in some way structurally controlled or modified, then it is logical to expect structural features to be observable from the first-order grade patterns of mineral deposits. The expectation that grade patterns should reflect structural geology is because metallic constituents are mobilised and emplaced by hydrothermal fluid flow through highly permeable zones formed from deformation (eg Cox, Etheridge and Wall 1987; Hobbs 1987; Marshall and Gilligan 1987; Cox 2005). The grade patterns therefore should mimic the significant structures that controlled the fluid flow thus revealing the structural architecture of the mineralisation.

Surprisingly, this assumption, although entirely reasonable, has not been a focus of research on ore deposit genesis (Cowan 2012, 2013). In this paper, some grade patterns at deposit scales are shown, along with their structural interpretation. These examples clearly illustrate that structural geology plays a central role in the distribution of mineralisation in all types of deposits. With better structural understanding of grade patterns, geologists can better predict the spatial grade continuity and can minimise geological misinterpretation. In addition, the knowledge of structural geometry can be used to fast track the geological modelling process. Although implicit geological modelling methods have been developed over the last 15 years and are favoured in this paper (Lajaunie, Courrioux and Manuel 1997, Cowan *et al* 2002, 2003; Chilès *et al* 2004; Cowan, Lane and Ross 2004), the analytical method discussed in this paper is independent of the modelling approach; it can be used before using either explicit or implicit modelling methods.

DOWN-PLUNGE PROJECTION METHOD—A 'RECENT' GEOLOGICAL APPLICATION OF PERSPECTIVAL ANAMORPHOSIS

The technique used for the structural analysis of grade data is the well-established down-plunge map projection (Figure 1). Used in conjunction with implicit modelling methods, this technique allows structurally accurate geological bodies to be constructed (Figure 1d).

There are a few examples of down-plunge projection in structural geological literature (Bailey and MacKin 1936; Charlesworth, Langenberg and Ramsden 1976; Kilby and Charlesworth 1980; Elliott 1983; Langenberg and Ramsden 1980). By far the most common use of this method is to determine the true profile shapes of folds from mapped geometries (eg Simon and Gray

[4] This paper focuses on grade data. Additional data such as logged lithological data are used in the analysis where available; however, analytical data, especially assays, are the only geological data available at all exploration and mine sites. These analytical datasets are much more reliable than subjectively obtained logged data.

1982; Ragan 1985; Cowan 1999; Treagus, Treagus and Droop 2003).

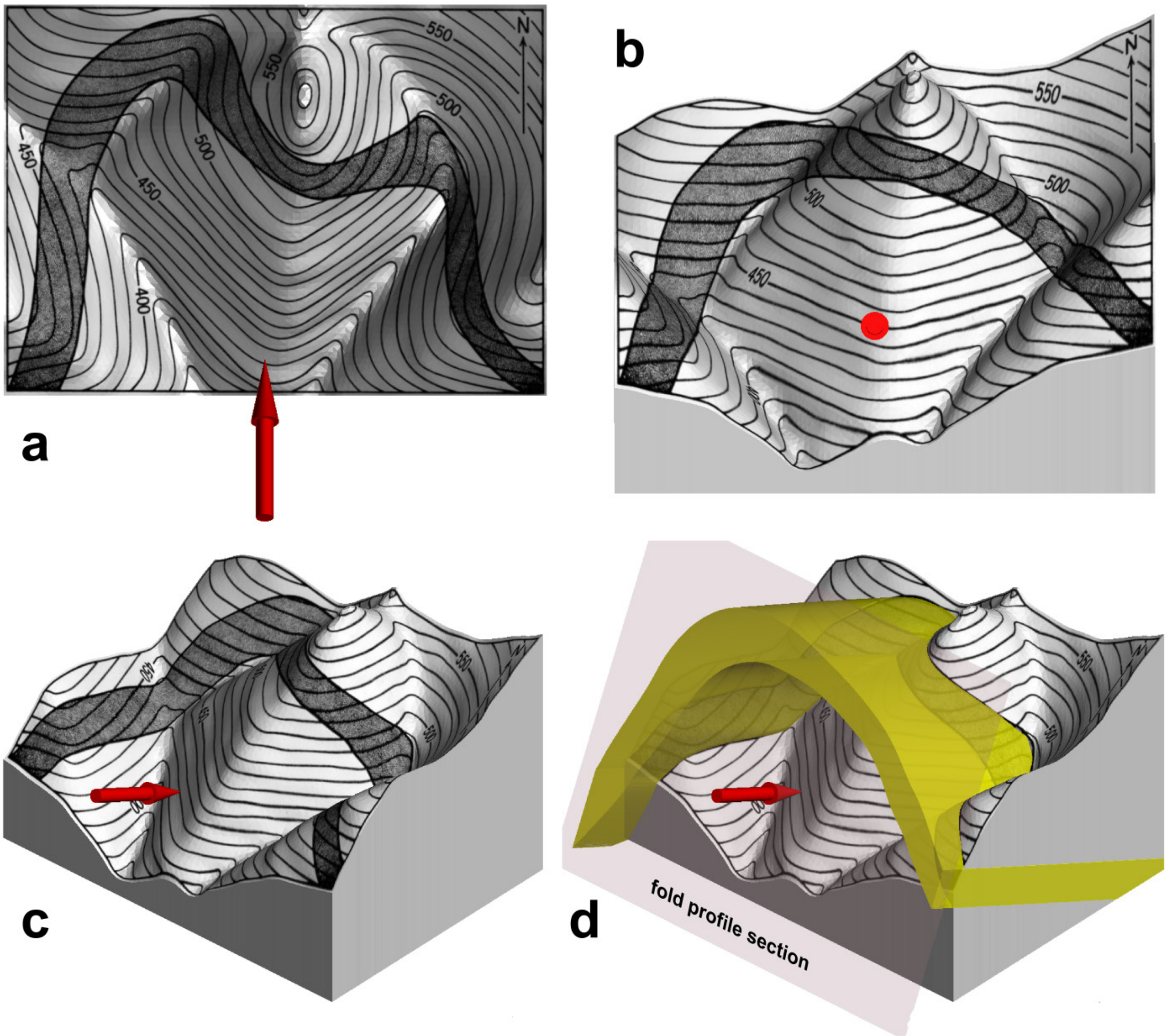

Figure 1. Down-plunge projection of a mapped lithological unit, with the down-plunge direction indicated by the red arrow in each image: a) map view; b) down-plunge view to 25° to North reveals a fold profile view; c) oblique view; d) modelled folded unit using down-plunge projection view as reference line using an implicit modelling software. Fold profile section is orthogonal to the fold plunge indicated by the red arrow. Map courtesy of Ragan (1985, figure X14.2)

The description of down-plunge projection by MacKin (1950) indicated that the method was not restricted to the visualisation of cylindrical folds, but was also used in the analysis of faults (see also Threet, 1973). MacKin (1950) noted that the method had been used by European geologists for half a century prior to the publication of his paper, so this method has now been well established for more than a century. MacKin (1950, p. 56) described down-plunge projection as a very powerful structural interpretation method that may short-cut many years of geological mapping:

'The writer was introduced to the method by E. B. Bailey in 1936, when he was privileged to watch Bailey apply it in grasping, literally at a glance, the structural significance of a swirling outcrop pattern in the Pennsylvania Piedmont that had been missed by two generations of competent geologists by whom the area had been mapped.'

The significance of this statement is difficult to comprehend; thus, down-plunge projection may have been underappreciated by the geological community. How could MacKin's (1950) claim that down-plunge projection was powerful enough to instantly solve geological problems that were unsolved by two generations of geological mapping? This seems like a preposterous claim as the down-plunge projection technique is a simple viewing methodology, whereas geological mapping, in comparison, involves a lot of time and carefully considered geological analysis. The following non-geological examples may convince those who are sceptical of MacKin's claim (1950).

