Reports

Recognition of a Hidden Mineral Deposit by an Artificial Intelligence Program

Abstract. *A computer program that uses artificial intelligence techniques has successfully identified the location of a porphyry molybdenum deposit. Given geological maps of readily available predrilling exploration data for Mount Tolman in Washington State and using rules obtained from a porphyry molybdenum exploration specialist, the program (called PROSPECTOR) identified the location of previously unknown ore-grade mineralization. This appears to be the first reported determination of the location of mineralization by such a computer-based approach.*

Expert systems are a class of largely experimental computer programs that have emerged from research in artificial intelligence (*1*). They attempt to encode valuable knowledge and judgment for the purpose of making that expertise more broadly available than in the past. We report here the outcome of the first predictive test of PROSPECTOR, an expert system that has been under development at SRI International since 1974 for the purpose of encoding special expertise in mineral exploration and resource evaluation (*2*).

Thus far, nine different mineral experts have participated in the attempt to encode expertise in the form of sets of rules called inference networks (*3*). PROSPECTOR's earlier inference networks focused on using regional geological information to evaluate the permissibility of any given environment for different types of deposits, including porphyry systems, uranium, lead-zinc, volcanogenic, polymetallic, and nickel sulfide types. The more recent inference networks for porphyry systems, which we describe here, work in conjunction with site-specific map-based information and regional information to compute a map of the favorability of any chosen area for intense porphyry system mineralization. Such expertise is generally used both in recognizing the more promising mineral prospects in a large number of alternatives and in targeting initial exploration test holes.

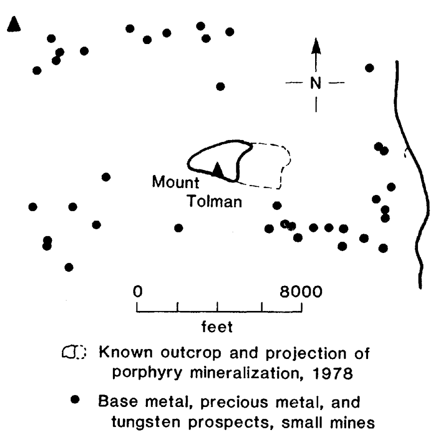

Fig. 1. Test area in eastern Washington. The numerous prospects and small mines shown reflect the extensive history of exploration in the Mount Tolman area (triangles designate mountains). The contours show the outcrop and projection of porphyry molybdenum mineralization as estimated in 1978 after exploration drilling and drifting. PROSPECTOR subsequently evaluated early prospecting data from this exploration project and obtained the results shown in Fig. 5.

The initial testing of PROSPECTOR programs involved post hoc analysis of early prospecting information from known mineral discoveries and nondiscoveries. The results indicated generally excellent fidelity of the encoded expertise (*3, 4*). This report concerns the first experiment in which PROSPECTOR (or any similar program that we know of) was applied to the problem of selecting sites that might be geologically favorable for intense mineralization before exploration was completed. This experiment required the use of much less certain information than in post hoc analysis but also produced a good test of overall validity for the computer program (*5*).

Inference networks, based primarily on the expertise of one of us (V.F.H.), were constructed to look for and evaluate evidence of the "porphyry molybdenum" mineralizing process. The hood type (for example, Climax, Colorado) and the zoned vertical cylinder type (for example, Compaccha, Peru) were treated as morphological end-members in one continuum of porphyry molybdenum types. The inference networks, described in (*5*), reflect information about fluorine, tungsten, magnetite, tourmaline, pyrrhotite, pyrite, hydrothermal alteration (including potassic, phyllic, greisen, argillic, and propylitic alteration), fluid inclusion data, intrusive compositions, stockwork types and location, geological contacts, faults, structures (radial, concentric, and domal), magnetic anomalies, and induced polarization anomalies. We chose to restrict information in the program to concepts mentioned in the literature prior to the beginning of inference net construction in 1978 (*6*), even though a wider base of restricted "in-house" information was available in industry. [See (*7*) for an updated review of porphyry molybdenum systems.]

