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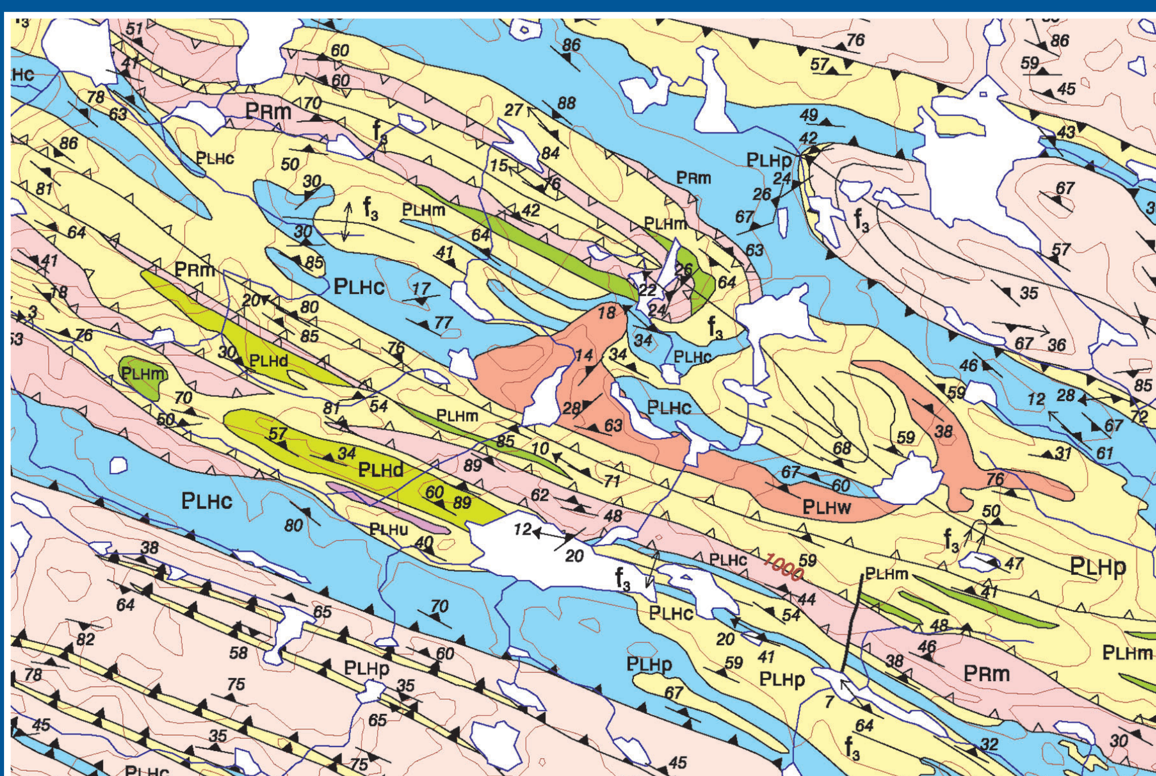
ANALYSIS OF IMPROVED GOVERNMENT GEOLOGICAL MAP INFORMATION FOR MINERAL EXPLORATION: INCORPORATING EFFICIENCY, PRODUCTIVITY, EFFECTIVENESS, AND RISK CONSIDERATIONS

R. Bernknopf, A. Wein, M. St-Onge, and S. Lucas



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Cover illustration
Portion of one of the Geological Survey of Canada's finer resolution bedrock maps for southern Baffin Island (Nunavut, Canada). The map published at 1:100 000 scale documents the distribution of principal tectonostratigraphic units of the Lake Harbour Group: psammite and pelite (PLHp map unit) in yellow, marble (PLHc map unit) in blue, gabbro (PLHm map unit) in dark green, diorite (PLHd map unit) in pale green, peridotite (PLHu map unit) in purple, and leucogranite (PLHw map unit) in reddish brown. The stratigraphic basement (PRm map unit) to the Lake Harbour Group is shown in pink. Two generations of thrust faults (open and closed teeth on hanging wall of individual faults), post-thrusting folds (F_3 fold axes), and structural point data (strike and dip of planar fabric; trend and plunge of linear fabric) are also shown.

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ANALYSIS OF IMPROVED GOVERNMENT GEOLOGICAL MAP INFORMATION FOR MINERAL EXPLORATION: INCORPORATING EFFICIENCY, PRODUCTIVITY, EFFECTIVENESS, AND RISK CONSIDERATIONS

Abstract

This bulletin/professional paper focuses on the value of geoscientific information and knowledge, as provided in published government bedrock geological maps, to the mineral exploration sector. An economic model is developed that uses an attribute-ranking approach to convert geological maps into domains of mineral favourability. Information about known deposits in these (or analogous) favourability domains allow the calculation of exploration search statistics that provide input into measures of exploration efficiency, productivity, effectiveness, risk, and cost stemming from the use of the published geological maps. Two case studies, the Flin Flon Belt (Manitoba and Saskatchewan) and the south Baffin Island area (Nunavut), demonstrate that updated, finer resolution maps can be used to identify more exploration campaign options, and campaigns thats are more efficient, more effective, and less risky than old, coarser resolution maps when used as a guide for mineral exploration. The Flin Flon Belt study illustrates that an updated, coarser resolution bedrock map enables improved mineral exploration efficiency, productivity, and effectiveness by locating 60% more targets and supporting an exploration campaign that is 44% more efficient. Refining the map resolution provides an additional 17% reduction in search effort across all favourable domains and a 55% reduction in search effort in the most favourable domain. The south Baffin Island case study projects a 40% increase in expected targets and a 27% reduction in search effort when the updated, finer resolution map is used in lieu of the old, coarser resolution map. On southern Baffin Island, the economic value of the updated map ranges from CAN$2.28 million to CAN$15.21 million, which can be compared to the CAN$1.86 million that it cost to produce the map (a multiplier effect of up to eight).

Résumé

Le présent document paper porte sur la valeur au secteur de l'exploration des ressources minérales de l'information et des connaissances géoscientifiques fournies par les cartes géologiques du socle publiées par le gouvernement. Les auteurs ont créé un modèle économique qui utilise une approche de classement hiérarchique des attributs permettant de transformer les cartes géologiques en domaines de favorabilité pour les ressources minérales. Le recours à l'information sur des gîtes connus à l'intérieur de ces domaines de favorabilité (ou de domaines analogues) permet le calcul de statistiques ayant trait aux recherches liées aux activités d'exploration. Ces statistiques fournissent les éléments permettant de mesurer les taux d'efficience et de productivité, les risques et les coûts liés aux activités d'exploration, résultant de l'utilisation des cartes géologiques publiées. Deux études de cas, celle de la ceinture de Flin Flon (au Manitoba et en Saskatchewan) et celle de la région sud de l'île de Baffin (Nunavut), démontrent que des cartes à plus grande résolution mises à jour, opeuvent servir à cerner un plus grand choix de campagnes d'exploration caractérisées par un plus haut taux d'efficience et d'efficacité et qui présentent moins de risques que les anciennes cartes à moindre résolution lorsqu'elles sont utilisées comme guide aux fins de l'exploration minérale. L'étude de cas de la ceinture de Flin Flon permet d'illustrer que le recours à une carte géologique du socle à moindre résolution mise à jour, favorise une amélioration des taux d'efficience, de productivité et d'efficacité en localisant 60 % plus de cibles et en augmentant de 44 % le taux d'efficience de la campagne d'exploration. Une résolution encore plus élevée permet de réduire de 17 % supplémentaires les efforts consacrés à l'exploration dans tous les domaines favorables et de 55 % les efforts consacrés à l'exploration dans le domaine le plus favorable. L'étude de cas de la région sud de l'île de Baffin prévoit une augmentation de 40 % dans le nombre de cibles prévues et une réduction de 27 % des efforts consacrés à l'exploration, lorsqu'une carte à plus grande résolution mise à jour est utilisée plutôt que l'ancienne carte à moindre résolution. Dans le cas de la région sud de l'île de Baffin, la valeur économique de la carte mise à jour se situe entre 2,28 millions de dollars canadiens et 15,21 millions, et peut être comparée au coût de 1,86 million de dollars canadiens associé à la production de la carte (soit un effet multiplicateur de huit).

SUMMARY

Mineral exploration is one of the many uses of geological maps that are provided as a public good in Canada and the U.S.A. A public good is defined as something that is readily available to all for numerous purposes, and its use by one user does not degrade its utility nor does it exclude use by others. Other uses of geological maps include land-use planning, environmental-impact assessments, and hazard evaluation. This bulletin/professional paper focuses on the value of geoscientific information and knowledge, as provided in published government bedrock geological maps, to the mineral resource exploration sector. It is assumed that the government considers mineral exploration investment and location of exploration targets as desirable in that they can ultimately benefit society in an environmentally neutral and sustainable way. The authors propose an economic model that links mineral exploration investment decisions to information contained in bedrock geological maps. The model uses an attribute-ranking approach to convert the geological maps into domains of mineral favourability (the likelihood of a geological setting containing an exploration target), which are treated as the potential search areas of exploration campaigns. Information about known deposits in these (or analogous) favourability domains allows one to retrospectively (or prospectively) calculate exploration search statistics for these domains. These statistics provide input into measures of exploration campaign efficiency, productivity, effectiveness, risk, and cost stemming from the use of the published geological maps.

Examination of less area per target is more efficient and more expected targets per are examined is more productive. One says a map is more effective if it can be used to identify feasible exploration campaigns that yield higher expectations of the number of targets to be found. The risk of an exploration campaign is monitored by the probability of finding at least a predetermined number of targets. The cost of an exploration campaign is the sum of search unit examination costs and target drill-testing costs.

The decision model is constructed from the measures of exploration efficiency, productivity, effectiveness, risk, and cost to suggest how companies might have optimally invested in exploration if the maps, statistics, and measures had been available when exploration decisions were made. The authors then compared the decisions based on information contained in maps of different ages (vintage) and resolutions (scales) in two case studies.

SOMMAIRE

L'exploration minérale représente l'une des nombreuses activités qui ont recours aux cartes géologiques offertes à titre de bien public au Canada et aux États-Unis. Un bien public est disponible et facilement utilisable par la collectivité à de nombreuses fins, sans que son utilisation par une personne ne réduise son utilité pour d'autres utilisateurs, ni ne les prive de son utilisation. Ces cartes s'avèrent utiles pour d'autres activités, notamment l'aménagement du territoire, l'évaluation des incidences environnementales, ainsi que l'évaluation des risques. Le présent document porte sur la valeur, au secteur de l'exploration des ressources minérales, de l'information et des connaissances géoscientifiques fournies par les cartes géologiques du socle publiées par le gouvernement. L'hypothèse adoptée veut que le gouvernement considère souhaitables les investissements en matière d'exploration minérale et la détermination de cibles de prospection minière puisqu'ils peuvent, en fin de compte, faire bénéficier la société d'une approche durable, sans effet sur l'environnement. Les auteurs proposent un modèle économique qui lie les décisions en matière d'investissements liés à l'exploration minérale à l'information représentée sur les cartes géologiques du socle. Le modèle utilise une approche de classement hiérarchique des attributs permettant de transformer les cartes géologiques en domaines de favorabilité (la probabilité qu'un cadre géologique renferme une cible d'exploration) pour les ressources minérales, qui sont considérés comme d'éventuelles régions de recherche lors de campagnes d'exploration sur le terrain. Le recours à l'information sur des gîtes connus à l'intérieur de ces domaines de favorabilité (ou de domaines analogues) permet le calcul rétrospectif (ou prospectif), pour les domaines en question, des statistiques de recherche ayant trait aux activités d'exploration. Ces statistiques fournissent les éléments permettant de mesurer les taux d'efficience, de productivité et d'efficacité, ainsi que les risques et les coûts liés aux activités d'exploration résultant de l'utilisation des cartes géologiques publiées.

Il est plus efficient d'examiner un secteur de superficie plus limitée par cible et plus productif de trouver plus de cibles que prévu par secteur examiné. On juge qu'une carte est plus efficace si elle peut servir à identifier les campagnes d'exploration réalisables susceptibles de hausser les attentes quant au nombre de cibles à découvrir. Les risques liés à une campagne d'exploration sont contrôlés par la probabilité de découvrir au moins un certain nombre prédéterminé de cibles. Les coûts d'une campagne d'exploration représentent la somme des coûts liés à l'étude des unités d'exploration et des coûts relatifs aux essais de forage.

Le modèle décisionnel est élaboré à partir de la mesure des taux d'efficience, de productivité et d'efficacité, ainsi que des risques et des coûts liés aux activités d'exploration, dans le but d'indiquer comment les sociétés d'exploration auraient pu investir de manière optimale dans les activités d'exploration si des cartes, des statistiques et des mesures avaient été disponibles au moment de la prise de décisions. Les auteurs ont ensuite comparé les décisions en se basant sur l'information représentée sur des cartes de diverses époques et à diverses résolutions (échelles) dans deux études de cas.

The case studies, the Flin Flon Belt of Manitoba and Saskatchewan, and the south Baffin Island area of eastern Nunavut (a mature mining district and a frontier region in Canada, respectively) demonstrate that updated, finer resolution maps provide more detailed and accurate information than older, coarser resolution maps when used as a guide for mineral exploration. As a general rule, incorporating new knowledge improves the quality of a map's information, whereas using a finer resolution (i.e. larger scale) increases the quantity of a map's information. Relative to the old, coarser resolution maps, the updated, finer resolution maps better delineate both favourable domains (with higher expected target densities) and unfavourable domains (with lower expected target densities). The analysis herein supports the statement that: "as a consequence of an increase in the quality and quantity of information either the same output can be achieved for less resources or for the same input, output can be increased". Thus, the updated, finer resolution map enables an improved mineral search that is more efficient and more productive. In addition, the increased productivity combined with the number of search units (i.e. search area) delineated by favourable domains on the updated, finer resolution map leads to exploration campaigns that are less risky and more effective for a set budget.

The authors surmise that the quantity and quality of the information derived from the updated, finer resolution map increases the attractiveness of investment to the mineral exploration industry. The authors estimate the value of the updated, finer resolution geological information as being the expected additional exploration investment (as per best business practice) relative to the investment based on information contained in the older, coarser resolution map only. The additional investment can be compared to the cost of producing the updated map. Implicit in this comparison is the idea that more investment in exploration is desirable and each additional dollar of exploration investment is assumed to be of equal benefit to society: firstly, as recompense for the cost of producing the map; and secondly, in terms of the economic activity stimulated.

