Presidential Address

Geologic Analogy: A Vital Field Component of Mineral Exploration

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Analogy—partial similarity or resemblance—has been employed widely in the physical and natural sciences, and since the time of the ancient Greeks, has contributed to numerous important advances and breakthroughs (Leatherdale, 1974; Biela, 1991). As espoused more than a century ago by G.K. Gilbert (1886), analogy plays a particularly important role in geology because it is fundamentally a descriptive rather than an analytical science, in which reasoning based directly on observation of partly preserved Earth features is the norm.

Economic geology is a broadly based and somewhat hybrid subject that harnesses most other geologic disciplines to the study of mineral deposits. Field observation, at all scales from the metallogenic to the microscopic, underpins the practice of economic geology, especially its application to mineral exploration. Geologic analogy is identified as the unsung constituent in the classification, synthesis, and modeling of the observational data used by explorationists and is embodied in the exploration process in numerous ways at a variety of scales. Nevertheless, as in all fields of geology, analogic reasoning is interwoven with other principles and attributes, including uniformitarianism, multiple working hypotheses, creativity, experience, and plain genius.

EXPLORATION APPLICATIONS

Geologic analogy has a long history of application to mineral exploration. The Romans learned to recognize that gossans derived from massive sulfide are potential sources of precious metals in the Iberian pyrite belt. In more recent times, the colonial Spaniards focused attention on epithermal quartz veins impregnated with manganese oxide, the supergene oxidation product of manganoan carbonate, when exploring for silver in the central Andes. Generations of prospectors during the nineteenth and twentieth centuries continued to develop familiarity with geologic features that were considered diagnostic of deposit types of interest, with the relevant features being sought wherever prospecting was carried out. This same overall approach is still applied widely by successful explorationists, albeit with the benefit of better geologic data and understanding.

At the most basic level, exploration geologists use analogy, often subconsciously, as part of their thought processes during everyday fieldwork, especially when making and interpreting geologic maps. For example, a geologist spots a powdery white substance in decomposed and limonitic calcareous rock and suspects it to be smithsonite, as previously observed over some zinc deposits. Or he/she sees transparent crystalline aggregates lining irregular cavities in highly silicified andesitic volcanic rocks and thinks they resemble hypogene alunite occurring alongside some high-sulfidation epithermal gold deposits.

At a more advanced level, an appreciation of specific analogies between deposits in different parts of the world can lead to recognition of features that are indicative exploration tools. Such breakthroughs often occur both unexpectedly and instantaneously. Examples might include: K silicate alteration in porphyry copper deposits commonly contains abundant hydrothermal magnetite in both veinlet and disseminated forms where gold contents are high (Sillitoe, 1979); porphyry copper leached cappings are typically characterized by fluffy, purplish-red hematite lining pyrite boxworks where underlain by multicyclic chalcocite enrichment blankets (Anderson, 1982); and low-sulfidation epithermal veins typically display delicate crustiform banding if bonanza gold ± silver grades are present.

The ultimate use of analogy in economic geology is in synthesis of extensive data sets for analogous mineralized systems, preferably both productive and barren ones, to generate descriptive or empirical models for mineral deposit types. The importance of analogy in model

··· from 4 PRESIDENTIAL PERSPECTIVE, CONT.

enhanced quality and scope. For the less developed world, agencies such as UNESCO and the International Development Banks might consider investing in such courses. SEG could use funds from its Foundation to underwrite course development, with the costs for travel and stipends for the instructors provided by host governments, local companies, and international aid agencies. Such courses should have moderate life-spans, be improved continuously, and be accompanied by high quality manuals.

I encourage your input. Should we supplement university programs, and what are the subject areas most needed? Do university departments in the developed nations agree with this type of SEG endeavor, or should we stay out of the education business? Does industry accept that there is a need for such courses, or should we stick to our approach of short courses associated with conferences? Are international aid agencies interested in working with us? The cost of delivering such courses is beyond the scope of SEG's funding sources. Who can help us with this? I encourage you to send me your comments on our role in the education field, as well as more on the public policy intervention issue. If you want to go "public" with these, write to the *Newsletter*!

construction is emphasized by frequent use of specific deposit or district names to denominate widely recognized deposit types. We are all familiar with Cyprus, Kuroko, and Besshi types of VMS deposits, Carlin, Bendigo, Homestake, and Witwatersrand types of gold deposits, Climax-type molybdenum deposits, Mississippi Valley-type lead-zinc deposits, and Superior-type iron formations, for example.

The best deposit models are constructed by geologists who are conversant in the field with large numbers and varieties of analogous deposits. A well-known example is the porphyry copper model relating porphyry stocks to laterally and vertically zoned alteration and mineralization assemblages (Lowell and Guilbert, 1970). This model was influential (and, like most models, also widely abused) in numerous copper exploration programs. When the modeling is carried out by experts on a particular deposit type, additional analogous deposits may be culled reliably from the geologic literature, as exemplified in the compendium by Einaudi et al. (1981) of skarn types and their hydrothermal evolution.

