3D Geological Modelling Conference

Current 3D geological modelling practices and R&D in the mining/exploration industries, government organisations and academia

Abstracts Volume

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Conference theme: Discuss the current practices in 3D geological modelling in the mining/exploration industries, government organisations and academia at all scales: applications, current state of the art, challenges, latest and future advances. The conference is organised by the Loop3D foundation and we encourage attendance and presentations from everyone.

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AN INTEGRATED FAIR MODELLING APPROACH TO MAP AUSTRALIA'S SUBSURFACE

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To reach Australia's net zero emissions targets by 2050, the growing demand for base and precious metals necessitates a comprehensive knowledge of the subsurface geology to support increased resource exploration and manage competing land uses effectively and responsibly. Despite the abundance of subsurface data commonly used to build regional 3D geological models, inconsistencies in distribution, quality, and format hinder the creation of uniform national subsurface models.

Through the Australian Government's landmark investment of $3.4 billion over 35 years (2024-2059), the Resourcing Australia's Prosperity initiative will deliver accelerated and enhanced precompetitive geoscience, data analysis and decision support tools to enable an improved characterization of the geological properties and architecture of the subsurface.

Building on the success of the Australian Government-funded Exploring for the Future program (2016-2024) which delivered world-leading public geoscience products and tools, we introduce an open-source subsurface modelling methodology that provides the ability to generate an updatable seamless national chronostratigraphic framework at continental scale (Figure1, Bonnardot et al., 2024). This methodology, aligned with the FAIR (Findable, Accessible, Interoperable, and Reusable) principles, facilitates the assessment of the i) depth and spatial extent of prospective rocks for minerals or energy, ii) depth to aquifers and iii) depth to potential geological storage to inform resource exploration and development decisions.

Based on precompetitive geoscience data, approximately 26% of Australia's subsurface has been mapped through regional models, detailing the depth and thickness of key stratigraphic sequences, including the Cenozoic, Mesozoic, Paleozoic, and Neoproterozoic eras (Figure 2). Combined with Australia's layered geology map (Sanchez et al., 2024), this work lays the foundation for an integrated geological framework that supports data-driven decision-making for decarbonization strategies, land-use management, exploration strategies, and water management.

Bonnardot M.-A., Wilford, J., Rollet, N., Moushall, B., Czarnota, K., Wong, S.C.T. and Nicoll, M.G.2020. Mapping the cover in northern Australia: towards a unified national 3D geological model. Exploring for the Future Extended Abstracts. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/134507

Bonnardot, M.-A., Grose, L., Wilford, J., Du, Z., Hope, J., Wong, S. C. T., Vizy, J. and Rollet, N. 2024. Unearthing Australia's subsurface secrets - An integrated FAIR modelling approach. Exploring for the Future Extended Abstracts, Geoscience Australia, Canberra. https://dx.doi.org/10.26186/149719.

Geoscience Australia and Australian Stratigraphy Commission, 2024. Australian Stratigraphic Units Database. http://www.ga.gov.au/data-pubs/datastandards/stratigraphic-units

Geoscience Australia, 2024. Geophysical Archive Data Delivery System. https://portal.ga.gov.au/persona/gadds

Geoscience Australia, 2021. Borehole Database (BOREHOLE). https://dx.doi.org/10.26186/126310

Mathews E.J., Czarnota, K., Meixner, A.J., Bonnardot, M.-A., Curtis, C., Wilford, J., Nicoll, M.G., Wong, S.C.T., Thorose, M. and Ley-Cooper, Y.2020. Put all your data "eggs" in one basket: development of the Estimates of Geological and Geophysical Surfaces (EGGS) database. Exploring for the Future Extended Abstracts. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/132526

Raymond O.L., Liu S., Gallagher R., Zhang W. & Highet L.M., 2012. Surface Geology of Australia 1:1 million scale dataset 2012 edition. Geoscience Australia, Canberra. http://pid.geoscience.gov.au/dataset/ga/74619

Sanchez, G., Liu, S., Stewart, A.J., Bonnardot, M.A., Beyer, E.E., Czarnota, K., Highet, L.M., Woods, M., Brown, C.E., Clark, A., Connors, K., Wong, S., Cloutier, J. 2024. World first continental layered geological map of Australia. Exploring for the Future Extended Abstracts,Geoscience Australia,Canberra. https://dx.doi.org/10.26186/149391

Vizy J. & Rollet N. 2024. Australian Borehole Stratigraphic Units Compilation (ABSUC) 2024 Version 2.0. Geoscience Australia, Canberra. https://dx.doi.org/10.26186/149324

Wilford J., et al., 2020. Uncover-ML – A machine learning pipeline for geoscience analysis. Exploring for the Future Extended Abstracts. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/134466.

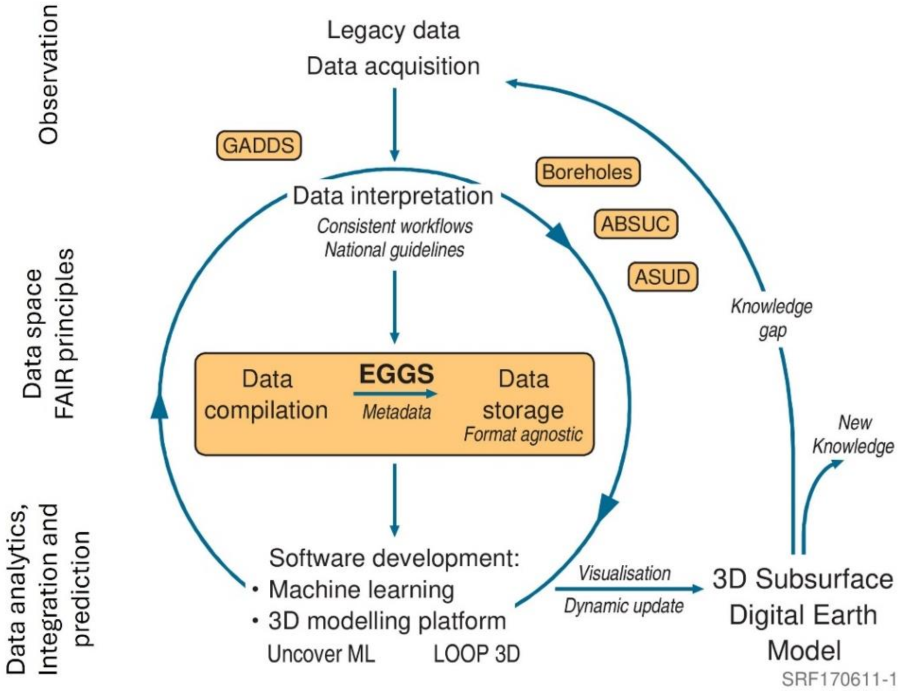

Figure 1. 3D subsurface modelling workflow. GADDS: Geophysical Archive Data Delivery System (Geoscience Australia, 2020; 2024), ASUD: Australian Stratigraphy Units Database (Geoscience Australia and Australian Stratigraphy Commission, 2024); Boreholes (Geoscience Australia, 2021); ABSUC: Australian Borehole Stratigraphic Units Compilation (Vizy and Rollet, 2024); EGGS: Estimates of Geological and Geophysical Surfaces (Mathews et al., 2020); Uncover ML (Wilford et al., 2020); Loop 3D (https://loop3d.org/)

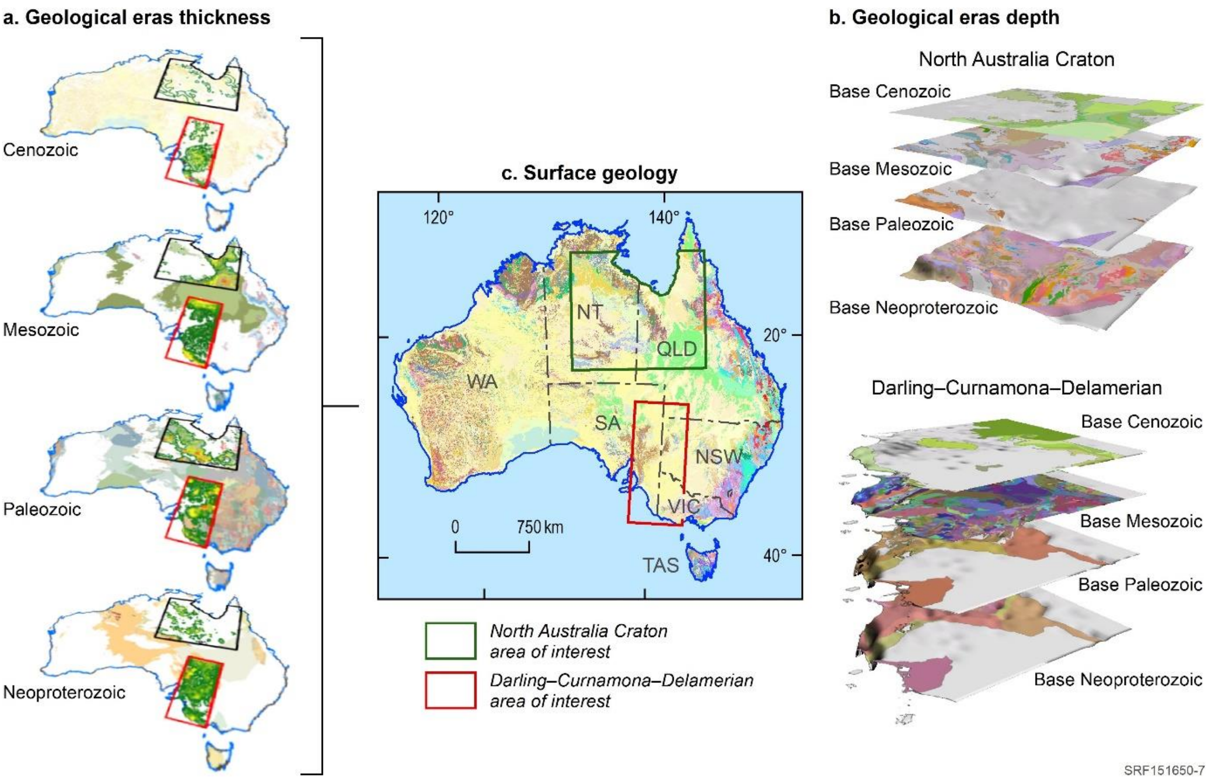

Figure 2. Layered cover model. (a) 100m contours of geological eras thickness shown on the interpreted geological era mega sequence tops from Sanchez et al. (2024). (b) Depth to the base of geological eras from this paper and Bonnardot et al. (2020) overlain by the layered geology (Sanchez et al., 2024). (c) Surface geology (1:1 M) from Raymond et al. (2012).

Improving the understanding of the geology, ore genesis and structural control of the Nifty copper deposit: the Nifty 3D model

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The world-class syn-deformational, sediment-replacement Nifty copper deposit is situated approximately 350 km southeast of Port Hedland in the Neoproterozoic Yeneena Basin (Paterson Orogen) in Western Australia. The Nifty mineralisation is hosted within the folded late-Proterozoic carbonaceous shales, turbiditic sandstones, dolomite, and limestone of the Broadhurst Formation. The region has a long and complex geological history, with the potential for multiple generations of fluid flow and mineralisation (Ribeiro et al. 2023). This has impeded a full understanding of the mineralisation phases and their controlling factors, making Nifty a poorly understood deposit.

Anderson et al. (2001) proposed that the deposit formed at ca. 717 million years ago, at least 100 million years after the deposition of the host sediments, suggesting that the formation of the Nifty deposit occurred during the Neoproterozoic Miles Orogeny, at the center of a zoned hydrothermal alteration system. Hickman (2023) suggests that a shift in stress orientation from NE-SW to ENE-WSW compression marked the late Miles Orogeny and concurrent copper mineralization in the area of interest. Huston et al. (2007) indicate that the Nifty deposit formed close to the timing of sedimentation, either syngenetically or diagenetically. It was later remobilised into its current position during the Miles Orogeny. However, no definitive age has been identified for the Miles Orogeny (Kelsey et al., 2024).

The early phase of 3D modelling at Nifty involved structural interpretation of the area of interest using SKUA-GOCAD. Faults and shear zones, both field mapped, and interpreted from magnetic and gravity data were reviewed and included in the 3D model. Constraining data used for the construction of the 3D faults include geological maps, geological cross-sections, well data, seismic data, AEM data, and regional 3D models.

Then, the modelled SE-striking Nifty Syncline, hosting the Nifty deposit mainly within the keel and northern limb of the syncline, and consisting of 8 horizons, was imported into the 3D program, to place the modelled horizons into their local and regional structural context.

Preliminary observations indicate that the Nifty syncline is located in in a highly deformed region defined by a network of NNW-, NE- and ENE-trending faults. At the camp scale, steeply dipping vertical faults offset the Nifty stratigraphy and associated mineralisation. It is possible that some of these faults predate mineralisation and may have acted as conduits for the mineralising fluids. The Nifty syncline is sub-parallel and located in proximity to the NNW-trending Southwest Thrust. This structure is a major basin-bounding fault, part of a larger fault system imaged in the seismic transect L211 18GA-KB1, that is exposed at surface and also coincides with a distinctive aeromagnetic lineament and abrupt changes in the character of the conductivity sections. This structure might have played a primary role in controlling mineralisation and acted as a pathway driving hydrothermal fluids from deep within the Yeneena Basin.

