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Mineral-potential Assessment by Consistency-driven Pairwise Comparisons

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Abstract — A consistency-driven pairwise comparisons method for mineral potential assessment is presented, using a simplified case of volcanic-associated massive sulfide type deposits as an example. Geological, geochemical, and geophysical criteria are considered on two levels: local and regional. The local geological criteria are subdivided into stratigraphy, lithology, alteration and/or mineralization, and structure. The concept of *geomerit* index and a procedure for computing this index are introduced. The method of consistency-driven pairwise comparisons can be combined with other quantitative and qualitative assessment methods, enhancing them by incorporation of nonmeasurable geological criteria (e.g., stratigraphy or lithology) and by computation of weights. The consistency-driven approach allows experts to refine at-times subjective judgments concerning exploration and land-use planning, and contributes to the improvement of mineral-potential assessments. **© 1997 Canadian Institute of Mining, Metallurgy and Petroleum.**

Basics of Mineral-potential Assessment

Assessing the mineral potential of an area is an important task for mining exploration companies and government land-use planners. Most mineral assessment methodologies are based on *return-on-investment* (ROI), economic activities, deterministic geological methods, geostatistical models, multivariate models, and favorability mapping (for details, see Harris and Rieber, 1993; Grunsky and Agterberg, 1992; Chung et al., 1992; Pan et al., 1992; Wright and Bonham-Carter, 1996). All the above are precise and powerful tools, but all require precise data which are rarely available. In his comprehensive monograph on assessment of mineral resources, Harris (1984) remarked that: "The inclination to base an assessment of metal endowment upon the opinion of experts seems to result naturally from the consideration of three central issues: 1) limitation on time: a survey of expert opinions can be performed quickly as compared to basing the assessment on multivariate statistical analysis of "hard" quantitative geological and mineral resource data; 2) a suitable control area for a multivariate model may not exist or cannot be identified except for very low level, general geological variables; and 3) usually, the level of information possessed by geologists who are experienced in exploration in the region of interest far exceeds that present in data that are available to the public, both with respect to basic geoscience data and deposit characteristics, but particularly concerning geoscience data."

The above remarks are crucial to understanding the consistency-driven pairwise comparisons approach. Nothing can substitute for precise methods (such as the above-mentioned methodologies), but in the absence of precise data one may be forced to a second-best alternative: expert judgment. Our approach helps to assess mineral potential in situations where precise data are lacking. The proposed methodology is particularly suited for assessment of individual exploration targets when a database of targets is maintained. Both precise and imprecise data that are currently available for the target area can be combined with the expert judgment of exploration specialists who have been assigned to assess the target. The method of consistency-driven pairwise comparisons builds internal consistency into the subjective judgments provided by experts by comparing two criteria at a time (Appendix B). The proposed methodology can also accommodate the outcome from other approaches. For example, the USGS Three-Part Quantitative Assessments (Singer, 1993), PROSPECTOR II (McCammon, 1993), and Favourability Mapping (Wright and Bonham-Carter, 1996) can be used as input criteria in a model based on consistency-driven pairwise comparisons. The above-mentioned approaches provide data on the favorability of tracts of land which can be easily incorporated into a model constructed for each case by the proposed methodology. Such a model can be used for the assessment of selected mineral exploration targets or known mineral occurrences within areas being reviewed by land-use planners.

A demonstration case presented in this paper includes (but is not limited to) geological, geochemical, and geophysical criteria on two levels: regional and local. It is important to have a tool for drawing final conclusions based on well understood geology and geochemistry, and supported by geophysical surveys and measurements. In the mineral potential assessment process, many factors with about the same degree of importance must be considered simultaneously, and assigning precise weights to them is important. Weights of evidence are computed on the basis of partial judgments expressed by comparing assessment criteria in pairs. Such judgments are analyzed for consistency and are enhanced with the help of software (the Concluder program discussed below).

The main goal of the consistency-driven pairwise comparisons approach to mineral potential assessment is establishing a *geological merit index (geomerit)* which one can use for drawing a final conclusion. *Geomerit* combines all possible aspects of mineral potential assessments. One of the most fundamental requirements for a fair assessment is a precise scoring system of all criteria, as well as the preferences to be employed during the assessment process by experts. This goal is achieved by using a structured approach to the conceptual model of assessment and by use of consistency-driven pairwise comparisons of assessment criteria. The structured approach results in a multilevel hierarchical structure in which each successive level is a refinement of a criterion which has too much weight by itself. The method of consistency-driven pairwise comparisons is applied to assessment criteria in pairs, as it is easier and more precise than looking at all criteria at once (Koczkodaj, 1996).

One needs to reflect on the measurement process in general to understand the essence and potential gain in the precision by pairwise comparisons relative to direct estimation (e.g., by a measurement or judgment). There is no standard measure (such as the cubic meter) for assessing environment or mineral potential. The lack of standard measure forces us to compare one object to another. Consider the example where two rocks, A and B, can be weighed if we have a scale. When a scale is not accessible, we often "weigh" them by taking one rock in each hand. Without using a standardized measuring device, it is easier to say that A is 1.5 times heavier than B rather than to guess the exact weight of each rock. Interestingly, the use of a standardized measure such as a kilogram is also a pairwise comparison. The statement "the weight of A is 2.5 kilograms" is an abbreviation of "by a pairwise comparison of A to one kilogram we have a factor of 2.5." Using pairwise comparisons is natural and need not be imprecise (see, for example, Saaty, 1977; Koczkodaj et al., 1992; Koczkodaj, 1993; Duszak et al., 1993; Bolger et al., 1993, 1995; Voogd, 1983; Nijkamp et al., 1990). For example, a Monte Carlo experiment with bars of randomly generated lengths showed 300% improvement of accuracy in estimation of their lengths by using pairwise comparisons. In the first part of the Monte Carlo experiment, respondents were asked to estimate the lengths directly, whereas in the second part, respondents were asked to do the same by comparing bars in pairs. An improvement from about 15% error to 5% error was observed and was verified statistically (Koczkodaj, 1996).