The century-old down-plunge projection is in fact a more 'recent' application of 'perspectival anamorphosis'—a practice of using oblique views to make sense of distorted shapes and images. This technique was first used by early Renaissance artists in the fifteenth century; the first known anamorphic drawings were by Leonardo da Vinci (1452–1519) (Schwartz 1998). "The Ambassadors", a famous portrait painted in 1533 by German artist Hans Holbein the Younger (1498–1543), depicts an anamorphic image of a skull that can only be deciphered at a very low viewing angle (~2°) from the painting surface (Figure 2). The skull is virtually unrecognisable when the painting is viewed in the normal front-on view (Figure 2a). The low-angle viewing of this painting (Figure 2b), and accompanying realisation of the viewer who recognises that this is a skull, is analogous to viewing fold profiles that are plunging low-angle to the erosion surface and the geologist coming to the understanding of the true geometry of the folds only in that down-plunge view. Interestingly, this same technique is used currently in the design of advertising logos for television (Brown and Mayfield, 1999), which are painted distorted on sporting fields but are undistorted and appear to sit upright only when viewed 'down plunge' through television cameras (Figure 3A). Continuing in the footsteps of Renaissance artists, modern artists continue to use perspectival anamorphosis to create spectacular works of art which can only be understood from a very narrow vantage point, but chaotic and incomprehensible in any other view (Figure 3B-D).

Figure 2. a) Hans Holbein the Younger's painting *The Ambassadors* (located at the National Gallery, London) depicts an anamorphic image of a skull that can only be recognised as a skull at a very low viewing angle of 2° from the surface of the painting in the direction of the red arrow; b) an undistorted view of the skull viewed along the arrow in (a). Both images are in the public domain (Wikipedia contributors 2011a, 2012a).

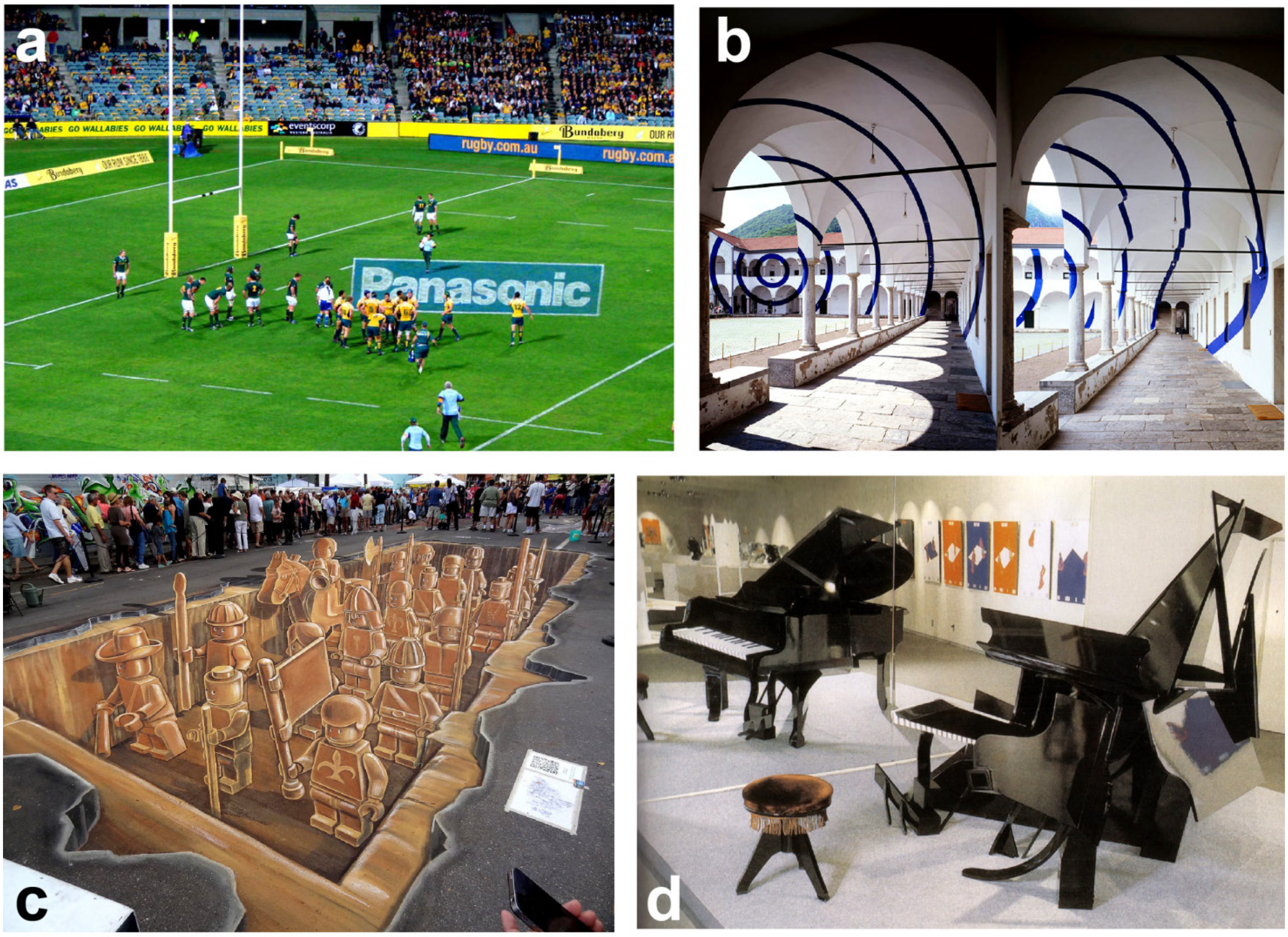

Figure 3. **Recent application of perspectival anamorphosis in advertising and in the arts. a) Anamorphic projection is used for a 'Panasonic' advertising logo at a rugby match so that it appears upright and undistorted from the viewpoint of the television audience. At any other viewing angle, the logo appears distorted (GrassAds Pty Ltd 2013); b) Felice Varini uses architecture and even entire villages as his 'canvas' for his large-scale paintings (Varini 2012). Varini's art makes sense from a particular vantage point, in this case revealing a 'bull's eye' ring pattern (left), but the paint marks make little geometrical sense from any other viewpoint (right) (from Slade 2013); c) Anamorphic chalk drawing on a road surface by artist Leon Keer viewed from the optimal vantage point (Wikipedia contributors 2011b; to see how this painting appears from other angles see Keer 2012); d) A sculpture by Shigeo Fukuda is a jumbled mess in the foreground, but the mirrored reflection provides an alternative view where it appears as an undistorted piano (Wikipedia contributors 2012b).**

As in the case of these anamorphic images and works of art, down-plunge projection reveals the most sensible image only at a specific, narrowly defined view line. The painting by Holbein (Figure 2), as well as modern application of the method (Figure 3), aptly illustrates how significant the down-plunge projection method can be; therefore, MacKin's following conclusion (1950, p. 58) should be taken seriously in the context of economic deposits:

'And if the purpose of the study of the district is economic, the grasp of the picture provided by the down-structure view may mean the difference between success and failure of the economic venture.'

This is a crucial statement that has as much relevance today as it had in 1950, particularly where there is evidence to suggest that practical application of this century-old method to analyse ore deposits has not been routinely applied by modern economic geologists[5]. Ironically, one of the rare discussion of ore

5 As at May 2013, a Google image search for "downplunge projection", "down plunge projection" "down-structure method" (in quotation marks) yielded no illustrations of ore deposits. A search using "down plunge projection" together with the word "ore" conducted using the online Monash University library search, resulted in no journal publications on ore deposits that have used this method for the analysis of mineralisation geometry.

deposits in the context of down-plunge projection was written by MacKin (1950). In the context of outlining modern geological interpretation techniques for the purposes of mineral resource estimation, MacKenzie and Wilson (2001, p. 113) advised geologists to not only interpret geological data in the traditional vertical section and plan views, but also make use of inclined sections to 'investigate trends and structures at optimal orientations'. This is the closest recommendation to that made by MacKin (1950) without specific reference to the down-plunge projection method.