The next phase of this research project involves analysis of well data, structural data and geophysical data at the camp scale to further integrate the Nifty 3D model within its local and regional structural context. This will assist in subsequent mineralogical modelling, identification of the mineralisation stages and sources of mineralization. This will possibly also lead to the production of mineral prospectivity maps integrating predictor variables (geophysical, geochemical, and geological datasets) through statistical correlation and distance interpolation.

References

Anderson, B.R., Gemmell, B.J., Berry, R.F., 2001. The geology of the Nifty copper deposit, Throssell Group, Western Australia: Implications for ore genesis. Economic Geology 96. https://doi.org/10.2113/gsecongeo.96.7.1535

Hickman, M.M., 2023. Structural control on copper mineralisation at Nifty, northwest Paterson Orogen, Western Australia: Geological Survey of Western Australia, Report 243, 83p.

Huston, D. L., Maas, R. and Czarnota, K., 2007. The age and genesis of the Nifty copper deposit: back to the future. Geoscience Australia Professional Opinion, 2007/03, 22pp.

Kelsey, DE, Ribeiro, BV and Kirkland, CL 2024. In situ mica Rb–Sr geochronology from the Rudall Province: searching for Miles: Geological Survey of Western Australia, Report 250, 40p.

Ribeiro, B. V., Kirkland, C.L., Hartnady, M.I.H., Martin, E.L., West, E., Polito, P., 2023. Multi-stage alteration at Nifty copper deposit resolved via accessory mineral dating and trace elements. Precambrian Res 388.

3-D SEISMIC REFLECTOR ORIENTATIONS FROM 2-D SEISMIC PROFILES ACROSS THE KALGOORLIE GREENSTONE BELT

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Abstract
A number of 2D seismic surveys have been shot in the Kalgoorlie Goldfields, employing both dynamite and, more recently vibroseis sources. To reduce costs, these 2D surveys have primarily been acquired along existing roads, which are often crooked, and have been processed using standard techniques that produce 2D migrated seismic sections. The polyphase deformational history of most greenstone belts means that they are structurally complex, even if a dominant structural strike direction can be inferred. Hence any three-dimensional information that can be extracted from existing 2D seismic reflection surveys is critical to improving our understanding of the structural controls on ore deposits in this area. For seismic profiles shot in 1999 by Geoscience Australia and in 2019 by the Geological Survey of Western Australia, a method analogous to semblance velocity analysis has been employed to derive semi-continuous estimates of 3-D reflector orientations along these crooked lines. (Seismic surveys that employ many off-line receivers allow a larger range of source-receiver azimuths, and can produce continuous reflector attributes). For each zero-offset time within a common depth point supergather, the semblance is calculated along 3-D travel time curves, and the dip and strike of the most coherent reflection is determined. Reflector orientations are generally well recovered where the range of available source-receiver azimuths is greater than ~20°, but the method breaks down at lower ranges where the seismic line is almost linear. The orientations of both moderately dipping volcanic stratigraphy and reflective faults can be recovered. Integration of these local orientation attributes into an interpretation of migrated seismic data requires that the orientations also be migrated. We use simple approaches to the 2-D migration of these attributes that utilises the apparent dip of reflections on the unmigrated stack to map reflector strike, for example, to a short linear segment depending on its original position and a migration velocity. Limited 3-D images that enhance reflectors with key strike directions can also be constructed as a point cloud using the available reflector orientation information, and these images have the potential to constrain 3-D geological and geophysical modelling studies.

1. Introduction

In Western Australia, many gold, nickel and lithium deposits are located within Archean cratons and their Proterozoic margins. With the recognition that faulting provides an important control on the migration of metal bearing fluids through the crust, and the distribution of deposits formed, it is important to map the present day geometry of the major faults throughout the crust and the shallow structures within the near-surface greenstone belts that have focused and trapped mineralizing fluids. Though surface geological mapping and drilling can constrain these features close to the surface, seismic reflection surveys are the only remote sensing technique that can map structures at depths up to 30 km or more with high resolution, typically 50-200 m. Consequently, a number of 2-D seismic surveys have been shot. These surveys have primarily been acquired along existing roads, which are often crooked, and have been processed using standard techniques that produce 2-D migrated seismic sections. Ideally, 3-D seismic surveys, in which an areal distribution of sources and receivers is used to produce a volumetric image, would be employed for subsurface imaging, but the large cost limits their use to high value targets whose location is spatially restricted. The polyphase deformational history of the crystalline crust and most greenstone belts means that they are structurally complex, even if a dominant structural strike direction can be inferred. Hence any three-dimensional information that can be extracted from existing, and perhaps future, 2-D seismic reflection surveys is critical to improving our understanding of the structural controls on gold, and other ore deposit genesis.

2. Kalgoorlie Seismic Surveys

In the greater Kalgoorlie area, four major government-funded seismic reflection surveys have been shot along existing roads, and are shown in Figure 1. The earlier dynamite surveys, BMR91 and 97AGS, were shot using recording systems with a relatively low channel count, which meant that the maximum source-receiver offset was usually <2 km; in addition, the lines of the 97AGS survey are short and quite straight. The later vibroseis surveys used more recording channels allowing a much larger maximum offset and higher nominal fold, which was necessary to obtain good quality stacked seismic images with this source type. Along crooked roads, the larger source-receiver offsets result in a much greater variation in source-receiver azimuths along the line, which perturbs the seismic velocities of dipping reflections used in processing for normal moveout correction of common depth point (CDP) gathered seismic data prior to stacking. This problem in conventional seismic data processing actually represents an opportunity to characterize the 3D geometry of subsurface reflectors, but suggests that the early dynamite seismic surveys with their smaller maximum offsets are less suitable for the type of analysis outlined below.

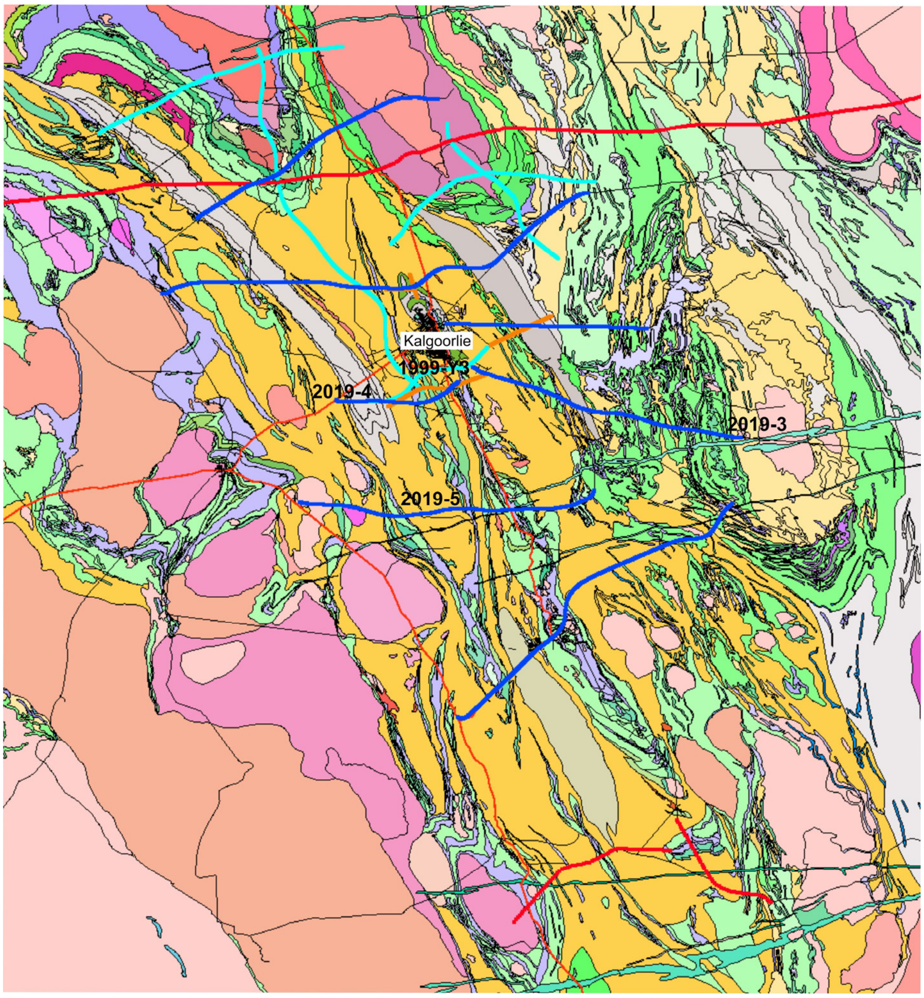

Figure 1: Seismic reflection surveys around Kalgoorlie superimposed on the local granite-greenstone geology: red – BMR91, orange – 97AGS, cyan – 99AGS, blue – GSWA2019

3. Estimation of 3D Reflector Orientations

In 2D crooked-line seismic processing, CDP bins are defined at regular intervals along a CDP slalom line that is a smoothed version of the acquisition profile, and the bins are extended away from the CDP line in an approximately perpendicular fashion. Seismic traces are allocated to the CDP bin in which their source-receiver midpoint lies. For a given source and receiver, the travel time of a reflection from an arbitrarily oriented planar reflector is approximated by:

$$T = \sqrt{T_0^2 + \frac{X^2(1-\sin^2\theta\cos^2\phi)}{V_{rms}{}^2}}$$

where T_o is the zero-offset time at the source-receiver midpoint, X is the source-receiver offset, V_{rms} is the root mean square (RMS) velocity of a horizontally layered medium, θ is the reflector dip, and ϕ is the angle between the source-receiver azimuth and the perpendicular to reflector strike (Levin 1971). An additional time correction can be applied to shift the zero offset reflection time from the source-receiver midpoint to the zero-offset time from the CDP bin centre, which provides a common reference point for all traces within a CDP gather. In the case of a linear reflection profile, it is impossible to distinguish the angles representing dip and strike from one another, because the angle ϕ has the same unknown value for all source-receiver pairs; any effect of reflector dip on travel time could equally be due to reflector strike. If the seismic line is crooked, however, a range of source-receiver azimuths will be recorded, allowing, in principle, the independent determination of the reflector's dip and strike.

To estimate reflection orientation, a measure of coherence, e.g. semblance, is calculated using an assumed root mean square (RMS) velocity function at each zero-offset time for a range of trial angles of dip and strike, which is measured from north, and using a given time window (Calvert 2017), for example 48 ms as commonly used for stacking velocity analysis. At each zero-offset time, the estimated dip and strike correspond to the angles associated with the maximum semblance, i.e. the most coherent reflection. Although the searched strike angle varies from -180º to +180º, only values between 0º and 180º are output because negative values are increased by 180º to ensure that the same value is output for reflectors with the same strike direction but opposite sense of dip; for example, reflectors dipping to the north and south will both be assigned a strike of 90º. It is additionally possible to repeat the estimation of an optimal dip and strike angle for a range of trial RMS velocity values, which can increase the computational cost by more than an order of magnitude, but when applied to subsets of the full dataset the velocity search can help constrain the dip-independent RMS velocity function used along the seismic line.

It is possible to estimate the relative errors in reflector dip and strike by defining a threshold, for example 90% of the maximum semblance, and find the range of dip and strike angles with semblance greater than this threshold: the greater these ranges, the greater the uncertainties in dip and strike. When the seismic line is linear, the angles representing dip and strike cannot be separated, as noted above, resulting in large errors in both dip and strike estimates. Along a crooked seismic profile, however, the distribution of source-receiver azimuths within a CDP gather varies, allowing the dip and strike to be well determined in realistic scenarios if a sufficiently large range of azimuths is present, for example where there is a large change in the direction of a seismic line (Bellefleur et al. 1997).

In practice, most single CDP gathers on a crooked seismic line contain an insufficient number of traces for a well-resolved analysis, but this limitation can be overcome by combining multiple CDP gathers into a much larger supergather that can be used for the estimation process. The estimation method assumes that reflections within the supergather originate from a planar interface; as more CDP gathers are combined, this assumption can break down, especially where the geology is complex, for example where folded boundaries are present.

Input seismic data are subject to a standard preprocessing sequence, including refraction statics, coherent noise attenuation, amplitude recovery, deconvolution or time-variant spectral whitening, automatic gain control (AGC), and first break muting. Usually, the original contractor CDP binning is replaced with custom linear CDP binning that minimizes later migration artefacts. In addition to producing the estimated dip and strike values at each zero offset time and CDP along a seismic line, an optimum "3-D stack", containing the most coherent reflections, as determined by the orientation analysis, is output. To aid interpretation, the dip and strike orientation attributes can be migrated under a 2-D assumption (Calvert and Doublier 2019), which allows them to be superimposed on a 2-D migration of the conventional stack, or the optimal stack output above.

4. Results

In addition to conventional processing of the 99AGS and 2019GSWA seismic surveys, 3D reflector orientations, i.e. reflector dip and strike angles, have been recovered where possible as outlined above, together with relative uncertainties that allow the exclusion of poor-quality results. For example, analysis of part of line GSWA2019-05 indicates that reflector orientations are well recovered where source-receiver azimuths are greater than approximately 30º (Figure 2).