In the last two decades or so, understanding of several mineral deposit models has benefited enormously from the discovery and study of modern analogues. Perhaps the most dramatic, albeit long-predicted, example is the discovery of VMS-type mineralization at a midocean ridge (Francheteau et al., 1979), and subsequently, in a variety of other submarine extensional settings. Our comprehension of the geometries and controls of high- and low-sulfidation epithermal deposits gained much from studies of their active analogues, geothermal systems (e.g., Henley and Ellis, 1983). SEDEX lead-zinc deposits still lack a known modern analogue, although continental-margin rifts like the Salton trough, California, with its associated base metal-rich, hypersaline geothermal system, have been proposed as appropriate sites (McKibben et al., 1988). Modern analogues of more deeply formed mineral deposits are, of course, more difficult to observe directly, although minor carbonate veins and associated hot-water seepages may be the surficial manifestations of orogenic (mesothermal) gold mineralization in rapidly uplifting collisional orogens like the Southern Alps of New Zealand (e.g., Templeton et al., 1999).

Empirical deposit models may be extended to include related deposit types and even to encompass mineralization and metal zonation at district scales. For example, on the basis of numerous analogous occurrences exposed over a range of erosion levels, it is evident that porphyry copper deposits and subvolcanic tin deposits are both transitional upward to advanced argillic lithocaps, potential hosts to high-sulfidation epithermal precious-metal deposits (e.g., Sillitoe, 1999). Familiarity with a wide variety of intrusion-centered ore districts enabled Emmons (1926) to define typical metal zonation, the pattern of which remains broadly valid today. Drawing analogies from extensive data sets can also lead to generation of crustal-scale empirical models, such as the continuum model for orogenic (mesothermal) gold deposition from deep granulite facies environments through to shallow, weakly metamorphosed crustal levels (e.g., Groves, 1993), and even global classification schemes, including Lindgren's (1933) classical depth-temperature subdivision of intrusion-related ore deposits.

Appreciation of specific analogies between broad spectra of mineral deposits, often triggered by major discoveries, has drawn attention recently to several new families or clans of deposits defined mainly on the basis of diagnostic mineralogic and metal content criteria. For example, discovery of the Olympic Dam deposit, South Australia, prompted characterization of intrusion-related Fe oxide Cu-Au-(U-REE) deposits containing abundant magnetite and/or hematite in conjunction with K, Na, and Ca silicate alteration assemblages (Hitzman et al., 1992). Similarly, discovery of Fort Knox, Alaska, promoted definition of gold deposits containing a partly lithophile (Bi-W-Mo-As-Sb) rather than the more usual chalcophile element suite in association with relatively reduced granitoid intrusions (Thompson et al., 1999). Both these deposit families or clans have become the subjects of widespread exploration attention.

Deposit models that are largely descriptive, although normally embodying several genetic connotations, have become increasingly influential in the practice of mineral exploration during the last two decades. Entire programs are commonly mounted on the basis of the perceived potential for specific deposit types, such as SEDEX lead-zinc in Queensland, Australia, or high-sulfidation epithermal gold in northern Perú. The importance of analogous deposits in program design may even lead to the overstated objective of "another Century" or "another Yanacocha." Although deposit models provide a handy summary and are useful for young players, a seasoned practitioner undertakes fieldwork armed not just with the published cartoons of the models, but with their basic ingredients: the memorized details of scores, if not hundreds, of analogous deposits and prospects. Given the globalization of mineral exploration in recent times, his/her list of analogous deposits is likely to cover most of the relevant metallogenic belts of the world.

When confronted with a new prospect, an expert on a particular deposit type often takes only a few hours to make relevant comparisons with analogous deposits and confidently place the new example in an appropriate vertical and lateral position within the overall deposit model. Sometimes, even a few drill cuttings from a known geologic environment may enable an experienced geologist to slot a prospect into the right deposit model. On other occasions, however, the fable of the blind men and the elephant applies, even when not in elephant country, at least until more critical information becomes available.

Geologic analogy is an important procedure in exploration because identification of one or more closely similar deposits elsewhere can facilitate geologic understanding, assist with selection of effective geochemical and geophysical techniques, guide the exploration process, and ultimately minimize drilling and overall exploration expenditure. Indeed, one of the questions most asked of consultants working internationally is "where have you seen another deposit like this one?" Not uncommonly, prospects are explored with an analogous deposit very firmly in mind. That was the case at McDonald, Montana, where the many analogies with the large, low-grade, low-sulfidation epithermal gold deposit hosted by nonwelded ashflow tuff at Round Mountain, Nevada, helped to guide and sustain the exploration effort (Enders et al., 1995). Nevertheless, care must always be taken not to overextend perceived analogies, leading to critical features being overlooked and force-fitting of prospects into inappropriate models.