We have become so accustomed to having standards that sometimes it is difficult to imagine a situation where no standard measure exists. For example, in the Red Lake mining camp, northwestern Ontario, an association between *Au* and arsenopyrite is well-established. Thus, an experienced gold prospector is unlikely to ignore the presence of arsenopyrite, although no precise measure exists which relates the degree of success in finding gold to the quantity of arsenopyrite present. Likewise, mineral potential assessments are commonly based on non-measurable criteria such as lithology, stratigraphy, and overall degree of alteration. Comparing assessment criteria in pairs is the key issue and solution to our problem. A similar assessment was used, with success, in a project for the Ministry of Northern Development and Mines in Ontario which concerned the rating of hazards for abandoned mines (Bolger et al., 1993, 1995; Duszak et al., 1993). mineral potential assessment is a similar problem but is based on different criteria. The higher the *geomerits,* the higher the chances for the presence of mineralization in a given site when compared with other sites.

The consistency-driven approach incorporates the reasonable assumption that by finding the most inconsistent judgments, one is able to reconsider his/her own opinions. The identification of inconsistencies is done by software which highlights criteria requiring reconsideration. This in turn contributes to improvements in the accuracy of judgments. A dynamic process of consistency analysis is facilitated by the software, which displays the most inconsistent judgments in a contrasting color on the computer screen as shown below. The results presented in this paper have been obtained using The Concluder software system. This is released to public domain and is available, together with the model, from the authors upon request. The system operates under MS Windows™ on personal computers and does not require any specific mathematical knowledge.

Four Cases of Mining Exploration Targets

An example of mineral-potential assessment by the method of consistency-driven pairwise comparisons is provided by the ranking of four exploration targets. The geological setting must be provided as a first step. Four hypothetical cases of mining exploration targets in Precambrian volcanic terranes of the Canadian Shield have been chosen to demonstrate this approach to mineral resource assessment. In all four cases it has been assumed that no diamond drilling, extensive stripping, underground development or bulk sampling have been completed. The four cases are:

Case 1. — **Northern Claybelt.** This example would be somewhat similar to the setting of the 1963 discovery of the Kidd Creek deposit near Timmins, Ontario, where regional geology and airborne geophysics were used to define an exploration target in an area of thick glacial cover. A few key outcrops were present which allowed explorationists to carry out a successful program.

Case 2. — **Narrow Greenstone Belt.** This case would relate to a narrow greenstone belt of the Superior Province where an exploration program has been defined with the use of government geological and geophysical survey maps. Outcrop density is sufficient to allow detailed geological mapping and sampling, although many primary volcanic textures and structures are deformed or obliterated by regional metamorphism. Drainage and soil conditions are suitable for geochemical work.

Case 3. — **Amphibolites in Granitic Gneiss Terrane.** This case relates to the investigation of regional airborne geophysical anomalies in gneissic terranes. Such a situation could result, for example, in the discovery of mineralized amphibolite zones, which have been interpreted as remnant volcanic units. This type of geological setting could occur in the Grenville Province.

Case 4. — **Abitibi Volcanic Terrane.** An example would be the Noranda camp which has been a center of extensive geological mapping and base-metal mining for more than half a century. Abundant outcrop and well-preserved volcanic features have enabled geologists to gain much knowledge over the years about the volcanic stratigraphy and its mineral potential.

Examining the above cases and reflecting on their diversity and complexity may help to understand why a better method for establishing assessment weights is needed. It may not be easy, especially for a less experienced explorationist, to prioritize the above cases and to commit substantial funds for mineral exploration projects at first glance. It has been shown using numerous examples (Saaty, 1977; Voogd, 1983; Nijkamp et al., 1990) that the pairwise comparisons method can be used to draw final conclusions in a comparatively easy and elegant way. The practical and theoretical virtue of the pairwise comparisons methodology is its simplicity and ease of use. It can be reduced to a common sense rule: *consider two factors at a time if you are unable to handle all of them at once.*

A mineral deposit model must be constructed as a next step toward comparing the above four types of exploration target. In this paper, a volcanic-associated massive sulfide deposit model has been used to provide a reasonably short presentation of the method of consistency-driven pairwise comparisons.

A Simplified Model for Volcanic-associated Massive Sulfide Deposits

A practical procedure for mineral potential assessment needs to be as flexible as possible. The simple assessment case, summarized in Appendix A, is restricted to the volcanic-associated massive sulfide deposit type. The method, however, is general, and is expandable to other types of mineral deposits without any additional theoretical concerns. The following mineral-resource assessments are based on the regional and local criteria of Rogers et al. (1995). Both of these are divided into *geological*, *geochemical*, and *geophysical* criteria which are used to create the hierarchical model shown in Figure 1.

The regional criteria include recognition on a regional scale of subaqueous, predominantly mafic volcanic sequences, or subaqueous bimodal mafic-felsic volcanic sequences with intercalated sediments. *Geochemical and geophysical* criteria can be obtained through reconnaissance surveys or from published government reports. These criteria serve to define the scale of the favorable terrane.