When in operation, the program uses the inference networks to ask such questions as whether, in the user's opinion, potassic alteration is present at the prospect in question. For this question, a definite "no" disqualifies the possibility for intense porphyry molybdenum mineralization. A positive or uncertain answer is only weakly favorable by itself but leads the program to request mapping of potassic alteration; with additional information, this could lead to a very favorable evaluation.

The test area—Mount Tolman in eastern Washington State—has a long history of prospecting and small-scale mining, with molybdenite first reported by Pardee in 1918 (*8*). Molybdenite was not the primary target initially, although exploration of the porphyry system had begun in 1964 and, with changing ownerships, has proceeded to this date (*9*). By 1978, drilling and drifting led to recognition of the porphyry molybdenum mineralization shown in Fig. 1. In 1979, after the PROSPECTOR molybdenum pro-

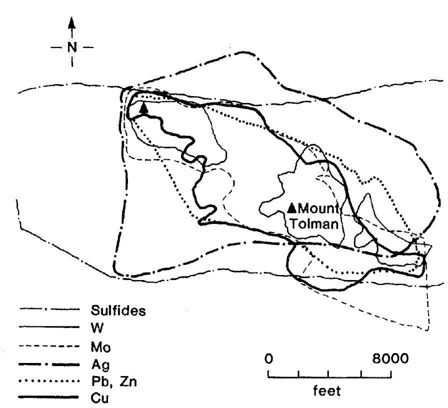

Fig. 2. Geochemical anomaly contours used by PROSPECTOR. Other information requested by the program includes the presence (or absence) of molybdenite, fluorine, tungsten, rhenium, magnetite, tourmaline, pyrrhotite, pyrite, hydrothermal alteration (shown in Fig. 3), stockwork compositions, geological contacts, faults, structures, magnetic anomalies, and induced polarization anomalies.

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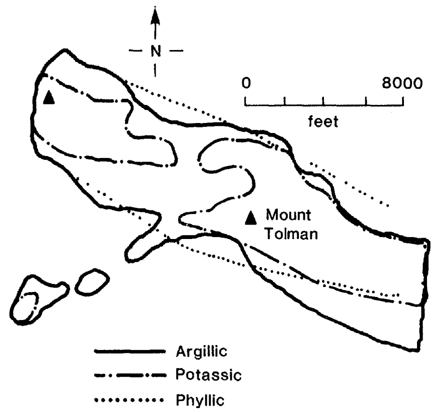

Fig. 3. The hydrothermal zoning information requested by PROSPECTOR includes the locations of the potassic, phyllic, greisen, argillic, and propylitic zones. This information is not always available. When evaluating early prospecting information from Mount Tolman, we had good maps limiting phyllic alteration, but we had to infer, with only moderate confidence, the limits of potassic and argillic alteration from less specific alteration mapping. Uncertain information can be used by PROSPECTOR, but it receives less weight. In this case, better information about potassic alteration would have had a significant effect on the final evaluation.

grams had been completed, the initial developers of the Mount Tolman prospect first made their geological data available to one of us (A.N.C.) (*10*). Since exploration and evaluation were again being conducted by a different group in 1978, this provided an excellent opportunity to test the overall validity of the porphyry molybdenum program.

In this experiment, PROSPECTOR utilized only the geological, geophysical, and geochemical information supplied by the group that terminated exploration in 1978. The most important map-based data are shown in Figs. 2 and 3. Both the hood and the zoned vertical cylinder programs yielded quite similar evaluations, which were completed in February and reported in April 1980 (*5*); the similarity in evaluations seems to indicate that the Mount Tolman deposit may lie between the hood and zoned vertical cylinder types. The results of the hood program are shown in Fig. 4.

