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Editorial

Preface and Introduction—Applied Structural Geology in Mineral Exploration and Mining

1. Introduction

This Special Issue of the *Journal of Structural Geology* is the outcome of a meeting on Applied Structural Geology for Mineral Exploration and Mining (Kal2002), held in September 2002, at Kalgoorlie, Australia, and convened by the Australian Institute of Geoscientists (AIG). Sponsors of the meeting were:

- Anglogold (Australia)
- Auriongold (now Placer Dome Asia Pacific)
- Australia's Paydirt
- Barrick (Australasia)
- Croesus Mining
- Gold Fields (St Ives)
- Hellman and Schofield
- The Specialist Group on Tectonics and Structural Geology of the Geological Society of Australia (SGTSG)
- Sons of Gwalia
- Straits Resources

One session at the meeting was devoted to discussion about Best Practice in Structural Geology, and another session discussed structural geology in the context of public (stock market) resources reporting. This report on these sessions makes an excellent introduction to the Special Issue. The aim of the best practice session was to provide a constructive, forward-looking focus for the application of structural geology to the exploration and mining industries. Whilst there are many areas for improvement, the participants noted the high quality of presentations at the meeting and the commitment of many companies to excellent structural geology. Although the focus was largely on the Australian scene, the issues have worldwide relevance.

2. What is applied structural geology?

Reading the abstract volume for the Kalgoorlie symposium, it is clear that two different meanings of Applied Structural Geology are used (S. Vearncombe, 2002): 'Structural Geology of Mineralisation' and 'Value Added using Structural Geology'. At this symposium, the published abstracts were strongly oriented towards the former, but the latter had arguably the larger representation in the oral presentations. Interestingly, many government and academic geologists emphasise the financial value of their work, in addition to academic merit.

3. The mineral exploration and mining industry

There have been immense changes in our industry, with numerous and on-going takeovers resulting in there being far fewer clients and employers, and an enormous level of redundancies. This partly reflects the low return on capital of operating mining companies (~5%) for the past 20 years and a loss of confidence in the exploration process (Leggo, 2002). Mineral exploration expenditure is at a low. For instance, Australian gold exploration spending in March 2002 was down to almost half that of the same period in 1997 (Australian Mineral Statistics, 2002). There are currently 55% fewer geoscientists working in Australia than there were at the end of 1996, primarily due to a sustained downturn in mineral exploration (Corbett, 2001). Amongst those remaining the unemployment rate of 14% masks a much higher rate of under-employment amongst the 20% of geoscientists who are self-employed. In Australia the un- and under-employment geologists' situation is probably the worst in the world, but globally very few geologists have a secure job. In our industry we need people with creative ideas, but these same people may be seen as hard to manage, and they are often managed out of the system. We express our concern at the continuing high level of redundancies associated with the ongoing take-overs and globalisation.

In this uncertain industry, the importance of mentoring needs to be further recognized and encouraged (Garwin, 2002). A mentor is a 'wise and trusted counsellor', who is available to students or coworkers for discussions that relate to that individual's professional and life interests. A successful mentoring program should include both industry- and university-based scientists. The mentor should provide guidance, lead by example, be a team player, and maintain a

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positive attitude. He or she opens doors of opportunity for those they advise. A mentor has the ability to develop an open and creative environment that encourages others to participate in learning-related activity. In addition, a mentor should recognise his/her limitations and be willing to direct others toward someone more knowledgeable, when appropriate (Garwin, 2002). This may be part of the role of a consultant, rather than a contractor; he/she is not just an expert, but must be accepted as part of the team.

4. Structural geology: an observational science with new constraining technologies

Structural geology has to date been a fundamentally observational science. For a holistic picture of structural geology, data collection and interpretation should be synchronous, intuitive and creative (Vearncombe and Vearncombe, 1998). Old-fashioned 'understanding' remains the catch phrase. Constraining techniques that provide rigour to the observational aspect of our science are being developed, and just some of these that were mentioned at the symposium are listed below:

- Modern geophysical techniques such as multiscale edge detection by wavelet analysis ('worming' e.g. Archibald et al., 1999).
- Three-dimensional computer models with rotational viewing of multiple-dimensional interpretations have improved visualisation of structures, and their evolution (e.g. Monteiro et al.).
- The SpaDiS™ system of spatial analysis, a product that has evolved from Fry analysis (Vearncombe and Vearncombe, 1999).
- The Leapfrog™ construction of three-dimensional geological models from raw drill-hole data (Cowan et al., 2002).
- Comparison with basic theoretical considerations of rock deformation and fluid flow (e.g. McKeagney et al., Sibson).
- The techniques of fractal geometry.
- Sequence stratigraphy.
- Balanced cross-sections.
- Analogue models (e.g. McClay et al., 2002).
- Numerical modelling—both physical and chemical (e.g. McLellan et al.).
- Qualitative and quantitative microstructural geology.