In the Flin Flon Belt case study, exploration campaigns are modelled retrospectively, that is, information about known mineral showings is used to estimate the *a priori* target densities explorers would have attached to the favourability domains. The Flin Flon Belt study illustrates that campaigns derived from the updated, coarser bedrock map enables improved mineral exploration efficiency, productivity, and effectiveness. The optimal exploration campaign of the updated, coarser resolution map locates 60% more expected targets and is 44% more efficient. Increased map resolution also has a positive effect on exploration efficiency

Les études de cas, celle de la ceinture de Flin Flon au Manitoba et en Saskatchewan et celle de la région sud de l'île de Baffin dans l'est du Nunavut (respectivement, un district minier parvenu à maturité et une région pionnière au Canada), démontrent que des cartes à plus grande résolution mises à jour, offrent de l'information plus détaillée et plus exacte que les anciennes cartes à moindre résolution lorsqu'elles sont utilisées comme guide aux fins de l'exploration minérale. En règle générale, l'intégration de nouvelles connaissances permet d'améliorer la qualité de l'information représentée sur les cartes, alors qu'une plus grande résolution (c.-à-d. une échelle plus grande) permet d'augmenter la quantité d'information représentée. Comparées aux anciennes cartes à moindre résolution, les cartes à plus grande résolution mises à jour permettent de mieux délimiter tant les domaines favorables (où on s'attend à de fortes densités de cibles) que les domaines non favorables (où on s'attend à des densités plus faibles de cibles). La présente analyse appuie l'énoncé affirmant que : « comme conséquence à l'augmentation de la qualité et de la quantité d'information, on peut soit obtenir le même résultat en utilisant moins de ressources, soit accroître les résultats en utilisant les mêmes ressources » [traduction]. Ainsi, les cartes à plus grande résolution mises à jour permettent d'améliorer la recherche des gîtes minéraux, la rendant plus efficiente et plus productive. En outre, la productivité accrue combinée au nombre d'unités de recherche (c.-à-d. les régions de recherche), délimitées par les domaines favorables sur les cartes à plus grande résolution mises à jour, permettent de réaliser des campagnes d'exploration moins risquées et plus efficaces en fonction d'un budget établi.

On suppose que la quantité et la qualité de l'information dérivée de la carte à plus grande résolution mise à jour permettent d'attirer davantage les investissements du secteur de l'exploration minérale. Les auteurs estiment que la valeur de l'information géologique mise à jour de la carte à plus grande résolution correspond aux investissements additionnels attendus pour l'exploration (en accord avec les meilleures pratiques de gestion), par rapport aux investissements réalisés suite au recours uniquement sur l'information représentée sur l'ancienne carte à moindre résolution. Les investissements additionnels peuvent être comparés aux coûts de production de la carte mise à jour. Dans cette comparaison, les auteurs supposent implicitement qu'il est souhaitable de susciter des investissements supplémentaires dans des activités d'exploration et que chaque dollar additionnel investi en exploration représente un avantage équivalent pour la société, d'abord comme compensation pour la production de la carte et ensuite comme moyen de stimuler l'activité économique.

Dans l'étude de cas de la ceinture de Flin Flon, les campagnes d'exploration sont modélisées de manière rétrospective. Ainsi, cela signifie que l'information sur des occurrences minérales connues est utilisée pour estimer a priori les densités des cibles que les prospecteurs auraient associées aux domaines de favorabilité. L'étude de la ceinture de Flin Flon permet d'illustrer que des campagnes s'appuyant sur une carte géologique du socle à moindre résolution mise à jour, entraîne une amélioration des taux d'efficience, de productivité et d'efficacité liés aux activités d'exploration minérale. La campagne d'exploration optimale, déterminée à l'aide de la carte à moindre résolution mise à jour, permet de localiser 60 % plus de cibles prévues et d'augmenter de and productivity especially in the higher favourability domains with higher expected mineral target densities. Increasing map resolution also provides the capability to define more favourability classes, thereby offering more exploration options. A comparison of updated maps of different resolutions shows that refining the resolution provides an additional 17% reduction in search effort across all favourable domains and a 55% reduction in search effort in the most favourable domain.

In the south Baffin Island case, exploration campaigns are considered proactively: the area is still largely unexplored and the exploration statistics are derived from an analogous area. The south Baffin Island study projects a 40% increase in expected targets and a 27% reduction in search effort when all favourable domains are searched and the updated, finer map is used in lieu of the old, coarser map. Since south Baffin Island is a frontier region and exploration cost estimates were available, this case study facilitates the economic analysis of the additional exploration investment that may be ultimately attributable to the production of the updated, finer resolution maps (published in 1999). Assuming exploration of the highest favourability class on the updated, finer maps at a minimum, estimation of the investment generated is within a range from CAN$2.28 million to CAN$15.21 million depending on the decision maker's tolerance for risk and need for efficiency. The return on the investment (expected number of targets per million dollars spent) declines from 6.6 to 5.1 when investment within the highest favourability domain is extended into exploration of all favourable domains on the updated map. This can be compared to a return of 4.7 for exploring favourable domains on the old, coarser map. The economic value of the updated map also ranges from CAN$2.28 million to CAN$15.21 million and can be compared to the CAN$1.86 million that it cost to produce the updated, finer resolution map (a multiplier effect of eight). Consequently in this case, the government can provide a public good and demonstrate that the cost of providing that information can be more than offset by the consequent economic activity of a specific user group. The actual translation of the exploration investment into societal benefits is beyond the scope of this work.

In summary, this study resulted in an innovative methodology for estimating the value of bedrock geological maps within the context of mineral exploration and in doing so, answers industry's need for "more robust and quantitative methodologies for measuring exploration effectiveness, and for informing management,

44 % le taux d'efficience de la campagne. Une meilleure résolution de la carte entraîne également des effets positifs sur l'efficience et la productivité liées aux activités d'exploration, particulièrement dans les domaines de favorabilité plus élevée où de plus grandes densités de cibles d'exploration minérale sont attendues. Une meilleure résolution de la carte permet également de déterminer plus de classes de favorabilité, offrant ainsi plus d'options pour l'exploration. Une comparaison des cartes à diverses résolutions mises à jour démontre qu'une résolution plus élevée permet de réduire de 17 % supplémentaires les efforts consacrés à l'exploration dans tous les domaines favorables et de 55 % les efforts consacrés à l'exploration dans le domaines le plus favorable.

Dans le cas de la région sud de l'île de Baffin, les campagnes d'exploration sont examinées de manière proactive : la région demeure en grande partie peu explorée et les statistiques ayant trait à l'exploration sont basées sur une région analogue. L'étude de cas de la région sud de l'île de Baffin prévoit une augmentation de 40 % dans le nombre de cibles prévues et une réduction de 27 % des efforts consacrés à l'exploration, lorsque tous les domaines favorables sont explorés et qu'une carte à plus grande résolution mise à jour est utilisée plutôt que l'ancienne carte à moindre résolution. Puisque la région sud de l'île de Baffin est une région pionnière et que des estimations des coûts d'exploration étaient disponibles, cette étude de cas facilite l'analyse économique des investissements additionnels aux fins d'exploration qui pourraient éventuellement être attribuables à la production des cartes à plus grande résolution mises à jour (publiées en 1999). En supposant, au minimum, l'exploration des domaines comportant la classe de favorabilité la plus élevée sur des cartes à plus grande définition mises à jour, l'estimation des investissements générés se situe entre 2,28 millions de dollars canadiens et 15,21 millions, selon la tolérance au risque et le besoin d'efficience du décideur. Le taux de rendement des investissements (nombre de cibles prévues par million de dollars investis) diminue de 6,6 à 5,1 lorsque l'investissement dans le domaine le plus favorable est étendu à l'exploration de tous les domaines favorables représentés sur la carte mise à jour. Cela peut se comparer à un taux de rendement de 4,7 pour l'exploration des domaines favorables déterminés à l'aide de l'ancienne carte à moindre résolution. De plus, la valeur économique de la carte mise à jour se situe entre 2,28 millions de dollars canadiens et 15,21 millions et peut être comparée au coût de 1,86 million de dollars canadiens associé à la production de la carte à plus grande résolution mise à jour (soit un effet multiplicateur de huit). Par conséquent, dans le cas présent, le gouvernement peut fournir un bien public et démontrer que le coût de cette information est plus que compensé par l'activité économique qui en résulte au sein d'un groupe particulier d'utilisateurs. La conversion proprement dite des investissements liés à l'exploration en termes d'avantages pour la société dépasse cependant la portée du présent document.

En résumé, la présente étude a permis d'élaborer une méthodologie innovatrice pour estimer la valeur des cartes géologiques du socle dans le contexte de l'exploration minérale et, se faisant, répond aux besoins du secteur industriel à la recherche de « méthodologies quantitatives plus robustes permettant de mesurer l'efficacité de l'exploration et d'informer les gestionnaires, les investors, and shareholders of exploration risk, reward, value, and progress to discovery". The methodology can be applied to other circumstances such as environmental assessments and land-use decisions, highlighting both the utility of the model and the value of the geological map information as a public good.

investisseurs et les actionnaires sur les risques, le rendement et la valeur de l'exploration, ainsi que sur la progression vers d'éventuelles découvertes » [traduction]. Cette méthodologie peut s'appliquer en d'autres circonstances, notamment pour des évaluations environnementales et des décisions sur l'utilisation des terres, soulignant à la fois l'utilité du modèle ainsi que la valeur de l'information représentée sur la carte géologique à titre de bien public.

The two case studies validated the model and demonstrated the potential economic benefits of the updated geological maps. Analysis of the case study areas using the model showed that the new maps provided more exploration options, reduced exploration risk, and improved efficiency and productivity. In other words, the updated maps supported more cost-effective exploration as the simulated exploration decision-making behaviour always prefers the most up-to-date and most detailed map information, and targets the highest favourability areas first to maximize return on investment.

Les deux études de cas ont permis de valider le modèle et de démontrer les éventuels avantages économiques des cartes géologiques mises à jour. L'analyse, à l'aide du modèle, des régions visées par les études de cas a montré que les nouvelles cartes offraient plus d'options pour l'exploration, réduisaient les risques liés à l'exploration et amélioraient l'efficience et la productivité. En d'autres termes, les cartes mises à jour favorisaient une exploration plus rentable, puisque les comportements simulés en matière de prise de décision dans le domaine de l'exploration préfèrent toujours avoir recours à l'information cartographique la plus actuelle et la plus détaillée, et visent, en premier lieu, les zones où la favorabilité est la plus élevée afin de porter au maximum le rendement des investissements.

INTRODUCTION

An explanation of the geological map as a public good sets the stage for the government's interest in the role that geoscientific information can have in attracting mineral exploration investment.

The geological map as a public good

In Canada, the federal Resources and Technical Surveys Act (http://laws.justice.gc.ca/en/R-7/100170, [accessed 2005-09-07]) establishes the basis for considering geological map information as a public good. In Chapter R-7, section 3, the duties of the Minister of Natural Resources Canada are specified as including the following:

> "The Minister shall:
>
> (c) make a full and scientific examination and survey of the geological structure and mineralogy of Canada; …(f) prepare and publish the maps, plans, sections, diagrams, drawings, documents and data that are necessary to illustrate and elucidate any reports of investigations and surveys made pursuant to this Act."

In Canada, the mineral exploration industry is largely dependent on published government maps to provide the regional geological context for mineral exploration. As providers of public geoscience information, the Geological Survey of Canada (GSC) and associated provincial and territorial partners generally bear the full cost (including all field, compilation, and publication costs) of producing new geological maps in areas deemed to be in need of updated and finer resolution geoscientific information. Thus, every year governments produce new geological maps and their use by mineral exploration companies can help target less risky investments more efficiently and effectively.

Geological maps have many characteristics of a public good: they contain general information with multiple applications, have a long life span (shelf life) with an absence of congestion costs, benefit from a jointness of supply, are publicly available, and are nonexclusive (*see* explanations below). Discussion of the public good provided by geological maps begins with the distinction between 'general' and 'specific' information (Bernknopf et al., 1993). As applied to geological map information, 'general' refers to information collected at a scale pertinent to a variety of regional planning decisions. Generally, the information can inform and/or influence land-use choices such as mineral exploration, waste repository site selection, recreational and conservation designation, establishment of ecological preserves, residential and commercial construction, or highway route selection to name a few. Furthermore, this information can be used to present alternatives and assess the impacts of various land-use decisions including environmental-impact assessments, hazard prevention and protection, engineering studies, and city planning (Bernknopf et al., 1993, 1997; Bhagwat and Ipe, 2000). Given the slow rate of decay of its usefulness, such information has a long life span or shelf life and there is a lack of congestion costs (one individual's use of the information does not degrade its value to another).

Conversely, ‘specific’ information tends to possess fewer of these characteristics. In the context of maps, ‘specific’ refers to information that is much more localized and narrower in focus. Groundwater monitoring of mitigation measures for acid leaching at a coal strip mine provides a good example. As the information becomes more specific, the range of applications becomes limited, and the number of actual and potential users becomes smaller. In another example, the collection of site-specific geological information to determine the economic and environmental feasibility of extracting a localized porphyry copper deposit would be of little use in road planning. In compiling ‘specific’ information for efficient mineral exploration, ‘general’ information is often necessary to provide background data for the search and complement relevant planning decisions, whereas ‘specific’ information is often necessary to locate and prioritize specific mineral targets.

Another characteristic of a public good that is satisfied by a geological map is that the per-unit production and distribution costs of regional geological map information are near zero, whereas the cost of collecting the information makes up almost 100 per cent of total costs. The jointness of supply characteristic occurs because the bulk of the costs of producing such maps are borne ‘up front’, whereas the actual production and distribution costs are relatively small, and the cost of serving an additional customer is small. For example, the per-unit cost of information collection and synthesis for a set of seven 1:100 000 scale maps of south Baffin Island is CAN$1.86 million (M.R. St-Onge, unpub. data, 2000), whereas the cost of production and distribution for the seven published maps are CAN$106 (2005 price) in paper format, and CAN$110 (2005 price) in digital format (Geological Survey of Canada, http://gsc.nrcan.gc.ca/bookstore/index_e.php, [accessed 2005-06-05]).

Maps are nonexclusive in use, that is, individuals are able to obtain map information for a nominal fee (paper or digital format), or often as free downloads from the World Wide Web. In the current study, the government bedrock geological maps are publicly available, are readily available in certain repositories or off government web sites, and are reproducible, so there is little reason to believe that any individual could be restricted from use.

The role of geoscientific information in attracting exploration investment

The 2002 World Mines Ministries Forum conference (J. Macdonald, unpub. manuscript, 2002; http://www.wmmf.org/historical, [accessed 2005-10-15]) discussed the role of geoscientific information in attracting mineral exploration investment. Finer map resolution and advances in mapping technology and geoscientific understanding have increased the accuracy and precision of geological maps that are available to various users including mineral explorers. Anecdotal evidence suggests that updated geoscience information attracts investment, especially from junior exploration companies, and reduces risk at the earliest and riskiest stages of exploration when generally only smaller budgets are available. Empirical evidence was provided by Scott et al. (2002), who applied a revealed preference technique using multiple regression to model the effect of age, type, and detail of government scientific data on total exploration dollars spent, to conclude that upgraded data sets accounted for 10% of the variance in proposed mineral exploration expense compared to a 5% contribution from old data sets. In the same study, an expressed preference procedure concluded that the perception of prospectivity at least doubled with the provision of the upgraded data sets.

The ultimate value of geoscientific information to the mineral explorer is different from the value to society (Gilbert, 1981). Scott et al. (2002) addressed the societal value of updated geological information derived from royalties and reinvestment. Reedman et al. (2002) observed that geological field surveys required for the production of new geological maps provide benefits from employment, charitable contributions, and their multiplier effects in developed countries.