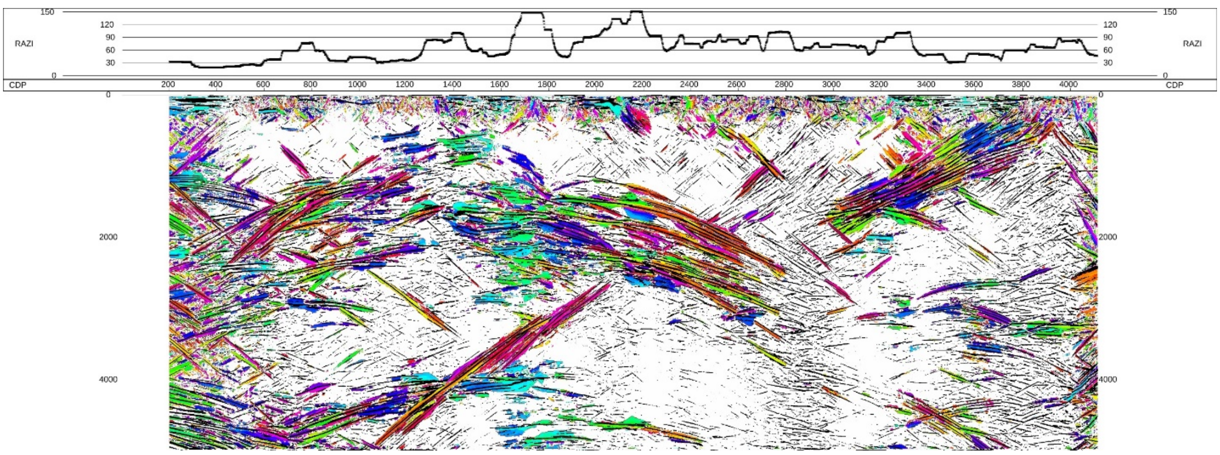

Figure 2: Estimated reflector strike superimposed on the most prominent reflections in the unmigrated stack of line GSWA2019-05. Strike values where the estimated error is >30º have been excluded. In the colour scale: strike values vary from 0º (red) to 60º (green) to 90º (cyan) to 120º (blue) to 180º (red). The range of source-receiver azimuths available for analysis is shown above, and varies from 20º where the acquisition road is nearly straight to 140º. Vertical exaggeration of 1 with velocity of 6500 m/s. Vertical axis is time in ms.

Estimated reflector orientations are obtained as a function of recording time for each CDP along a seismic line, and as such represent reflections in their unmigrated positions. After 2-D migration, the orientation attributes can be superimposed on migrated sections from conventional processing facilitating their interpretation, as shown for the composite east-west line in Figure 3.

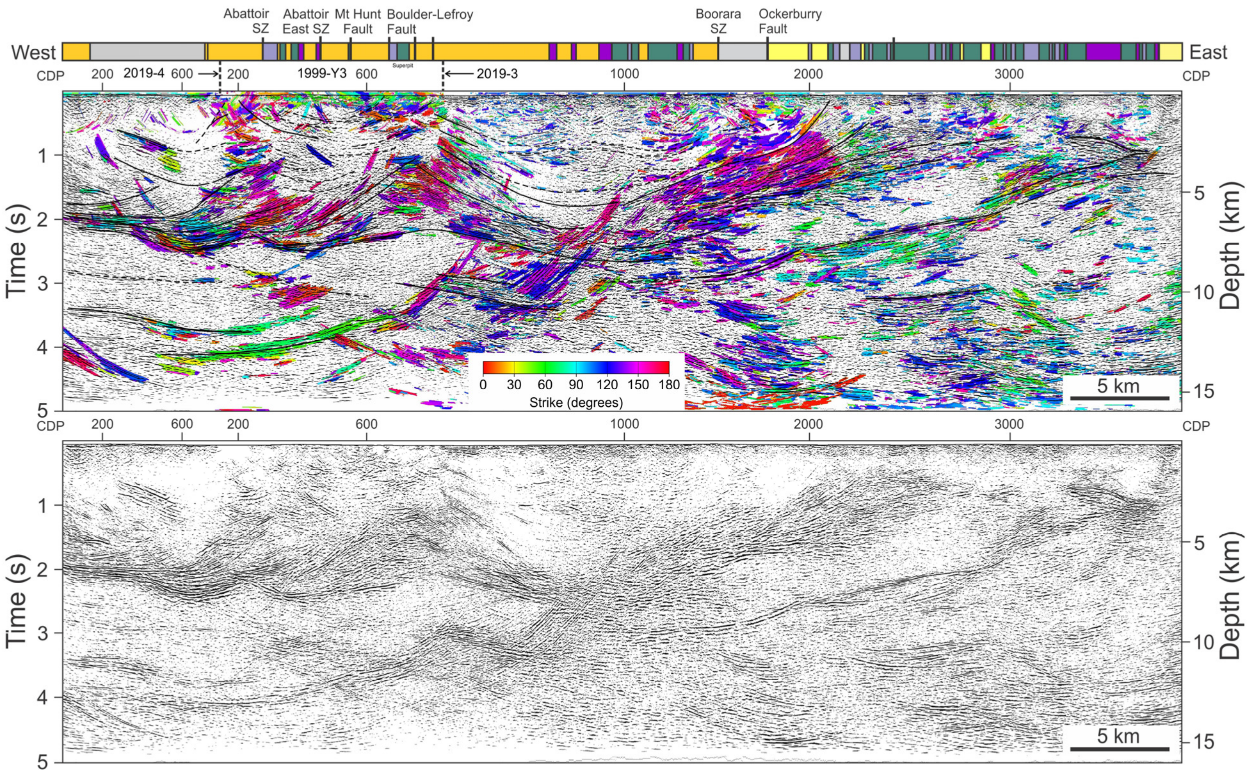

Figure 3: (top) 2-D migrated reflector strike estimates with interpretation superimposed on the migrated composite seismic profile created from lines 2019-4, 1999-Y3, and 2019-03; (bottom) uninterpreted migrated composite seismic profile.

With the geometrical information obtained from the point cloud output by the reflector orientation analysis, it is also possible to create a limited 3-D image of the subsurface, which can be presented as a perspective plot or as a depth slice. In Figure 4, for example, reflections in the depth range 1-5 km are shown, with some reflections originating up to 10 km from the roads where the seismic profiles were shot. Most reflections with strikes of 150-180 degrees (magenta-red) corresponding to the volcanic stratigraphy. Reflections with strikes of 60-90 degrees (green-cyan) at X=360-370 km probably originate within a less reflective volcaniclastic basin east of the Boulder-Lefroy Fault.

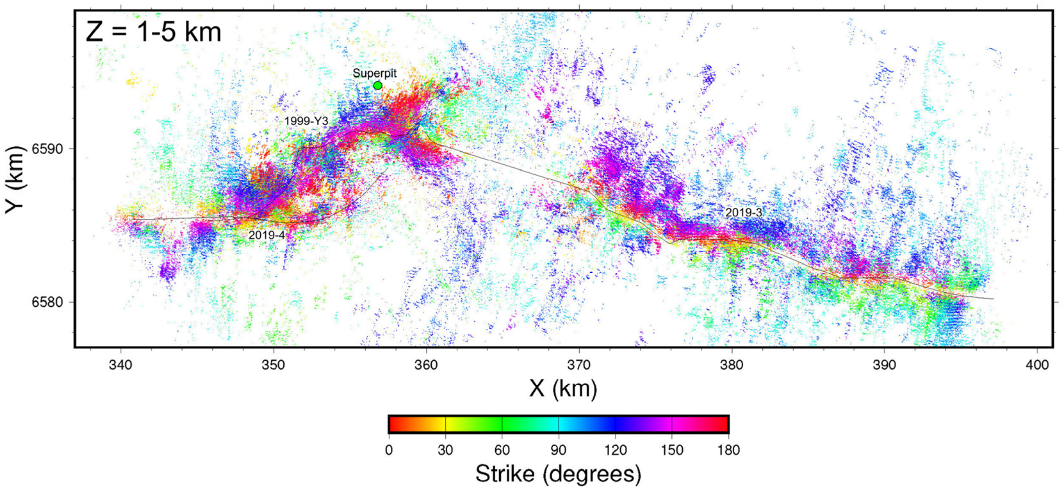

Figure 4: 3-D migrated reflector strike estimates from the composite seismic profile created from lines 2019-4, 1999-Y3, and 2019-03.

Interpretation of the seismic data can also be facilitated by display of only those reflections with a narrow set of strikes, for example those reflections with strikes that are mostly perpendicular to the direction of the seismic line. In Figure 5, reflectors with strike directions of SSE to SSW are shown in 3-D as viewed from the south. In this display, artefacts arising from the 2-D migration process are not present, and reflectors beyond the ends of the seismic line can be imaged. An approximately west-dipping discontinuity (dashed grey line) is better defined in the 3-D image, and separates the structures such as a regional decollement (green dashed line) and volcaniclastic basins (yellow and orange dashed lines) in the hanging wall from less reflective crust to the east. The grey, W-dipping fault truncates against E-dipping mid-crustal reflections that underlie the entire region, and likely extend to the top of the lower crust. In this example, interpretation is aided by the removal of the reflectors furthest from the seismic acquisition line.

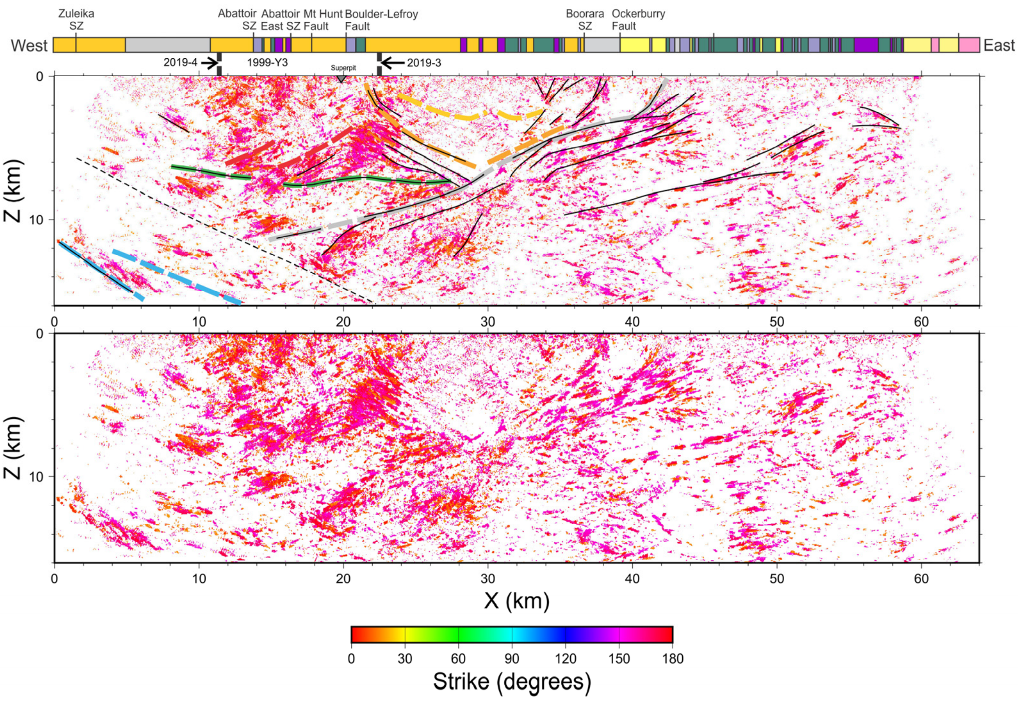

Figure 5: (top) 3-D migrated reflectors form the section in Figure3 limited to strike directions from 000-020º and 150-180º with interpretation; (bottom) Uninterpreted 3-D migration.

5. References

Bellefleur, G., A.J. Calvert, and M.C. Chouteau 1997. A link between deformation history and the orientation of reflective structures in the2.68-2.83 Ga Opatica belt of the Superior Province: J. Geophys. Res., 102, 15243-15257.

Calvert, A.J., 2017. Continuous estimation of 3-D reflector orientations along 2-D deep seismic reflection profiles: Tectonophysics, 718, 61-71.

Calvert, A.J., and M.P. Doublier 2019. Migration of reflector orientation attributes in deep seismic profiles: evidence for decoupling of the Yilgarn Craton lower crust: Solid Earth, doi10.5194/se-10-637-2019.

Levin, F.K., 1971. Apparent velocity from dipping interface reflections: Geophysics, 36, 510-516.

AI-Driven Approaches to Scalable 3D Geological Modelling: Methods, Applications, and Challenges

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Abstract

Artificial intelligence (AI)-based methods are emerging as an effective approach for 3D geological modelling, offering scalable and efficient solutions to integrate diverse datasets and constraints. Neural networks leveraging implicit neural representations (INRs) provide a powerful framework for constrained modelling, enabling the incorporation of stratigraphic relationships, geological observation constraints (e.g., interfaces, planar orientations, geological units), and novel regularization techniques that traditional methods would struggle to accommodate. We present an advanced INR-based approach (Hillier et al., 2023) applied to the Western Canadian Sedimentary Basin (WCSB), one of the world's most extensive 3D geological datasets, to support downstream critical mineral prospectivity analysis, groundwater management, and carbon sequestration. This case study demonstrates the method's computational scalability and its applicability to national-scale 3D geological modelling initiatives. Additional case studies from various geological contexts further highlight the approach's versatility and effectiveness in generating robust 3D geological models. Key challenges are discussed, including the selection of optimal activation functions and regularization strategies. Systematic evaluations and architectural comparisons provide practical guidelines for practitioners seeking to adopt AI-driven approaches in geological modelling. By addressing these challenges, we seek to advance AI-based methods.