Subsequent exploration drilling, consisting of five holes to the northwest of the known deposit shown in Fig. 1 and two holes to the southeast, together with core logging, mapping, and interpretation by molybdenum specialists, delineated a much larger reserve than had been recognized in 1978 (see Fig. 5). In light of this new knowledge, PROSPECTOR's February 1980 evaluations compare to the presently (December 1981) known geology of the Mount Tolman deposit (*11*) as follows. (i) The northwest target, largely unexplored prior to PROSPECTOR evaluation, now appears to represent a highly faulted and partially eroded section of porphyry molybdenum mineralization, involving sporadic ore-grade intercepts (*12*). (ii) The unfavorable area between PROSPECTOR's northwest and southeast targets now appears to represent erosional elimination of part of the single large deposit. (iii) The area rated favorably by PROSPECTOR completely overlies the deposit as now known; the most highly rated area overlies high-grade mineralization. In essence, drill holes in the highly rated areas tend to provide most of the definitive information about mineral grades and quantities. (iv) Termination of the southeast portion of the favorable zone represents the boundaries of geochemical sampling, some of which appear in Figs. 2 and 3. The deposit may extend farther, which now has been confirmed by subsequent drilling and mapping, although the extension is at great depth. (v) The weakest part of PROSPECTOR's evaluation was its failure to recognize the full extent of the deposit. Uncertainty concerning early map-based information, particularly the zone of potassic alteration, seems most responsible. (This type of problem did not arise with the post hoc tests, where much more complete information was available.)

Reconstructed cross sections show the deposit as a mineralized, platelike rind topping a large batholith, which is mor-

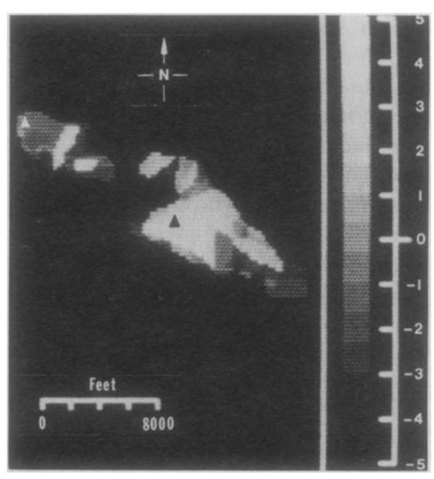

Fig. 4. The February 1980 PROSPECTOR evaluation for intense hood-type porphyry molybdenum mineralization based on prospecting and mapping which terminated in 1978. The favorability scale (−5 to +5) is brightness-coded as shown at the right. If the hood model holds, the map suggests either two separate deposits, structural modification of a single hood, or some other aberration. Because of the absence of data, the favorable zone terminates at the southeast end; the deposit may extend off the map area.

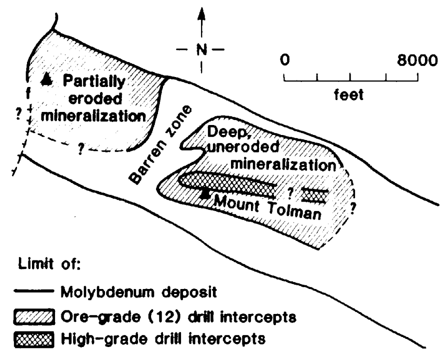

Fig. 5. Limits of the Mount Tolman porphyry molybdenum deposit as estimated in December 1981 (*11*). Mine geologists now believe that one large deposit extends from northwest to southeast. Recent drilling to the southeast of the previously known mineralization intercepted thick, intense ore-grade (*12*) mineralization in related structures. The open-ended map reflects the mine geologists' opinion that this boundary of the deposit has yet to be identified and may extend farther than shown. Recent drilling in the northwest produced two ore-grade intercepts, but with strong indications that faulting and erosion in this area broke the body of the deposit into small blocks of highly variable grade. Engineering factors limit the present mine plan even in the main body of mineralization.

phologically quite different from either of the two cases represented by the inference networks. Despite this unexpected difference (and recognizing that the full extent of porphyry molybdenum mineralization in the Mount Tolman area may not be known with great precision until more exploration and actual mining is done), it is clear that PROSPECTOR accurately identified the location of significant, previously unverified mineralization in a previously known system. We believe that this result was achieved because PROSPECTOR programming adequately reflects limited but appropriate selections from the knowledge and judgment of a known porphyry molybdenum expert.