With the advent of fast personal computers, the graphical display of the down-plunge projection view has become effortless (see Hansford and Collins [2007] who discuss this in the context of anamorphic images). Plotting of the projection on paper is no longer required as was the case for researchers in the 1970s and 1980s.

While the application of the down-plunge projection method to grade data to assist the structural interpretation of mineral deposits is entirely new, the projection must be relative to some geological feature seen in the mineralised pattern for this method to work. The direction in which we should be viewing is discussed in the context of structural symmetry.

STRUCTURAL SYMMETRY

Systematic studies of structural fabric analysis began with the work of Sander (1930) and was later expounded by researchers such as Knopf and Ingerson (1938), Patterson and Weiss (1961) and Turner and Weiss (1963). These early works were established on applying symmetry principles used in mineralogy to describe rock fabric relationships. Further work by structural researchers (eg Flinn 1962, 1965; Ramsay 1967) established that strain is a measureable quantity that can be inferred from rock fabric. These workers are a small sample of the large number of structural geologists from the last century who made great advances in the understanding of rock fabrics; their ideas have become the basis of modern structural analysis techniques. Much of the research work since has built on the key observations and concepts established by these pioneers of modern structural analysis more than 40 years ago.

The fabric of mineral deposits observed in grade distribution and symmetry reflects the structural state of the host rocks identified by these pioneering works. However, this should not be surprising if the assumption is true that grade distribution is controlled by structures through which hydrothermal fluids flow, and thus, by implication, the establishment of structural permeability during deformation plays a key role in the distribution of mineralisation in the deformed host rock (eg Cox, Etheridge and Wall 1987; Hobbs 1987).

Some representative structural symmetry systems observed in in real deposits are illustrated in Figure 4; the structural permeability created by these fabrics is interpreted to be the main control of grade distribution in this figure. The examples shown do not represent an exhaustive list and there would be limitless variations based on these basic geometries, combined with nested arrangements of these features at various scales. Therefore, it would be pointless to attempt to document, in Figure 4, the various permutations of structural geometries that could exist in nature. The objective of this paper is to describe a simple methodology for grade data interpretation; the ability to recognise structural features using the down-plunge projection method will depend on the structural geological experience of the geologist.

The most significant issue about the structural symmetry models illustrated in Figure 4 is not their differences, but their commonality. The strain states vary from brittle to ductile, and the degree of strain varies, but almost all symmetry systems illustrated (except Figure 4a, which does not possess any discernible linear fabric), have a common lineation feature that may persist across the entire deposit (Figures 4b to 4h), and, in the triclinic symmetry system[6], multiple localised linear orientations (Figure 4i). The first-order lineation (Figures 4b to 4h) is a feature either formed from an intersection of planar features or as the result of linear extension; the differences can only be distinguished by conducting field work and from independent geological observations. Such broad linear patterns of structural continuity that influence mineralisation were described by Laing (2005), although Laing used traditional structural analytical methods to determine this linear axis, whereas in this paper, grade data are primarily used to determine this orientation.

The quickest way to determine structural symmetry is to examine grade distribution at the deposit-scale

[6] Defined by three vectors that are not mutually orthogonal and of unequal length. Such symmetry results only in localised lineation orientations.

(Figures 4b to 4h), or identify local grade continuities for deposits with strongly triclinic symmetries (Figure 4i). The method discussed in the next section uses a key feature that is present in many mineral deposits—first-order grade lineation.

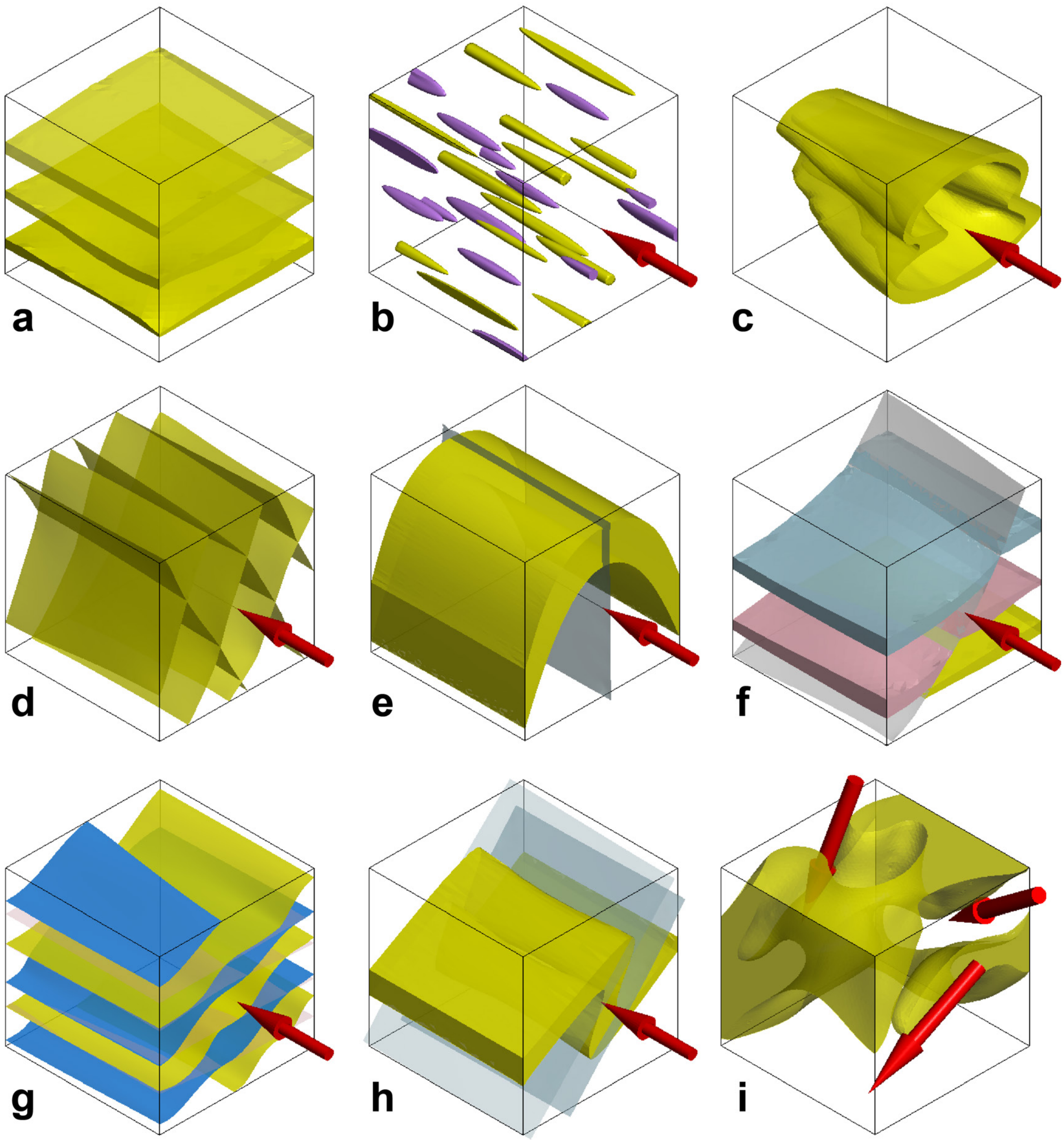

Figure 4. A selection of fabric symmetries of geological structures: a) bedding fabric representing axial symmetry, but linear axis is absent; b) pure linear fabric with axial symmetry; c) sheath fold with extreme stretch representing orthorhombic symmetry; d) conjugate fault system with orthorhombic symmetry; e) upright fold with orthorhombic symmetry; f) faulted bedded fabric with monoclinic symmetry; g) C-S fabric with monoclinic symmetry; h) overturned folding with monoclinic symmetry; i) multi-phase folding with triclinic symmetry. All examples except (a) and (i) display a first-order linear fabric (of either elongation or intersection lineation) that can be used for down-plunge projection. In (a) linear fabric is absent, and in triclinic fabric (i) there may be local linear axes as indicated by the arrows.