Hillier, M., Wellmann, F., de Kemp, E. A., Brodaric, B., Schetselaar, E., and Bédard, K. 2023. GeoINR 1.0: an implicit neural network approach to three-dimensional geological modelling, Geosci. Model Dev., 16, 6987–7012, https://doi.org/10.5194/gmd-16-6987-2023, 2023.

NEXT LEVEL FOR QGIS: 3D REPRESENTATION AND MODELISATION

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BRGM, the French geological survey, has been working for many years on the development of 3D modeling software to make it available, in particular, for modeling geologists. 3D modeling requires georeferenced data from a variety of sources: acquisition of contact and dip point data in the field, interpretation of geophysical data such as seismic data, electrical profile, gravimetry, magnetism, etc., and of course modeling algorithms.

The open-source community is very active in many fields. The QGIS open-source GIS software community has become very active and innovative. The growing popularity of QGIS, and its use by a large community of geoscientists as a data integration platform, motivated BRGM to integrate its 3D modeling tools. Software bricks have been redeveloped as plugins in QGIS. They not only provide an operational alternative to historical tools, but also offer a modular, scalable environment that can be recomposed according to production needs, adapted to modern computing resources and serving as an incubator for research projects.

Nevertheless, GIS software has been designed primarily for 2D, and the move towards 3D representation and use is driven by the emergence of new needs, such as BIM (Building Information Modeling) or the use of large point clouds like Lidar. This evolution now seems necessary. It calls for reflection and development supported by a 3D modeling community. Developments for 3D in QGIS are underway, such as 3D visualization, the representation of borehole data, or the development of functionalities in the elevation profile. Integrating 3D into QGIS requires all 2D and 3D communities to exchange ideas and make joint developments. To this end, BRGM has financed the development of functionalities in the elevation profile, which have been included in a QEP proposal. However, many other options, such as the ability to move around in 3D space, are developments that seem necessary if QGIS is to continue its evolution towards 3D. Collaborative efforts to invest in the development of 3D-related functionalities in the heart of QGIS would enable the rapid evolution of 3D functionalities useful to the whole community.

An open-source toolbox for 3D geological modelling in QGIS

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3D modeling is a major asset for the understanding and quantitative characterization of subsurface geology. Geological survey organizations have produced 3D models for decades and are nowadays facing new kinds of demands for increasingly complex accurate representations of the subsurface. New challenges include "usual" difficulties such as integrating large sources of heterogeneous data, handling a wide range of possible model scales (from urban to national), but also new requirements on model uses. As an example, models should be easily (if not automatically) updatable and computable on various environments (not only in desktop software, but also in web / platform environments), models should also serve for multiple purposes and applications (which requires generating various kinds of representations of a single model), etc.

In this talk, we present the toolbox we have been developing at the French Geological Survey over the last years to progressively replace our two historical and homemade solutions for 3D geological modeling (GDM and GeoModeller software). It contains two parts: a set of python and C++ libraries and a set of QGIS plugins. The libraries provide data structures and computational capabilities. They can be run on a wide range of software environments. The QGIS plugins provide access to 3D modelling capabilities to the geologists directly in the GIS environment without requiring them to have development skills. Throughout the presentation, we illustrate the main specifications we had for these developments, how the proposed solution answers them and provides an extensible basis for future developments. We also illustrate how we had to support the development of core QGIS functionalities to better manage 3D geological objects.

One of the key elements of the proposed toolbox is the numerical representation of the model architecture (the stratigraphic column defining the succession of the model units and the relations between stratigraphic surfaces). We use a binary space partition tree to represent it. Each leaf of the tree represents a geologic unit and will correspond to a (potentially empty) subset of the 3D space in the generated representations of the model. Each branch of the tree represents a stratigraphic interface and defines a binary partition of the 3D space (typically, older and younger deposits for stratigraphic surfaces). Each interface (branch) in the tree is assigned an implicit scalar function that permits to represent it in 3D and identify the associated two partitions. Any node (branch or leaf) of the subtree defined by this branch will then exist only in the corresponding partition ensuring the topological consistency of the 3D representations regarding the stratigraphic column.

One of the advantages of this definition of the model architecture is that it does not introduce any constraint on the way the mathematical function is defined or evaluated and therefore allows for mixing various modeling methods in a single model. Additionally, we can also consider attaching some mathematical function to the tree leaves (the units) to populate the model with parameters (facies, physical parameters...).

Incorporating structure into groundwater models

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Geological structural models are the underlying framework of groundwater models as they delineate the geometry of large-scale hydrogeological units. However, traditional groundwater modelling workflows do not easily accommodate structural model updates nor multiple interpretations where uncertainty exists. Simple interpolation or deterministic geological modelling software is typically adopted, which do not facilitate consideration of alternative structural models, despite structure being one of the biggest sources of uncertainty in groundwater models (Refsgaard et al., 2012). Secondly, it is cumbersome to update the flow model when new geological data and interpretation is undertaken as this requires an update of the spatial discretisation scheme and hence an update to all other aspects of the flow model.

In this research, we have combined LoopStructural (Grose et al., 2021) with the popular groundwater modelling code MODFLOW (Langevin et al., 2017) in a Python interface. This seamless workflow provides a method for live updating of flow models when new geological data is acquired, or probabilistic structural interpretations should be made. Using structural parameters, multiple structural realisations are generated which are carried through to the end of the groundwater modelling process (Figure 1) to quantify the influence of structural uncertainty on groundwater predictions. A key part of the workflow includes the use of unstructured grids, which adapt to each structural realisation. Furthermore, the workflow introduces the ability to inverse model structure using hydraulic observation data, which may alleviate the need for traditional Bayesian Model Averaging.

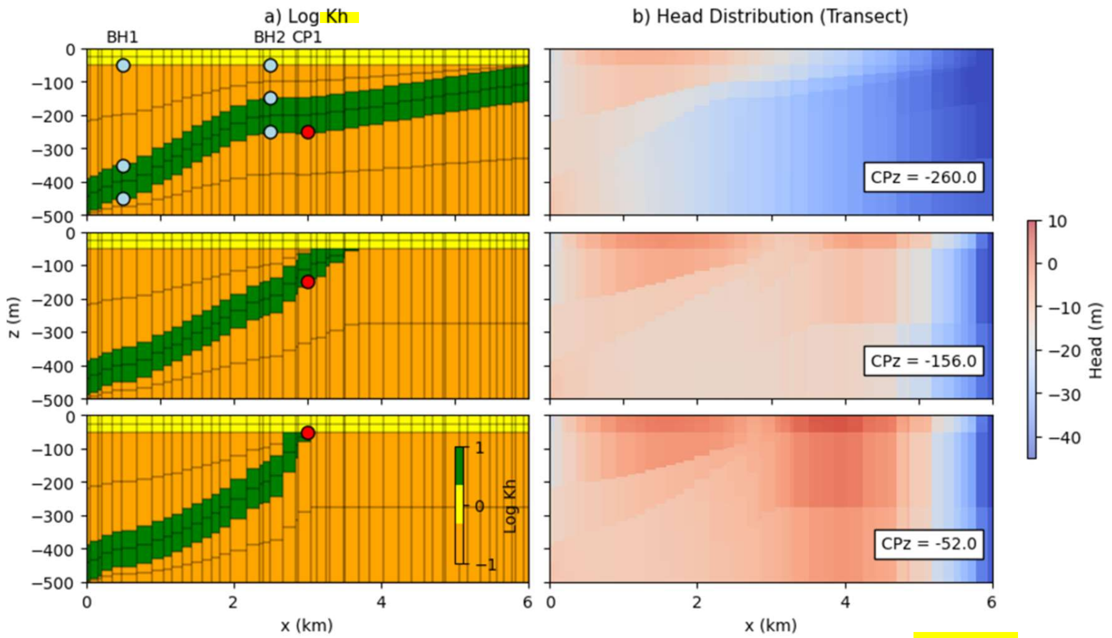

Figure 1. Generating multiple conceptual realisations and the resulting simulated hydraulic heads (In press.).

Grose, L., Ailleres, L., Laurent, G., & Jessell, M. 2021. LoopStructural 1.0: Time-aware geological modelling. Geoscientific Model Development, 14(6), 3915–3937.

Langevin, C. D., Hughes, J. D., Banta, E. R., Niswonger, R. G., Panday, S., & Provost, A. M. 2017. Documentation for the MODFLOW 6 Groundwater Flow Model: U.S. Geological Survey Techniques and Methods. USGS: Techniques and Methods 6-A55.

Refsgaard, J. C., Christensen, S., Sonnenborg, T., Seifert, D., Højberg, A. L., & Troldborg, L. (2012). Review of strategies for handling geological uncertainty in groundwater flow and transport modeling. Advances in Water Resources, 36, 36–50.

3D GEOLOGICAL MODELLING CONFERENCE ABSTRACTS

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Title: Workflow and challenges of regional geological models built from large multi-disciplinary datasets that underpin groundwater conceptualisation and modelling.

Geological models are fundamental for groundwater modelling impacts assessment, especially in regions with intensive resource development like the Surat Cumulative Management Area (CMA) in Queensland, Australia. The Office of Groundwater Impact Assessment (OGIA) is responsible for assessing and managing the cumulative impacts of coal seam gas and coal mining on groundwater systems within this region. This requires the development of 3D geological models that accurately capture the complex geological structures, stratigraphy, and hydrogeology. Over the years, OGIA has developed a range of geological models (OGIA 2019, 2021). This presentation focuses on the challenges encountered and the innovative solutions developed during the creation of regional-scale geological models within the Surat CMA. These models serve as case studies to highlight the complexities and approaches involved in this work.

The first case study focuses on the significant challenges encountered by OGIA in constructing the regional-scale geological model of the entire Surat CMA (OGIA 2019), around 300,000 km^2, which is the structural framework for the regional groundwater flow model. The diversity and volume of available data (wireline logs, water bore data, seismic data, etc.) pose significant hurdles for data integration and model construction within the confines of existing software.

The second case study is the development of a sub-regional geological model covering about 20,000 km^2 (paper in prep) to represent the architecture and complex fault structure of the Quaternary sediments and their juxtaposition with the underlying Jurassic sediments for the development of a groundwater impact model. Key challenges of this model involved the integration of multi-disciplinary interdependent datasets, including Airborne electromagnetics, to construct geologically sensible surfaces and the implementation of a stair-stepped corner point grid to preserve orthogonal grid cells and angled faults for subsequent flow modelling in MODFLOW-USG. Current-day modelling workflows do not easily meet these challenges and have necessitated the development of non-standard modelling approaches supplemented by custom in-house software.

OGIA 2019, *Updated Geology and Geological Model for the Surat Cumulative Management Area*, Department of Natural Resources, Mines and Energy, Queensland Government, Brisbane, Queensland.

OGIA 2021, *Geology and 3D geological models for Queensland's Surat and southern Bowen basins: stratigraphic framework, data, methods and results (OGIA21CD03)*, Department of Regional Development, Manufacturing and Water, Queensland Government, Brisbane, Queensland, accessed from <https://www.ogia.water.qld.gov.au/publications-reports>.

Regional prospectivity analysis applying fuzzy logic and machine learning - extending into 3D

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SRK Consulting (SRK) in partnership with DeepIQ and BHP have undertaken a recent regional scale (~25,000km^2) prospectivity study integrating both data driven (machine learning) and knowledge driven (fuzzy logic) workflows targeting large porphyry copper deposits in northern Chile. The project combined regional geological and structural interpretations, development of the porphyry mineral systems targeting framework and implementation of advanced data processing and machine learning to develop targets for follow up field investigations. This study expanded the typical 2D prospectivity analysis by applying the analysis in both 2D and 3D. Following this initial pilot study, the application of this integrated data driven and geological knowledge approach to prospectivity analysis was subsequently applied for a greenfield porphyry copper deposit study at a similar scale and an intrusion-related nickel deposits at a much larger scale. This abstract focuses on the 3D aspects of the northern Chile study with readers directed to Woodfull et al., (2023) for a more comprehensive overview of the study.

The initial study stages included data cleaning, integration and interpretations of a wide range of datasets with reprocessing and development of data enhancements to feed into the 2D and 3D targeting stages. A mineral systems approach was used to identify key feature elements specific to porphyry deposits for ingestion into the prospectivity workflows. Sparse/non-uniform data (e.g., geochemistry, drilling) were ultimately not used as inputs to eliminate potential spatial bias, instead using this data as confirmatory layers during target review and validation. Over fifty 3D elements were created for the 3D prospectivity analysis, replicating input features created for the 2D workflow. 3D modelling integrated several datasets including solid geology, cross sections, regional drill hole data and 3D geophysical inversion datasets (electromagnetics, magnetics and gravity). Features created included structural architecture (e.g., faults, crustal lineaments), lithology and intrusions (sub-split by age and intrusive type), alteration proxies, depth of cover, paleodepth and training sites (known porphyry deposits). A phase of 3D gravity and magnetic forward modelling was conducted to highlight areas of geophysical misfit with geometric updates conducted to resolve misfits. All raw data, 3D elements and mineral system proxies were attributed into regularized (500m) block model and then ingested into DeepIQ's cloud-based Data Studio platform where machine learning and fuzzy logic analysis was conducted. Structured learning using known deposits as the training datasets was conducted and machine learning completed using random forest and deep learning algorithms to make predictions across the model space.

