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Structural Modeling in 2D and 3D and with Time (4D) for Mineral Exploration and Mine Development

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Structures play a significant role in mineral systems by contributing to the plumbing system, the underlying connected network of fluid pathways. They contribute to both the system charge, i.e., the transport and focussing of mineral-bearing fluids from a (upper mantle) source, up through the crust, as well as contributing to the trap by creating space as well as impermeability with favourable trapping geometry. Less favoured are postmineralization structures that displace part of a mineralized volume. Hence, for optimal exploration and mine development, it is essential to have both a valid interpretation of the present-day structural framework as well as an understanding of how that framework changed shape through time with respect to the timing of mineralization.

Structural interpretation benefits from identifying the appropriate structural style(s). Comparing a limited data set with known, theoretical structural models and kinematic concepts helps to recognise patterns, structural hierarchy, and identifying options (and alternatives) for the dominant structural style(s) in areas without direct observations (yet). Where geologic histories are long and complex, this is not always trivial. In some cases it helps to restore the effects of one deformation phase to see through to a geometry at an earlier moment in time.

Complications at a range of scales may hinder interpretation. At deposit scale there is the mechanical stratigraphy—the relative strength of the various (stratigraphic) units, which dictates the amount and level(s) of detachment. Detachments have a direct effect on structural style, both in extension and shortening. At regional scale, complications are caused by older, inherited, weaknesses in underlying rocks that—when reactivated (particularly within a different regional stress field)—may lead to complex structures in overlying younger rocks, causing lateral breaks in structural trends. Of course Sod's law has it that these locations are often favourable for mineralization. Complexities at both scales obstruct predictability and interpretation in between and away from individual data points.

Interpretation uncertainty can be mitigated by both 2D, but especially 3D, seismic reflection data. Seismic can help constrain the structural framework geometry at the level of the deposit and deeper, beyond drill hole control. Acquisition and processing of seismic data in hard-rock terrain is not trivial (steep dips, high and heterogeneous velocities) and must be carefully designed and tailored to optimise results, particularly for the imaging of steep structures, but is done successfully.

The structural model can be further improved by digital kinematic analysis. This starts by restoring the effects of deformation to see if things fit back together to test for internal consistency (balancing), which then allows quantifying palaeogeometry by taking models back in geologic time step-by-step, restoring the effects of folding and faulting, (igneous) intrusion, sedimentation, and erosion. Individual structures and their role in the mineral system through time can be tested, quantified, and better understood. This helps reduce operational risks, both for minerals (brownfield) exploration and geotechnical aspects.

A number of examples will illustrate the usefulness of 2D, 3D, and 4D structural models.

The structural modelling challenge: Meaningfully ‘connect the dots’ with limited data