In the present bulletin/professional paper, the authors propose a hypothetical model of private-sector investment that directly links exploration decisions to information contained in bedrock geological maps, as an attempt to understand how an updated geological bedrock map would affect investment decisions. It assumes that exploration investment decisions are based on assessments of the likelihood of geological settings containing an exploration target (i.e. a mineralized feature or showing identified in the early stages of an exploration program, which might become a drilling target in a subsequent, more mature stage of exploration) and the resulting estimation of the efficiency, productivity, risk, cost, and effectiveness (number of targets) of mineral exploration reconnaissance campaigns. The optimal exploration campaigns suggested by maps of different ages and scales for the same region are compared to investigate the effect on exploration investment decisions of higher quality (updated) information and a greater quantity (finer resolution) of information. The quality of information has improved with recent advances in the understanding of fundamental earth science processes, including plate tectonics and mineralization, and the incorporation of more sophisticated and precise geothermal, geophysical, and geochronological information. The authors are able to quantify Reedman et al.’s (2002) essential argument that “as a consequence of an increase in the quality and quantity of information either the same output can be achieved for less resources or for the same input, output can be increased”. Less resource per unit of output is more efficient and more output per unit of resources is more productive. The results of the present study are also consistent with Swinden’s (1993) conclusion that the availability of recent maps and studies allowed BP-Selco to focus their exploration efficiently and effectively in Newfoundland. One says that a map is more effective if it can be used to identify feasible exploration campaigns that yield higher expectations for the number of targets to be found. In addition, the authors observe the effect of map age and scale on exploration risk expressed as the probability of finding a predetermined minimum number of targets.

The authors define the advantage (or value) of the updated geological information to the industry in a region as the difference between the exploration investments stimulated by the updated, finer resolution (i.e. large scale) geological map and those stimulated by the older map with a coarser resolution (i.e. smaller scale). The investment advantage to the exploration industry is equated to the benefit to society and compared to the cost of producing the map. The actual translation of the exploration investment into societal benefits is beyond the scope of this work.

The authors' analysis of bedrock maps used for exploration of a mineralization type proceeds as follows:

1) The geological (i.e. tectonostratigraphic) units and associations documented by each map are assigned mineralization favourability indices. The higher the index for geological favourability, the more likely mineralization is considered to have occurred in the geological units and associations assigned to it. A geographic information system is utilized to create a coverage (map) of favourability domains.

2) The search unit for the mineralization (an average projected surface area that uniquely hosts an exploration target) is determined. It is the area that could encompass one mineral deposit, as defined by the industry, but no more. Favourability domain target density (the proportion of search units containing a target) is estimated for each favourability domain using archived assessment reports and studies for a reference region. Some discussion is provided regarding uncertainty about the estimates of target densities.

3) The old, coarser resolution; updated, coarser resolution (if available); and updated, finer resolution maps are compared in terms of the optimal obtainable expected efficiency and productivity.

4) A representative optimal exploration campaign is found for each map using an economic decision-making model that maximizes effectiveness (target discovery) subject to efficiency, risk, and budget constraints.

5) The advantage or value of the updated, finer resolution map relative to the older, coarser resolution map is expressed as the difference in the expected exploration investments implied by each map's representative optimal campaign. Finally, the exploration investment advantage of the updated map is compared to the production costs of the map (total cost of associated new fieldwork and subsequent map publication).

The authors apply this approach in two case studies: the mature Flin Flon Belt area of Manitoba and Saskatchewan, and the frontier region of south Baffin Island in eastern Nunavut. The results from the Flin Flon Belt area study are counterfactual since the case considers the investment that the updated map might have inspired, if it had been available when the Flin Flon Belt region was explored. For the south Baffin Island case study the analysis is performed without knowledge of any prior mineral exploration.

In both case studies it is demonstrated that an updated, finer resolution map enables identification of exploration campaigns that enhance the feasibility or attractiveness of exploring a region by:

- reducing the number of expected search unit examinations (i.e. size of search area) to locate any fixed number of targets (increasing the efficiency of the search),
- increasing the expected number of targets for any given number of search unit examinations (increasing the productivity of the search),
- increasing the probability of locating a predetermined minimum number of targets (satisfying a risk criterion), and
- increasing the expected number of targets to be located (increasing the effectiveness of an exploration campaign).

For the south Baffin Island case study only, the authors project exploration investment under various decision-making criteria and produce a range of exploration investment outcomes. All of the exploration investment outcomes exceed the cost of producing the updated, finer resolution map.

STEP 1: FAVOURABILITY INDICES AND DOMAINS

Mineral exploration decisions are commonly made with some level of uncertainty about the general geological context and the occurrence or distribution of geological units considered most favourable for the type of mineralization of interest. Generally, exploration geoscientists use both physical and economic information to evaluate opportunities for mineral development (Singer and Kouda, 1999a).

Singer and Kouda (1999b) and Harris et al. (2003) compared a variety of favourability mapping techniques that associate geoscientific variables (lithology or rock type, structure, geophysics, geochemistry, etc.) with mineral occurrences. Any such technique could be employed to provide the favourability domain input into the present decision-making model. This study uses expert opinion in lieu of a mathematical method. For each map, an expert assigns a favourability index to each rock unit or contact between rock units depending on how pertinent, in their knowledge and experience, the rock unit or contacts might be for a given mineralization type (M. Einaudi, pers. comm., 1999). A geographic information system is used to convert the geological maps into coverages (maps) of the favourability domains prescribed by experts. Thus, contiguous rock units and/or contacts assigned the same favourability index are aggregated into a polygon and the collection of all the polygons for the same favourability index represents the domain of the favourability index with finite area. The procedures used to identify and buffer contacts are described in Appendix A.

In this study, no attempt is made to estimate potential geological endowment — number of deposits, grade, or tonnage, as discussed in Harris (1984). Geological endowment models can serve the purpose of more confidently and definitively choosing verified targets for mining and economic planning. In contrast, this study's favourability assignments assist with the selection of areas for further investigation in the early stages of an exploration program and the assessment of the associated investment.

STEP 2: TARGET DENSITIES

For each favourability domain the authors calculate a point estimate of the mineral target density, defined as the proportion of search units containing an exploration target, and attempt a measure of uncertainty about the point estimate.

Point estimate of target density per search unit

The following steps are used to produce the point estimate of mineral target density (the proportion of search units containing a target) for each favourability domain:

- A reference region is chosen that is either the study area itself when it is a mature mining region, or a geologically analogous region (based on established regional tectonostratigraphic correlations) when the study area is a frontier region with little mining history.
- The mineral exploration literature and/or an expert are consulted to determine the average aerial extent of a unique mineral exploration target for the given mineralization type. This defines the area of a search unit such that multiple mineral deposits within a search unit are counted, in the industry, as one deposit, and in the present study as one exploration target. Thus, a search unit can contain either 0 targets or 1 target. The authors recognize, however, that exploration targets and economic deposits are three-dimensional entities, a complexity not addressed in the current analysis.
- Using a geographic information system, the area of each favourability domain is calculated. The number of search units contained within the favourability domain f on map θ is denoted n_f^θ.
- Known mineral deposits and showings are overlain on a favourability domain map to count t_f^θ, the number of exploration targets contained in favourability domain f on map θ.
- If possible, k_f^θ, the proportion of the surface area of favourability domain f actually explored to produce the target information, would be determined. Since it is unlikely that land has been uniformly searched across all favourability domains it would be more realistic to factor in the extent of area searched when calculating exploration target densities. In the absence of further information k_f^θ is assumed to equal 1. The authors suspect that it is more likely that lower percentages of land have been searched in lower favourability domains. For example, half of the highest favourability domain may have been explored for targets compared to 10% of a less favourable domain.
- The empirical target density for each favourability domain f for map θ, $\hat{p}_f^\theta = t_f^\theta / k_f^\theta n_f^\theta$ is derived as the empirical proportion of search units that contain an exploration target in favourability domain f, with $0 \le \hat{p}_f^\theta \le 1$. Note that the empirical target density is expressed in terms of a search unit so estimates will differ from those based on square kilometres.

Uncertainty about the estimates of target density

Ideally, a mineral exploration decision depends not only on the point estimates for target densities, but also on the uncertainty of those estimates as a function of the quality and quantity of information. Singer et al. (2005) observed that little published information is available concerning the variability of deposit densities within deposit types. They investigated deposit density variability in nineteen porphyry copper control permissive areas (where permissive area is akin to an aggregation of all favourable domains). In the present study some of the exploration target density variability is explained by using more than one favourability class. Another source of variability relates to the quantity of information (the sample size) and the magnitude of the target density: the greater the sample size and the smaller the target density, the more statistically confident the estimate.

Regarding search units within a favourability domain as independent Bernoulli trials with true (but unknown) probability p_f^θ of containing a target and probability $1 - p_f^\theta$ of not containing a target, an approximate large-sample $100(1-\alpha)\%$ confidence interval for p_f^θ is given by

$$\hat{p}_f^\theta - z_{\alpha/2}\sqrt{\frac{\hat{p}_f^\theta \hat{q}_f^\theta}{k_f^\theta n_f^\theta}} < \hat{p}_f^\theta < \hat{p}_f^\theta + z_{\alpha/2}\sqrt{\frac{\hat{p}_f^\theta \hat{q}_f^\theta}{k_f^\theta n_f^\theta}}$$

where $\hat{q}_f^\theta = 1 - \hat{p}_f^\theta$ (Walpole and Meyers, 1989). In other words, this confidence interval can be interpreted as having a $100(1-\alpha)\%$ chance of containing p_f^θ. A confidence interval bounded only from below has a $100\left(1-\frac{\alpha}{2}\right)\%$ chance of containing p_f^θ. Confidence intervals are a function of the observed target density and the number of search units within the favourability domain on the map providing the estimate.

The confidence-interval approximation procedure is unreliable for cases with $n_f^\theta \hat{p}_f^\theta < 5$. In addition, the method is only partially satisfactory, even if the independence assumption holds, due to the general lack of information about k_f^θ (the proportion of a favourability domain actually explored to produce the target information). Both the estimate and the confidence surrounding it are distorted by using $k_f^\theta = 1$, causing one to underestimate the target density and overestimate the confidence in one's estimates. This is particularly true for the larger, less favourable domains that will, in all likelihood, have been less intensively explored.

STEP 3: MINERAL EXPLORATION EFFICIENCY AND PRODUCTIVITY

The authors measured expected mineral exploration productivity and efficiency to compare two geological maps covering the same region. Although the mineral exploration literature makes reference to the efficiency of exploration (Reedman et al., 2002), the authors know of no formalization of this term in the context of information provided by bedrock geological maps. Consequently, in this section, the related measures of exploration efficiency and productivity are defined, discussed, and modelled.

Exploration efficiency is the expected number of search unit examinations (i.e. search area) required to find a target, and is the inverse of the target density. Since exploration efficiency changes across favourability domains, expected exploration campaign efficiency depends on the extent of the campaign. The more search unit examinations required to find a target, on average, the less efficient the exploration campaign. The expected efficiency of the campaign can be computed, *a priori*, from the target densities. Model 1, defined below, solves for the most efficient search campaign that minimizes the expected number of search unit examinations to locate a fixed number of targets. It provides the means to compare the exploration efficiency of campaigns derived from different geological maps of the same region.

Expected mineral exploration productivity is the expected number of targets to be found per search unit examination and therefore, it is the target density at that location. Since target density (productivity) changes across favourability domains, exploration campaign productivity depends on the extent of the campaign. Model 2, defined below, solves for the most productive exploration campaign given a fixed number of search unit examinations. Thus, the expected exploration productivity of campaigns derived from different geological maps of the same region can be compared.

Model 1: minimizing the search area

The most efficient exploration campaign is described by the number of search unit examinations in each favourability domain that minimizes the total number of search unit examinations to find a specified expected number of exploration targets, *t*.

$$S^\theta(t) = \frac{\min}{\bar{x}} \sum_{f=0}^{F^\theta} x_f \qquad (1)$$

$$\text{subject to} \sum_{f=0}^{F^\theta} x_f \hat{p}_f^\theta = t$$

$$0 \le x_f \le n_f^\theta, \forall f$$

where

θ designates the map being used,

t is a specified expected number of targets to be found,

$S^\theta(t)$ is the minimum expected number of search unit examinations to find the specified number of exploration targets t using map θ,

x_f is the decision variable representing the number of search unit examinations in favourability domain f,

F^θ is the highest favourability index and 0 is the lowest favourability index on map θ,

$\bar{x}$ is the vector of decision variables $(x_0, \ldots, x_{F_\theta})$,

n_f^θ is the number of search units available in favourability domain f on map θ, and

$\hat{p}_f^\theta$ is the point estimate of the target density for favourability domain f on map θ.

The optimal decision for map θ is a vector of the optimal number of search unit examinations in each favourability class to find the expected number of exploration targets t, $\bar{x}^\theta(t) = (x_0^\theta(t), \ldots, x_{F^\theta}^\theta(t))$. The optimal decision is to search in the highest favourability domains until the specified number of targets is attained. The search effort savings of using the updated map to find an expected number of t targets is a function of the difference between the optimal objective function values, $(S^0(t) - S^U(t))$, where θ = U for the updated, finer resolution map and θ = O for the original old, coarser resolution map.

Model 2: maximizing the expected number of exploration targets

The most productive exploration campaign is described by the number of search unit examinations in each favourability domain that maximizes the expected number of targets to be found in a specified number of search unit examinations, *s*.

$$T^{\theta}(s) = \max_{\bar{x}} \sum_{f=0}^{F^{\theta}} x_f \hat{p}_f^{\theta} \tag{2}$$

$$\text{subject to} \sum_{f=0}^{F^{\theta}} x_f = s$$

$$0 \le x_f^{\theta} \le n_f^{\theta}, \forall f$$

where

θ designates the map being used,

s is a specified number of search unit examinations,

$T^{\theta}(s)$ is the maximum expected number of targets found in s search unit examinations,

x_f is the decision variable representing the number of search unit examinations in favourability domain f,

x_f^{θ} is the decision variable specifying the number of search unit examinations in favourability domain f on map θ,

F^{θ} is the highest favourability index and 0 is the lowest favourability index on map θ,

$\bar{x}$ is the vector of decision variables $(x_0, \ldots, x_{F^{\theta}})$,

n_f^{θ} is the number of search units available in favourability domain f on map θ, and

$\hat{p}_f^{\theta}$ is the point estimate of the target density for favourability domain f on map θ.

The optimal decision for map θ is a vector of the optimal number of search units examined in each favourability class to find the most exploration targets using a specified total number of search unit examinations s, $\bar{x}^{\theta}(s) = (x_0^{\theta}(s), \ldots, x_{F^{\theta}}^{\theta}(s)$ The most productive exploration campaign is to search favourability classes with the highest target density until the designated number of search units is exhausted. The gain in expected productivity of s search unit examinations using the updated map is the difference between the optimal objective function values, $(T^{U}(s) - T^{O}(s))$, where the updated and old maps are designated U and O, respectively.