MAXIMUM INTENSITY PROJECTION (MIP)

The fabric of grade data can be determined simply by viewing the raw grade data, often at the entire deposit-scale, and assisted with a computer rendering method called Maximum Intensity Projection or MIP (see Wikipedia Contributors 2013, which has a useful rotating MIP image). MIP was originally called 'Maximum Activity Projection' by its inventors Wallis et al (1989).

MIP is a quick and very simple computer rendering method originally used in medicine to analyse 3D voxel datasets of computed tomography (CT) data. It was used long before the availability of computers capable of applying relatively more graphic-intensive 3D rendering methods (eg Fishman et al 2006; Röber 2000). MIP works by projecting 3D voxel values along a ray orthogonal to the monitor plane, with the points with the highest value along the line taking precedence for display over lower values that lie along the same ray. The highest value along the ray is then displayed on the monitor as a 2D image. Effectively, this display method is a simple 2D projection technique, just like shining a light onto a 3D object to cast a 2D shadow on the wall. As an additional feature, MIP incorporates the scalar values assigned to each point with the projection so it works like an X-ray image, where the highest grade points are more prominent than the surrounding lower grade values; thus, spatial changes in grade values can be detected in the projected view. Although MIP was originally used in the analysis of full 3D CT data, the author has applied this method on hundreds of mineral deposits of all types and has shown that this technique is very effective for the analysis of both sparse and dense drill hole data (Figure 5).

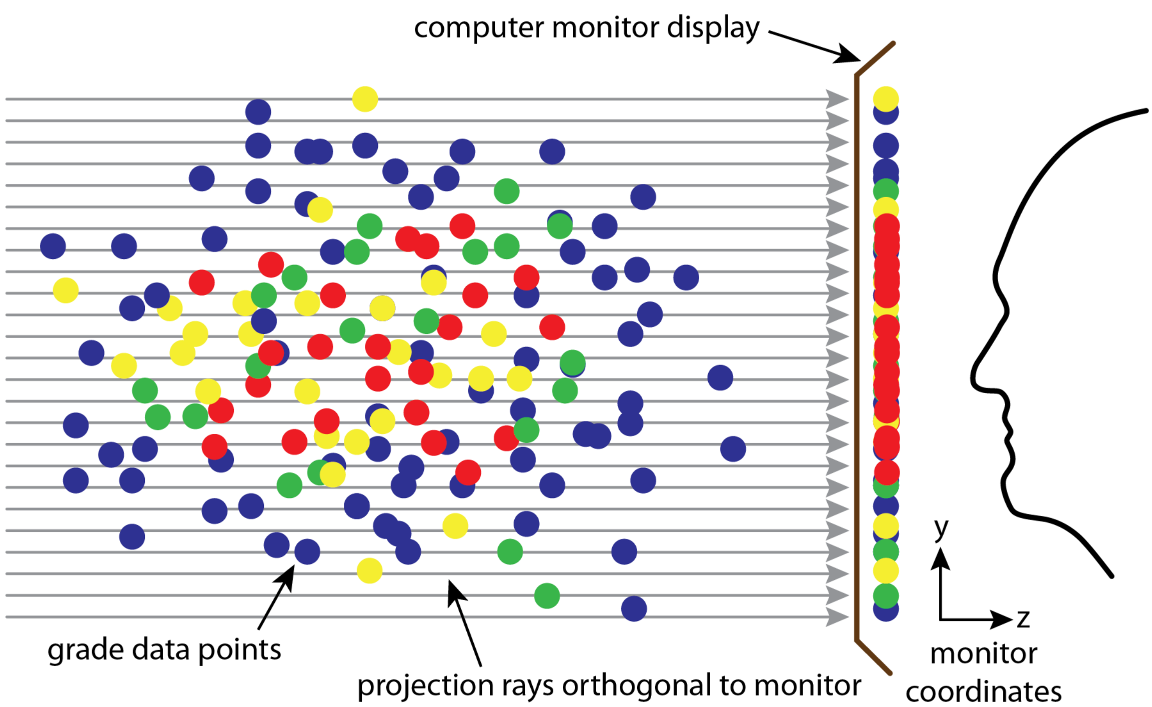

Figure 5. Schematic cross-sectional view of a computer monitor showing how maximum intensity projection (MIP) works with grade point data. The highest grade point values from the cloud of grade data are projected to the front of the computer monitor along a path orthogonal to the monitor (ie parallel to the z-axis of the monitor coordinates).

Instead of working with drill hole interval data, the author has found that desurveyed mid-point data (expressed as x,y,z,grade) is best suited for the effective interpretation of data (Figure 5). Visualising a volume dataset can be achieved by simply increasing the point size of the assay points so that gaps between the points are filled in, thus producing simulated 3D volume data. This allows an almost 3D volume MIP analysis of drill hole data to be conducted just by using the 'z index' ordering capability in Open Graphics

Library[7]. The ‘z’ in the ‘z index’ refers to the computer monitor coordinate axis orthogonal to the computer screen, in which objects that are located far from the viewer are ‘mapped’ behind objects that are close to the viewer. The default 3D rendering of grade point data using the z index would render the closest points (low values of z) in front of points that are further away (high values of z). In most mineralised systems, the high grades are surrounded by low grades, so the default is to render the lower grades in front of the high grades, thus masking the high-grade core. However, if the z index is ordered according to the grade values rather than the distance away from the observer, then the highest grade points are always rendered in front of lower grade points, thus creating an X-ray effect, which lets the geologist view through the low grades to the high-grade core of the mineralisation (Figure 5). The 3D positions of high-grade points relative to the lower grade envelope can be quickly assessed by rotating the MIP-rendered grade dataset on a computer monitor. The major advantage of MIP is that it requires very little computer graphical processing power; therefore, it is easy to program this display method into any mining software product currently available[8].

Combining the MIP method of data display with physical rotation of the data into down-plunge view (cf. MacKin, 1950) allows the geologist to quickly determine the linear grade alignment in sparse assays sampled with drill holes. The informal term introduced in this paper to describe this analytical method is ‘X-ray plunge projection’. Using X-ray plunge projection, a geologist with structural analytical experience can rapidly identify the structural geometries of mineral deposits, often within minutes of viewing the data. Such rapid and accurate geological interpretations are not possible with relatively more complex and expensive 3D modelling methods, including both explicit and implicit modelling methods (cf. Cowan et al 2003). However, when combined with implicit modelling, the use of X-ray plunge projection can result in very accurate geological models for resource evaluation purposes.

[7] or ‘OpenGL’ is a cross-language, multi-platform application programming interface for rendering 2D and 3D computer graphics.

[8] As at May 2013, MIP is only available commercially in Leapfrog software, where this switch is called ‘enhance high values’.

Geostatistical rationale for the use of MIP-assisted X-ray plunge projection

In resource evaluation, mineral deposits are subdivided into volumes in which each volume is characterised by approximately homogeneous grade, variance, and geometrical continuity. This volumetrically constant state is referred to as stationary behaviour of grade data (Isaaks and Srivastava 1989, Armstrong 1989). The grade continuity within these volume domains can then be summarised with an experimental variogram, which in turn can be generalised as a variogram model that quantifies the spatial correlation for grade interpolation.

In constructing an experimental variogram a line is taken through the data and the difference between two samples at a specified distance along this line is calculated, a third sample along this line at 2x the distance is selected and the difference to the first calculated and plotted on a graph of distance verses difference plot, this is repeated a specified number of times to complete the variogram, this process of defining a variogram model for each domain assumes that the grade behaves approximately in a rectilinear fashion. The condition of rectilinear grade continuity within a domain is an approximation of true natural grade continuity, but such an approximation has proven practical application in the estimation of grade distribution of mineral deposits. The largely rectilinear nature of grade continuity is the reason why X-ray plunge projection works in practice; therefore, X-ray plunge projection and variography should interact very well for the data analysis prior to resource estimation of mineral deposits.