A local geological criterion was established initially through consistency-driven pairwise comparisons of the criteria present in the local criteria group (consisting of local geological, geochemical, and geophysical criteria; present in the second level in Figure 1). This resulted in a very large weight (about 50%) for the single *local geological* criterion. Therefore, the following four additional subcriteria were included as relevant to the localization of volcanic-associated massive sulfide deposits (Lydon et al., 1984): 1) stratigraphy, 2) lithology, 3) alteration and/or local mineralization, and 4) structure. Inaccuracy in the evaluation of a criterion with very high weight could decisively contribute to significant error in the final score (geomerit). Splitting each large contributing criterion into subcriteria is therefore a natural simplification.

Local geochemical and geophysical criteria are based on the field techniques judged appropriate by the exploration team. Assessments can be based on the significance of survey results rather than the number of techniques employed. Geochemical criteria could include sampling of bedrock in addition to soils.

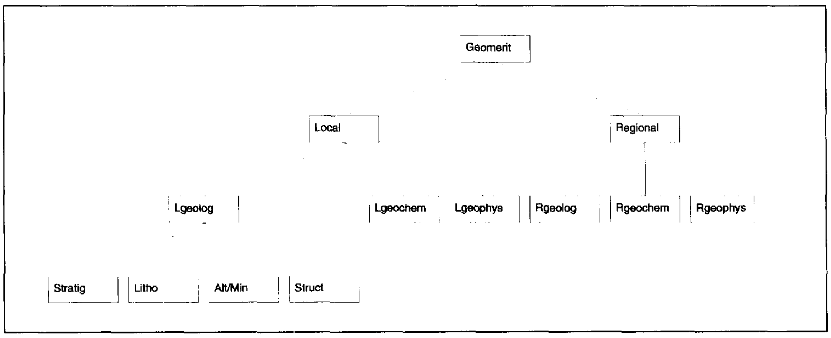


Fig. 1. A hierarchical model of *geomerit* index for volcanic-associated massive sulfide deposits. Each subsequent level in the tree is a refinement (split) of the *geomerit* index. The model has three regional and six local criteria. L prefix=local, R prefix=regional.

Assessment of *stratigraphy* is based on the presence and extent of tholeiitic or calc-alkaline mafic volcanic sequences (for copper-zinc targets) or sequences of non-alkaline felsic volcanic rocks and argillaceous to arenaceous clastic sediments zinc-lead-copper targets). The *lithology* criterion requires assessment based on the presence/abundance of key rock types such as rhyolites, phreatic explosion breccias, debris flows, etc. *Structure* would be assessed based on the recognition of synvolcanic fractures or other structural features deemed significant to the exploration model. The *alteration and/or local mineralization* criteria are assessed on the basis of presence/abundance of hydrothermal alteration and/or indications of sulfide mineralization.

The above list is not exhaustive and does not pretend to be complete. It can be expanded by incorporating factors ranging from economic to environmental to lithogeochemical.

Development of Weights and Interpretation of Results

General Considerations

Devising a conceptual model of assessment is the next step required by the consistency-driven pairwise comparisons method. The procedure usually starts (after an appropriate feasibility study and data gathering, which are not addressed here) with a listing of all possible criteria. In our case, the criteria mentioned in the preceding section are used. The next step is to group them together. A rule of thumb proposed by Saaty (1977) is that no group should have more than seven criteria. A larger number of criteria in one group is impractical because the number of all combinations of pairs grows rapidly (for seven criteria it is 21). A practical solution for groups with more criteria is to split them into subgroups which create the next level. If there are, for example, 30 criteria, splitting them into five groups of six is as good a solution as a split into: 4, 5, 3, 7, 6, and 5, or any other arrangement. It is important to group criteria on the basis of natural affinity. A purely mechanical split (e.g., by alphabetical order) is not recommended, as it may be much harder to compare such criteria on a pair-by-pair basis. In our case, the split was a natural one involving regional and local criteria (Fig. 1).

A scale of 1 to 5 (Table 1) can be used to compare criteria in pairs for expressing an expert's preferences. The reasoning for the selection of the scale is outside the scope of this paper, but it should be noted that for precise measurements one can use intermediate values (e.g., 3.142); use of a wider scale for subjective assessments may only confuse the user. Based on our experience with the presented method (Duszak et al., 1993; Bolger et al., 1993, 1995), a scale of 1 to 5 is effective for the consistency-driven pairwise comparisons.

The correctness of individual preferences is a subjective matter that does not have an impact on the principles of the presented procedure. The model, however, can handle all imaginable cases based on the user's personal preferences. For example, if one considers alteration/mineralization to be far more important than lithology, the model can accommodate this preference (provided that the judgments of the mineral deposit expert are sufficiently consistent).

The challenge posed to the pairwise comparisons method comes from the lack of consistency in judgments which arise in the real world. The basics of consistency analysis are shown in Appendix C (the successful use of the method does not require an understanding of all mathematical aspects of the consistency analysis, but certainly this can contribute to the increased confidence in the final results). Although the consistency analysis may seem complicated, the software developed for this analysis makes it easy to use (most of our users consider it equivalent to playing a video game). During the analysis, the most inconsistent combinations of criteria are displayed visually. By decreasing or increasing a previously entered value (by a relative comparison of two criteria), the user develops an intuition as to what should be changed to achieve an acceptable level of consistency. Changing the numbers simply in order to achieve lower inconsistency is not advisable. Leaving the highly inconsistent judgments unchanged may in fact be a better alternative than trying to please the system by entering meaningless numbers, that is, it is impossible to draw creative conclusions from "deceptive" data, or data that have been deliberately created.