Unfortunately, the commercial potential of any observational science is limited as the process is person-dominated and the observations vary with the individual operator. Structural geologists are not frightened of new technologies, nor are they slow to adapt to them, but there are remarkably few commercially-viable technologies that originate within structural geology (J.R. Vearncombe, 2002). New technologies are needed to provide improved data collection and analysis independent of personal observation. The commercially-viable technologies provide market differentiation, with the latter a move from time-based fees to product-deliverable charging. Commercially viable technologies have the potential to promote and grow the minerals industry in much the same way that 3D seismicity has done for the petroleum industry. Examples of structural geology-derived technologies are listed above, along with other techniques, some of which may present future commercial opportunities.

5. Structural geology in the context of the exploration and mining industry

Although the understanding of structures, deformation mechanisms, and relationship of structural controls to fluid flow and mineralisation processes continues to progress, the effective application of these advances to the mining industry lags behind. This lag between structural understanding and application has occurred for a number of reasons detailed by McCuaig (2002) from which the following is a summary:

- In exploration, there is commonly a focus on genetic models that encourage a restrictive and limited view of ore deposit styles rather than the mineralising processes.
- There is sometimes a lack of understanding of mining requirements in exploration, of the exploration process among the mining community, and of both mining and exploration among some structural geologists. This hinders effective communication of structural information and knowledge.
- When good structural geology is carried out on projects, it is all too rarely effectively communicated or utilised in downstream mining processes such as resource estimation and geotechnical engineering.
- Industry geologists often plead a lack of time to undertake structural analysis, which may also be perceived as an arduous task. The geology section of a mine is often the first port of call for any task and mapping commonly falls through the slats in time management. Mapping standards have dropped, and sometimes mapping is not happening when it should. Time is becoming an even more precious commodity for the operations geologist with the staff reductions that have swept through the industry in the past five years.
- Where structural mapping is carried out, the focus is usually on data collection and storage rather than data interpretation and building an understanding to resolve key issues for exploration and mining teams.

- Geologists should collect and interpret structural data in the context of the issues that need to be addressed. It is understanding and the 3D interpretation of these data that needs to be achieved, not just data. Interpretation should begin from the time the first data are collected. Hypothesis formulation and testing is a critical element of this process that is commonly not included at the early stages of a project. The interpretation of structure is iterative in the same way as stratigraphic sequence interpretation, and will develop during mapping. This process will last for at least the mine lifetime or the duration of an exploration program.

6. General practice in structural geology

Structural geology is critical to finding, evaluating and mining deposits and the effects are manifest at all scales. Yet, it is commonly the basic techniques that are disregarded or under-utilized (Davis, 2002). Structural geology is especially difficult in terrains that lack significant outcrop, such as the gold- and nickel-rich Yilgarn Craton, Australia, where scientific inquiry has proceeded by model-deductive (or Darwinan) methods but rarely by inductive (or Baconian) methods (Moores and Twiss, 1995). These two contrasting methods are well illustrated in this issue. The model-driven approach is taken by Cox and Rumming, who test a model of earthquake aftershock against the geological and geophysical data, and by Laing, who proposes a model for the development of extensional veins. The Baconian approach is illustrated by Tripp and Vearncombe, who recognised a series of structures in aeromagnetic imagery, followed these into gold deposits, developed a model from the observations and then expanded it into a targeting tool, and by the papers by Betts et al., Blenkinsop, Craw and Campbell, Stephens et al. and Stone and Archibald, who report observations on a wide range of scales that are synthesized into final models.