The solutions from the two models are related. If s is the expected optimal efficiency for t targets then t is the expected optimal productivity for s search unit examinations. Figure 1 illustrates the optimal efficiency versus productivity curves for hypothetical old and updated maps of the same region. The updated, finer resolution map identifies three favourable domains, whereas the old, coarser resolution map identifies only one favourable domain. Each map has a favourability 0 domain that is not represented in Figure 1 because it is assumed to be of no interest. If favourability 0 domains were explored in addition to the more favourable domains, the whole region would be under exploration with the same outcome for both maps; it would be as if there were no geological maps available to guide exploration. Exploring favourability domains in descending order of favourability is always the optimal strategy. The slopes of the line segments in Figure 1

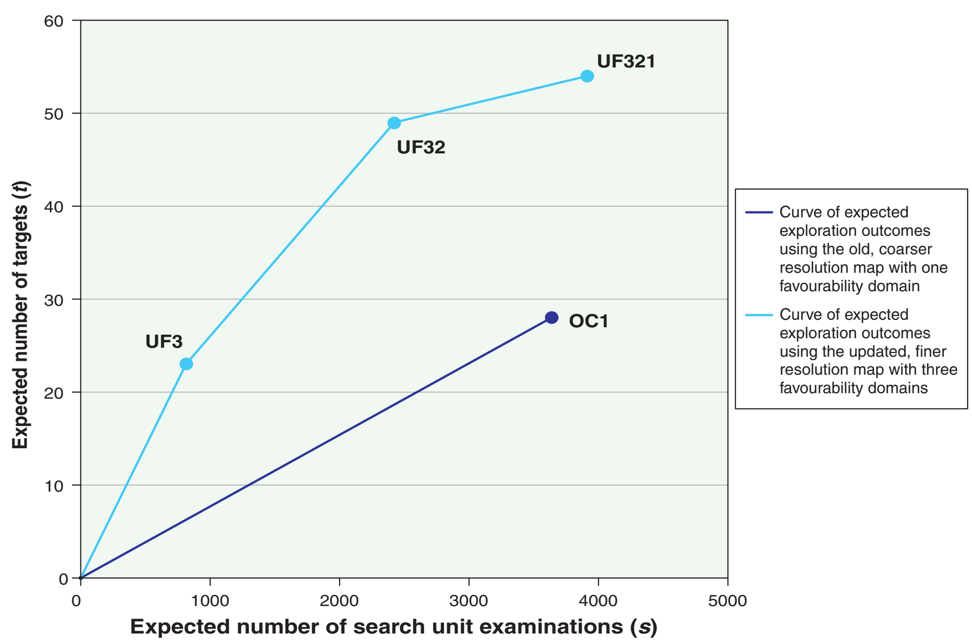


Figure 1. Illustrative expected efficiency versus expected productivity curves; UF3 corresponds to examination of all search units in favourability domain 3, UF32 in favourability domains 3 and 2, UF321 in favourability domains 3, 2, and 1 on the updated, finer resolution map, whereas OC1 corresponds to examination of all search units in favourability domain 1 on the old, coarser resolution map. The horizontal axis, *s* is the expected number of search units examined and the vertical axis, *t* is the expected number of targets to be found.

are the target densities corresponding to the favourability domains. Hence, the decreasing slope of the lines for the updated map as exploration exhausts one favourability domain and moves to the next most favourable domain. The labelled points in Figure 1 show the efficiency and productivity of the campaigns that fully search a set of favourability domains. For example, U32 is described by the vector of search examinations undertaken in each favourability domain $(0, n_2^U, n_3^U)$ denoting complete exploration of favourability domains 3 and 2 of the updated map. The horizontal difference between the two curves at target level *t* is the expected number of search unit examinations avoided by using map U to find *t* targets as opposed to map O. It is the gain in expected campaign efficiency given a goal of *t* expected targets. The vertical difference between the two curves at search unit examination level *s* is the increase in the expected number of targets found when examining *s* search units on map U instead of on map O. It is the gain in expected exploration campaign productivity for a given number of search unit examinations, *s*.

A high favourability domain that has a higher target density will have fewer expected searches to yield one target and consequently, will be more efficient. The same domain will, however, be limited in terms of the total number of targets (due to the smaller area generally associated with high favourability domains). A lower favourability domain will be less efficient to explore, but in some cases may yield a greater number of exploration targets due to a larger domain area.

A third model, discussed next in step 4, allows for the more likely outcome of each map suggesting an exploration campaign that does not have the same expected number of search unit examinations or the same expected number of exploration targets to be found. This third model is an 'economic' model that expands the decision framework to include exploration risk and budget concerns. The notion of productivity is replaced by effectiveness, which encompasses the number of expected targets to be found by an exploration campaign in the absence of a constraint on the number of search unit examinations.

STEP 4: ECONOMIC MODEL (MODEL 3)

Information is only of value if it affects a decision. Stanley (1994) presented a comprehensive review of the literature, spanning a 30 year period, that evaluates resource information according to its effects on societal costs and benefits, budget planning, and government policies. Stanley (1994) ranked various geoscientific survey methods including aeromagnetic, geochemical, and geological surveys. Herein the present authors propose a model in which exploration investment responds to the provision of geological map information from the public sector to the exploration industry. In the present analysis, the exploration geoscientist designs and evaluates regional exploration campaigns on the basis of expected exploration efficiency, effectiveness, risk, and cost.

Exploration campaign statistics

The exploration campaign, $\bar{x}$, for map θ, is described by specifying the number of search unit examinations x_f^θ in each favourability domain $0 \le f \le F^\theta$, with, $\bar{x} = (x_0, \ldots, x_{F_\theta})$. The total number of search units involved in the campaign is

$$u_{\bar{x}} = \sum_{f=0}^{F^\theta} x_f$$

and the campaign target density or expected proportion of campaign search unit examinations containing a target is the weighted sum of target densities of the favourability domains included in the campaign:

$$d_{\bar{x}} = \sum_{f=0}^{F^\theta} \frac{x_f}{u_{\bar{x}}^\theta} \hat{p}_f^\theta .$$

Constrained optimization model

The collective exploration industry is modelled as a conventional economic agent who seeks to make investment decisions that maximize economic benefits indicated by a map V^θ (the expected number of targets to be found) subject to an exploration risk constraint (R), an industry guideline for exploration efficiency (target density constraint : TD), and a budget constraint (Q; Lichtenberg, 1991; Bernknopf et al., 1997):

$$V^\theta = \frac{\max}{\bar{x}} \left(\sum_{f=0}^{F^\theta} x_f \hat{p}_f^\theta \right)$$

$$\text{subject to } 0 \le x_f \le n_f^\theta$$

$$u_{\bar{x}} = \sum_{f=0}^{F^\theta} x_f$$

$$d_{\bar{x}} = \sum_{f=0}^{F^\theta} \frac{x_f \hat{p}_f^\theta}{u_{\bar{x}}} \ge E \tag{3}$$

$$I_s u_{\bar{x}} + I_t u_{\bar{x}} d_{\bar{x}} \le M$$

$$B_{u_{\bar{x}}, d_{\bar{x}}}(t-1) \le 1 - P$$

where

θ designates the map being used,

V^θ is the optimal expected benefit (number of targets) of exploration for map θ,

x_f is the number of search units examined in favourability domain *f*,

F^θ is the highest favourability index and 0 is the lowest favourability index,

$\bar{x}$ is the vector of decision variables $(x_0, \ldots, x_{F^\theta})$,

$\hat{p}_f^\theta$ is the point estimate of the target density for favourability domain *f* on map θ,

$d_{\bar{x}}$ is the target density per search unit of campaign $\bar{x}$ using map θ,

$u_{\bar{x}}$ is the number of search units examined in campaign $\bar{x}$ using map θ,

M is the financial budget available,

I_s is the cost of examining a search unit,

I_t is the cost of pursuing a target,

$B_{u_{\bar{x}},d_{\bar{x}}}(t-1)$ is the cumulative binomial distribution that is the probability of finding no more than $t-1$ targets,

P is the minimum allowed probability of finding at least t targets or an industry risk standard, and

E is a minimum allowed campaign target density, or industry efficiency standard.

The objective function $V^{\theta} = \frac{\max}{\bar{x}}\left(\sum_{f=0}^{F^{\theta}} x_f \hat{p}_f^{\theta}\right)$

The objective function of the third model maximizes the expected number of targets found by an exploration campaign. An isobenefit curve of value B is prescribed by the number of searches u and target density d that have a constant product, $B = ud$. The curve represents an equal amount of benefit resulting from trading off the number of exploration campaign search units examined for campaign target density. Two levels of expected benefit of exploration are shown as 'Isobenefit curve 1' and 'Isobenefit curve 2' in Figure 2. Each of the constraints is discussed in turn below.

Budget constraint $Q(I_s, I_t, M) = I_s u_{\bar{x}} + I_t u_{\bar{x}} d_{\bar{x}} \leq M$

Exploration cost per search unit examination, I_s multiplied by the number of search units examined yields the total campaign unit search exploration costs. Target exploration cost, I_t multiplied by the expected number of targets (number of search units examined multiplied by the expected campaign target density) yields the total expected campaign target exploration cost. The sum of these investment terms must be less than or equal to the total budget M, that has been allocated for exploration. The budget constraint is the curve labelled 'Exploration budget (I_s, I_t, M)' in Figure 2.

Risk constraint $R(P,t) = B_{u_{\bar{x}},d_{\bar{x}}}(t-1) \leq 1-P$

In a specific exploration effort, risk arises from the possibility of failure to find, and investment loss from not finding a deposit (Singer and Kouda, 1999a). Discovery risk is particularly high in unexplored areas that lack field verification of hypothetically suitable areas for a given type of mineralization (Cheng and Agterberg, 1999). There are, however, a number of ways to reduce discovery risk in mineral exploration including searching for deposit types that have a high probability of being located (Singer and Kouda, 1999a) and incorporating multiple deposit types into the search.

The economic model presented here treats target discovery as successful if at least one target (or a minimum number of targets) is found (target discovery success is different from commercial success, which of course depends on finding

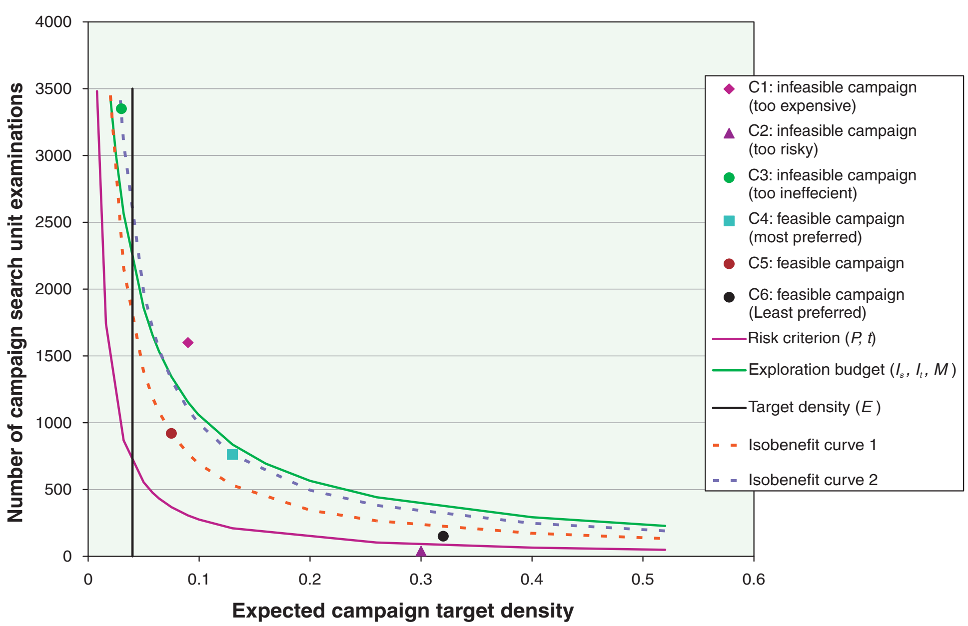


Figure 2. Exploration preference and feasibility: unfeasible, feasible, and preferred feasible exploration campaigns. The three constraints utilized are the risk criterion, the exploration budget, and efficiency (target density), which enclose a feasible decision space. Campaigns (C) are labelled 1 through 6. Campaigns C5 and C4 lie on isobenefit curves 1 and 2, respectively, with 1<2.

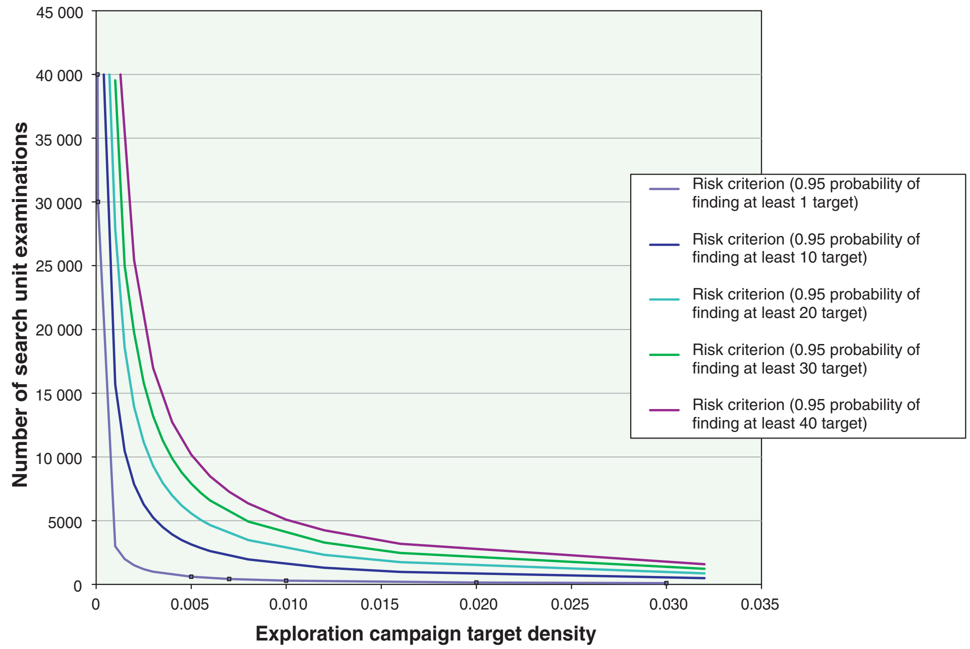


Figure 3. Sensitivity of the risk constraint to the minimum number of targets. 10, 20, 30, and 40) to be found with probability 0.95.

economic deposits). The likelihood of target discovery is a function of the favourability of the geology or campaign target density explored, and the number of search unit examinations undertaken. Singer and Kouda (1999a) used the probability of finding at least one deposit as a measure of risk. The present authors adopt and generalize this risk expression. The approximate probability that an exploration campaign finds at least one target is:

$$P(z \geq 1) = 1 - (1 - d_{\bar{x}})^{u_{\bar{x}}} \quad (4)$$

where z is the number of targets found.

The risk criterion is:

$$1 - (1 - d_{\bar{x}})^{u_{\bar{x}}} \geq P \quad (5)$$

where P is an industry threshold probability for success. The authors think of it as the minimum risk that investors will tolerate.