High inconsistency (detected by the software) indicates that the user should reconsider the comparisons of the three criteria that contribute most to the inconsistency. In some cases, changes will need to be extensive and the entire model may need revamping. This may require refinements of the definitions of the criteria, or adding new criteria, or dropping some of them. It is an interactive process requiring input from knowledgeable exploration specialists. In practice, inconsistent judgments are unavoidable when at least three factors are independently compared against each other (see Appendix C for more explanations; in cases involving only two criteria inconsistency does not occur, and only inaccuracy results). All of the above computations, including the final weights, are done automatically by the soft-

Table 1. Codes for expressing degree of preference/importance between criteria when compared in pairs

Code	Preference/importance	Description and possible interpretation
1	Equal or unknown	Often an initial value for assessing factors. Expresses equality of our preference/importance or lack of definite opinion. Also used for expressing uncertainty.
2	Moderate	One factor is slightly more important than the other (preferred, better, bigger, etc.).
3	Strong	One factor is more important than the other (strongly preferred).
4	Very strong	Very strong preference/importance (slightly lower than the absolute preference/important below).
5	Absolute	The strongest possible preference/importance (should not be overused.)
1.4, 3.21, etc.	Intermediate values	Used for expressing degrees of preference /importance between the above grades.

ware. It is not important to address all mathematical aspects of obtaining the final weights (see Appendices B and C).

An Example

The main goal of this approach is to obtain assessments of mineral-resource potential. One of the initial steps is to assign numerical values to the entire list of criteria (Fig. 1) using past exploration experience, intuition, and common sense. With numerical values assigned to each criterion, one can easily construct the pairwise comparisons matrix **A** (see Appendix B) by simple division of the assigned numerical values for the corresponding criteria. In our case, we may assign numerical values to all nine criteria, e.g., 20 to *stratigraphy* and 8 to *lithology*. The assigned numerical values can be used to establish an initial value of the relative comparison of *stratigraphy* against *lithology* as 2.5 (given by 20/8). After a careful examination of the matrix created with these quotients, we may, for example, discover that certain ratios are too small, whereas others are beyond common sense. One may create inconsistencies by changing the ratios, which can be handled by the method, as explained later in this section. The computer program locates and highlights the most inconsistent judgments, which can be improved by re-examining the criteria.

We can begin by examining criteria in the *local geology* group (Fig. 2). This group is introduced as a refinement of the local geology factor which, after computing the pairwise comparisons of the second level consisting of *local geology*, *geochemistry*, and *geophysics* (Fig. 1), was found to have the most decisive weight (about 50%) among all local factors. Figure 2 shows two screens with relative comparisons forming initial and enhanced matrices. Scores in the most inconsistent triad are highlighted by the software. In this example, we have assigned the relative importance of 1.5, which is between *equal* and *moderate* importance according to Table 1, to *Stratig* (stratigraphy) when compared to *Litho* (lithology). This assigned value is for illustrative purpose only, as the software can process any reasonable preferences. *Stratig* (stratigraphy) in comparison to *Alt./Min.* (alteration and/or mineralization) has been assigned a value of 2 (*moderate importance*). Similarly, the initial values for *Stratig* against *Struct*, *Litho* against *Alt./Min.*, and *Litho* against *Struct*, were given a value of 3 (*strong importance* according to Table 1). The initial assessment of *Alt./Min.* against *Struct* was set to *moderate importance* (of one criterion over another) and is reflected by 2 in the last column of row three (left image in Fig. 2). The maximal inconsistency computed for the above judgments is 0.56. This value is unacceptably high (exceeding 0.33 as explained in Koczkodaj, 1993), and indicates that relative comparisons of the criteria in this group are internally inconsistent, which reflects a tendency of human nature to overestimate criteria. After applying the consistency analysis (Appendix C), the judgments were refined by the software, which identifies the most inconsistent judgments. As a consequence, the relative importance of *Stratig* versus *Alt./Min.* was changed after careful reconsideration (often based upon additional research and/or measurements) from 2 to 3, resulting in a decrease of inconsistency from 0.56 to 0.50 (an intermediate value not shown in Fig. 2). As well, the relative importance of *Alt./Min.* against *Struct* was modified from 2 to 1 (right image in Fig. 2). The new inconsistency index was computed as 0.33, which is an acceptable threshold of consistency (see Appendix C and Koczkodaj, 1993 for details).

	Stratig	Litho	Alt/Min	Struct
Stratig	1.0	1.5	2.0	3.0
Litho		1.0	3.0	3.0
Alt/Min			1.0	2.0
Struct				1.0

inconsistency = 0.56

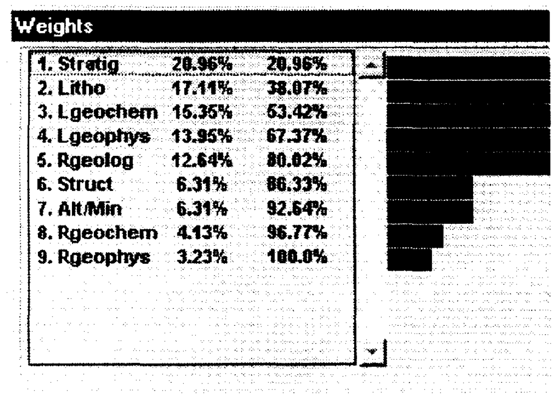
	Stratig	Litho	Alt/Min	Struct
Stratig	1.0	1.5	3.0	3.0
Litho		1.0	3.0	3.0
Alt /Min			1.0	1.0
Struct				1.0

inconsistency = 0.33

Fig. 2. Initial (image on left) and enhanced (image on right) relative judgements for the *local geology* group of criteria. Abbreviations used: *Stratig* for stratigraphy, *Litho* for lithology, *Alt./Min.* for alteration and/or mineralization, and *Struct* for structure.