An application of X-ray plunge projection

The synthetic data illustrated in Figure 6 was generated and used by the author as a teaching aid for 3D modelling and the application of X-ray plunge projection. The dataset of a fold-shaped ‘ore deposit’ was developed by first constructing a wireframe object that represents a cylindrical fold object with a finite thickness (Figure 6d), and the physical wireframe object was inserted into some drill holes. Points that fell into the object were attributed as +1 (ore) and all external points were attributed as -1 (waste); effectively, an indicator set of data that may represent two lithologies (ore and waste) can be prepared from any drill hole dataset. The objective of this exercise is to model the boundary between the ore and waste zones (ie isosurface=0) as quickly as possible. The geologists were not told that this was a fold geometry, just as they would not know what geometry they were modelling if they were using real drill hole data. The first task in the exercise is to determine the geometry of the ore body.

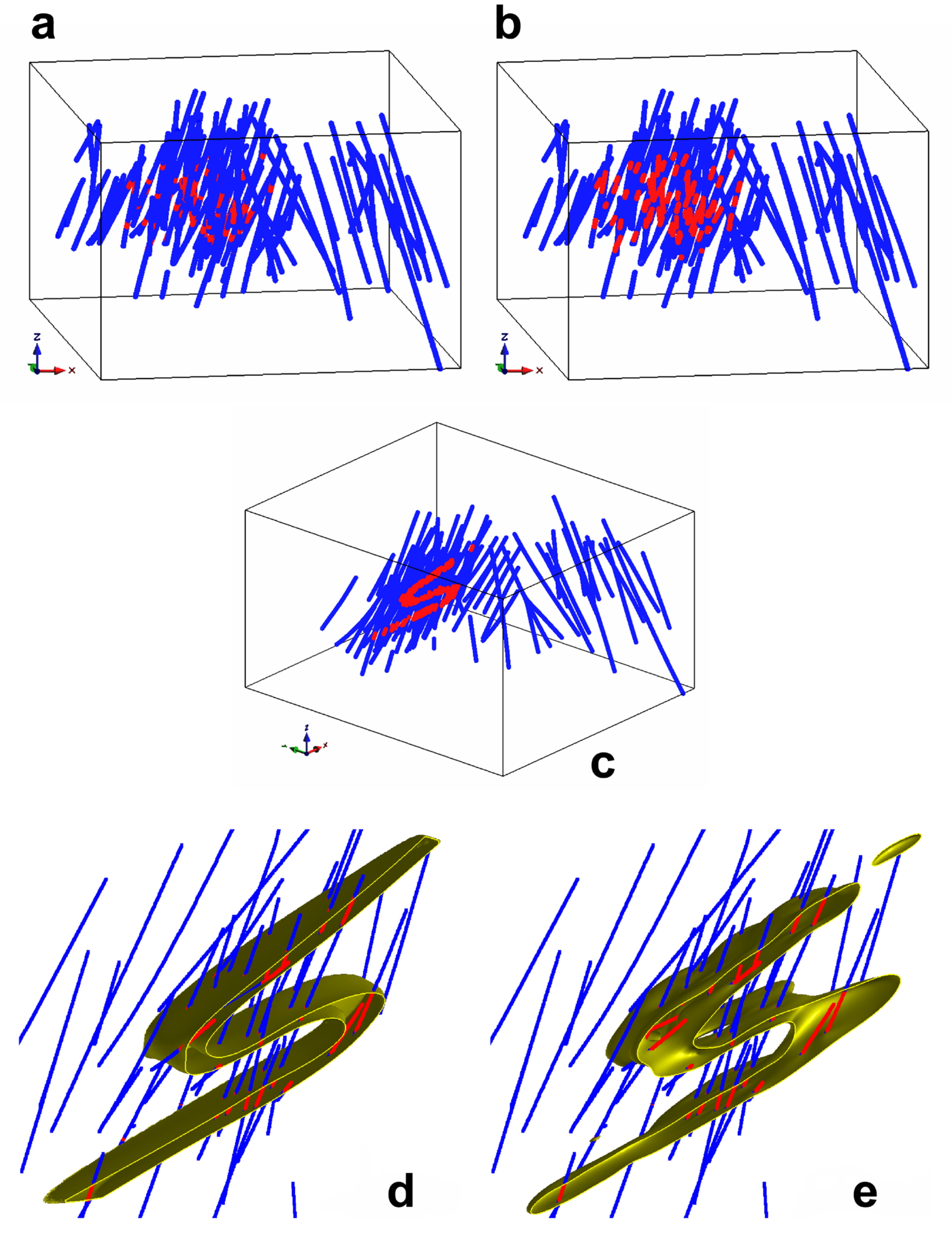

Figure 6. A synthetic grade dataset with 'ore' in red and 'waste' in blue: a) low grades surround the high grade so the geometry of the ore cannot be deciphered easily; b) MIP on an arbitrary viewing direction yields nothing that is geologically sensible; c) only the down-plunge orientation reveals a fold profile; d) original fold-shaped mesh object used to create the data; e) ore boundary is modelled using implicit modelling software without the need for digitisation.

The 'ore' intervals are hidden behind the 'waste' data (Figure 6a), but the high-grade values project to the foreground when MIP is switched on (Figure 6b). At an arbitrary orientation the MIP rendering on the monitor makes little geological sense (Figure 6b), but along a certain orientation a fold profile view is revealed (Figure 6c). This orientation can be found by turning on the MIP and then rotating this data in space until a distinctive fold profile pattern emerges in the monitor. Although the MIP view is 2D, the primary 3D point dataset can be rotated and that the X-ray view will be progressively displayed at all orientations. There is only a very narrow orientation range where the fold pattern emerges using MIP; this is the fold plunge direction and is also the most continuous direction of the 'ore' body. This orientation is the X-ray plunge projection line.

This exercise illustrated in Figure 6 has been repeated by hundreds of geologists with wide range of experience since 2003 during geological modelling training sessions by the author, and every time the down-plunge orientation was replicated by all geologists to within a cone of approximately 5°. The visually estimated principal directions of the grade distribution are then used to guide implicit modelling, which can be accomplished rapidly and accurately; similar models can be generated by many geologists without resorting to time-consuming and inaccurate sectional digitisation (Figure 6e). For this exercise, a typical implicit modelling process assisted by X-ray plunge projection takes minutes. Furthermore, because the axis of the fold is identified and because this orientation can be replicated accurately by many geologists, the resulting models of the fold are virtually identical to each other. Thus the speed of modelling and the reproducibility of the geological model by multiple geologists is improved. A hand-digitised model which has been meticulously constructed from one section to another using traditional explicit methods, cannot replicate the accuracy of the model illustrated in Figure 6e.

Conversely, the blind use of implicit modelling methods without structural geological context is not encouraged; this approach will only yield the incorrect answer more quickly than traditional sectional digitisation. Sensible results cannot be expected from using implicit modelling as a geological modelling tool if implicit modelling is left to default isotropic processing parameters. A blind, 'black-box' approach to isotropic implicit data modelling is severely limited as it will not necessarily reveal structural geometry, even from a perfectly manufactured dataset (eg Figure 6). In this respect, traditional methods of sectional digitisation conducted in sections orthogonal to the principal axes of the object, will yield better results if used in conjunction with X-ray plunge projection than a blind implicit modelling approach that ignores structural geometry.

The key to using X-ray plunge projection on real data is understanding the structural geological patterns of the grade data as revealed by MIP; it is wrong to assume that implicit modelling alone will help the geologist understand the geology any better (Barnes and Gossage, 2014). A sound approach is for the geologist to understand the geology using MIP before beginning the modelling process.