Alternatively, for a given probability of success P, the number of search unit examinations $u_{\bar{x}}$ required to find at least one target is:

$$\log(1 - P) / \log(1 - d_{\bar{x}}) \leq u_{\bar{x}} \quad (6)$$

If this criterion is not satisfied, the campaign target density is too low and/or not enough search area is contained in the exploration campaign.

More generally, particularly in a frontier region, the risk criterion may require a minimum number of targets t greater than 1 to be found with probability P. In this case, the authors embellish the above risk criteria and use the cumulative binomial distribution,

$$B_{u_{\bar{x}} d_{\bar{x}}}(t) = \sum_{j=0}^{t} \left(\frac{u}{t} \right) d^{j} (1 - d)^{u-j}$$

to derive the probability of success as:

$$P(z \geq t) = 1 - P(z \leq t) = 1 - B_{u,d}(t - 1) \quad (7)$$

For a particular campaign, $\bar{x}$ the risk constraint becomes:

$$B_{u_{\bar{x}}, d_{\bar{x}}}(t - 1) \leq 1 - P. \quad (8)$$

More realistically, the risk criterion must operate with other economic objectives and constraints because a campaign with a very low target density can satisfy the risk criterion if a large enough area is contained in the campaign. In Figure 2, the line labelled 'Risk criterion (P, t)', which represents the combinations of target density and number of search unit examinations that yield a probability P of finding at least t targets, illustrates the sensitivity of the number of search unit examinations required to satisfy the risk criterion as the target density moves towards 0.

Figures 3 and 4 explore the sensitivity of the risk constraint to the minimum number of targets required and to the probability of finding the minimum number of targets, respectively. A higher risk constraint reduces the space of feasible solutions; the higher the constraint, the more stringent the condition. In Figure 3 it is evident that the risk constraint rises more slowly as the minimum number of targets is increased. In contrast, Figure 4 exhibits increasing sensitivity to the probability of success: a move from 0.81 probability to 0.95 probability is of a similar magnitude to the move from 0.95 probability to 0.99 probability.

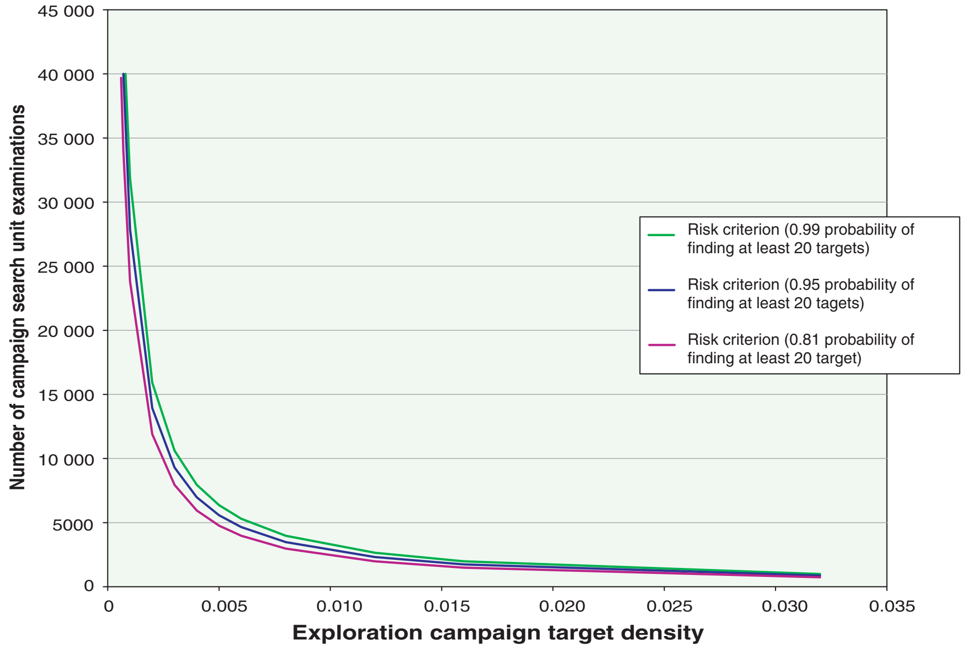


Figure 4. Sensitivity of risk constraint to the probability (0.81, 0.95, and 0.99) of finding at least 20 targets.

Campaign target density constraint $TD(E) = d_{\bar{x}} \geq E$

The efficiency constraint requires the target density to be greater than or equal to *E*, an industry or regional minimum return on exploration investment. The campaign target density constraint is the vertical line labelled 'Target density (*E*)' in Figure 2. It is a simple constraint, but it is interesting to look at it in the context of the risk constraint and whether it is stated to protect the decision maker from exploration campaigns that are placed near the steeper slope of the risk constraint where the number of search unit examinations required to satisfy the risk constraint is very sensitive to the target density estimate.

Feasible and optimal solutions

Based on a geological map, an exploration campaign $\bar{x}$ can be defined as a spatial allocation (by favourability class) of search unit examinations. In Figure 2, the authors plot six sample exploration campaigns to illustrate feasible and infeasible campaigns with respect to the three constraints discussed above and to demonstrate a preferred exploration campaign that sits on the highest isobenefit curve. The campaigns are plotted against target density, risk, and budget constraints. The feasible region of the graph that satisfies all three constraints is the region circumscribed by the three constraint curves. The exploration campaign labelled C3 is infeasible because it fails to satisfy the target density (efficiency) and budget constraints. The exploration campaign labelled C2 is infeasible because it does not satisfy the risk constraint. Despite an attractive target density there are not enough search units contained in this exploration campaign to assure a high probability of success. In the C1 campaign, exploration is infeasible because the investment required exceeds the budget. The feasible campaigns are C4, C5, and C6, but some feasible allocations are more effective than others and sit on higher isobenefit curves. Plotting isobenefit curve 1 and isobenefit curve 2 that fit the C4 and C5 feasible campaigns reveals that the C4 exploration campaign is preferred over C5.

Optimization of the economic model identifies the exploration campaign that promises the most benefits (targets) out of all the feasible solutions that meet the risk, budget, and expected efficiency constraints. The decision constraints and the optimization of the expected number of targets determine simultaneously the number of search unit examinations in each favourability class and the average target density of the optimal exploration campaign $\bar{x}^{\theta} = (x_0^{\theta}, \ldots, x_{F^{\theta}}^{\theta})$.

Similar to the first two models, the optimal campaign for model 3 exhausts favourability domains in descending order of favourability until one of the constraints is binding, if a feasible solution exists. If there is no feasible optimal solution to the third model for map θ then it is interpreted to mean that the information contained in map θ does not stimulate any mineral exploration in the region. Experience with the geological data suggests that it is most likely that if feasible solutions exist, then either the efficiency or budget constraints become binding. Although the risk constraint could theoretically be

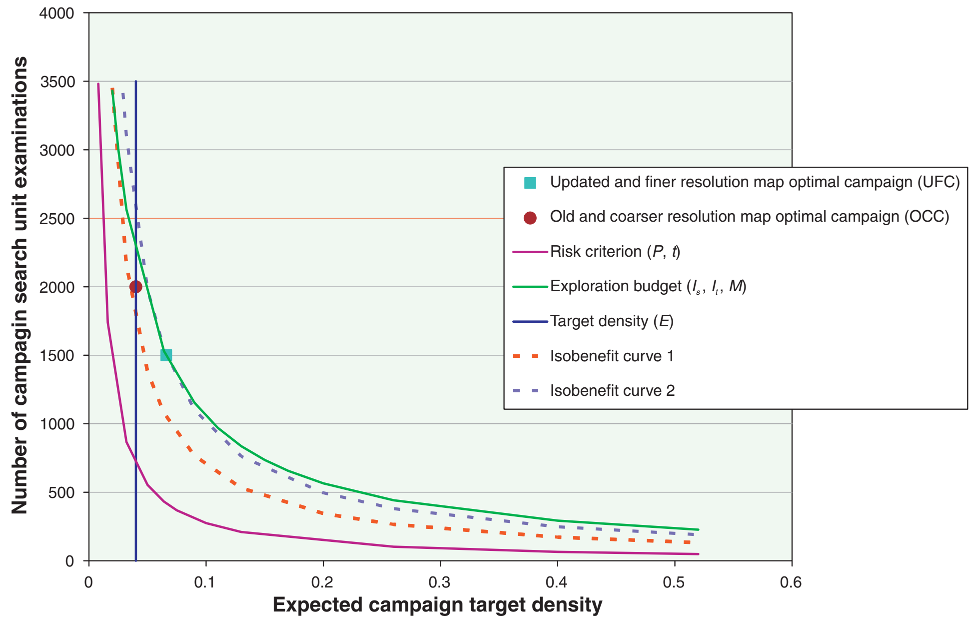


Figure 5. Comparison of optimal exploration campaigns derived from two different maps. The three constraints (risk criterion, exploration budget, and target density (efficiency)) enclose a feasible decision space. Campaigns OCC (based on the old, coarser resolution map) and UFC (based on the updated, finer resolution map) lie on isobenefit curves 1 and 2, respectively, with 1<2. Constraint parameters defined in the text.

binding, the decline in the campaign target density tends to be overwhelmed by the increase in the number of search unit examinations available as the area of search is expanded. Thus, the authors observe that the risk (probability of finding at least a given number of targets) and effectiveness considerations favour exploration, whereas the efficiency and budget considerations impose limits on the exploration. These opposing forces in the objective function and constraint set ensure that the form of the optimal solution identifies exploration campaigns that search the higher favourability classes for as long as the efficiency and budget constraints are satisfied. The conditions for the optimal solution are contained in Appendix B.

Relative effectiveness of the maps

Figure 5 illustrates the case of both the old and the updated maps providing feasible optimal campaigns. The optimal solutions of each map can be compared to determine if the improved map information has improved effectiveness that is illustrated by the shift of the isobenefit curve with the updated map and if $V^U - V^O > 0$. As indicated in Figure 5, an improvement is achieved with a movement from the optimal campaign with the old map (OCC) to the optimal campaign with the updated map (UFC). In this example, the coarser map exploration decision is bound by the efficiency constraint, whereas the updated map exploration decision is bound by the budget constraint. If a map does not have a feasible solution, its isobenefit curve is at the origin.

STEP 5: VALUE OF IMPROVED MAP INFORMATION

The exploration activity of examining search units and pursuing targets is translated into investment dollars to provide a value for the map information. For each map, the optimal or most preferred exploration campaign $\bar{x}^\theta$ contains a total of $u_{\bar{x}^\theta}$ search unit examinations with an average target density $d_{\bar{x}^\theta}$ such that the total advantage of updated information relative to the old information (for example) is the difference in exploration investment stimulated by the geological maps:

$$V_1 = V^U - V^O = I_s(u_{\bar{x}^U} - u_{\bar{x}^O}) + I_t(u_{\bar{x}^U} d_{\bar{x}^U} - u_{\bar{x}^O} d_{\bar{x}^O}) \quad (10)$$

where $u_{\bar{x}^\theta} = 0$ if there are no feasible solutions to the economic model for map θ. Although a finer resolution map may reduce search investment (due to more efficient mineral exploration), the increase in target investment is likely to be greater. The authors note that once the budget constraint is binding, then although improved information would increase the effectiveness of the optimal exploration campaign, the investment will have run out.

The investment advantage of the improved information can be compared with the production cost of the updated map. Thus, each expected additional dollar of exploration investment is assumed to be of equal benefit to society: firstly, as recompense for the cost of producing the map; and secondly, in terms of the economic activity stimulated.

APPLICATION OF THE MODEL

Assumptions of the analysis

A number of assumptions are inherent to the analysis presented in this paper:

- Mining companies collectively choose exploration programs by considering risk, efficiency, cost, and benefits (number of targets) in the particular way modelled here.
- The geological maps and other geophysical, geochemical, and geochronological data are representative of the knowledge at the time of map making and sufficient to determine favourability domains for each map.
- In the absence of government-produced geological maps, firms would not — of their own volition — create comparable maps of any significant portion of the south Baffin Island or Flin Flon Belt case study areas.
- For statistical purposes, it is assumed that the regions analyzed are unbiased samples of broader geographic regions that share the same geology and that search results within each favourability class are independent.
- Mineral occurrences found to date are comprehensive. In truth, regions such as the Cape Smith Belt remain to be fully explored. Consequently, the estimation of the target densities for the corresponding favourability domains is conservative.
- The assignment of known mineral occurrences to older maps may overestimate the performance of those maps. Subsequent knowledge may have assisted in the discovery of some of the mineral occurrences incorporated into the analysis of the older maps.
- The analysis uses surface geology only. Consequently, the information utilized could lead to inaccuracies in the analysis, as the three-dimensional geometry of lithological units and structures is not addressed.
- The analysis assumes that all exploration targets are equally desirable to find; however, it is likely that more favourable regions not only have higher target densities as per the authors' analysis (*see* 'Case studies'), but also that these same regions contain mineral occurrences with higher grades and tonnages (e.g. Carlson, 1991, and references therein; Singer et al., 2001, and references therein). If so, this implies that the economic benefits of finding targets in more favourable areas have been underestimated in the present analysis.
- Exploration under hydrographic features (lakes, rivers) is allowed.

Table 1. Summary of case studies.

	Flin Flon Belt	South Baffin Island
Exploration status	Mature	Frontier
Analytical strategy	Hindsight retrospective and/or ex post	Predictive and/or forward looking and/or ex ante
Value of map information in terms of:	Exploration efficiency, effectiveness, and risk	Exploration efficiency, effectiveness, risk, and economic value of updated map information
Map comparisons	Old, coarser resolution vs. clipped, updated, coarser resolution vs. clipped, updated, finer resolution	Old, coarser resolution vs. updated, finer resolution
Exploration target data	Flin Flon Belt	Cape Smith Belt analogue

CASE STUDIES

In the remainder of the bulletin/professional paper, the authors model efficiency, productivity, risk, and cost of mineral exploration campaigns derived from bedrock geological maps in the mature Flin Flon Belt and the frontier south Baffin Island exploration regions. Table 1 summarizes the analyses that depended on the age and resolution of bedrock geological maps available in each case study area. The Flin Flon Belt case study in Manitoba and Saskatchewan provides the opportunity to separate both the effects of updating a map and of refining the map resolution on exploration efficiency, effectiveness, and risk. Because the old map covers a smaller area than the updated map, the analysis is limited to the area common to both. The analysis of the Flin Flon Belt maps is carried out as though all the potential exploration benefit of the updated maps has already been realized. The authors did not have the exploration history to pursue estimates of future discoveries in the region. The analysis serves to test the method for the second case study, south Baffin Island, an underexplored frontier area of eastern Arctic Canada. The south Baffin Island case study compares an old, coarser resolution geological map to an updated, finer resolution geological map. Because there has been no significant mineral exploration or resource extraction in south Baffin Island, the analysis depends on the crucial assumption that the geology of parts of south Baffin Island is comparable to that of northern Quebec (a more mature mining district) as has been documented by recent fieldwork and tectonic studies (*see* 'South Baffin Island case study'). The analysis of south Baffin Island proceeds through all five steps of the authors' approach including an assessment of the value of the information.