Values below the main diagonal in Figure 2 do not need to be entered by the user. They are reciprocal to the corresponding values in the upper triangle (Appendix B). If a group of experts participates, we may also employ other techniques for converging on a consensus estimate (e.g., Delphi process originated by the Rand Corporation for using multiple experts' opinions) or take a geometric average of judgments made individually. The geometric averaging of results reduces any undue influence by the "dominant personalities" which are sometimes present on an exploration or management team. The problem of ranking by a group has been recently addressed by Janicki and Koczkodaj (1996).

When an acceptable consistency level is achieved, the weights derived by the software for all criteria (shown in Fig. 3) are used to compute the *geomerit* indexes for the



1. Stratig	20.96%	20.96%
2. Litho	17.11%	38.07%
3. Lgeochem	15.35%	53.42%
4. Lgeophys	13.95%	67.37%
5. Rgeolog	12.64%	80.02%
6. Struct	6.31%	86.33%
7. Alt/Min	6.31%	92.64%
8. Rgeochem	4.13%	96.77%
9. Rgeophys	3.23%	100.0%

Fig. 3. Final weights of assessed criteria computed and displayed by *The Concluder software program.*

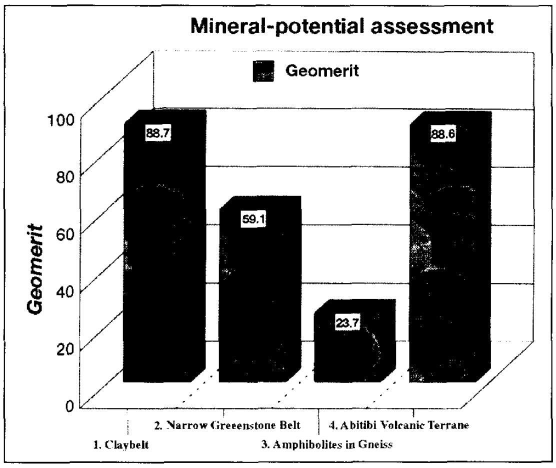


Fig. 4. Graphical representation of four assessed hypothetical case histories. The *geomerit* index values from left to right are 88.7, 59.1, 23.7, and 88.6.

exploration targets (presented in Table 2 and Fig. 4). It should be emphasized that the weights listed in Table 2 and Figure 3 are valid only for the model for which they were assessed. In our case, the model pertains to volcanic-associated massive sulfide deposits. Weights for models of other types of mineral deposit can be derived in the same manner by an exploration team using the consistency-driven pairwise comparisons method.

Interpretation

Geological evaluation scores for each criterion (column *a* in Table 2) can then be awarded by the explorationist. These are multiplied by the respective weights and divided by 5 (which is the maximum score) to produce a *sub-geomerit* index (column *b* in Table 2). The total of all *sub-geomerit* indexes in column *b* of Table 2 produces the *geomerit* index for an exploration target or deposit. The subsequent evaluation of exploration targets by *geomerit* index allows the exploration manager to set budget priorities.

The mineral exploration summary and assessment scores for the four cases introduced at the beginning of the paper are compiled in Appendix A. Table 2 presents the final *geomerit indexes* computed by the software on the basis of the consistency-driven pairwise comparisons. The evaluations of criteria are shown in columns *a* and *b* of Table 2 for each of the four cases, with a graphical representation of the final *geomerit* results in Figure 4. The weights in Table 2 are computed by the software (on the basis of the mathematics explained in Appendix B) by synthesizing all judgments of partial pairwise comparisons. In brief, it is done by building matrices of pairwise comparisons for each group of criteria and their refinements. Once the weights for the model for volcanic-associated massive sulfide deposits are established, a mining exploration specialist is in a better position to conduct mineral potential assessments. The four cases outlined earlier in the paper have been evaluated for volcanic-associated massive sulfide deposits using the information listed in Appendix A. Evaluation scores between 0 and 5, with 0 expressing the lowest and 5 the highest value, are assigned to each criterion by the specialist on the basis of knowledge of the case (e.g., alteration/mineralization) and interpretation of survey results such as geophysical records. The evaluation scores shown in Appendix A are then multiplied by the weights, which are supplied by the consistency-driven analysis, for each criterion; the *geomerit* indexes which are then computed for each case are displayed on the computer screen. Table 2 shows a compilation of all evaluation scores and *geomerit* indexes.

The Claybelt and Abitibi Volcanic Terrane cases received very high *geomerit* scores (88.7 and 88.6 respectively), which reflect their high mineral potential. The example of Amphibolite in Gneiss received a relatively low score of 23.7. The Greenstone Belt, with a *geomerit* score of 59.1, is inferred to have moderate mineral potential. As a result, an exploration manager would have greater confidence in justifying expenditures for advanced exploration projects in the Claybelt and Abitibi cases, relative to the Amphibolite example. Similarly, land-use planners would be more comfortable in defending *mining-use* designations for lands in the Claybelt and Abitibi areas.