STRUCTURAL PATTERNS OF REAL DEPOSITS

Grade control data

Closely-spaced grade control data are ideal for practising X-ray plunge projection. Grade control data in Figure 7 are from a gold deposit that is hosted within a fold hinge. The traditional vertical section and longitudinal views (Figure 7a and b respectively) even with MIP do not reveal clear structural controls of the mineralisation. This is despite the fact that the plunge of this deposit is low at around 28° so the vertical section (Figure 7a) is very close to being orthogonal to the plunge of the fold axis.

By loading the grade control data into the viewer and using MIP, the fold axial trend can be quickly established; the fold profile view is shown in Figure 7c. The plunge-orthogonal view, or the profile plane of the fold, reveals the structural controls of this deposit within the fold hinge (Figure 7d). Grade distribution orthogonal to the grade lineation is clearly partitioned and controlled by bedding anisotropy, the axial planar faulting, and structural permeability produced by other non-axial planar faults that contain the fold axis, such as faults that propagate from fold limbs and cross-cut the axial plane.

All of the intersecting structural fabrics shown can result in a complex pattern, especially when viewed in plan. However, when viewed in the true fold profile plane, the patterns make sense geologically (Figure 7c, d). The intersecting planar anisotropies form a structural permeability zone that is effectively linear in continuity (Figure 7b) and reflects the grade distribution in the fold hinge. Although this pattern can be understood with relative ease when dense grade control data is analysed by X-ray plunge projection, the geologist's structural geological skills are essential to interpret sparse exploration data.

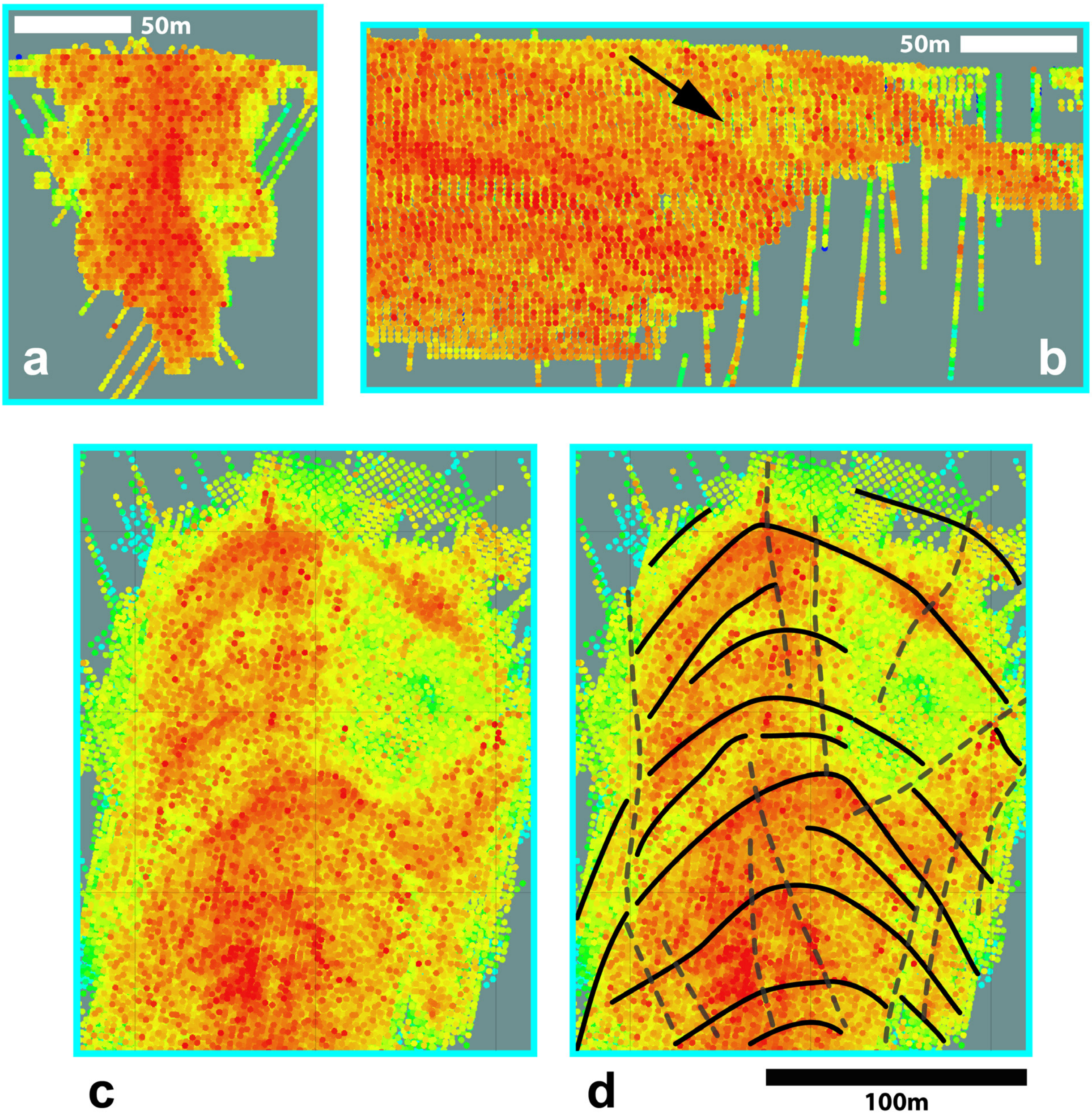

Figure 7. Grade control data from a plunging anticlinal fold hinge with an average plunge of 28°. All images of grade interval mid-points are shown with MIP rendering: a) traditional vertical section view reveals some intersecting patterns of grade continuity, but patterns are not clear; b) the longitudinal section reveals the plunge of grade continuity indicated by the arrow; c) viewing down-plunge, parallel to the arrow shown in (b); d) interpreted bedding (solid black lines) and fault (dashed grey lines). The grade lineation (seen in b) is the result of intersecting bedding and faults developed in the fold hinge, but this structural relationship can only be seen in the very narrow view-line parallel to the plunge of the fold (c, d).

Exploration data

Eleven real deposits of various commodities are shown in Figure 8. All sections are orthogonal to the longest axis of the mineralisation continuity identified by X-ray plunge projection, and all are views of the entire deposit. With the exception of Figures 8e and 8g, which are mixtures of exploration and grade control data, all other data represent exploration drilling. The following structural controls can be seen in the grade data. Figures 8a and 8b are orthorhombic fault-controlled mineralisation with the highest grades occurring along the fault intersections (refer to Figure 4d); Figure 8c is bedding cross-cut by normal faults, with a linear grade continuity at the bedding and fault intersections (Figure 4f); Figures 8d to 8i are orthorhombic as well as monoclinic fold systems with largely fold-axis parallel mineralisation (Figures 4e and 4h); Figure 8j represents a monoclinic C-S fabric (cf. Berthé et al 1979) at the deposit-scale with the grade continuity parallel to foliation (S) and the C-S intersection (Figure 4g); Figure 8k shows sheath folds with the grade continuity parallel to the extreme extension lineation (Figure 4c).

The examples in Figure 8 illustrate the power of using the X-ray plunge projection method to identify the first-order structural details. They also highlight that the structural controls can be established early for virtually any deposit using grade data alone without the need for interpolation of grade using implicit modelling software or extensive sectional digitisation.