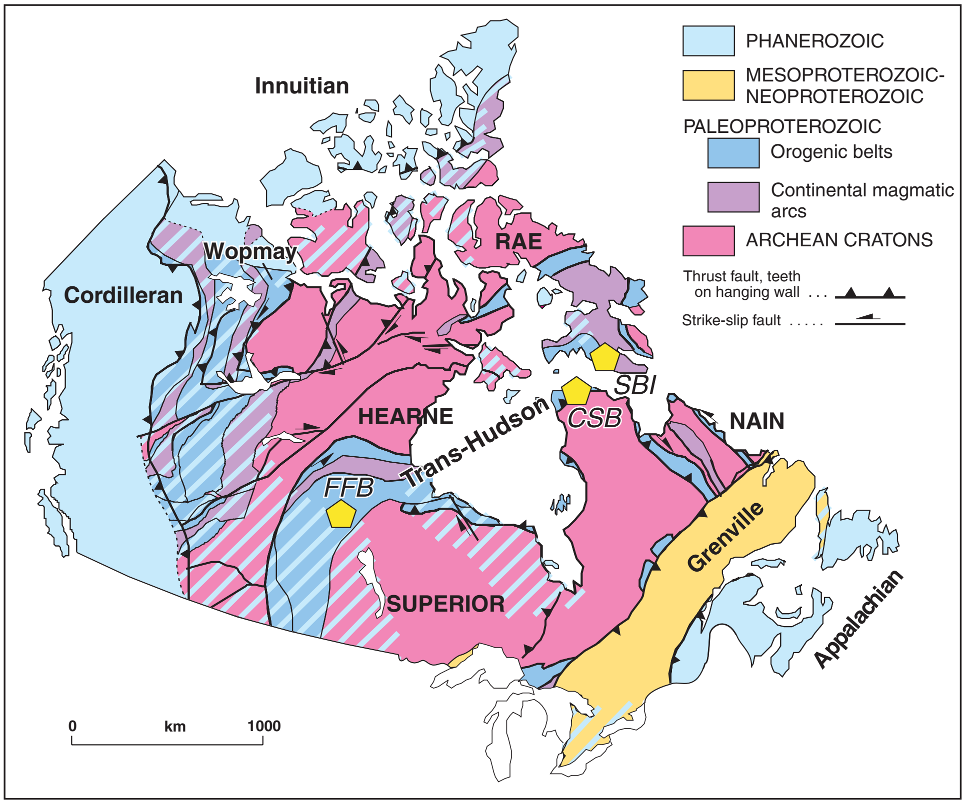


Figure 6. Simplified geological map of Canada, *modified after* Hoffman (1988, 1989), Ross et al. (1995), and Wheeler et al. (1996). Blue diagonal stripes represent areas where the Precambrian basement is covered by the Phanerozoic platformal cover, which is not illustrated. Upper-cased names are Archean cratons; lower-cased names are Proterozoic and Phanerozoic orogens. Locations of case study areas discussed in the text are indicated with the yellow symbols (CSB =

Figure 6 provides the locations of the Flin Flon Belt, the Cape Smith Belt, and south Baffin Island within a broad geological context for Canada.

FLIN FLON BELT CASE STUDY

Introduction

This application of the model is based on geological mapping of the Flin Flon Belt that was compiled in the NATMAP Shield Margin Project completed in 1998 (Lucas et al., 1999). The National Geoscience Mapping Program (NATMAP) aimed to foster a multidisciplinary team approach to bedrock and surficial mapping and related research; combine the efforts of the federal, provincial, territorial, and university scientists; and utilize digital information technology for more efficient interdisciplinary research and map production. Flin Flon is one of the largest Proterozoic volcanic-hosted massive-sulphide (VMS) districts in the world, from which more than 107 million tonnes of sulphide-rich ore have already been extracted from 25 deposits, with a further 58 million tonnes remaining in 43 subeconomic deposits (Syme and Bailes, 1993; Syme et al., 1999, and references therein). The district also contains productive gold deposits; however, the future of the Flin Flon and Snow Lake mining communities and the Flin Flon smelter facility was uncertain in the early 1990s due to a lack of defined long-term ore reserves. All mining ceased in the Snow Lake camp in late 1993, only to strongly rebound in 1995 with the reopening of the old Nor Acme gold mine (now called the New Britannia mine) and the discovery of the Photo Lake Cu-Zn-Au deposit.

Geological maps

Prior to the NATMAP project, a compilation of the Snow Lake–Flin Flon–Sheridon area existed (Bailes, 1971). The original Bailes (1971) map was prepared as a 1 inch to 1 mile compilation (1: 63 360 scale) and subsequently reduced to a 1 inch to 4 miles map (1: 253 440 scale) for publication. The latter map was digitized for this project and used as the old, coarser resolution geological map for the Flin Flon area (Table 2). The NATMAP project produced the updated, coarser resolution and updated, finer resolution maps as described below for the Flin Flon Belt (Table 2).

Three fundamental objectives for the NATMAP project were defined at its onset (Lucas et al, 1999): 1) bedrock and surficial mapping supported by thematic geological, geochronological, and geophysical studies; 2) development of an interpretive map of pre-Phanerozoic geology immediately south of the exposed Precambrian Canadian Shield margin; and 3) development of a digital geoscience database housing an extensive set of both existing and new data, including regional compilation maps.

The updated, coarser resolution map is a set of synoptic maps of the shield margin area that were produced at a scale of 1:325 000 (Table 2). These document the bedrock geology of the exposed Precambrian Shield, the Western Canada Sedimentary Basin, and the pre-Phanerozoic Precambrian basement. The updated, finer resolution map (Table 2) is a 1:100 000 scale bedrock geology compilation based on more than 70 sources ranging in publication date from 1944 to 1997 (NATMAP Shield Margin Project Working Group, 1998). The recently mapped areas (e.g. Flin Flon area, Snow Lake area, Kisseynew Domain) are shown in considerably more detail than areas that are documented with information derived from the older maps. The 1:100 000 scale compilation maps were based on fieldwork carried out at 1:20 000 scale to 1:50 000 scale. Considerable effort was made to produce a seamless geological coverage, but the limitations inherent in any compilation apply.

The following sections present the analysis of the Flin Flon maps of different ages and scales illustrating the efficiency, effectiveness, and risk improvements stemming from the production of an updated map with finer resolution.

Table 2. Geospatial data used for the Flin Flon Belt case study area.

Coverage	Format	Scale	Area (km^2)
Old, coarser resolution map of bedrock geology	Polygon	1:253 440	11 197
Updated, coarser resolution map of bedrock geology	Polygon	1:325 000	17 288
Updated, finer resolution map of bedrock geology	Polygon	1:100 000	17 288
Mineral showings	Point	n/a	n/a
n/a = not applicable			

Table 3. Favourability indices for the old, coarser resolution Flin Flon Belt map (Bailes, 1971).

Favourability index	Rock units on map
0	All rock units except A1 and A2
1	A1, A2

Table 4. Explanation of geological unit coding scheme for the old, coarser resolution Flin Flon Belt map favourability indices (Bailes, 1971).

Geological unit code	Geological unit	Rock type
A1	Amisk Group	Pillowed basalt and andesite; includes many small, related intrusions and interbedded basic to intermediate fragmental volcanic rocks.
A2	Amisk Group	Rhyolite, dacite, quartz, porphyry; includes acidic crystal tuff and siliceous, carbonate-rich tuff.

Table 5. Favourability indices for the updated, coarser resolution Flin Flon Belt map (NATMAP Shield Margin Project Working Group, 1998).

Favourability index	Rock units on map
0	Nonjuvenile arc rock
1	All juvenile arc rock

Favourability indices

This study evaluates the available bedrock geological maps for the Flin Flon Belt in terms of their usefulness in mineral exploration for volcanic-hosted massive-sulphide mineral targets that are hosted by juvenile arc rocks (Syme and Bailes, 1993; Lucas et al., 1996; Syme et al., 1999). The volcanic-hosted massive-sulphide exploration target favourability indices for different ages and scales of maps are based on the different geological interpretations that are inherent to or limited by the resolution of the different ages of mapping efforts.

For the old, coarser resolution (Tables 3, 4) and updated, coarser resolution (Table 5) maps, $\theta = \mathrm{OC}$ and UC, a binary system of favourability indices is created where:

- Favourability 0 = geology in search unit is not likely to contain an exploration target, and
- Favourability 1 = geology in search unit is favourable for containing an exploration target.

For the updated, finer resolution map analysis, $\theta =$ UF, a more complex favourability ranking is possible as the geological information presented on the maps allows for increased distinction of rock types. The index is based upon the likelihood of volcanic-hosted massive-sulphide exploration targets being hosted by subsets of juvenile arc rocks, as well as being localized at or near contacts between key units (*see* below):

- Favourability 0 = geology in search unit is not likely to contain an exploration target,
- Favourability 1 = geology in search unit is somewhat favourable for containing an exploration target,
- Favourability 2 = geology in search unit is favourable for containing an exploration target, and
- Favourability 3 = geology in search unit is most favourable for containing an exploration target.

Table 6. Favourability indices for the updated, finer resolution Flin Flon Belt map (NATMAP Shield Margin Project Working Group, 1998). For the geological contacts in the third column, there are a variety of alternative scenarios represented by the coding scheme. The "or" indicates that the units in the series are substitutable, and the "+" refers to a contact between two series of units. For the favourability 3 index, possible contacts between units include J4a and J1a, J4a and J1b, J4a and J1d, J4a and J12c, J4b and J1a, J4b and J1b, J4b and J1d, J4b and J12c, J4c and J1a, J4c and J1b, J4c and J1d, and/or J4c and J12c.

Favourability index	Rock units on map	Rock contacts on map
0	Nonjuvenile arc rocks, other juvenile rocks	None
1	J1(b, d), J2(a–c), J3a, J6(a, b), J13c	None
2	J1a, J4c, J5(a–d), J7(a, b), J12c	None
3	J4(a, b)	J4a or J4b or J4c + J1a or J1b or J1d or J12c

Table 7. Explanation of geological unit coding scheme for the updated, finer resolution Flin Flon Belt map favourability indices (NATMAP Shield Margin Project Working Group, 1998).

Geological unit code	Geological unit	Rock type
J1a	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Tholeiitic basalt, basaltic andesite, gabbro
J1b	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Calc-alkaline basalt, basaltic andesite
J1d	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Basalt, basaltic andesite (geochemical affinity unknown)
J2a	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Ferrobasalt, rhyolite, crystal tuff
J2b	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Basalt, synvolcanic dykes and sills
J2c	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Gabbro, ferrogabbro, quartz ferrodiorite sills
J3a	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Andesite
J4a	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Rhyolite to dacite
J4b	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Felsic gneiss
J4c	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Felsic to intermediate gneiss ± garnet
J5a	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Mafic volcaniclastic rocks (tuff, breccia, wacke)
J5b	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Pillow fragment breccia
J5c	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Mafic volcaniclastic rocks (heterolithological breccia, predominantly mafic)
J5d	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Undivided mafic volcaniclastic rocks and flows
J6a	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Intermediate tuff, lapilli tuff, breccia
J6b	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Intermediate to felsic volcaniclastic rocks and flows, derived gneiss
J7a	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Felsic tuff, lapilli tuff, breccia, heterolithologic breccia
J7b	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Dacite tuff, lapilli tuff
J12c	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Tonalite, quartz diorite
J13c	1.92–1.87 Ga volcanic, intrusive, and sedimentary rocks of juvenile arc affinity	Rhyolite, dacite; quartz porphyry, feldspar porphyry, quartz-feldspar porphyry

The highest favourability index includes felsic rocks (rhyolite or dacite) in contact with mafic units (basalt or basaltic andesite). The proximity to synvolcanic felsic plutons, considered to be a key element of volcanic-hosted massive-sulphide deposit models, is not considered in this study. Table 6 explains the details of the favourability index for the updated, finer resolution map. Table 7 provides a description of the coding scheme for individual geological map units.

One caveat of the analysis is that it is focused on surface geology only. The information used could lead to inaccuracies in the analysis, as the three-dimensional geometry of lithological units and structures was not addressed.

Flin Flon Belt favourability domains and target densities

The favourability domains of the old, coarser resolution $(\theta = \mathrm{OC})$; updated, coarser resolution $(\theta = \mathrm{UC})$; and updated, finer resolution $(\theta = \mathrm{UF})$ Flin Flon Belt maps are depicted in Figures 7, 8, and 9. The search unit (projected surface area extent for a unique exploration target) size of 0.45 km^2 for a massive-sulphide exploration target was adopted from Singer et al. (2001). Information on the known exploration targets and their distribution in the study area was compiled within the NATMAP project. In this analysis, exploration targets are associated with the highest favourability domain identified within 100 m of the target due to the shallow to moderate angle at which the mineralized zones and geological boundaries can lie within the study area.

Table 8. The number of 0.45 km^2 search units, exploration targets, and the target density for each favourability domain per map covering the old, coarser resolution Flin Flon Belt map map area, calculated according to step 2.

Favourability domain of the map	Number of search units	Number of targets	Target density per 0.45 km^2
Old, coarser resolution map			
OC0	21247	24	0.0011
OC1	3636	28	0.0077
Updated (clipped), coarser resolution map			
UC0	21616	7	0.0003
UC1	3267	45	0.0138
Updated (clipped), finer resolution map			
UF0	22155	6	0.0003
UF1	1008	5	0.0050
UF2	998	19	0.0190
UF3	722	22	0.0305