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2. For a technical description of PROSPECTOR,

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4. J. Gaschnig, "Development of uranium exploration models for the PROSPECTOR consultant system" (contract 14-08-0001-17227, Artificial Intelligence Center, SRI International, Menlo Park, Calif., March 1980).
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6. The rules used in PROSPECTOR incorporate information that has been published in the following references: K. A. Vaslov, *Geochemistry of Rare Elements* [Academy of Sciences, U.S.S.R., Z. Lerman, Transl. (Israel Program for Scientific Translations, Jerusalem, 1966)]; V. F. Hollister, *Min. Mag.* **122**, 187 (1970); *Trans. Soc. Min. Eng. AIME* **255**, 45 (1974); ——, E. B. Sirvas, *Miner. Deposita* **9**, 261 (1974); G. J. Neuerburg, T. Botinelly, J. R. Watterson, *U.S. Geol. Surv. Proj. Pap. 704* (1974); V. F. Hollister, *Miner. Deposita* **10**, 141 (1975); *Trans. Soc. Min. Eng. AIME* **258**, 137 (1975); ——, J. M. Allen, S. A. Anzalone, R. H. Seraphim, *Can. J. Earth Sci.* **12**, 807 (1975); G. J. Neuerburg, *U.S. Geol. Surv. Open File Rep. 78–130* (1978); ——, H. N. Barton, J. R. Watterson, E. P. Welsch, *U.S. Geol. Surv. Open File Rep. 78–383* (1978); J. E. Sharp, *Econ. Geol.* **73**, 369 (1978); *ibid.*, p. 369; S. R. Wallace, W. B. MacKenzie, R. G. Blair, N. K. Muncaster, *ibid.*, p. 325; A. Sutulov, Ed., *International Molybdenum Encyclopedia* (Miller Freeman, San Francisco, 1978), vol 1; R. H. Sillitoe, *Min. Mag.* **142**, 550 (1980).
7. F. E. Mutschler, E. G. Wright, S. Luddington, J. T. Abbott, *Econ. Geol.* **76**, 874 (1981).
8. J. T. Pardee, *U.S. Geol. Surv. Bull.* (1918), p. 677.
9. The Bear Creek exploration group explored the Mount Tolman area between 1964 and 1978; the Amax exploration group subsequently explored the property and proceeded with mine planning. Amax reportedly discontinued plans for mining this and other molybdenum properties subsequent to the initial submission of this report (W. Utterback, personal communication).
10. R. Babcock, personal communication.
11. W. Utterback, Mount Tolman project geologist for Amax, provided the data for Fig. 5 (December 1981). The Amax exploration group has highly specialized expertise in porphyry molybdenum, which includes and exceeds the kind of expertise incorporated into PROSPECTOR. PROSPECTOR is intended to help groups that do not have highly specialized expertise in the prospect type they are working with, which is commonly the case.
12. By "ore grade" we mean an ore mineral content greater than the planned mine cutoff grade. Because of a multiplicity of engineering, economic, environmental, and social factors, not all ore-grade rock is profitable to mine.
13. The development of PROSPECTOR occurred over several years with efforts from many people including both computer scientists at SRI International and consulting geologists. In particular, R. Reboh, the current project director, was responsible for system implementation and personally contributed many key technical innovations. K. Konolige developed the inference network compiler and P. Barrett the map data facilities that enable PROSPECTOR to work with and display map-based information. M. Einaudi contributed substantially to the design of many logical constructs fundamental to the accurate expression of geological judgment and reasoning. This test would not have been possible without gracious and extensive assistance from the Collville Confederated Tribes exploration group, the Bear Creek exploration group, and the Amax exploration group. This work was sponsored by the U.S. Geological Survey under a series of contracts and by the National Science Foundation under grant AER 77-04499; any opinions, findings, conclusions, or recommendations in this report are ours and do not necessarily reflect the views of either the U.S. Geological Survey or the National Science Foundation.