Both empirical and genetic models may be used in exploration, depending on the mineral deposit type (Thompson, 1993); however, it is the former, based largely on field relations and characteristics supported by analogy, that often proves the most effective and predictive, albeit always provisional and subject to addition and modification. The genetic model for porphyry copper deposits, for example, underpins and verifies the empirical model, but genetic models for some deposit types are of very limited use in exploration because there is no agreement on which of several alternatives is correct. An excellent example of this deficiency is provided by sediment-hosted (Carlin-type) gold deposits, for which the ore fluid has been variously modeled as a product of basin dewatering, metamorphic dehydration, convective meteoric water circulation, or distal modification of

to page 8 • • •

· · · from 7 PRESIDENTIAL ADDRESS, CONT.

magmatic fluid, and the gold source as proximal or much deeper sedimentary sequences or magmas (e.g., Hofstra et al., 1999). Clearly, only "exclusive possessors of the truth" would dare to formulate exploration strategy for sediment-hosted gold using a genetic model, or in the latest parlance, a "process-oriented approach"! Notwithstanding the genetic confusion, application of an empirical model to sediment-hosted gold exploration in Nevada has been rewarded with considerable success. By the same token, however, the lack of a definitive genetic model has seriously inhibited effective sediment-hosted gold exploration elsewhere.

Analogy also plays a major role in both the design and interpretation of geochemical and geophysical exploration programs. Distinctive geochemical signatures are often equated automatically with specific deposit types: Cu-Mo-(Au) with porphyry copper, Au-As-Sb-(Hg) with sediment-hosted (Carlin-type) gold, and Au-Cu-As-(Ag-Bi-Sb-Te) with high-sulfidation epithermal precious-metal deposits. Similarly, certain coincident magnetic, chargeability, and radiometric responses could signify the existence of porphyry copper or Fe oxide Cu-Au-(U-REE) systems, whereas coincident conductivity and gravity highs may pinpoint VMS deposits and CSAMT resistors may outline ore-bearing siliceous alteration in high-sulfidation epithermal systems.

TRAINING REQUIREMENTS

The future of successful mineral exploration requires new generations of geologists who possess the powers to recognize and interpret a wide range of geologic features and to effectively apply existing deposit models in real field situations around the world. It also requires the innovators who will add to and modify the existing models, and perhaps more importantly, develop models for currently undefined deposit types. These activities, from basic recognition and interpretation of geologic features to construction of new models, will involve geologic analogy at a wide variety of scales.

As remarked by a number of commentators recently, training of young geologists in field skills and techniques leaves much to be desired, and apparently, continues to decline in many parts of the world. This is particularly so when it comes to preparation of geologic maps and sections, which are the basic means of recording, synthesizing, and interpreting geologic observations in the field. Only on the basis of direct experience of multiple examples of similar geologic features or relationships can geologists learn to apply the concept of analogy to full effect. Too much geologic education nowadays seems to rely on classroom study of geologic phenomena as opposed to their direct inspection and recording in field situations. Consequently, young (as well as many older) geologists are often well informed about a particular mineral deposit model, but have great difficulty in recognizing its component parts in weathered outcrop, and especially, underground or in drill core and cuttings. Assuredly, the promise of peering at screens for "virtual field trips" will never substitute for the real thing.

Throughout the profession, we must endeavor to maximize the field exposure of our young explorationists to geologic localities and environments of relevance to the deposit type(s) they are exploring for. Two adages spring to mind in this regard: "...the best geologist is he who has seen the most rocks" (attributed to H. H. Read, famous for his work on granites) and "geologists find only what they are looking for." Therefore, an explorationist unfamiliar with the field characteristics of, say, VMS deposits in a tropical environment is far less likely to find one in the Philippines than the colleague who has visited representative VMS deposits throughout the southwestern Pacific region under the tutelage of a VMS expert. The explorationist provided with this introductory VMS experience will no doubt have drawn certain analogies between the deposits visited and, thereby, obtained a clearer picture of the exploration objective and the range of field characteristics to be looked for. One recalls Louis Pasteur's aphorism: "in the fields of observation chance favors only the minds which are prepared."