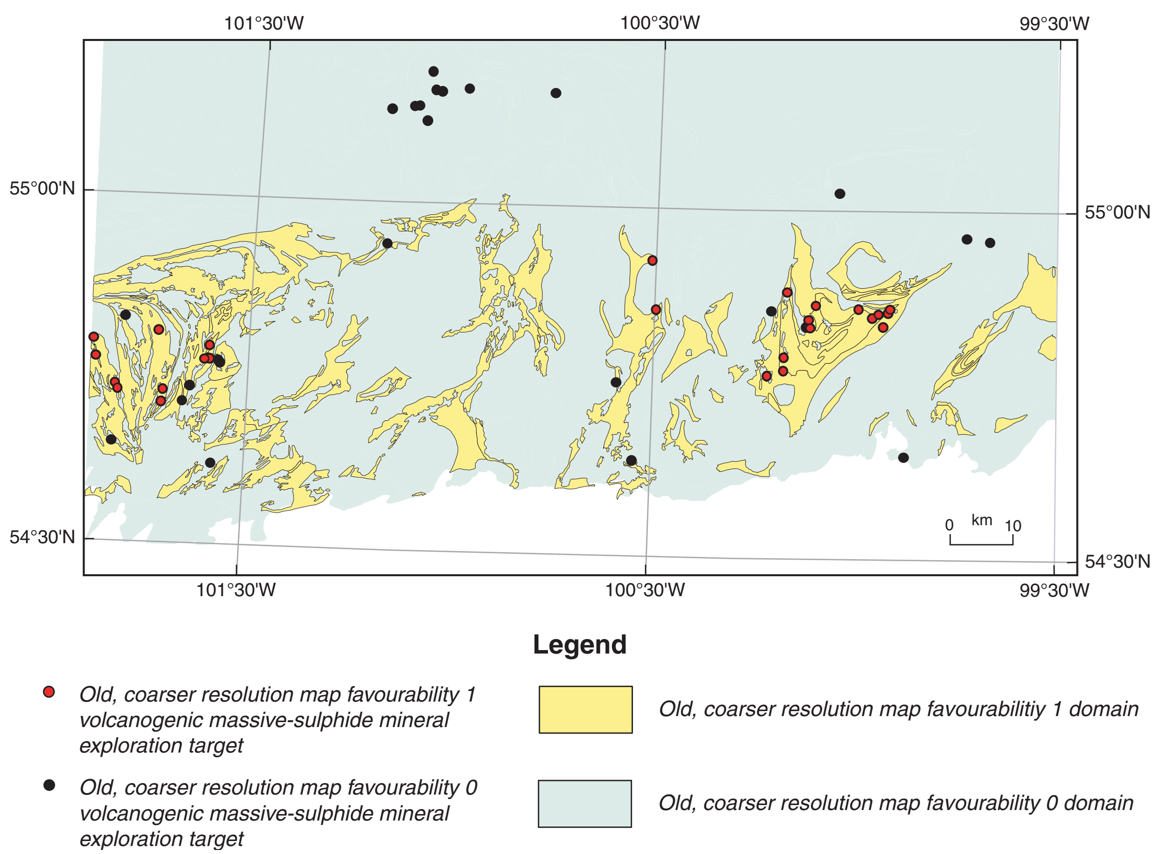
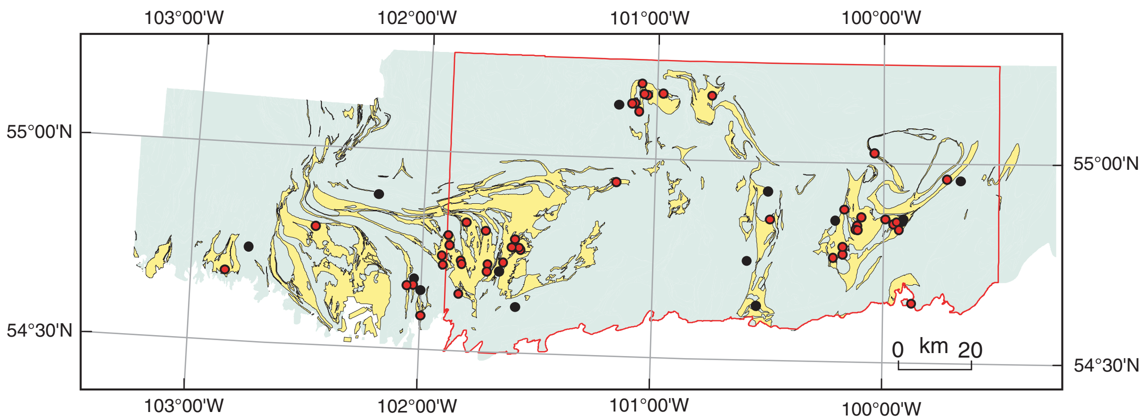


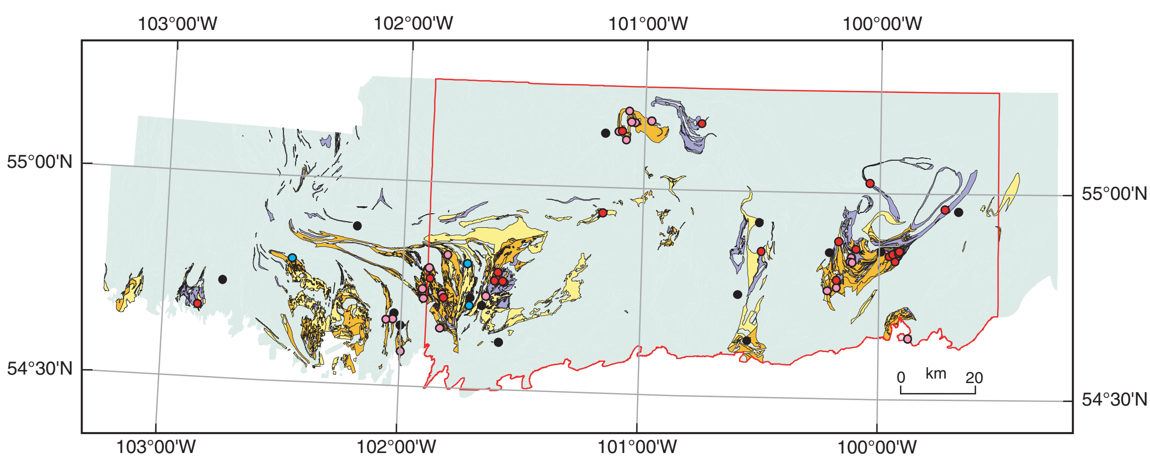
Figure 7. Old, coarser resolution Flin Flon Belt map highlighting volcanic-hosted massive-sulphide favourability domains (as defined in Tables 3 and 4) and mineral exploration targets. Hydrographic features (lakes, rivers) are omitted for clarity.



Legend

- Updated, coarser resolution map favourability 1 volcanogenic massive-sulphide mineral exploration target
- Updated, coarser resolution map favourability 0 volcanogenic massive-sulphide mineral exploration target
- Old, coarser resolution map extent
- Updated, coarser resolution map favourability 1 domain
- Updated, coarser resolution map favourability 0 domain

Figure 8. Updated, coarser resolution Flin Flon Belt map highlighting volcanic-hosted massive-sulphide favourability domains (as defined in Table 5) and mineral exploration targets. Old, coarser resolution map area outlined in red. Hydrographic features (lakes, rivers) are omitted for clarity.



Legend

- Updated, finer resolution map favourability 3 volcanogenic massive-sulphide mineral exploration target
- Updated, finer resolution map favourability 2 volcanogenic massive-sulphide mineral exploration target
- Updated, finer resolution map favourability 1 volcanogenic massive-sulphide mineral exploration target
- Updated, finer resolution map favourability 0 volcanogenic massive-sulphide mineral exploration target
- Old, coarser resolution map extent
- Updated, finer resolution map favourability 3 domain
- Updated, finer resolution map favourability 2 domain
- Updated, finer resolution map favourability 1 domain
- Updated, finer resolution map favourability 0 domain

Figure 9. Updated, finer resolution Flin Flon Belt map highlighting volcanic-hosted massive-sulphide favourability domains (as defined in Tables 6 and 7) and mineral exploration targets. Old, coarser resolution map area outlined in red. Hydrographic features (lakes, rivers) are omitted for clarity.

The target densities by favourability class listed in Table 8 are derived using the method described in step 2. The target estimates are conservative since they are based on a compilation of deposits and showings from 1998 (not including exploration targets subsequently identified) and are based on total (versus explored) area for each favourability domain (i.e. k_f^θ is unknown).

As is obvious from Table 8, the updated maps are more discerning at providing a context for volcanic-hosted massive-sulphide mineralization than the old map. This is illustrated by a higher target density for the favourability 1 domain on the updated, coarser resolution map (UC1) compared to that for the old, coarser resolution map (OC1). Comparison of the updated maps in Table 8 shows that the finer resolution map further supports the delineation of two additional favourability domains with higher target densities. Consequently, the target densities for the updated map 0 favourability domains (UF0) are lower than the target densities for the 0 favourability domains on the old maps (OC0 and UC0).

Efficiency and productivity of Flin Flon Belt maps for mineral exploration

The results of applying the first two models for the minimization of the mineral exploration search (maximizing exploration efficiency) and the maximization of mineral exploration productivity for each map age and resolution are presented in Figure 10 for maps covering the old, coarser resolution map area. As demonstrated above, it is most efficient, productive, and effective to explore the highest favourability areas first. This is reflected in the progressively decreasing slope for segments of the line for a map containing geology that is interpreted to have more than one favourable domain (e.g. the line for the updated, finer resolution map on Fig. 10). The horizontal distance between the graphed lines on Figure 10 represents the number of additional searches required by the older or coarser resolution maps to yield the same expected number of targets (and is a measure of the comparative efficiency of the different maps). The vertical distance between the graphed lines on Figure 10 shows the additional expected number of targets for the same search effort across the maps (and is a measure of the comparative productivity of the different maps). The updated, finer resolution map is superior in both dimensions. This result is consistent with the accepted geological interpretation for this area and the assumptions utilized in the authors' model for an exploration campaign.

A comparison of coarser resolution maps of two different ages suggests that substantial gains are made from updating a coarser resolution map. The vertical difference between the two curves for the coarser resolution maps on Figure 10 portrays up to an 80% increase in expected targets found for a given number of search unit examinations. If all favourable land is explored on both maps, the updated, coarser resolution map is expected to locate 60% more targets than the old, coarser resolution map (Fig. 10). Therefore exploration companies can expect to achieve 160–180% of the results they would expect if they had based their exploration campaigns on the old, coarser resolution map only. Likewise exploration efficiency is increased due to an up to 44% reduction of search effort for a given number of expected targets (indicated by the horizontal difference between the old and updated, coarser exploration trajectories in Fig. 10). Refining the resolution of a map from the updated, coarser resolution to the updated, finer resolution map provides for a 2% increase in the expected total number of targets found by exploring all

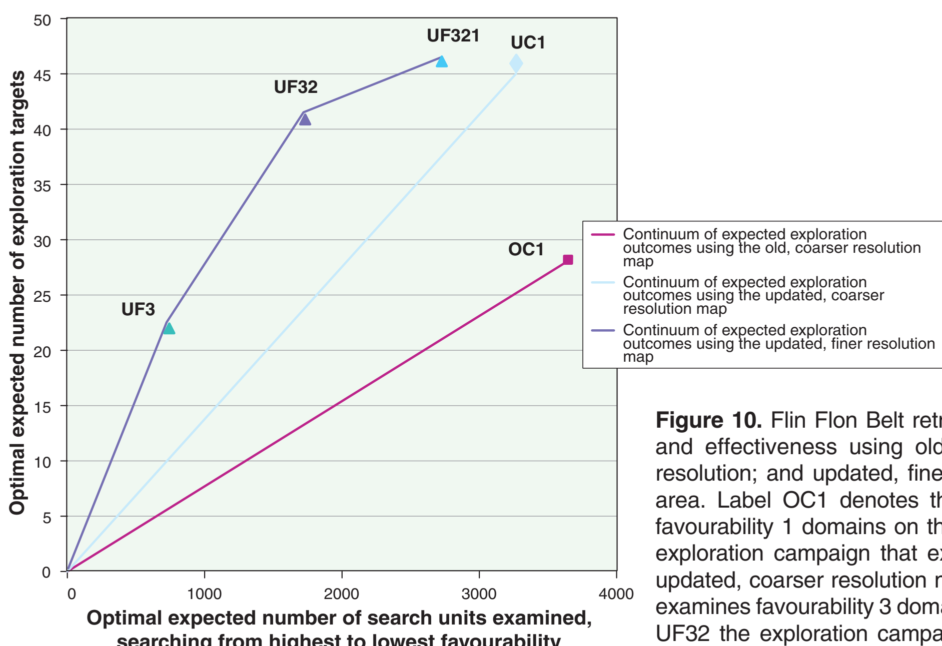


Figure 10. Flin Flon Belt retrospective, mineral-exploration efficiency and effectiveness using old, coarser resolution; updated, coarser resolution; and updated, finer resolution maps covering the old map area. Label OC1 denotes the exploration campaign that examines favourability 1 domains on the old, coarser resolution map; UC1, the exploration campaign that examines favourability 1 domains on the updated, coarser resolution map; UF3, the exploration campaign that examines favourability 3 domains on the updated, finer resolution map; UF32 the exploration campaign that examines favourability 3 and 2 domains on the updated, finer resolution map; and UF321, the exploration campaign that examines favourability 3, 2, and 1 domains on the updated, finer resolution map.

favourable regions on both maps; however, the efficiency gains indicated by the horizontal differences across the range of outcomes are more substantial with a minimum 23% reduction in search effort for a given number of targets. The most impressive gains in efficiency and productivity occur when the highest favourability domain (favourability 3) on the updated, finer resolution map is compared to the highest favourability domain on the updated, coarser resolution map (favourability 1 domain). Utilization of the favourability 3 domain on the updated, finer resolution map results in a 55% reduction of search effort to locate an expected 22 or fewer targets, and more than doubles the productivity. These results support the hypothesis that updated geological maps lead to more productive and efficient exploration relative to pre-existing information.

Flin Flon Belt mineral exploration campaign risk and benefit

The authors use the Flin Flon Belt data with the economic model efficiency and risk constraints to illustrate the relative advantages of updated maps and finer resolution maps. The following possible (retrospective) exploration campaigns are considered: favourability 1 domains as defined by the old, coarser resolution map (OC1); favourability 1 domains as

Table 9. Number of search units, target density, and expected number of targets contained in the exploration campaigns examined for each available Flin Flon Belt map. Label OC1 denotes the exploration campaign that examines favourability 1 domains on the old, coarser resolution map; UC1 denotes the exploration campaign that examines favourability 1 domains on the updated, coarser resolution map; UF3 denotes the exploration campaign that examines favourability 3 domains on the updated, finer resolution map; UF32 denotes the exploration campaign that examines favourability 3 and 2 domains on the updated, finer resolution map; and UF321 denotes the exploration campaign that examines favourability 3, 2, and 1 domains on the updated, finer resolution map.

Retrospective exploration campaign	Number of search units	Campaign target density per 0.45 km^2	Expected number of targets
Old, coarser resolution map			
OC1	3636	0.0077	28
Updated, coarser resolution (clipped to old map area)			
UC1	3267	0.0138	45
Updated, finer resolution map (clipped to old map area)			
UF3	722	0.0305	22
UF32	1720	0.0238	41
UF321	2728	0.0169	46

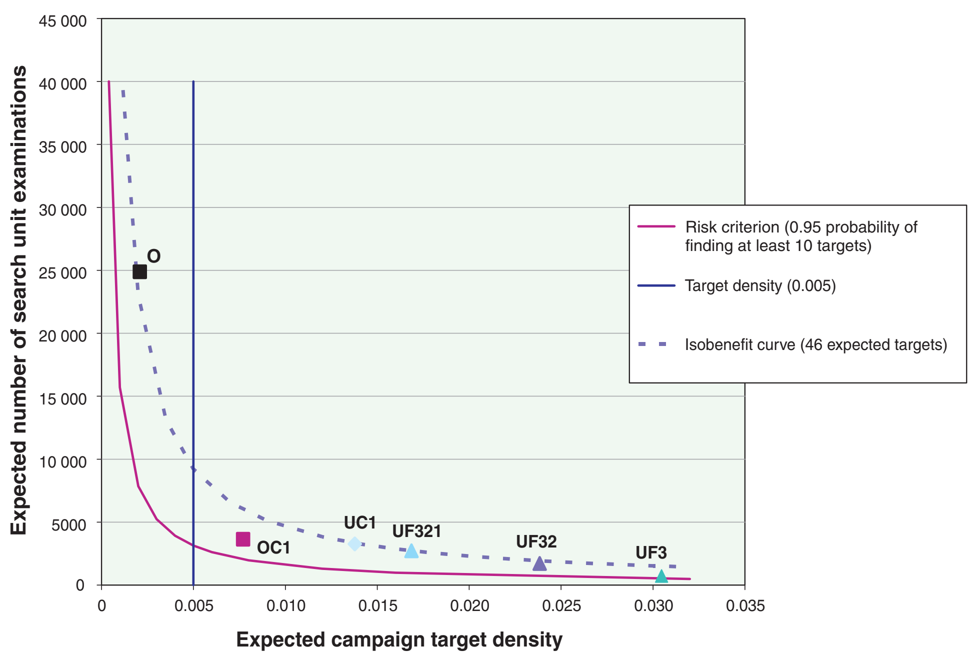


Figure 11. Flin Flon Belt exploration campaigns within the context of selected risk (0.95 probability of finding at least 10 targets) and target density (campaign target density is at a minimum 0.005) constraints and an isobenefit curve of 46 expected targets. Label OC1 represents exploration of the favourability 1 domains on the old, coarser resolution map; UC1 represents exploration of the favourability 1 domains on the updated, coarser resolution map; UF3 represents exploration of the favourability 3 domains in the updated, finer resolution maps; UF32 represents exploration of favourability 3 and 2 domains on the updated, finer resolution map; UF321 represents exploration of the favourability 3, 2, and 1 domains on the updated, finer resolution map; and O represents exploration of the whole area.

defined by the updated, coarser resolution map (UC1); favourability 3 domains as defined by the updated, finer resolution map (UF3); favourability 3 and 2 domains as defined by the updated, finer resolution map (UF32); and favourability 3, 2, and 1 domains as defined by the updated, finer resolution map (UF321). This choice of exploration campaigns is consistent with the above observation that geological map information assists in ordering the examination of search units from highest to lowest favourability. Each campaign target density, expected number of search unit examinations, and expected number of targets is detailed in Table 9.