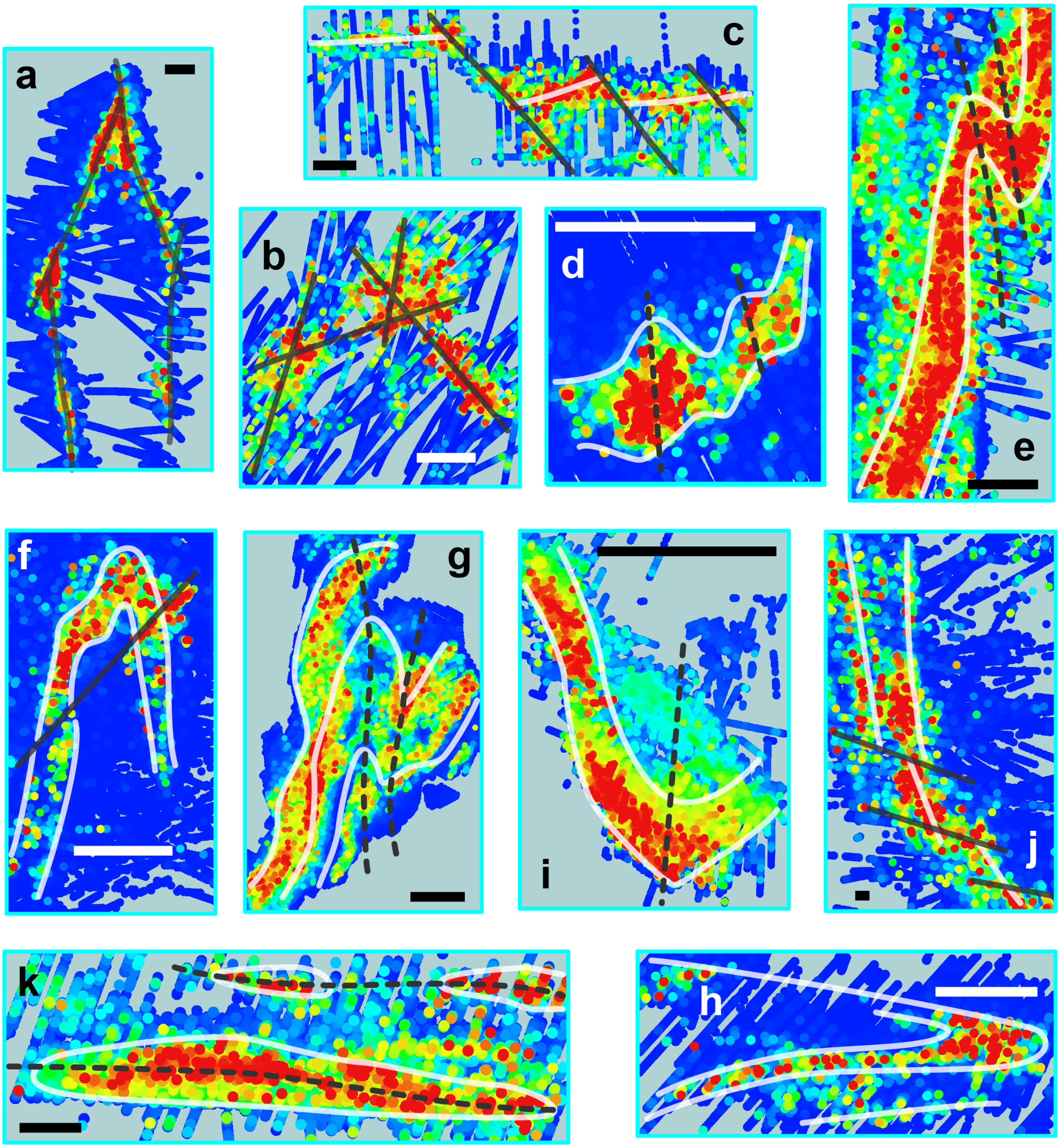

Figure 8. Structural interpretations of the plunge-orthogonal MIP grade renderings of a wide range of commodities. Dark grey lines are faults; white lines are traces of bedding or foliation; dashed black lines are traces of axial planes. Scale bars are all 100 m and views are at or near entire deposit scale.

Testing deposit-scale hypotheses with field work

It is important to ground-truth and test the various hypotheses generated from the interpretation of X-ray plunge projection views. First the structural controls are accurately estimated from the first-order scale, using grade distribution as the primary source of structural information. Once structural hypotheses are established to explain the grade distribution, the collection of traditional structural data follows in the field. Field investigation is focussed on areas in the model that are likely to provide key information to test the alternative models, rather than the traditional exhaustive collection and analysis of structural data. This is referred to as an 'outside-in' approach to structural geological analysis (as opposed to traditional 'inside-out'), because the extrapolation of structural analysis is from the first-order deposit-scale to the field-scale (or bench-scale or stope-scale), rather than the other way around. There are several advantages of using this 'outside-in' method of structural analysis of drill hole assay data, including:

- The much shorter timeframe to produce the model.
- The close correspondence with the aims of resource evaluation. (That is, the resource geologist is interested primarily in the geometry and shape of the grade envelope and the expected internal distribution of grade and controls—both aspects can be addressed with this combined X-ray plunge projection and field analysis approach)
- The multi-hypothesis approach that is testable, as structural prediction is made using one variable (grade distribution) and predicts patterns in another independent set of variables at a different scale (structural patterns in the field).

DISCUSSION

Structural geology as the framework for interpretation

Geologists generally accept that tectonic processes — in one form or another—are responsible for the formation of nearly all mineral deposits on Earth. If almost all deposits are structurally controlled or modified in some way, then it is logical to expect that structural features should be observable from the grade distribution patterns of mineral deposits. However, history shows that fundamental structural geological concepts and analytical techniques developed over the last century have not played a central role in the understanding of the geometry and fabric of mineral deposits. Although the economic geology literature is replete with ore genesis models, there is little published evidence to suggest that the majority of these theoretical models have considered primary deposit geometry and structural fabric information in the formulation of those models (Cowan 2012, 2013). This can be judged from skimming through most economic geology journal articles. In fact, one of the most evident examples portraying a lack of geometric detail of ore deposits is the Society of Economic Geologist's One Hundredth Anniversary Volume (Hedenquist et al. 2005). Most genetic ore deposit models in this volume are shown as schematic diagrams with little real data to substantiate the geometries discussed.

In the last 40 years, the majority of ore deposit research work had not adequately considered the true 3D geometry of deposits; this is a surprising oversight as many thousands of geologists around the world model deposits every day using 3D software, and they have done so since the 1980s. It would appear that little or no geometric or structural information is being fed back into academia to assist with refining the theoretical ore deposit models. Perhaps this reflects the section-by-section mechanical and non-geological approach to geological modelling prevalent in the minerals industry, rather than a desire to understand the geology of grade and lithological distributions in space. With the introduction of implicit modelling (Cowan et al 2003), geologists who previously digitised in drill hole section fences can now generate 3D models rapidly. However, the basic incorporation of 3D structural understanding into the geological modelling process has not changed and remains virtually non-existent a decade after implicit modelling was introduced.

The traditional process of sectional digitisation are slowly being replaced by implicit modelling, and it is only a matter of time before implicit modelling becomes an industry 'best practice' for geological modelling. Currently, the blind mechanical or 'algorithmic' approach to modelling remains popular with many implicit modellers. Ironically, with it comes the increased risk of generating misinterpretations at much faster rate than with sectional digitisation. Added to this new environment where fast modelling is possible, generating multiple geological models or interpretations is becoming popular in current practice, which is purported to reduce mining and exploration risk (eg Jackson et al 2003, Srivastava 2005). However, there is no sense in generating multiple model realisations devoid of structural geological understanding, when most mineral deposits are structurally controlled or modified. With structural understanding, a single model that incorporates structural knowledge by the application of X-ray plunge projection analysis is likely to reduce uncertainty, compared to multiple models that are completely devoid of first-order structural understanding of the deposit. There also is simply no shortcut to the modelling process other than a solid education in structural geology, irrespective of the claims of marketing material of software vendors.

The MIP-assisted plunge projection method can be applied to most deposits regardless of commodity and structural style. Some deposits may require domaining of the weathered profile from the fresh rock lithologies, but the author's experience is that many grade distributions altered by surficial processes still reflect the primary structural controls in the grade (eg Standing 2012).

Determining the deposit-scale structural controls is the single most important step in the understanding of the deposit, and in turn provides a solid framework for the modelling process.