Table 2. Weights and evaluation of cases

Criterion name	**Weight**	**1. Claybelt**		**2. Greenstone**		**3. Amphibolites**		**4. Abitibi**	
		a	**b**	**a**	**b**	**a**	**b**	**a**	**b**
Regional geological criteria	12.64%	5.0	12.6	2.5	6.3	0.5	1.3	5.0	12.6
Regional geochemical criteria	4.13%	0.0	0.0	1.5	1.2	0.0	0.0	3.0	2.5
Regional geophysical criteria	3.23%	4.0	2.6	4.5	2.9	2.5	1.6	5.0	3.2
Local stratigraphy	20.96%	5.0	21.0	3.0	12.6	1.0	4.2	5.0	21.0
Local lithology	17.11%	5.0	17.1	3.0	10.3	1.0	3.4	5.0	17.1
Local alteration/mineralization	6.31%	4.0	5.0	3.5	4.4	4.0	2.5	4.5	5.7
Local structure	6.31%	5.0	6.3	2.0	2.5	0.5	0.6	3.5	4.4
Local geochemical criteria	15.35%	3.0	9.2	2.5	7.7	2.0	6.1	4.0	12.3
Local geophysical criteria	13.95%	4.0	11.2	4.0	11.2	0.5	1.4	3.5	9.8
Geomerit index			88.7		59.1		23.7		88.6

a — evaluation score provided by explorationists.
b — evaluation score multiplied by the weight and divided by 5, which is the maximum score. Each b value is a sub-geomerit index.

Consistency analysis (Appendix B) and refinement of judgments is supported by the user-friendly software system. The computed weights and structured approach contribute to an increased level of confidence for mineral-potential assessment in a comparatively short period of time, thereby producing less risk of budget or land misallocations.

Conclusions

This paper proposes a methodology based on pairwise comparisons which may be used for building logical models for assessing mineral potential. The volcanic-associated massive sulfide type of deposit has been used as one instance of such a model. Models for other mineral deposit types (e.g., lode gold) can be constructed by utilizing in-house expertise and published information on mineral deposit types (cf. Eckstrand et al., 1996). The mineral potential assessment may be modeled in many different ways, although identification of major criteria is an essential component in building any model. Once this is done, the final weights can be easily computed from the relative pairwise comparisons. The model demonstrated in this paper may be useful for mineral assessment of exploration targets and land-use study areas, even in its current simplified form (as presented for reason of illustration).

The outlined methodology is flexible and allows consideration of all criteria (evidence) at hand, without restriction to factors such as areal extent, tonnage and grade, etc. For example, the occurrence of a single outcrop of rhyolite or "mill rock" within an area under exploration, although statistically insignificant, could be an important clue for the mineral deposit specialist. The consistency-driven pairwise comparisons method allows the expert to make use of such information in the assessment process, and contributes to the reliability and consistency of such assessments.

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Appendix A: Geological Evaluation Summary for Exploration for Volcanic-associated Massive Sulfide Deposits in Four Geological Terranes

	Criteria	Evaluation Score	Geological features
			Northern Claybelt
Regional	Geological	5	Bimodal mafic — felsic assemblage, sparse outcrop but traceable for several kilometres. Some coarse felsic pyroclastic breccia.
	Geochemical	?	No data available.
	Geophysical	4	Strong airborne EM anomaly coinciding with regional mafic -felsic contact. No magnetic response.
Local	Stratigraphy	5	Possible felsic dome at regional andesite – rhyolite contact.
	Lithology	5	Very coarse rhyolite pyroclastic breccia, some thin tuffite beds.
	Alt./Min.	4	Trace chalcopyrite and sphalerite throughout breccia.
	Structure	5	Tuffite beds trace out possible dome structure.
	Geochemical	3	Enrichment in MgO, FeO, CO_2 and Zn.
	Geophysical	4	Ground EM anomalies in vicinity of potential felsic dome.
			Narrow Greenstone Belt
Regional	Geological	2.5	Narrow amphibolitic greenstone belt displaying relict pillow units, some coarse pyroclastic volcanic rocks. Belt 3 km long and 500 m wide. Gradual contacts with surrounding granitic terrane.
	Geochemical	1.5	Above-background Cu detected in stream-sediment survey.
	Geophysical	4.5	Distinct linear airborne EM anomaly, weak magnetic anomaly.
Local	Stratigraphy	3	150 m wide by 500 m long volcanic breccia unit interbedded in pillowed flow assemblage.
	Lithology	3	Volcanic breccia of intermediate composition. Pillow lavas amphibolitic, probably basalts.
	Alt./Min.	3.5	Disseminated pyrrhotite and trace chalcopyrite throughout breccia unit.
	Structure	2	Pillows deformed parallel to strike of breccia unit. Some graphitic shear zones parallel to strike.
	Geochemical	2.5	Anomalous Cu in soil survey over breccia unit.
	Geophysical	4	Ground EM anomalies along strike of graphitic shear zones. Moderate magnetic anomaly over breccia zone.
			Amphibolites in Granitic Gneiss
Regional	Geological	0.5	High-grade granitic terrane with distinct broad fold structures visible on air photos and contour maps. Amphibolite zones throughout.
	Geochemical	0	Negative results from stream sediment geochemical survey.
	Geophysical	2.5	Regional airborne survey with weak EM anomalies following structural trends. No magnetic response.
Local	Stratigraphy	1	Amphibolite zone 300 m long and up to 20 m wide within granitic gneisses.
	Lithology	1	High-grade metamorphic zone of possible volcanic origin.
	Alt./Min	4	Numerous sulfide stringers with a few small chalcopyrite patches.
	Structure	0.5	Amphibolite zone deformed into augen-shaped lenses.
	Geochemical	2	Spotty anomalous Cu in soils down-ice from main zone.
	Geophysical	0.5	Weak ground EM and magnetic response.
			Abitibi Volcanic Terrane
Regional	Geological	5	Calc-alkaline volcanic sequence with abundant exhalite units and several felsic pyroclastic centers. Regional-scale air photos indicate major cross-fault intersects largest felsic center.
	Geochemical	3	Anomalous base metal contents in exhalite units.
	Geophysical	5	Complete airborne EM — magnetic coverage. Abundant low-response EM anomalies, little magnetic response. Several moderate to strong EM anomalies, the strongest in vicinity of cross-fault and volcanic center.
Local	Stratigraphy	5	Four well-developed felsic centers in a 1 km thick sequence of interbedded flows, pyroclastics, and several thin exhalite units.
	Lithology	5	Predominantly rhyolite flows, rhyolitic and andesitic pyroclastic breccia and tuff, silicified andesite flows, and abundant exhalite. Outcrop of millrock in largest of rhyolitic centers.
	Alt./Min.	4.5	Zones of sericitic alteration. Abundant malachite staining on exhalite beds.
	Structure	3.5	Sericitic zones mainly in vicinity of interpreted cross-fault.
	Geochemical	4	Silica enrichment near base of felsic centers. Anomalous Zn, Cu and Cd in exhalites.
	Geophysical	3.5	No significant correlation with ground EM and magnetic surveys. Strong IP response at largest felsic center.