20 April 1982

Carbonate Dissolution and Sedimentation on the Mid-Atlantic Continental Margin

Abstract. *The calcium carbonate content was determined for core tops from two transects on the upper slope to lower rise on the mid-Atlantic continental margin. Carbonate content in the sediment increases from ~ 5 percent (by weight) on the upper slope to more than 30 percent on the upper rise. A zone of low-carbonate content extends from 3000 to 4400 meters. Below 4400 meters, the percent carbonate increases. An examination of dissolution indices in these core tops indicates that the low-carbonate zone is associated with intense dissolution. Below 4400 meters, dissolution decreases and carbonate is well preserved. The decrease in dissolution occurs where the high-velocity core of the Western Boundary Undercurrent is first encountered.*

In an effort to examine the effects of dissolution on carbonate sedimentation, gravity-core tops from two transects on the upper slope to lower rise on the mid-Atlantic continental margin—one off Chesapeake Bay and the other north of Hudson Canyon—were analyzed (Fig. 1). The southern transect includes 26 cores at depths from 1378 to 4647 m; the northern transect includes 30 cores at depths from 593 to 4974 m, but no samples were recovered from 3319 to 4371 m.

The percentage (by weight) of calcium carbonate for each core top was plotted against water depth (Fig. 2A). Both transects show similar variations in the carbonate content with depth. Values increased from ~ 5 percent on the upper slope to ~ 35 percent on the upper rise. On the southern transect, carbonate reached its maximum value, 33.1 percent, at 2900 m and then dropped to 21.5 percent at 3210 m. A similar decrease occurred on the northern transect, where the carbonate content reached its maximum, 35.7 percent, at 3100 m and then dropped to 23.5 percent at 3319 m. Because of the sampling gap, the full extent of the carbonate drop on the northern transect cannot be determined. Below 3200 m on the southern transect, the carbonate content increased to 29.4 percent at 3800 m, decreased to 22.5 percent at 4300 m, and increased to more than 30 percent below 4500 m. On the northern transect, below the sampling gap, carbonate values were high (> 25 percent) but variable.

It can be inferred from these data that the major break in carbonate sedimentation occurs on the upper rise, at about 2900 m on the southern transect and 3100 m on the northern transect. Below this sedimentation break, carbonate values are generally lower but do not exhibit the expected monotonic decrease with depth (*1–4*). In fact, the carbonate content ac-

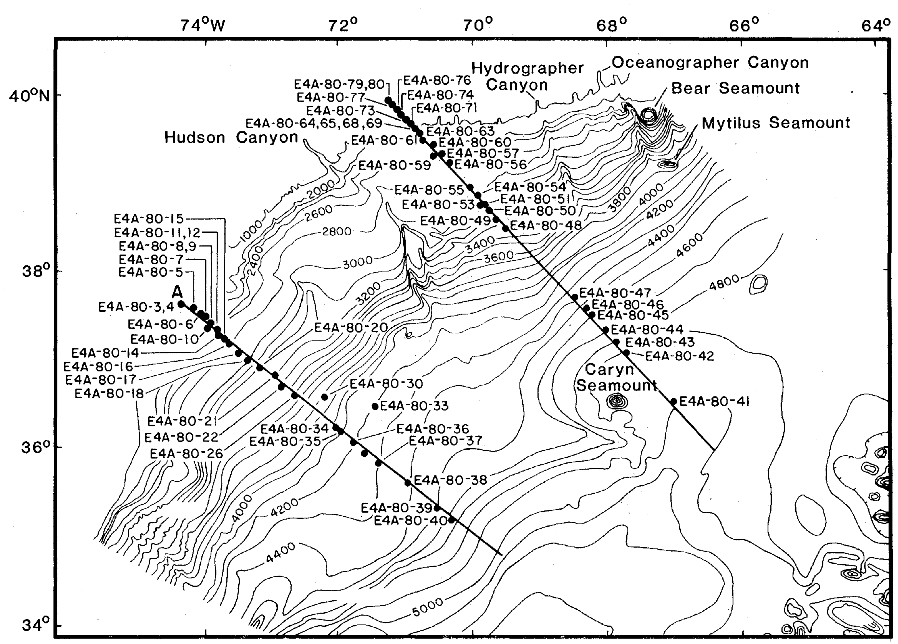

Fig. 1. Locality map showing the distribution of cores used to examine the depth distribution of calcium carbonate (Fig. 2A). Dissolution indices (Fig. 2B) were calculated from a subset of these cores and includes all the R.V. *Eastward* samples analyzed by Bulfinch *et al.* (*15*) for evidence of high-velocity bottom currents.