Structural geology experience is essential

Experience in 3D geological modelling is not required to successfully apply the X-ray plunge projection strategy described in this paper. However, geologists or non-geologists who may have extensive experience in software-based 3D modelling or resource estimation, but who have little or no structural geological field experience, cannot be expected to be able to reasonably interpret structural details from grade distributions if they have not seen them before.

It cannot be stressed enough that the prerequisite for a successful 'outside-in' approach to structural geological analysis, as outlined in this paper, is that the geologist is trained in advanced levels of structural geology as well as being competent with structural mapping, preferably with experience in mapping multiply deformed terrains. Without this training and experience, the expected structural features and alteration patterns seen at various scales in grade data, ranging from brittle to ductile (Figures 3 and 7), cannot readily be identified or understood in the context of paragenetic history by the geologist. The techniques discussed in this paper are not black-box methods, but are based on well-established methods of structural analysis developed over the last century (eg Sander 1930, MacKin 1950, Flinn 1962, Ramsay 1967). These methods are merely transferred from their traditional field application to the interpretation of drill hole grade data. While computer software and hardware replaces tools like the compass and map for the geologist to conduct structural analysis at the deposit scale, the skills of the interpreter originate from good field geology practices and not from skills that are gained from computer-based modelling.

MODELLING MINERAL DEPOSITS — A THREE-TIERED PUZZLE

The methodology introduced in this paper effectively represents a three-tiered puzzle. That is, an interpretation of grade data from a mineralised system is a puzzle within a puzzle within a puzzle, and the three 'puzzle levels' are:

1. Identification of the appropriate direction of view using MIP or 'X-ray' view. In many deposits there is effectively only a single view direction which makes geometric sense for the grade data, so this is the first level of the puzzle. There is potential to automate this step; however, in sparsely drilled prospects, or in cases where there are many plunge directions (Figure 4i), the judgement comes down to human experience at identifying patterns as a result of seeing many datasets from all types of deposits.

2. The second level of the puzzle is to comprehend the MIP patterns seen in the down-plunge projection view. Practical field and theoretical experience in structural geology is essential for an accurate geological assessment.

3. The last puzzle level is the approach to geological modelling. Although this step is not discussed in this paper, the effective use of information identified at Level 2 above is key to enable accurate geological modelling necessary for resource evaluation. Implicit modelling is favoured, because it saves time and improves precision, but as long as the first two levels are solved, traditional explicit modelling methods can also be used.

Solving each puzzle level in sequence can ultimately unlock the most accurate interpretation and geometry of mineral deposits. Importantly, each step can only be achieved armed with the appropriate knowledge and skills outlined above.

However, most deposit analysis stumbles at Level 1 and goes off on a tangent simply because the view orientation to conduct the geological interpretation is inappropriate. Typically, this is because the geologist used traditional sectional interpretation methodology, which is currently the most popular method of geological interpretation; however, the author does not believe that this technique is beneficial as the plunge direction of mineral deposits has no relationship to the drill hole fence line orientation (Barnes and Gossage, 2014). The Canadian Institute of Mining, Metallurgy and Petroleum Guide to Geological Modelling (CIM, 2003) appears to have recognised this issue, and the guidelines for interpretations made in 3D software stop short of recommending that geologists conduct 2D interpretations in traditional sections and plan views. Instead, CIM's recommendation is for geologists to validate the interpreted models 'on plan and orthogonal section to evaluate the reliability of the geological interpretation'. Because sectionally digitised interpretations have proliferated in the industry, this recommendation is a bold move by the CIM, but it is consistent with the findings of this paper and is an example of modern geological best practice.

Another recent trend to modelling mineral deposits is that of trying to solve Level 3 of the puzzle without first questioning or solving the previous levels, which are essential for effective and accurate geological modelling. Unfortunately, this approach is how workflows of some implicit modelling software packages are designed today. This data-centric modelling workflow, then followed by interpretation depends entirely on meaningful patterns 'falling out' of the data, which in most cases does not occur unless the data are very densely sampled. Companies who rely on such software workflows will fail to extract maximum benefit from their data, and may also be unknowingly introducing interpretation uncertainty into their resource evaluation process. In contrast to slow sectional digitisation, modern implicit methods of geological modelling allow any number of very precise geological models to be constructed from drill hole and mapped data. This capability is both a blessing and a curse, as all models will perfectly honour the drill hole data and can be created very rapidly even by a software user who may not have the appropriate education in geology. Any number of these models will look "real" as they honour the data, but in reality can be all geologically inaccurate, and this is unfortunately the expected consequence of skipping straight to solving Level 3 of the puzzle.

CONCLUSIONS

Virtually all mineral deposits are emplaced during the formation of structural permeability or have been altered in geometry during deformation, yet curiously, structural geology remains an underappreciated subdiscipline in economic geology. Generally, geologists who model geology for resource evaluation purposes do not consult structural geologists for modelling tasks or advice, or study structural geology literature. Yet the author's research and practical experience, some of which is outlined in this paper, shows that understanding the structural geology will place any mineral deposit in a geologically logical framework for mining and near-mine exploration success. With this modernised version of down-plunge projection, it is now possible to expose a wealth of information that can immediately benefit any open pit and underground mining operation that has grade control datasets gathering dust in their archives. The knowledge gained from such an exercise can then be extrapolated to intelligent interpretation of relatively less dense grade data from exploration drilling. First-order structural geological understanding should form a core of knowledge to guide not only geological modelling, but also form a framework for variography and resource estimation (Laing 2005).

The emphasis on structural geology creates challenges. Anecdotally, the author is aware that very few geologists are versed in structural geology. It is estimated that 50% of the time, or more, drill core orientation and the quality of data are suspected to contain errors or mistakes (Holcomb 2013; Davis 2013, 2014), and the author believes that this reflects the general state of the minerals industry not caring about structural geological issues. By contrast, a 50% failure rate would not be tolerated for the quality assurance/quality control of assay data. Although technologies such as the down-hole televiewer are likely to replace manual structural core logging in some suitable operations (eg Gradim et al 2014), the collection of high-quality structural data will still require interpretation and formulation of a sensible geological understanding of any deposit. While traditional methods have relied on the 'inside-out' method of structural geological investigation, it is possible to obtain the structural context at the deposit scale and work from the 'outside-in', resulting in a much more cost-effective and more accurate method of geological interpretation that can be used for both mineral resource evaluation and exploration.

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The idea that structural geology should be a key component of first-order scale interpretation of mineral deposits, and form a cornerstone for geological modelling, began when the author joined SRK Consulting as a structural geological consultant in 1999. The combination of rapid 3D interpolation with structural geological practice was formulated by the author and this led to the author contacting ARANZ in April 2001 as a result of a Google search. The author led the design and marketing of Leapfrog® software from 2001 to 2007 as General Manager of Zaparo Ltd, a joint venture company between SRK Consulting Australia and ARANZ. ARANZ programmers developed Leapfrog® under the direction of Dr Hughan J Ross, the then Chief Software Architect of Leapfrog®. Careful consideration was made so that a structural geological framework for modelling, as outlined in this paper, was implemented in the design of Leapfrog® and Hughan was instrumental in understanding and incorporating the structural geological techniques to Leapfrog® and making the tools workable. Hughan is thanked for being a good listener, and for reaching significant developmental milestones for Leapfrog® software with me; one of which was the incorporation of MIP rendering in Leapfrog® (now marketed as Leapfrog® Mining), which to this day is an industry first. Dr Peter Williams, the former Managing Director of SRK Consulting, and Mr Jim Turpin, former Business Manager of Leapfrog® at ARANZ, are both thanked for their tireless support during the development of Leapfrog® from 2001 through 2007. Ian Mayfield is thanked for providing permission to use the Rugby Union image from the GrassAds website, and a copy of the relevant patent.

The concepts summarised in this paper were formulated by the author independently of ARANZ. The use of X-ray plunge projection as a practical structural geological tool is previously unpublished and, as at August 2013, the workflows presented here are not incorporated in any known commercial software workflow.

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