Appendix B: Basic Concepts of Pairwise Comparisons

The method of pairwise comparisons was first presented in embryonic form for binary choices by Fechner (1860), and formalized by Thurstone (1927) after considerable extension to general choices.

An n by n pairwise comparisons matrix is defined as a square matrix $\mathbf{A} = [a_{ij}]$ such that $a_{ij} > 0$ for every $i,j = 1,\ldots,n$. Each a_{ij} expresses a relative preference of criterion (or stimulus) s_i over criterion s_j for $i,j = 1,\ldots,n$ represented by numerical weights (positive real numbers) and w_i and w_j respectively. The quotients $a_{ij} = w_i/w_j$ form a pairwise comparisons matrix:

$$\mathbf{A} = \left| \begin{array}{cccc} 1 & a_{12} & \ldots & a_{1n} \\ 1/a_{12} & 1 & \ldots & a_{2n} \\ \\ \ldots & \ldots & \ldots & \ldots \\ 1/a_{1n} & 1/a_{2n} & \ldots & 1 \end{array} \right|$$

A pairwise comparisons matrix $\mathbf{A}$ is called *reciprocal* if $a_{ij} = 1/a_{ji}$ for every $i,j = 1,\ldots,n$ (then automatically $a_{ii} = 1$ for every $i = 1,\ldots,n$ because they represent the relative ratios of a criterion against itself). A pairwise comparisons matrix $\mathbf{A}$ is called *consistent* if $a_{ij} \cdot a_{jk} = a_{ik}$ holds for every $i,j,k = 1,\ldots,n$ since $w_i/w_j \cdot w_j/w_k$ is expected to be equal to w_i/w_k. Although every consistent matrix is reciprocal, the converse is not generally true. In practice, comparing s_i to s_j, s_j to s_k, and s_i to s_k often results in inconsistency among the assessments in addition to their inaccuracy; however, the inconsistency may be computed and used to improve the accuracy (for details, see Koczkodaj, 1993).

The first step in pairwise comparisons is to establish the relative preference of each combination of two criteria. A scale from 1 to 5 can be used to compare all criteria in pairs. Values from the interval $[1/5,1]$ reflect inverse relationships between criteria, since $s_i/s_j = 1/(s_j/s_i)$. The consistency-driven approach is based on the reasonable assumption that by finding the most inconsistent judgements, one can then reconsider one's own assessments. This in turn contributes to the improvement of judgmental accuracy. Consistency analysis is a dynamic process which is assisted by the software.

The central point of the inference theory of the pairwise comparisons is Saaty's Theorem (Saaty, 1977), which states that for every n by n consistent matrix $\mathbf{A} = [a_{ij}]$ there exists positive real numbers $w_1,\ldots,w_n$ (weights corresponding to criteria $s_{1,..n..}$,s) such that $a_{ij} = w_i/w_j$ for every $i,j = 1,\ldots,n$. The weights, w_i, are unique up to a multiplicative constant. Saaty (1977) also discovered that the eigenvector corresponding to the largest eigenvalue of $\mathbf{A}$ provides weights w_i which we wish to obtain from the set of preferences, a_{ij}. This is not the only possible solution to the weights problem. In the past, a least-squares-solution was known, but it was far more computationally demanding than finding an eigenvector of a matrix with positive elements. Later, a method of row geometric means was proposed (Jensen, 1984), which is is the simplest and the most effective method of finding weights. A statistical experiment (Herman and Koczkodaj, 1996) demonstrated that the accuracy, that is, the distance from the original matrix $\mathbf{A}$ and the matrix $\mathbf{A}'$ reconstructed from weights with elements $[a_{ij}] = [w_i/w_j]$, does not strongly depend on the method. There is, however, a strong relationship between the accuracy and consistency. Consistency analysis is the main focus of the consistency-driven approach.