Outcomes from both the fuzzy logic and machine learning analysis in both 2D and 3D showed good correlation with known mineral deposits providing good confidence in results. The machine learning method enabled rapid interrogation of large amounts and provided more objective outcomes, minimising human bias of more traditional knowledge driven techniques. By integrating the parallel knowledge driven approach allowed mineral system elements to be tested and provided an additional layer of validation to the machine learning results. Interestingly the machine learning process was ultimately found to only rely on only a few key exploration layers driving prospectivity results. Both the 2D and 3D outcomes were also found to show good correlation, however, clear variances were apparent reflecting geometric and spatial differences when integrating the depth dimension. The use of 3D modelling enabled better understanding of the region from a geometric perspective particularly geometries of intrusions as well as paleodepth for preservation of the porphyry system. The process highlighted the importance of several key mineral system elements and 3D interactions, enabling the interplay of targeting elements to be evaluated in real space and highlighting favorable target areas. The use of the machine learning and fuzzy logic workflow in 3D ultimately proved to be a successful method, complementing the 2D workflow in identifying target areas for follow-up field investigations with several highly favorable target areas identified.

Woodfull, C., Rieuwers, M., Avasarala, V., Stuart-Smith, P., Jupp, B., Cate, A., McMahon, T., Blaser C., Roche, R., Busuttil. 2023. Prospectivity Analysis for Large Porphyry Copper Deposits – An Integrated Geological Knowledge and Machine Learning Approach. 26th World Mining Congress.

The challenges of geological modelling with blast hole measure while drill data

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Blast hole measure while drill (MWD) data have the potential to improve the accuracy of geological models between exploration drill holes. These data include drill penetration rates, torque, weight on bit, air pressure and rotation speed, and are being recorded routinely across global mining operations. Raw penetration rates may be used by trained geologists to adjust geological wireframes and to interpret structural features within mining pits. However, the challenge in allowing mainstream use of these data is the ability to normalise data for a range of different drilling, equipment and geological variables. This research collated one million blast holes from 10 different iron ore mines in the Pilbara region of Western Australia to better understand these variables and their relative influence on penetration rates.

Results show that different drill rigs produce vastly different penetration rates, while different drill bits and the life of those bits altered penetration rates up to 25%. The depth within individual blast holes also had a significant impact on MWD parameters, with blast damage and drilling practices such as hole conditioning causing peaks and troughs in data. Depth of blast holes from a mine's original topography also influenced penetration rates, regardless of rock type. Likewise, the angle of bedding relative to the direction of drilling showed a consistent relationship whereby bedding at 30-40 degrees to the drilling direction penetrated slowest. Finally, drilling above or below the water table affected penetration rates but was dependent on rock type.

These results demonstrate that MWD data cannot be normalised using drilling variables such as weight on bit, air pressure and rotation speed alone. Any machine learning methods must incorporate equipment and geological variables or risk the potential for misinterpretation.

PRELIMINARY MAGNETIC AND GRAVITY INVERSIONS FOR THE YAOURÉ GREENSTONE BELT, IVORY COAST, WEST AFRICA

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Abstract

Greenstone belts are thick supracrustal sequences dominated by mafic volcanic rocks and minor sedimentary components, characterized by significant deformation and greenschist-facies metamorphism. As primary components of Archean-Proterozoic cratons, they host orogenic gold and potentially komatiite-hosted nickel ores. Geophysical inversion offers a robust method for obtaining geometric and physical property parameters of the subsurface of these sequences, aiding in resource exploration (Williams, 2009; Singh et al., 2019). The region has a lower sequence comprised of metabasalts and mafic intrusions and an upper sequence comprised of volcaniclastic rocks. Both units are intruded by granodiorites. We utilized the open-source Tomofast-x software (Giraud et al., 2021; Ogarko et al., 2024), to conduct 3D geophysical inversions of airborne gravity and magnetic data. Our investigation mapped the subsurface distribution of density and magnetic susceptibility across the belt using multiple inversion strategies. For density modeling, we employed three distinct approaches: inverting six independent components of full-tensor gravity gradiometry, the Tzz component, and the Tz component of gravity. Magnetic susceptibility inversions utilized trend-removed total magnetic intensity data. Results show positive density contrasts predominantly in the basalt units and mafic intrusions, while higher magnetic susceptibilities concentrate in volcano-sedimentary units. Notable features include a high-density contrast east of the Yaouré gold mine, potentially indicating an intrusion, and a pronounced magnetic contrast below a major northeast-southwest fault, where the dip of the magnetic body aligns with the mapped eastward-dipping geology.

References

Giraud, J., V. Ogarko, R. Martin, M. Jessell, and M. Lindsay, 2021, Structural, petrophysical, and geological constraints in potential field inversion using the Tomofast-x v1.0 open-source code: Geoscientific Model Development, 14, 6681–6709.

Ogarko, V., K. Frankcombe, T. Liu, J. Giraud, R. Martin, and M. Jessell, 2024, Tomofast-x 2.0: an open-source parallel code for inversion of potential field data with topography using wavelet compression: Geoscientific Model Development, 17, 2325–2345.

Singh, R. K., V. P. Maurya, Shalivahan, and S. Singh, 2019, Imaging Regional Geology and Au – Sulphide mineralization over Dhanjori greenstone belt: Implications from 3-D Inversion of Audio Magnetotelluric data and Petrophysical Characterization: Ore Geology Reviews, 106, 369–386.

Williams, N. C., 2009, Mass and magnetic properties for 3D geological and geophysical modelling of the southern Agnew–Wiluna Greenstone Belt and Leinster nickel deposits, Western Australia: Australian Journal of Earth Sciences, 56, 1111–1142.

INVESTIGATING THE EFFECTS OF WAVELET COMPRESSION ON GRAVITY INVERSION WITH EXAMPLES FROM THE EASTERN YILGARN CRATON, WESTERN AUSTRALIA

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Australia is a global leader in high quality public geophysical and geological datasets, repurposing legacy datasets is cheaper and more efficient than conducting new surveys. One way to integrate multiple datasets is through inversion constraints or a joint inversion. A limiting factor of these multiphysical subsurface models is computational memory. Wavelet compression decreases the memory required for inversions with minimal impact on the final result. The Harr and the Daubechies D4 wavelets are commonly used to compress the sensitivity matrix (Li and Oldenburg, 2003).

This research explores how model size affects the compression rate and compression error, at this stage for single physics inversion. By running a series of unconstrained gravity inversions with model size varying between 4.2x10^5 to 1.2x10^7 cells and compression rates varying between 10^{-4} and 1 we established a power law relationship. The final equation to calculate the compression rate, Cr_{haar}, needed to achieve a compression error, c_e, for a model with n cells is as follows:

$$Cr_{haar}(n, c_e) = \frac{1}{(4.86 \times 10^{-4} c_e + 8.36 \times 10^{-5})n^{0.872}}$$

This relationship predicts the necessary compression rate from model size and compression error. It is determined that for most models a maximum compression error of 1% is required to decrease visual artifacts in the final model. At 7% compression error the distribution of densities remains accurate but appears overly distorted, Figure 1. A benefit of being able to predict the compression rate is a more accurate estimation of computer resources. Inversions are run using Tomofast-x (J. Giraud et al 2021, V. Ogarko et al. 2024) and are run over the Eastern Goldfields region of the Yilgarn Craton.

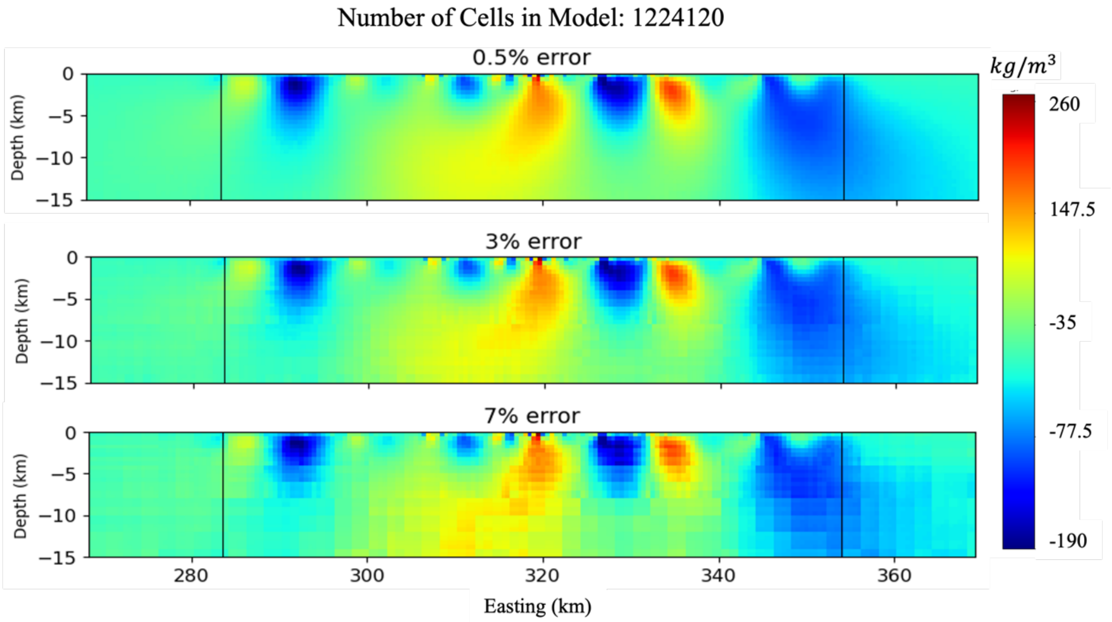

Figure 1: Final density model from gravity inversions over the Eastern Goldfields using wavelet compression with compression rates 0.0143, 0. 0034, and 0.0014 resulting in compression errors of 0.5%, 3%, and 7%.

J. Giraud, V. Ogarko, R. Martin, M. Jessell, and M. Lindsay. 2021. "Structural, petrophysical, and geological constraints in potential field inversion using the Tomofast-x v1.0 open-source code", Geosci. Model Dev., 14, 6681–6709 p

Li, Y., Oldenburg, D. W. 2003. Fast Inversion of Large-Scale Magnetic Data Using Wavelet Transforms and a Logarithmic Barrier Method. Geophysical Journal International 152 (2), 251–65 p.

V. Ogarko, K. Frankcombe, T. Liu, J. Giraud, R. Martin, and M. Jessell. 2024. "Tomofast-x 2.0: an open-source parallel code for inversion of potential field data with topography using wavelet compression", Geosci. Model Dev., 17, 2325–2345 p

3D BASIN-SCALE GEOLOGICAL MODELLING FOR EVALUATING PETROLEUM POTENTIAL IN THE JEJU BASIN, KOREA

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Abstract

This study focuses on basin-scale 3D geological modeling to evaluate petroleum potential over a large area. The study area is a rift basin that extended from the Eocene to the Miocene and was subdivided into several sub-basins. In the late Miocene, compressional deformations and subsequent subaerial exposure resulted in significant erosion and a widespread regional unconformity. Previous studies revealed that this area possesses high petroleum potential; however, available datasets are limited, consisting of only a few well data points and a 2D seismic dataset. To construct successful 3D geological and petroleum system model, we concentrated on two key issues: (1) the spatial distribution of lithology in relation to depositional environments, and (2) the estimation of erosional volume of deformed sedimentary units. To model the spatial distribution of lithology and depositional changes, this study developed depositional trend map through both quantitative and qualitative analyses. Geological interpretations derived from well-cuttings and well-log analyses provided interpretations for vertical depositional changes, which were correlated with seismic facies analysis to extend interpretations into 3D space. From these interpretations, we generated a qualitative geological trend map. Additionally, a paleo-depositional thickness map was created to quantify the thickness of depositional units excluding the effects of structural deformation and erosion. These maps were integrated to produce a regional trend map for stochastic lithology simulations. To estimate erosional volume, this study mapped and flattened uneroded key horizons that preserved their original shapes, being aligned with the top erosional horizon. This process enabled the calculation of erosional volume, which, along with the geological trend map, served as a crucial input for modeling lithology distribution and petrophysical properties. Despite the systematic workflow, several challenges remain in constructing an accurate 3D geological model: (1) high uncertainty in the undrilled sedimentary succession, (2) difficulties in correlating 2D seismic data with large spacing between track lines, and (3) challenges in mapping reasonable horizons within the complex reverse fault zone. We believe that these limitations are able to be crucial research items at developing a successful basin-scale 3D modeling.

Stochastic modelling of the Lower Burdekin Delta aquifer

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The spatial heterogeneity of aquifer properties plays an important role in the movement of groundwater and contaminants (Pirot et al., 2015). Thus, groundwater resource management decisions rely on the quality of groundwater models developed from heterogeneity characterization. This research presents a new stochastic facies-modeling algorithm to represent the heterogeneous deposits of deltaic sediments, in order to improve subsurface modelling of the Lower Burdekin Delta aquifer (Australia).