Geometric analysis and integration of scale in all data sets, whether it be interpretations from drilling, field mapping, aeromagnetic and gravity images or seismic profiles, are fundamentally important to deriving the best possible geological interpretation (Smith, 2002). Many structures are fractal within a deformation zone, and it is important to up- and down-scale in interpretation (illustrated by the papers of Kreuzer, Peters and Roache). Microstructural analysis is one of the more powerful structural techniques that is dramatically under-utilized within the exploration and mining industry. Competent petrologists give an indication of the overprinting history of the minerals where several stages are present. However, an indication of the age and controls of growth with respect to structures such as cleavages and mylonitic fabrics can rarely be given from un-oriented samples. As orientated sections cost the same as un-oriented thin sections, simple benefit analysis will show that the resulting petrological description is significantly improved (Davis, 2002). We also note that the recent advances in microstructural geology (e.g. electron backscatter diffraction) can be applied to deformed ore phases and have the potential to revolutionise the quantitative analysis of deformation associated with ore body formation. The power of microstructural analysis linked with deposit- and regional-scale geology is illustrated in the paper by Jolley et al.

7. Structural geology in mining and exploration

To effectively apply structural geology in the mineral exploration and mining process, it needs to be integrated with all available geoscience datasets, including geophysics, geochemistry (whole-rock and specialised techniques), alteration, geochronology, basin analysis, and understanding of mineral systems from a process point of view. Structural geology is not effective, nor even truly possible, as an isolated endeavour.

To improve the image of structural geology in the mineral exploration and mining process one must take an avid interest in the issues facing the downstream users of structural information in the mining process. For example, what information do the exploration, resource estimation and geotechnical engineering teams require, and how will they need it communicated? A way in which this could be actively promoted would be for non-industry structural geologists to spend time in industry, possibly on secondment.

Personalised selling of an individual structural geologist (commonly but not always a consultant) is perhaps a natural product of a difficult and contracting market. On a positive note, the authors observe that since this topic was raised at the symposium there have been major achievements counteracting the negative aspects of past selling methods. Constructive marketing now promotes structural geology for the benefit of the complete profession.

Ground support and health and safety are important aspects of (structural) geology with clear financial benefits. Geotechnical engineers face the problem of much sparser datasets, and are often uncomfortable extrapolating away from datapoints. Here the structural geologist adds value by placing geotechnical data into a geological context.

The paper by Smith inter-relates structural and rock mechanic geology in the context of block size. By communicating closely with the engineers, the geologist can help to constrain geotechnical domains that are based on solid geological understanding.

Our relationship with society in general is interlinked to that of our industry, and we need to promote our industry and specifically structural geology when we communicate to non-geologists.

8. Reporting and communicating structural results

If there is a critical weakness in our application of structural geology to the industry it is a failure to communicate. The observational and three-dimensional nature of the science can make communication difficult. However, consideration of the appropriate sort of structural geology for the audience will help. We need to market structural geology in a production environment, and hence we have to show financial benefits. White (2002) lists a variety of reporting credentials that are repeated below in a modified form:

- Structural jargon must be kept to a minimum and any jargon used must be clearly defined.
- Maps must keep to convention, which may be in-house, and be consistent with the use of symbols. When presenting structural data ensure that maps are not clogged, use layers determined by relevance to the project. Include all data in basic references layer(s), and all workings leading to an interpretation.
- Always distinguish field-based and observational data from interpretation. Give sources of interpreted data.
- The robustness of structural data used in structural interpretation should be stated and the confidence in interpretations should be quantified wherever possible. Interpretations can be given as an estimated percentage; probabilities should be estimated wherever possible (cf. De Wit, 1982).
- Interpretations should be sound and reported clearly and logically. If data give ambiguous interpretations, this should be clearly stated.
- Data should not be over-interpreted.

9. JORC code and structural geology

The Joint Ore Reserves Committee (JORC) Code has been developed in association with AIG, the Australasian Institute of Mining and Metallurgy and the Mining Council of Australia to set out minimum standards, recommendations and guidelines for public reporting of exploration results, Mineral Resources and Ore Reserves in Australasia (JORC, 1999). Because the JORC code is widely accepted it has been a lead for other countries and by the end of 2001 the new or updated Codes of Australia, South Africa, Canada, USA, Western Europe, UK and Ireland were very similar to the 1999 JORC Code (McKay et al., 2002).