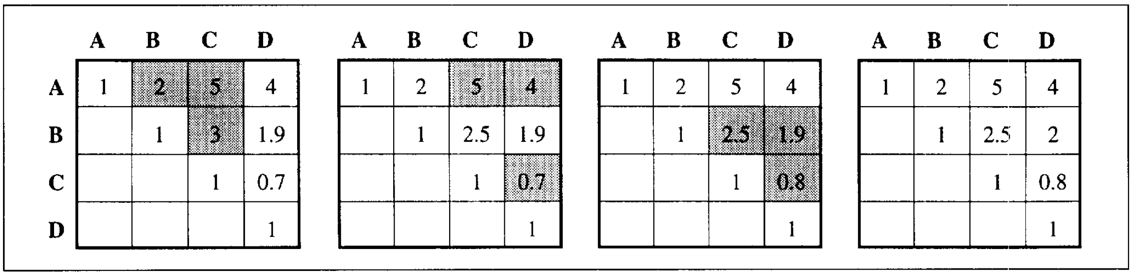
An important problem is how to begin the analysis. Assigning weights to all criteria (e.g., $A = 18$, $B = 27$, $C = 20$, $D = 35$) seems more natural than the above process. In fact it is a recommended practice to start with some initial values. The above values yield the ratios: $A/B = 0.67$, $A/C = 0.9$, $A/D = 0.51$, $B/C = 1.35$, $B/D = 0.77$, $C/D = 0.57$. Upon analysis, these may look somewhat suspicious because all of them round to 1, which is of equal or unknown importance. This effect frequently arises in practice, and experts are tempted to change the ratios by increasing some of them and decreasing others (depending on knowledge of the case). The changes usually cause an increase of inconsistency which, in turn, can be handled by the software analysis because it contributes to establishing more accurate and realistic weights. The pairwise comparisons method requires evaluation of all combinations of pairs of criteria, and can be more time-consuming because the number of comparisons depends on n^2 (the square of the number of criteria). However, it leads to an increase in accuracy (> 300%), as was demonstrated by a Monte Carlo experiment with bars of randomly generated lengths (Koczkodaj, 1996). The complexity problem has been addressed and partly solved by the introduction of hierarchical structures (Saaty, 1977). Dividing criteria into smaller groups is a practical solution in cases in which the number of criteria is large.

Appendix C: Consistency Analysis

Consistency analysis is critical to the approach presented here because the solution accuracy of *not-so-inconsistent* matrices strongly depends on the inconsistency (Herman and Koczkodaj, 1996). The consistency-driven approach is, in brief, the next step in the development of pairwise comparisons.

The challenge to the pairwise comparisons method comes from a lack of consistency in the pairwise comparisons matrices which arises in practice. Given an n by n matrix $\mathbf{A}$ that is not consistent, the theory attempts to provide a consistent n by n matrix $\mathbf{A}'$ that differs from matrix $\mathbf{A}$ "as little as possible". A statistical experiment (Herman and Koczkodaj, 1996) showed, however, that the accuracy of weights does not strongly depend on the method. In particular, the geometric means method produces results similar to the eigenvector method (to high accuracy) for the ten million cases tested. There is, however, a strong relationship between accuracy and consistency. This is the main focus of the consistency-driven approach based on the triad-based inconsistency introduced by Koczkodaj (1993).

Unlike the old eigenvalue-based inconsistency (Saaty, 1977; Koczkodaj, 1993), the triad-based inconsistency locates the most inconsistent triads. This allows the user to reconsider the assessments included in the most inconsistent triad. It has been shown (Holsztynski and Koczkodaj, 1996)



	A	B	C	D
A	1	2	5	4
B		1	3	1.9
C			1	0.7
D				1

	A	B	C	D
A	1	2	5	4
B		1	2.5	1.9
C			1	0.7
D				1

	A	B	C	D
A	1	2	5	4
B		1	2.5	1.9
C			1	0.8
D				1

	A	B	C	D
A	1	2	5	4
B		1	2.5	2
C			1	0.8
D				1

Fig. C1. An example of the process of consistency improvement.

that the global inconsistency decreases with the reduction of the local inconsistency. Algorithms for reducing the triad inconsistency in pairwise comparisons can be improved by orthogonal projections (Holsztynski and Koczkodaj, 1996).

Readers might be curious, if not suspicious, about how one could arrive at values such as *0.70* or *1.90* as relative ratio judgments. In fact the values were initially different, but have been refined and the final weights calculated by the consistency analysis. It is fair to say that making comparative judgments of rather intangible criteria (e.g., stratigraphy) results not only in imprecise knowledge, but also in inconsistency in our own judgments. The improvement of knowledge by controlling inconsistencies in the judgments of experts, that is, the *consistency-driven approach*, is not only desirable but is essential.

In practice, inconsistent judgments are unavoidable when at least three factors are independently compared against each other. For example, let us look at the ratios of the four criteria *A*, *B*, *C*, and *D* in Figure C1. Suppose we estimate ratios *A/B* as *2*, *B/C* as *3*, and *A/C* as *5*. Evidently something does not "add up" because *(A/B)* • *(B/C) = 2* • *3 = 6*, which obviously is not equal to *5* (that is *A/C*). With an inconsistency index of *0.17*, the above triad (with highlighted values of *2*, *5*, and 3) is the most inconsistent in the entire matrix (reciprocal values below the main diagonal are not shown in Fig. C1). A rash judgment may lead us to believe that *A/C* should indeed be *6*, but we do not have any reason to reject the estimation of *B/C* as *2.5* or *A/B* as *5/3*. After correcting *B/C* from *3* to *2.5*, which is an estimate and is usually based on additional knowledge gathering, the next most inconsistent triad is *(5, 4, 0.7)* with an inconsistency index of *0.13*. An adjustment of *0.7* to *0.8* makes this triad fully consistent (*5* • *0.8* is *4*), but another triad *(2.5, 1.9, 0.8)* has an inconsistency of *0.05*. By changing *1.9* to *2* the entire table becomes fully consistent. The corrections for real data are done on the basis of professional experience and case knowledge by examining all three criteria involved.

An acceptable threshold of inconsistency is *0.33* because it means that one judgment is not more than two grades of the scale (Table 1) "different" from the remaining two judgments (Koczkodaj, 1993). There was no need to continue decreasing the inconsistency, as only its high value is harmful; a very small value may indicate that the artificial data were entered hastily without reconsideration of former assessments.