Relying on the conceptual geological model developed by McMahon (2004), we propose an object-based stochastic facies modeling algorithm to represent the main sediments of the aquifer (clay, sand and intermediate sediments), where clay lenses and sand lenses are represented by truncated ellipsoids. Then, extracting facies information from legacy boreholes allows us to compute summary statistics for the study site, that are then used to calibrate the stochastic algorithm via Bayesian optimization (Mockus, 2002).

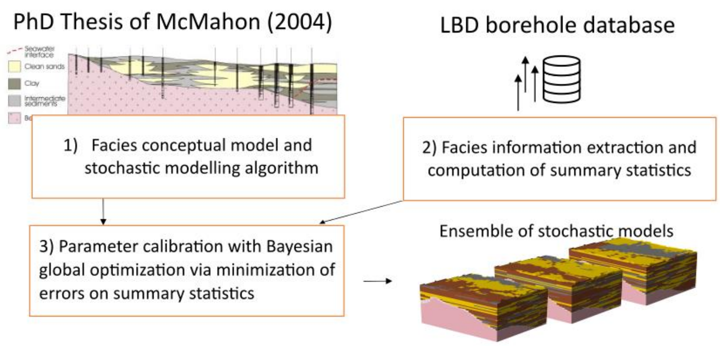

Figure 1: workflow of the proposed stochastic modeling approach.

The resulting calibrated algorithm generates models that reproduce global facies proportions and global cumulative distribution functions of facies thicknesses. The stochastic simulation of sediment distributions is expected to provide novel inputs to groundwater models of the Lower Burdekin Delta, which are needed to assess the movement of various solutes, including seawater intrusion, within this important aquifer system.

References

McMahon, G. A. 2004. An integrated hydrogeological/hydrogeochemical approach to characterising groundwater zonations within a quaternary coastal deltaic aquifer: The Burdekin River delta, North Queensland (Doctoral dissertation, Queensland University of Technology).

Mockus, J. 2002. Bayesian heuristic approach to global optimization and examples. Journal of Global Optimization, 22(1), 191-203.

Pirot, G., P. Renard, E. Huber, J. Straubhaar, and P. Huggenberger. 2015. Influence of conceptual model uncertainty on contaminant transport forecasting in braided river aquifers. Journal of Hydrology, 531, 124-141.

Acknowledgments

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GEOTECHNICAL STRUCTURAL MODELLING – EXPLICIT WAY TO CONTROL GEOTECHNICAL RISK

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Ground failure is a major geotechnical hazard in both open cut and underground mining, that can potentially result in significant safety risks, production delays, and financial loss. It is essential to explicitly map, characterize, and model geometry and estimate the properties of all faults, and associated structures, to assess their failure risk and implement them into subsequent geotechnical pit design changes. Integration of high-resolution data and good geological understanding of the studied region is crucial for construction of valid structural 3D models.

In this work, we present a workflow implemented by the BHP Coal team to provide suitable 3D structural models. As part of the process, the acquisition of all geophysical and spatial data was reassessed to improve its aerial coverage and data resolution. Using a pit by pit approach, all faults are mapped and validated by downhole geophysics and OTV/ATV data, while major faults are enlarged for further modelling. All faults are validated with high resolution photogrammetry of mined areas and checked against available 3D seismic and aero electromagnetics data sets. Such observation control points supported by carefully designed construction lines are used as input for final fault modelling utilizing implicit algorithms (e.g. GoCAD or Vulcan Geology Core).

The data driven fault confidence is mapped using a simple traffic light control system to improve communication of uncertainty with stakeholders. Implemented Fault Register online platform control modelled fault versioning allowing our stakeholders to contribute into modelling for reconciliation purposes.

This comprehensive modelling workflow serves to uplift a mine design confidence and contributes to safety improvement in the mining environment. It has received positive technical feedback within the business creating strong support for this type of the work and providing a base work to be applied across other assets.

INTERROGATING ARCHEAN DOMES: INSIGHTS FROM BARCODED MAGMATIC STRATIGRAPHY AND 3D MODELLING

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To capture the structural controls on komatiite-associated nickel mineralization in Archean terranes, like that of the Widgiemooltha Dome of the Yilgarn Craton, it is critical to understand both the magmatic stratigraphy and subsequent deformation. The dome is characterised by polydeformed, interleaved mafic and ultramafic rocks surrounding a granite core. Using a chemostratigraphic approach, a barcoding system of magmatic units in the Eastern Goldfields Superterrane of the Yilgarn Craton has been developed using multi-element geochemical data (Smithies et al., 2022). The use of this system can inform our understanding of the camp- to regional-scale architecture, resolve the early deformation history, and shape targeting criteria for nickel and gold mineralization. We address three critical components: 1) the stratigraphy of the Widgiemooltha Dome and host komatiite sequences, 2) the structural and tectonic evolution of the dome, and 3) the exploration potential for the mafic-ultramafic sequences and specific structural settings around the dome. Here we integrate publicly available geological, geophysical, and geochemical databases with new and existing company data, including geochemistry, structural data and 3D modelling.

We present a newly defined stratigraphy for the Widgiemooltha Dome where the basal unit comprises primitive, uncontaminated low-Th basalts, which consistently underly nickel-bearing komatiite layers around the dome. The komatiite is overlain by thin occurrences of strongly contaminated low-Th basalts, with the upper stratigraphy dominated by basaltic to doleritic high-Th, siliceous basalts. Based on the defined stratigraphy and magmatic textural features, we establish a stratigraphic younging direction that can be used to constrain 3D models. When integrated with structural logging and 3D modelling, we document extensive early tectonic repetition around the dome associated with layer-parallel tectonic fabrics, attributed to thrusting (local D_1). Evidenced by a pervasive tectonic fabric, strain is predominantly localised along lithological and magmatic contacts including orthomagmatic massive and semi-massive Ni ores along the lower komatiite contact. Both the contacts and high-strain zones have been folded during the regional-scale ENE-WSW shortening (local D_2), which generated the dominant anticline-syncline pairs of the camp-scale architecture. Sulfide accumulations are documented in parasitic F_2 fold hinges.

The presence of thrust faults and sinistral strike-slip faults on the eastern limb, as well as positive flower structures in the southern apex, are attributed to progressive deformation and a rotation of the shortening direction to ESE-WSW. Higher strain and dextral oblique movement are noted in the more steeply dipping western limb, which is well-illustrated in the 3D geological model, associated with more extensive mechanical remobilisation of sulfides. In areas of lower strain, both magmatic and early structural features are preserved, as noted in parts of the Cassini nickel sulfide deposit in the southern apex of the dome. We suggest that such an approach is necessary for working in poly-deformed terranes with structural repetitions and high rheological contrasts, greatly complementing mapping and exploration efforts.

Smithies, R., Lowrey, J., Sapkota, J., De Paoli, M., Hayman, P., Barnes, S., Champion, D., Masurel, Q., Thebaud, N., and Grech, L. 2022. Geochemical Characterization of the Magmatic Stratigraphy of the Kalgoorlie and Black Flag Groups–Ora Banda to Kambalda Region. Report 226, Geological Survey of Western Australia, 100 p.

FAULT SLIP TENDENCY, NUMERICAL AND 3D MODELLING APPLIED TO TARGET RANKING AT NORTH STAWELL

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The localisation of fluids within major shear zones and fault systems plays a critical role in controlling the regional distribution of orogenic gold deposits. Structural geologists have long observed the association between ore deposits and major fault structures. However, identifying which faults are critical for mineralisation remains a significant exploration uncertainty, as orogenic belts typically contain hundreds to thousands of faults capable of focusing fluid flow and enabling mineralisation. The Stawell Zone constitutes the westernmost segment of the Delamerian Orogen in Victoria. It is bounded by the Moyston Fault to the west and the Avoca Fault to the east. Within the westernmost 15 km, between Moyston (west) and Coongee faults (east), the Stawell Zone consists of Cambrian metasedimentary rocks and Low-K tholeiitic basalts of the Moornambool Metamorphic Complex. These rocks exhibit a metamorphic gradient, with amphibolite facies metamorphism adjacent to the Moyston Fault, contrasting with the lower greenschist facies observed in sedimentary rocks near the Coongee Fault. Exploration within the Stawell Zone has primarily targeted analogues of the Magdala deposit, where gold mineralisation is strongly associated with segments of the Stawell Fault that are subparallel to the contact between basaltic units and carbonaceous metasedimentary rocks, such as the Albion Formation. This structural and lithological configuration has been pivotal in guiding mineral exploration activities across the Stawell zone. Our study introduces a novel regional fault analysis approach, employing fault-slip tendency as a proxy for fluid flow, under the premise that faults with higher slip tendency exhibit enhanced fluid flow capability. Fault-slip tendency is quantified as the ratio of shear stress acting on a fault plane to the normal stress resisting fault movement. We integrated fault slip tendency analysis with numerical modelling of the deformation stress field into a three-dimensional model to evaluate and rank exploration targets along a 60 x 12 km area of the NW-trending Stawell Zone. 3D meshes of primary and secondary faults, constructed from airborne gravity gradiometry, magnetic data and GSV structural datasets, were assessed for slip tendency under a regional stress regime defined by the structural evolution of the Magdala deposit. This analysis generated a fault slip tendency along fault zones, identifying more dynamically active fault zones based on their orientation and time-space stress field evolution. Additionally, regions of greater dilation around basalt domes, derived from numerical modelling, the orientation of basalt long axes, the presence of carbonaceous metasedimentary rocks, and drilling depth were integrated to prioritise exploration targets within the Stawell Zone.

GEOCHEMICAL MAPPING OF DOLERITE DYKES: CHALLENGES AND SOLUTIONS IN AUTOMATED BLOCK MODELLING

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Automation in geomodelling and block estimation has significantly streamlined mine planning and production cycles, offering substantial time savings compared to traditional workflows. For bulk commodities such as bauxite, high-density drill sampling and assay programmes are critical for accurately delineating ore distributions and geometries. These programmes are often constrained by compressed timelines, budgetary limitations, and incomplete datasets.

This study explores the impact of dolerite dyke networks on interpretation using automated modelling workflows for bauxite deposits. Due to similar geochemical signatures, dolerite dykes pose challenges to automatic domain coding and flagging processes, complicating orebody characterisation. Utilisation of assay data resulted in the implementation of an automated geochemical cutoff and domain coding approach, which identifies and delineates dolerite dykes with a high level of spatial detail.

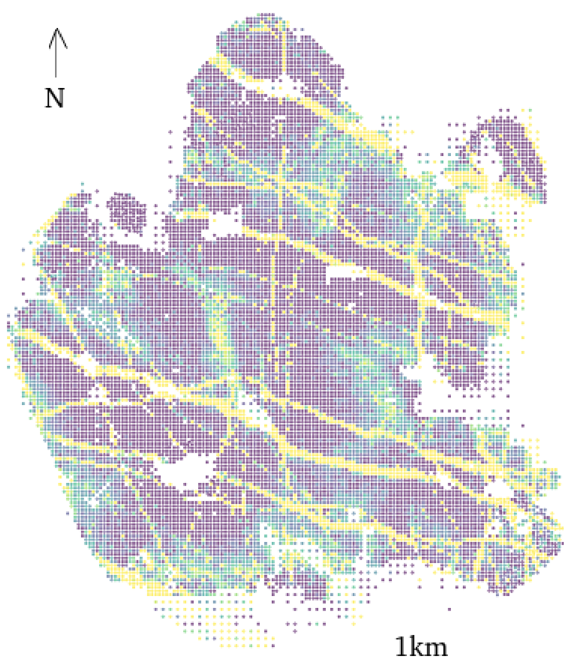

Figure 1: Dyke presence at a drillhole location is deduced from its geochemistry.
The density of drilling helps finely delineate the dykes geometries.

The amended workflows improve block modelling accuracy and additionally support mine planning optimisation by reducing the mining footprint and reducing resource misclassification. This study provides enhanced geological insights into the dyke swarms of the Darling Scarp and Yilgarn Craton, potentially demonstrating broader application for structurally complex deposits.