The discussion that follows is based on discussions at the Kalgoorlie Conference. The geometry and shape of the deposit and the distribution of the grade and rock boundaries are important when describing the style and nature of the mineralisation. Regrettably, structural geology is often the poor relation in these studies and its absence increases the risk associated with any resource development project (Baxter, 2002). One geologist reported that he had found 20 resource reports from the past year (out of a total of 24 examined) that did not in his opinion comply with the geological guidelines of the JORC code as identified in Table 1 of the Code. Other symposium participants supported this point, complaining that the geology, unlike the statistics, is not being audited. Resource estimation reporting tends to be all numbers and no geology. Geostatistical parameters should be established after the geometry is defined.

At the stage of determination of proven and probable reserves it is necessary to include an assessment of the geotechnical parameters and among these are the presence of structures adjacent to or within the mineralisation. Geological mapping is a very important tool to identify these zones. Particularly in underground mines it is essential to determine the potential hanging wall rock failures as they can lead to massive dilution of the mineralisation if not managed. Detailed understanding of the structural geology at the stage of estimation of ore reserves can minimise the risk in the estimation. Structural geology provides information on the shape of the mineralisation, potential planes of weakness (hence dilution) and the principal directions of continuity of grade.

Noting that JORC is about how Exploration Results and Resource estimates are reported to the public, and does not dictate how Resource/Reserve estimates are prepared, the subgroup of symposium participants involved with resource evaluation recommended the following:

- The geology, and specifically the structural geology, should be overarching and not an adjunct to a resource evaluation.
- The JORC committee emphasise to all involved in public reporting their guidelines with respect to the geology of exploration results and resources.
- Geologists should proof or audit a resource evaluation, and the geology in a report should be audited either 'in house' or externally.
- The true widths of drill intersections of ore-bearing hosts should be quoted as standard practice.

10. University education

Talking about undergraduate level education, it was observed by academics and industry delegates that there is an international deterioration in mapping skills. Although the reasons for this deterioration are numerous and complex, a significant contributory factor is seen to be a reduction in the amount of time students spend in the field. One academic stated that it is "easier to get money to set up a virtual field trip than for the field trip itself". Industry delegates observe that whilst industry may not regularly or systematically perform classic mapping exercises it uses maps as the fundamental information level. The best understanding of a map comes from someone with field map training, and industry recognises that mapping skills are an essential requirement of graduate geologists. Universities are therefore strongly encouraged to maintain, if not increase, student field programs. Some of the papers delivered at the conference illustrated superbly how important surface and underground mapping is to understanding ore geology, and that some excellent mapping is in fact being carried out both within house and by consultants (Miller and Wilson; Peters; Roache; Tunks et al.).

Regarding research degrees, several delegates commented that it is "frightening how targeted PhD research has become" and there is "little space of (for) individual experiment in many modern PhD studies". This may partly be a function of how research is funded: an extreme view of academic research funding in the UK, Australia and the USA would be that the outcome of research has virtually to be decided before the funding application is made. Industry sponsored research may also be limited by expectations. The change from 'risky' or experimental research towards predictable outcome research is also driven by the demand for publications. Making a similar point to the one above, but phrased differently it was argued that "research students should be just that, not research assistants and their theses their own independent research, not an extension of the supervisor's research program". Doctoral research (and research in general) should strive for wisdom, as opposed to routine application of methodologies and existing knowledge.

11. Conclusion

In summary it can be said without exaggeration that there are a number of crisis areas in structural geology with respect to the exploration and mining industry at present, ranging from lack of security in employment and the global down-turn in exploration, to deteriorating field skills in graduate geologists. The conference clearly felt the need to articulate these issues and to act on them. On the other hand, the excellent and highly varied nature of the science presented at the conference showed that the discipline has both a great deal to offer and to learn from the exploration and mining industry.

12. Organisation of the special issue

The papers fall into two general groups: regional and deposit scale studies. Within the regional group, a subdivision can be made between gold and non-precious metal mineralization, and the deposit scale studies fall into amphibolite or greenschist facies subgroups. Within each group, papers have been arranged in an order reflecting the approximate age of mineralisation, youngest first.

It is worth pointing out that the papers show many processes common to the different scales, and to the different metamorphic grades. A notable feature of this Special Issue is its multidisciplinary scope: various papers illustrate that geochemistry, isotope studies and metamorphic petrology are invaluable adjuncts to structural geology. Volcanology, seismology, basin analysis, and numerical modelling play important roles in other papers. This diversity of approach may partly reflect the nature of the problem of ore genesis, which requires lateral thinking.

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