SEG'S ROLE

It is vital that fieldwork is re-emphasized at both undergraduate and graduate levels, with the university fraternity acknowledging that geologic mapping is one of the most intellectually demanding activities in any academic curriculum. Undergraduate fieldwork must emphasize mineral and rock recognition, and criteria for determination of relative timing relations between different rock, fault, alteration, and vein types. Topics for graduate research in economic geology need to include a substantive field mapping component, a plea already made in a Presidential Address nearly 40 years ago (Park, 1964). Furthermore, as advocated in last year's Presidential Address (Kesler, 1999), the research should be designed to tackle specific problems of practical interest to the exploration community. These criteria are rigorously applied by the SEG when selecting topics to be supported by its globally available student research grants, which will shortly top US$100,000 annually. Investigations to test poorly understood or contentious genetic models for economically important mineral deposit types, like that conducted recently on the linkage between the porphyry and high-sulfidation epithermal environments at Lepanto in the Philippines (Hedenquist et al., 1998), would be high on any list of desirable topics. But a fluid inclusion and light stable isotope study of samples collected from yet another epithermal vein system is just not good enough, especially if the "box of rocks" approach lamented by Hunt (1991) happens to be applied.

Advanced field training of young explorationists as part of continuing professional development can be carried out in-house by employers, using either company or external experts on the deposit type under review. An attractive alternative, however, is the Field Training Course initiative to be commenced by the SEG in 2001. Although many SEG-sponsored activities are field based, these new courses are designed to bring participants up to speed in the geology and appraisal of particular mineral deposit types or environments. Specific emphasis is to be placed on geologic setting, characteristics, controls, and analogies, including mineral, metal, and alteration zoning and application of geochemical and geophysical techniques. Hands-on field inspection of all relevant geologic features, including mineral and alteration recognition, is to be supplemented by classroom instruction and discussion. The courses are to be given on deposit types or topics of current exploration interest, in countries where exploration for the deposit type is particularly active, and by geologists noted for their field-oriented expertise in the subject concerned.

In summary, I would like to make a plea, to educators and employers alike, to refocus on fieldwork. The provision of future generations of effective explorers, and more importantly, future generations of mineral discoveries will depend on it. Furthermore, more than any other geologic discipline, fieldwork promotes independent critical thought, testing of multiple hypotheses, integration of diverse data sets, a team approach and, perhaps above all else, humility (Allen, 1999)—all highly desirable traits in an explorationist. Sound field training will make more explorationists into effective geologic analogists, which can only maximize the chances of discovery.

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An apology is due to geologists with interests that diverge from mine for the rather parochial nature of the examples selected to illustrate various points in this address, but we all tend to be limited by our own experience. I am most grateful to Jeff Hedenquist for comments on the thoughts expressed but, above all, to John Thompson for sage and timely reviews not only of this address but also of my four Presidential Perspectives during the last 12 months. The clients who shared the costs of the long-haul flights on which these various sermons were penned also deserve acknowledgment.

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SEG FOUNDATION

New cornerstones for today and the future

ROGER A. NEWELL
SEG Foundation President

The SEG Headquarters dedication ceremony on June 10th marked one of the most meaningful events in our Society's history, and the membership will benefit for many years to come from programs generated and coordinated from our new headquarters. Through the vision and generosity of the Anonymous Donor and the organizational ability of John Thoms, the headquarters building is now a functioning reality. As John retires after eight years from his volunteer position of Executive Director, we are pleased to announce that he has agreed to accept a newly created position, as Director of Development for the Foundation. The SEG Executive Committee and the Council, and the Foundation's Trustees have unanimously approved this appointment, which will be come effective in July. John will maintain an office in the headquarters building. In recognition of his many substantial contributions to SEG as a volunteer, John received the Society's Marsden Award for 1999 in Salt Lake City. During the headquarters dedication ceremony, John also was presented with a special plaque for his extraordinary contributions, and I am sure this plaque will be proudly displayed in his new office.

As previously reported, the Foundation's Student Grants Program under the direction of the Society's past president and current SEGF vice president Richard Nielsen, awarded a total of $86,500 to 57 economic geology students. Funding for these awards comes from core assets in the McKinstry, Hickok-Radford and BHP funds. In cooperation with the Hickok-Radford principals, certain administrative aspects of the fund were revised and the Foundation contributed $65,000 to the fund to ensure that it will continue to remain a source for future student grants. We are also pleased to announce that Allan Juhas will be assisting Richard Nielsen in administering the Student Grants Program.

The Foundation believes in advancing the science and understanding of economic geology beyond student graduation, and our support should be expanded to assist new graduates in finding early employment. During the headquarter's dedication ceremony one of the program speakers, Katja Freitag, Past President of the SEG Student Chapter at Colorado School of Mines, highlighted the fact that upon graduation, students may take jobs in other fields due to the lack of opportunities in economic geology. The Foundation should consider ways of assisting graduating students, especially those who have received Foundation grants, with their networking and initial job searches. The listing of graduating student resumes on our website might be a place to start. It is important that SEG's programs influence and impact our professional activities, and we should determine how we can assist recent graduates as they begin their careers.