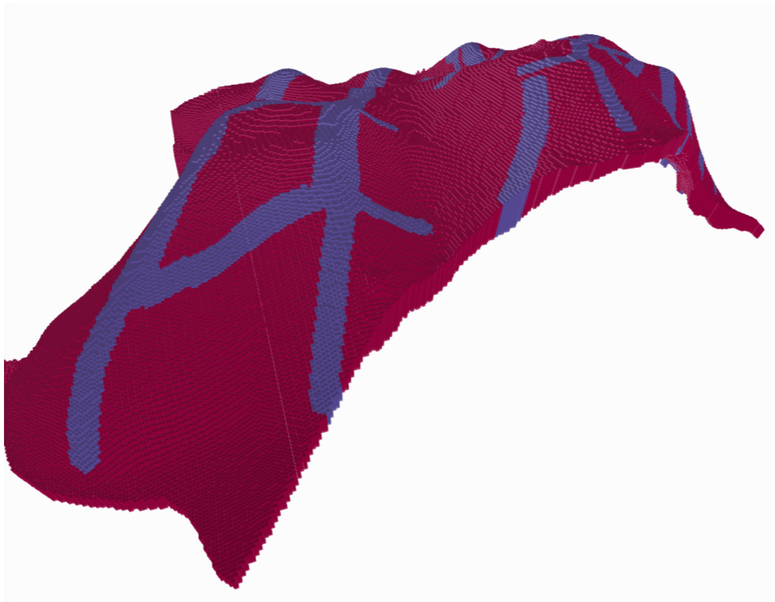

Figure 2: Estimation blocks are coded as granite and dolerite to guide lithological domain interpretation, grade estimation and geotechnical properties

REFERENCES

Hickman AH , Smurthwaite AJ , Brown IM , Davy R (1992) Bauxite mineralisation in the Darling Range, Western Australia. Geological Survey of Western Australia, Report No. 33. pp27

Lloyd, S. P. (1957). Least squares quantization in PCM. Technical Report RR-5497, Bell Lab

A KNOWLEDGE-DRIVEN MODELING FORMALISM FOR AUTOMATIC STRUCTURAL INTERPRETATION

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Building structural models of geological entities is generally addressed as an interpolation problem that requires human experts to interpret input data and use knowledge (Wellmann and Caumon, 2018). Although experts can effectively interpret, their interpretations can be subjective and occasionally prone to error (Bond, 2015). This is largely due to under-sampling of data, requiring experts to make choices in the selection and preparation of these data and knowledge (Bond et al., 2012), and selection and configuration of modeling algorithms (Caumon et al., 2009). Modeling algorithms also do not reflect the complex expert interpretation process, as they incorporate only a portion of the knowledge typically held by experts and have limited ability to directly interact with experts during the interpretation process itself. This makes it challenging to build geologically complex models and systematically identify and address inconsistencies in a model. A crucial step toward resolving these issues is the formalization of the interpretation process and the explicit use of formalized knowledge. In this work we develop and prototype such a formalization. A prototype algorithm and tool (Figure 1) are presented and applied to simple folding structures, and the results are favorably compared to existing approaches. This comparison highlights the potential of the proposed approach to reduce the need for expert involvement and increase the range of knowledge utilized.

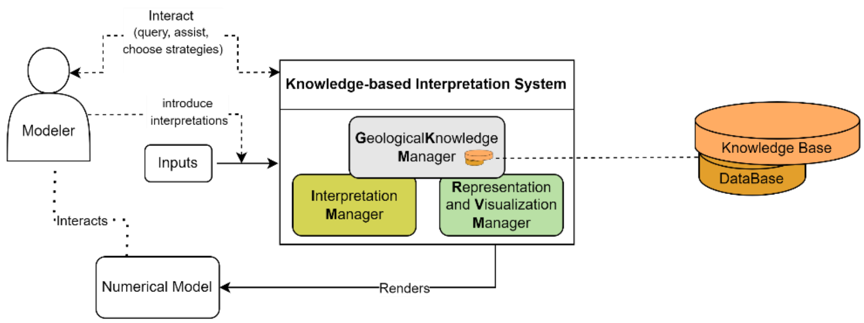

Figure 1: General architecture of the proposed knowledge-based interpretation system. The system comprises three main components: a Geological Knowledge Manager, an Interpretation Manager, and a Representation and Visualization Manager. The system is supported by an external knowledge base that structures essential knowledge elements explicitly. A user interface facilitates interaction with the system during interpretation and engagement with the generated numerical model.

References

Bond, C.E., 2015. Uncertainty in structural interpretation: Lessons to be learnt. Journal of Structural Geology 74, 185–200. https://doi.org/10.1016/j.jsg.2015.03.003

Bond, C.E., Lunn, R.J., Shipton, Z.K., Lunn, A.D., 2012. What makes an expert effective at interpreting seismic images? Geology 40, 75–78. https://doi.org/10.1130/G32375.1

Caumon, G., Collon-Drouaillet, P., Le Carlier de Veslud, C., Viseur, S., Sausse, J., 2009. Surface-Based 3D Modeling of Geological Structures. Math Geosci 41, 927–945. https://doi.org/10.1007/s11004-009-9244-2

Wellmann, F., Caumon, G., 2018. 3-D Structural geological models: Concepts, methods, and uncertainties. Advances in Geophysics 59, 1–121. https://doi.org/10.1016/bs.agph.2018.09.001

Geological ontologies for the mineral exploration domain – a review

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In the era of generative AI and advanced computational modelling, standardised knowledge representation has become crucial for geoscience applications, particularly in mineral exploration. Geological ontologies serve as foundational frameworks for structuring domain knowledge, yet their effectiveness in supporting mineral exploration workflows still needs to be evaluated. Effective knowledge representation frameworks are becoming increasingly critical as the field moves toward integrating AI-driven approaches with traditional geological knowledge.

This presentation systematically reviews existing geological ontologies, explicitly focusing on their potential application in mineral exploration and deposit modelling. We evaluate these ontologies through dual perspectives: FAIR principles (such as documentation, accessibility and usability) and how appropriate they are for geoscientific applications (focusing on mineral system concepts and exploration workflows). Our assessment framework examines how different ontologies handle complex geological relationships, process-based knowledge representation, and integration with computational modelling requirements.

The findings highlight critical gaps between theoretical knowledge representation and practical needs in mineral exploration. We particularly examine how existing ontologies support or limit the implementation of process-based triggers and geological rule systems - essential elements for modelling mineral-forming systems. This review provides strategic insights for practitioners and developers working on knowledge-driven approaches to mineral exploration, particularly those integrating semantic frameworks with computational methods.

Fault data association with graph in mining context

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Faults are a favourable factor for the development of strategic mining resources (e.g., Mirzaie et al., 2015; Rabeau et al., 2013). Defining the geometry of faults in the subsurface using 3D models is, therefore, important for exploring and managing mining resources. However, the accuracy of these model depends on the quality and quantity of input data. Two types of data are generally considered to map faults in the subsurface: seismic images and borehole images. Borehole images are high-resolution data that provide only local information; for instance, on fault observations, dip, dip direction and fault aperture can be identified. Conversely, seismic data provide information on a much larger scale but at a lower resolution. Faults are identified as “fault sticks” on 2D seismic images, with some characteristics such as the slope, the throw and the length. Considering these sparse and incomplete data, several fault networks can be drawn.

To assess the associated uncertainty, Godefroy et al. (2019) uses a graph to represent the potential that two observations belong to the same fault object. Expert structural knowledge is translated into parametric functions to estimate this potential. Originally, this methodology was developed for the association of seismic data. In this presentation, new rules are proposed to manage interpretations of borehole images in a mining context. In some cases, the definition of rules is complexed and potentially be directly learned on analogue with machine learning. Therefore, the approach is supplemented using Random Forest (Breiman, 2001) to infer such rules and reproduce them. The problem is considered as a probability estimation from a training set of features and class, indicating whether a pair of observations belong to the same fault (associated) or are disjoint. Fault characteristics of paired observations are combined to form features, and the training set is either defined from analogue models or a small part of the area of interest that is already associated. Results show the ability of the Random Forest to effectively retrieve the main structures, and open new perspectives to combine expert knowledge with machine learning.

Breiman, L., 2001. Random Forests. Machine Learning 45, 5–32. https://doi.org/10.1023/A:1010933404324
Godefroy, G., Caumon, G., Laurent, G., Bonneau, F., 2019. Structural Interpretation of Sparse Fault Data Using Graph Theory and Geological Rules: Fault Data Interpretation. Math Geosci 51, 1091–1107. https://doi.org/10.1007/s11004-019-09800-0
Mirzaie, A., Bafti, S.S., Derakhshani, R., 2015. Fault control on Cu mineralization in the Kerman porphyry copper belt, SE Iran: A fractal analysis. Ore Geology Reviews 71, 237–247. https://doi.org/10.1016/j.oregeorev.2015.05.015
Rabeau, O., Royer, J.-J., Jébrak, M., Cheilletz, A., 2013. Log-uniform distribution of gold deposits along major Archean fault zones. Miner Deposita 48, 817–824. https://doi.org/10.1007/s00126-013-0470-7

Capturing permeability anisotropy in complex geological settings: implications for mineral exploration

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Permeability is a key parameter governing fluid flow in porous media and its accurate representation is crucial in geological fluid flow simulations. However, the complexity of permeability distributions in geological systems often leads modellers to make simplifying assumptions, which may have a significant impact on fluid flow predictions. One commonly overlooked aspect is permeability anisotropy, which, despite its importance, is frequently disregarded due to the additional effort required for model setup and the computational cost associated with its inclusion. As a result, permeability is commonly assumed to be isotropic or to have simple horizontal/vertical anisotropy, which is unrealistic in most cases.

In this study, we demonstrate how even minor misalignments in permeability anisotropy can significantly influence fluid flow direction and magnitude, particularly in thin stratigraphic units. To address this issue we propose two approaches for populating models with anisotropic permeability aligned with geological layering.

The first method uses stratigraphic forward modelling to estimate the permeability distribution in a sedimentary basin, including both its magnitude and orientation, which is subsequently used in fluid flow simulations. An example from the McArthur Basin of Northern Australia (Sheldon et al., 2023) demonstrates the impact of permeability anisotropy on fluid pathways through the sediments, with implications for sediment-hosted mineralisation.

The second method utilises a synthetic potential field aligned with geological horizons (e.g. folded stratigraphic layers) to define the direction of permeability anisotropy (Poulet et al., 2023). The method is demonstrated using a conceptual model of the Sheep Mountain Anticline (Laramide Province, USA), which includes folded sedimentary rocks intersected by faults. Lastly, we illustrate the critical role of permeability anisotropy in controlling supergene mimetic martite-goethite deposits through a case study from the Hamersley Basin in Western Australia (Poulet et al., 2022), underscoring its broader significance in fluid flow modelling for mineral exploration and other purposes.

References:

Poulet, T., Giraldo, J. F., Ramanaidou, E., Piechocka, A., & Calo, V. M. (2022). Paleo stratigraphic permeability anisotropy controls supergene mimetic martite goethite deposits. *Basin Research*. https://doi.org/10.1111/bre.12723

Poulet, T., Sheldon, H. A., Kelka, U., & Behnoudfar, P. (2023). Impact of permeability anisotropy misalignment on flow rates predicted by hydrogeological models. *Hydrogeology Journal*. https://doi.org/10.1007/s10040-023-02708-4

Sheldon, H. A., Crombez, V., Poulet, T., Kelka, U., Kunzmann, M., & Kerrison, E. (2023). Realistic permeability distributions in faults and sediments: The key to predicting fluid flow in sedimentary basins. Basin Research. https://doi.org/10.1111/bre.12792

3D GEOLOGICAL MODELS AND PROCESS UNDERSTANDING FOR MINERAL EXPLORATION

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Three-dimensional (3D) geological models are powerful tools with a wide range of applications for many kinds of subsurface analysis, including resource exploration and management. We present two case studies illustrating how 3D models with contrasting styles in construction, complexity, and source of data combined with geomechanical deformation – fluid-flow numerical simulations can be used as tools to better understand the formation of hydrothermal ore deposits and to aid mineral exploration.

The first example illustrates how geometrically simple models can improve understanding of the structural controls and influence of granitic bodies on tungsten mineralisation in the Hodgkinson Province of North Queensland, Australia. Numerical simulations of coupled deformation and fluid flow are used to explore how varying fault orientation, proximity of faults to granitic intrusions and deformation directions would have affected strain localisation and fluid focusing at the time of mineralisation. The workflow for constructing the 3D models in this example allows the user to specify a range of strike, dip, and thickness of fault zones, which is useful for exploring controls on mineralisation where these fault parameters are not well-constrained (Schaubs and Poulet, 2023). 3D meshes are then constructed by extrapolating the fault traces according to the specified dip and dip direction.

The second example showcases the use of geometrically complex 3D models in deformation – fluid-flow simulations. The simulations represent hydrothermal fluid flow associated with gold mineralisation around Cambrian basalt domes north of Stawell, Victoria, Australia, with the geometry of the domes being constrained by gravity inversions. Several prospective areas are modelled with varying deformation directions based on published interpretations (Miller et al., 2006). Numerical meshes where constructed by isosurfacing the voxel outputs of gravity inversions and selecting a suitable density corresponding to the surrounding geology. As there is uncertainty in the extent and size of the basalt bodies, these simulations provide a first step in guiding exploration. As the exact position of the basalts based on the gravity inversions need to be verified, this modelling can be used as a focus for drilling. There is significant strike length of basalt bodies and geology to be explored; reducing this by even a small percentage may help reduce exploration time and costs. Despite the uncertainty of the thickness of the basalts and the nature of their upper surface, along with other geologic constraints, these models can be used to guide exploration, where areas displaying increased dilation may be indicative of *loci* of both extensional vein-hosted and disseminated gold typical of basalt-dome-related deposits in this region.

The two examples presented here have very different levels of geometric complexity and methods for mesh construction. The Hodgkinson Province example enables efficient use of 2D GIS data and for multiple scenarios to be quickly tested. Mesh construction in the Stawell example, with its more complex 3D geometries, is much more labour-intensive but allows for more complex and realistic geometries to be included. Both examples highlight the importance of 3D models (e.g., Loop, Leapfrog, Gocad) that can easily be modified to accommodate new data, different concepts, or varying degrees of uncertainty, as well as be easily exported to numerical meshes.

References:

Miller, J.M., Wilson, C.J.L., Dugdale, L.J., 2006. Stawell gold deposit: a key to unravelling the Cambrian to Early Devonian structural evolution of the western Victorian goldfields. Aust. J. Earth Sci. 53, 677‑695.

Schaubs, P and Poulet, T. 2023. Simulating fluid flow in fault-hosted mineral systems. Geological Society of Australia, Australian Earth Sciences Convention (AESC), Perth Convention and Exhibition Centre, Perth, Western Australia June 27-30.

3D Modelling and Surface Curvature Analysis of the Osterhorngruppe Nappe: Insights into Detachment Kinematics and Salt Tectonics in the Northern Calcareous Alps

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The geometry of nappes in fold-and-thrust belts is an important indicator of the kinematics governing thin-skinned tectonics, especially in flat-lying nappe stacks where multi-layer detachment mechanisms may be active. The Osterhorngruppe in the Northern Calcareous Alps (NCA) represents a relatively undeformed flat-lying nappe, making it an ideal area to investigate the interplay of detachment processes and geometry (Neubauer et al., 1999). The critical interface between the Osterhorn-Tirolic nappe, the underlying Bajuvaric nappe, and the Rhenodanubian Flysch basement offers unique insights into the tectonic evolution of the NCA (Mandl, 1999). Recent studies highlighting the role of Permian evaporites in Eastern Alpine tectonics further raise questions about the potential influence of salt tectonics in this region (Fernández et al., 2020).

This study presents detailed 3D geological models of the Osterhorngruppe and its associated thrust sheets, coupled with surface curvature analysis (Lisle, 1994), to evaluate competing hypotheses (Corbel & Wellmann, 2015) for detachment kinematics. Specifically, we test scenarios involving evaporite-controlled detachments and investigate how salt tectonics may have contributed to the observed structural configuration. Furthermore, the application of different interpolation methodologies, such as universal co-kriging in Gempy (Varga et al., 2019) and implicit neural representations in GeoINR (Hillier et al., 2023), reveals distinct geometric features that impact kinematic interpretations.

Our results underscore the importance of integrating advanced modelling techniques with field observations to refine our understanding of fold-and-thrust belt kinematics and the role of detachment layers in tectonic evolution. This work contributes to the broader discussion on the mechanisms shaping the Eastern Alps and offers a framework for future studies in analogous geological settings.

References

Corbel, S. and Wellmann, J.F. (2015) Framework for multiple hypothesis testing improves the use of legacy data in structural geological modeling. GeoResJ, 6, 202–212. doi: 10.1016/j.grj.2015.04.001.

Fernández, O., Habermüller, M. and Grasemann, B. (2020) Hooked on salt: Rethinking Alpine tectonics in Hallstatt (Eastern Alps, Austria). Geology, 49, 325–329. doi: 10.1130/G47981.1.

Hillier, M., Wellmann, F., de Kemp, E.A., Brodaric, B., Schetselaar, E. and Bédard, K. (2023) GeoINR 1.0: an implicit neural network approach to three-dimensional geological modelling. Geoscientific Model Development, 16, 6987–7012. doi: 10.5194/gmd-16-6987-2023.

Lisle, R.J. (1994) Detection of Zones of Abnormal Strains in Structures Using Gaussian Curvature Analysis. AAPG Bulletin, 78, 1811–1819.

Mandl, G. (1999) The Alpine sector of the Tethys shelf – Examples of Triassic to Jurassic sedimentation and deformation from the Northern Calcareous Alps. Mitteilungen der Österreichischen Geologischen Gesellschaft, 92, 61–77.

Neubauer, F., Genser, J. and Handler, R. (1999) The Eastern Alps: Results of a two-stage collision process. Mitteilungen der Österreichischen Geologischen Gesellschaft, 92, 117–134.

Varga, M. de la, Schaaf, A. and Wellmann, F. (2019) GemPy 1.0: open-source stochastic geological modeling and inversion. Geoscientific Model Development, 12, 1–32. doi: https://doi.org/10.5194/gmd-12-1-2019.

Spatial error constraints reduce overfitting for potential field geophysical inversion

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Geophysical inversion is crucial for characterising Earth's structure and is widely used by resource explorers to convert gravity, magnetic, seismic, and electrical data into petrophysical models. However, due to inherent ambiguity, various models can fit the data, necessitating constraints like geological models and petrophysical data to narrow down solutions. These constraints, like the data, contain noise and errors, leading to uncertainties in the final model. The inversion aims to find the best solution by minimising the misfit between data and model, but uncertainties in data lead to uncertain and potentially misleading models, prone to overfitting. Overfitting occurs when the model fits data noise, creating false anomalies which can be mistaken as targets.
This study describes using spatial error constraints derived from geophysical data to mitigate overfitting in geophysical inversion. Spatial error estimates are obtained through a geostatistical model using Integrated Nested Laplacian Approximation (INLA). A case study in East Kimberley, northern Western Australia, uses the Tomofast-x platform for gravity inversion. Different percentiles from the geophysical model were tested to see if extreme gravimetry values should be considered. Results show that using spatial error constraints reduces overfitting, although varying percentiles offers limited additional benefits.

Discovering Open File 3D Geoscience Models: A Survey of the WAMEX Database

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Resource companies invest significant resources in the development of sophisticated 3D models of the subsurface to inform exploration and production strategies. These models, while critical to advancing understanding and decision-making in the sector, are often submitted in proprietary software systems, limiting their accessibility for external research and academic collaboration. The challenges are further compounded by the diversity of delivery formats and specialized software used to create these models, creating barriers to interoperability and broader engagement. Where computer science fields are applied to geoscience, it is common to encounter calls for FAIR data principles and to move away from propriety data formats (Ma, 2023). This holds particularly true for fields like data science where the technology, and the research are intrinsically linked (Sonnenburg, 2007).

The more recent trend towards cloud-based distribution by leading 3D modeling software providers introduces additional hurdles. Cloud-based access models often restrict data portability and limit the ability to independently analyze or repurpose subsurface models outside of proprietary platforms. Formative work has been done in the generation of extensive sets of synthetic 3D models to facilitate research outcomes. (Jessell, 2021) However, publicly accessible, geologist defined 3D subsurface models are becoming increasingly valuable for fostering innovation, cross-disciplinary research, and academic training in geosciences and resource management.

The WAMEX database operated by the Geological Survey of Western Australia, contains many open file 3D models across a variety of commodity groups (Riganti, 2015). This presentation explores a selection of publicly available 3D subsurface models that can be found within the WAMEX database, and provides a detailed characterization of their features, formats, and potential applications. By highlighting the opportunities and challenges associated with these models, the talk underscores their role in bridging the gap between proprietary industry practices and open scientific inquiry, while advocating for enhanced accessibility to drive progress in resource exploration and geoscientific research.

Anumber	Geological Summary	Software
A90315	The Doolgunna Project by Sandfire Resources includes a number of tenements including the DeGrussa VHMS Cu-Ag deposit. Included in this report is a 3D resource model.	Surpac
A93519	The Teutonic Bore Project in Western Australia's northeastern Goldfields includes the Jaguar and Bentley Mines, both volcanic-hosted massive sulphide deposits, and the historic Teutonic Bore Mine.	Vulcan
A96734	The Central Yilgarn Iron Project (CYIP) by Jupiter Mines focuses on two major deposits in Western Australia: the Mt Ida Magnetite and Mt Mason Hematite deposits.	DataMine

References

Jessell, M. G. (2021). Into the Noddyverse: A massive data store of 3D geological models for Machine Learning & inversion applications. *Earth System Science Data Discussions*, pp.1-19.

Ma, X. (2023). Data science for geoscience: Recent progress and future trends from the perspective of a data life cycle.

Riganti, A. F. (2015). 125 years of legacy data at the Geological Survey of Western Australia: Capture and delivery. *GeoResJ*, pp.175-194.

Sonnenburg, S. B. (2007). The need for open source software in machine learning.

Trans-dimensional geometrical inversion applied to undercover exploration using gravity data in the Boulia region (Australia)

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An innovative approach to geometrical inversion using a trans-dimensional (trans-d) strategy is presented and applied to gravity data. Established geometrical inversion methods rely on fixed-dimensional models assuming that the number and nature of rock units required to describe the subsurface are known a priori, with the risk of failing to adequately capture geological variability and complexity. The trans-d approach (e.g., Sambridge et al. 2006) is a Bayesian method that adapts model complexity to the geophysical data. Following this philosophy, the proposed trans-d approach incorporates prior information from a structural geological model derived through geological modelling and populated with density values. The parameters that are perturbed consist of the number of rock units necessary to fit the gravity data, their geometry, and their density.

Unlike other studies conducting trans-d inversions with the addition and removal of 1D/2D layers, the proposed method is specifically designed for 3D applications. Building up from Giraud et al. (2024a, b), trans-d is achieved with the "birth" of rock units, i.e., the addition of a new rock unit in the model, and, conversely, the "death" of a rock unit. For implicity, the subsurface discretization remains unchanged throughout the inversion. Several millions of 3D models are sampled employing a Marko chain Monte Carlo algorithm. To exploit the wealth of information in such large collections of models, an innovative posterior analysis technique is utilized. For visualization, the workflow of Portes et al. (in press) is applied to 3D. A dimensionality reduction technique (t-SNE) is applied and the models are projected onto a 2D space. This workflow is extended with a clustering algorithm grouping models into families presenting similar characteristics, allowing for the compact visualization and interpretation of a large numbers of models.

The proposed method is applied to data from the Boulia region (Queensland, Australia), an area prospective for various commodities. A subset of this region was selected where prior geological modelling, based on borehole information and seismic interpretations, fails to explain the gravity data, indicating the absence of important information and observations. To address this gap, trans-d geometrical inversions were performed, sampling over 3 million models. The results suggest the presence of two previously unaccounted-for positive density anomalies between 1-4 km depth, aligned N-S. Among the identified scenarios, one prominent family suggests that the two anomalies are in close proximity, while others indicate that they may be connected. Additionally, some scenarios suggest the presence of a smaller anomaly with a negative density contrast in the south. By reducing the gravity data misfit by a factor of 10 and discovering previously unknown units while accounting for prior geological modelling, this example demonstrates the effectiveness of the proposed trans-dimensional approach in resolving unsampled geological structures. Moreover, it highlights the added value of this method compared to more conventional inversion techniques.

References

Giraud, J., M. Rashidifard, V. Ogarko, G. Caumon, L. Grose, J. Herrero, P. Cupillard, M. Lindsay, M. Jessell, and L. Aillères, 2024a, Transdimensional geometrical inversion: Application to undercover imaging using gravity data: International Workshop on Gravity, Electrical & Magnetic Methods and Their Applications, Shenzhen, China, May 19–22, 2024, 167–170.

Giraud, J., M. Ford, G. Caumon, V. Ogarko, L. Grose, R. Martin, and P. Cupillard, 2024b, Geologically constrained geometry inversion and null-space navigation to explore alternative geological scenarios: a case study in the Western Pyrenees: Geophysical Journal International, 239, 1359–1379.

Portes, L., G. Pirot, M. Nzikou, J. Giraud, M. Lindsay, M. Jessell, and E. Cripps, In pressFeature fusion-enhanced t-SNE image atlas for geophysical discovery: Nature Scientific Reports.

Sambridge, M., K. Gallagher, A. Jackson, and P. Rickwood, 2006, Trans-dimensional inverse problems, model comparison and the evidence: Geophysical Journal International, 167, 528–542.

Machine Learning Gravity Inversion with Geological Constraints

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Integrating geological and petrophysical constraints into geophysics inversion has the potential to enhance subsurface imaging by improving accuracy and reducing ambiguities. This study presents a novel machine-learning framework for gravity inversion that incorporates geological constraints using convolutional neural networks (deep learning). The training dataset is generated via synthetic geological models created with the Noddy geological modeling system (Jessell, 1981; Jessell and Valenta, 1996), ensuring a controlled and geologically realistic training environment.

We incorporate geological maps as direct inputs to the neural network, offering structural and petrophysical context that enhances the inversion process. For certain simplified scenarios, the results show notable improvements in resolving subsurface structures compared to classical inversion techniques performed using the Tomofast-x platform (Giraud et al., 2021; Ogarko et al., 2024).

Additionally, we outline future advancements using physics-informed neural networks (PINNs) to further embed physical laws and geophysical equations directly into the inversion process. This hybrid approach aims to marry the benefits of machine learning with the rigor of traditional physics-based methods, paving the way for more robust and interpretable inversions.

This research highlights the promise of machine learning methods in geophysical inversion and their ability to complement and improve upon classical approaches through the integration of geological knowledge.

Giraud, J., V. Ogarko, R. Martin, M. Jessell, and M. Lindsay. 2021, Structural, petrophysical, and geological constraints in potential field inversion using the Tomofast-x v1.0 open-source code, Geosci. Model Dev., 14, 6681–6709 pp.

Jessell, M. W. 1981. NODDY – An interactive map creation package, Unpublished MSc, University of London.

Jessell, M. W. and Valenta, R. K. 1996. Structural Geophysics: Integrated structural and geophysical mapping, in: Structural Geology and Personal Computers, edited by: DePaor, D. G., Elsevier Science Ltd, Oxford, 542 p.

Ogarko, V., K. Frankcombe, T. Liu, J. Giraud, R. Martin, and M. Jessell. 2024, Tomofast-x 2.0: an open-source parallel code for inversion of potential field data with topography using wavelet compression, Geosci. Model Dev., 17, 2325–2345 pp.