In Figure 11 the campaigns are plotted with respect to a risk and a target density constraint and an isobenefit curve. Exploration campaign UC1 plots farther away from the risk constraint than does exploration campaign OC1. Although the use of a finer resolution map to explore all favourable area (UF321) versus exploration campaign UC1 has less dramatic effects in terms of reducing risk, the gain is clearly an improved efficiency and an improved campaign target density. Whereas exploration of favourability 3 or favourability 3 and 2 domains on the finer resolution map are more resilient to the target density constraint, they are least resilient to the risk constraint simply because exploration of less land will yield fewer targets when compared to other, bigger campaigns. Exploration campaign UF321 is the most effective campaign as it sits on the highest isobenefit curve. Whereas exploring the whole map area (represented by 'O' in Fig. 11) also yields a result that sits on the isobenefit curve of 46 targets, the dramatic difference in the number of searches required to find these targets demonstrates the value of having the updated map from the perspective of exploration efficiency and productivity.

In summary, the Flin Flon Belt case study confirms the utility of the model and supports the underlying assumptions. The updated maps provide more exploration options, reduce exploration risk, and improve efficiency and productivity. In other words, the updated map provides for more cost-effective exploration. Furthermore, the case study also demonstrates the productivity and efficiency gains for exploration in using the finer resolution, updated map as opposed to the coarser resolution, updated map (as evidenced in Fig. 10 and Table 9).

SOUTH BAFFIN ISLAND CASE STUDY

Introduction

The second case study illustrates the full implementation of the five-step approach developed in this study and provides an example of a forward-looking analysis. South Baffin Island in Nunavut is a frontier region of the eastern Canadian Arctic without a previous history of significant mineral exploration or mining. Consequently, the south Baffin Island case study depends on a crucial geological correlation: that the regional magmatic event, with which magmatic massive-sulphide mineralization is associated (St-Onge and Lucas, 1994), led to the formation and isolation of a microcontinent approximately 1.92–1.87 billion years ago (St-Onge et al., 2000), and is documented both in the Ni-Cu-PGE-producing Cape Smith Belt of northern Quebec and in the underexplored, but prospective south Baffin Island area (case study area; Fig. 6). In other words, the correlation of the geology on both sides of Hudson Strait as demonstrated by St-Onge et al. (1999a, b, 2001, 2002) is a basic premise of the present study, and includes the following five critical assemblages of rocks from different stages in the tectonic evolution of the Hudson Strait area:

- The lower plate Archean Superior Craton,
- The 2.04–1.96 billion-year-old Povungnituk Group (siliciclastic rocks and tholeiitic flood basalts),
- The 1.88–1.87 billion-year-old Chukotat Group (layered mafic-ultamafic sills and komatiitic to tholeiitic basalts),
- The 1.93–1.88 billion-year-old Lake Harbour Group (continental clastic wedge and carbonate strata) and the Blanford Bay assemblage (siliciclastic rocks), and
- The 1.86–1.82 billion-year-old calc-alkaline Narsajuaq magmatic arc.

The following sections provide information on the ages and resolutions of available geological maps for the Cape Smith Belt and south Baffin Island areas, definitions of the respective favourability indices, and geographic information system representation of the favourability domains. The empirical exploration target densities and their statistical uncertainties are derived for the Cape Smith Belt area and utilized in the subsequent analysis of the south Baffin Island maps, hinging on the geological equivalence between regions as outlined above. Similar to the Flin Flon Belt case study, exploration campaigns are analyzed with respect to efficiency (and productivity), effectiveness, and risk. In addition, a budget constraint is constructed and the economic model is solved for various exploration efficiency and risk conditions. A range of exploration campaigns is then evaluated to determine the possible additional exploration investments stimulated by the production of the updated, finer resolution maps for the south Baffin Island area. The investment results are then compared to the map production costs incurred by the GSC to estimate the net economic benefit to the country of the updated information.

Geological maps

The GSC provided the following maps: the older, coarser resolution (1:250 000 scale) Cape Smith Belt maps (Taylor, 1982); the updated, finer resolution (1:50 000 scale) maps for the eastern Cape Smith Belt (St-Onge and Lucas, 1990); the older, coarser resolution (1:506 000 scale) south Baffin Island maps (Blackadar, 1967); and the updated, finer resolution (1:100 000 scale) south Baffin Island maps (St-Onge et al., 1999b). The relative resolution between old and updated maps in both the Cape Smith Belt area and the south Baffin Island area is consistent at 5:1. Magmatic massive-sulphide deposits as a whole are the elements of interest in this case study, and are relevant to areas of and contacts between sulphidic metasedimentary units and layered ultramafic-mafic sills (St-Onge and Lucas, 1994), that are found both in the Cape Smith Belt and the south Baffin Island map areas (St-Onge et al., 1999a, 2002). Map details are summarized in Tables 10 and 11.

The updated, finer resolution maps for south Baffin Island are comparable to the updated and finer resolution maps for the Cape Smith Belt because each one of the updated maps is not simply the result of an incremental technological advance in map making, but, in fact, represents a new synthesis of geological knowledge and information following new integrated fieldwork in each respective area. Therefore, in this study, the authors assert an equivalence of tectonic and lithological context for magmatic massive-sulphide mineralization between the Cape Smith Belt and the south Baffin Island area (St-Onge et al., 1999a), as well as an equivalence in geological knowledge as contained in updated map information in both areas (St-Onge and Lucas, 1990; St-Onge et al., 1999b). This allows the present authors to apply information on the mineral exploration target densities derived from the extensively explored Cape Smith Belt area to the frontier south Baffin Island area where such information is not yet available.

Cape Smith Belt favourability domains and exploration target densities

Four favourability classes were identified for both the finer and coarser resolution maps available for the Cape Smith Belt. Favourability in this analysis is based upon the likelihood of magmatic massive-sulphide targets being hosted by sulphidic sedimentary rocks, as well as the proximity to key contacts between units:

- Favourability 0 = geology in search unit is not likely to contain an exploration target,
- Favourability 1 = geology in search unit is somewhat favourable for containing an exploration target,
- Favourability 2 = geology in search unit is favourable for containing an exploration target, and
- Favourability 3 = geology in search unit is most favourable for containing an exploration target.

Table 12 lists the diagnostic rock units and/or contacts between units as assigned to each favourability index for the analysis of the old, coarser resolution Cape Smith Belt geological map $(\theta = \mathrm{OC})$, and Table 13 provides a description of the coding scheme for individual geological map units.

Table 14 lists the rock units and contacts allocated to each favourability index for the Cape Smith Belt updated, finer resolution maps $(\theta = \mathrm{UF})$, and Table 15 details the related geological coding scheme. The consequent geographic information system favourability maps, resulting from the translation of the map rock units and contacts into their favourability indices for the old, coarser resolution and updated, finer resolution maps for the Cape Smith Belt, are shown in Figures 12 and 13. The Raglan panels in the Cape Smith Belt, which are the focus of the magmatic massive-sulphide mineralization in this area (St-Onge and Lucas, 1994), were captured manually using a geographic information system.

Table 10. Geospatial data used for the Cape Smith Belt area.

Coverage	Format	Scale	Area (km^2)
Coarser resolution bedrock geology	Polygon	1:250 000	11 349
Finer resolution bedrock geology	Polygon	1:50 000	11 349
Magmatic massive-sulphide showings	Point	n/a	n/a
n/a = not applicable			

Table 11. Geospatial data used for south Baffin Island case study area.

Coverage	Format	Scale	Area (km^2)
Coarser resolution bedrock geology	Polygon	1:506 880	31 256
Finer resolution bedrock geology	Polygon	1:100 000	31 256

Table 12. Favourability indices for the Cape Smith Belt old, coarser resolution maps (Taylor, 1982). For the geological contacts in the third column, there are a variety of alternative scenarios represented by the coding scheme. The "or" indicates that the units in the series are substitutable, and the "+" denotes a contact between two series of units. For example in the favourability 2 domain, possible contacts between units include Aub and Asc, Aub and Aqz, Aub and Ash, Aub and Asl, Agb and Asc, Agb and Aqz, Agb and Ash, and/or Agb and Asl.

Favourability index	Units	Contacts
0	All other units	None
1	Asc, Aqz, Ash, Asl, Aub, Agb	None
2	None	Aub or Agb + Asc or Aqz or Ash or Asl
3	None	Same as favourability 2, but in Raglan panels[1]
[1]Raglan panels are geographically located in the centre of the Cape Smith Belt, and have a different tectonostratigraphic context that leads to a higher favourability index (St-Onge and Lucas, 1994).		

Table 13. Explanation of geological unit coding scheme for the Cape Smith Belt old, coarser resolution map favourability indices (Taylor, 1982).

Geological unit code	Geological unit	Rock type
Asc	Povungnituk Group	Schist of sedimentary origin
Aqz	Povungnituk Group	Quartzite
Ash	Povungnituk Group	Shale
Asl	Povungnituk Group	Slate
Aub	Chukotat Group	Ultramafic rock
Agb	Chukotat Group	Gabbro

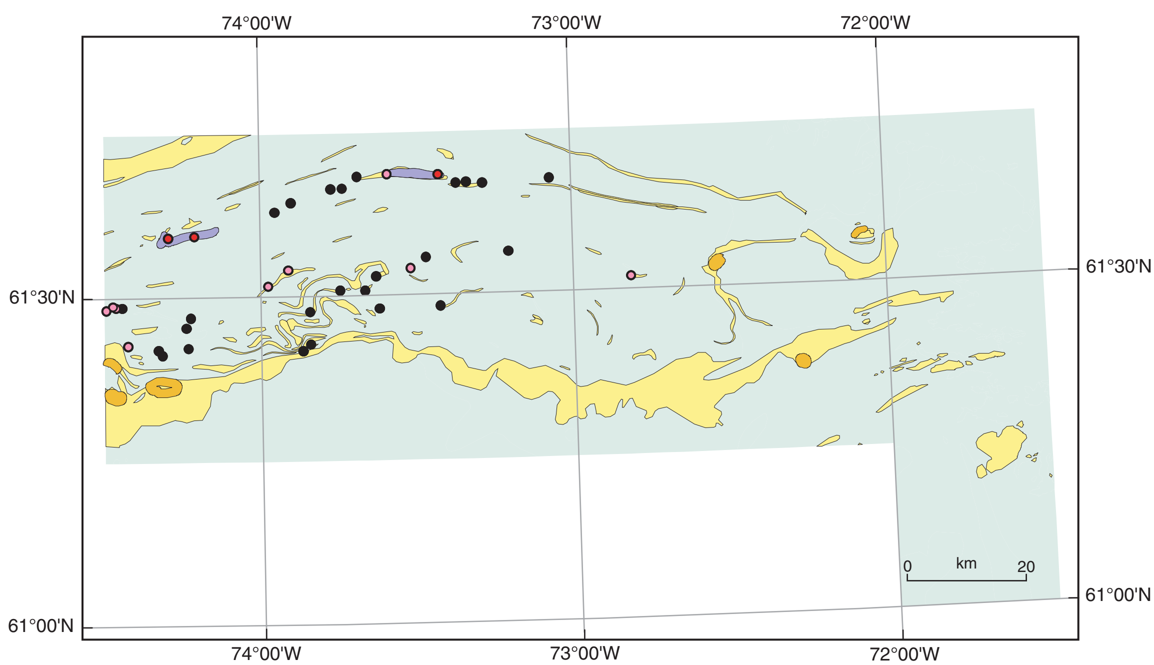
Table 14. Favourability indices for the updated, finer resolution maps, Cape Smith Belt (St-Onge and Lucas, 1990). For the geological contacts in the third column, there are a variety of alternative scenarios represented by the coding scheme. The "or" indicates that the units in the series are substitutable, and the "+" denotes a contact between two series of units. For example, in the favourability 2 index, possible contacts between units are Ga and PPse, Ga and PPv, Pe and PPse, and/or Pe and PPv.

Favourability index	Units	Contacts
0	All other units	None
1	PPse, PPv, Ga, Pe	None
2	None	Ga or Pe + PPse or PPv
3	None	Same as favorability 2, but in Raglan panels[1]

[1]Raglan panels are geographically located in the centre of the Cape Smith Belt, and have a different tectonostratigraphic context that leads to a higher favourability index (St-Onge and Lucas, 1994).

Table 15. Explanation of geological unit coding scheme for the updated, finer resolution map favourability indices, Cape Smith Belt (St-Onge and Lucas, 1990).

Geological unit code	Geological unit	Rock type
PPse	Povungnituk Group	Semipelite, pelite, micaceous sandstone, ironstone, dolomite
PPv	Povungnituk Group	Volcaniclastic sedimentary rock, minor sandstone
Ga	Chukotat Group	Gabbro, layered peridotite-gabbro sills
Pe	Chukotat Group	Peridotite, layered peridotite-gabbro sills



Legend

- Old, coarser resolution map favouability 3 magmatic massive-sulphide mineral exploration target
- Old, coarser resolution map favourability 1 magmatic massive-sulphide mineral exploration target
- Old, coarser resolution map favourability 0 magmatic massive-sulphide mineral exploration target

- Old, coarser resolution map favourability 3 domain
- Old, coarser resolution map favourability 2 domain
- Old, coarser resolution map favourability 1 domain
- Old, coarser resolution map favourability 0 domain

Figure 12. Old, coarser resolution Cape Smith Belt map highlighting magmatic massive-sulphide favourability domains (as defined in Tables 12 and 13) and mineral exploration targets. Hydrographic features (lakes, rivers) are omitted for clarity.

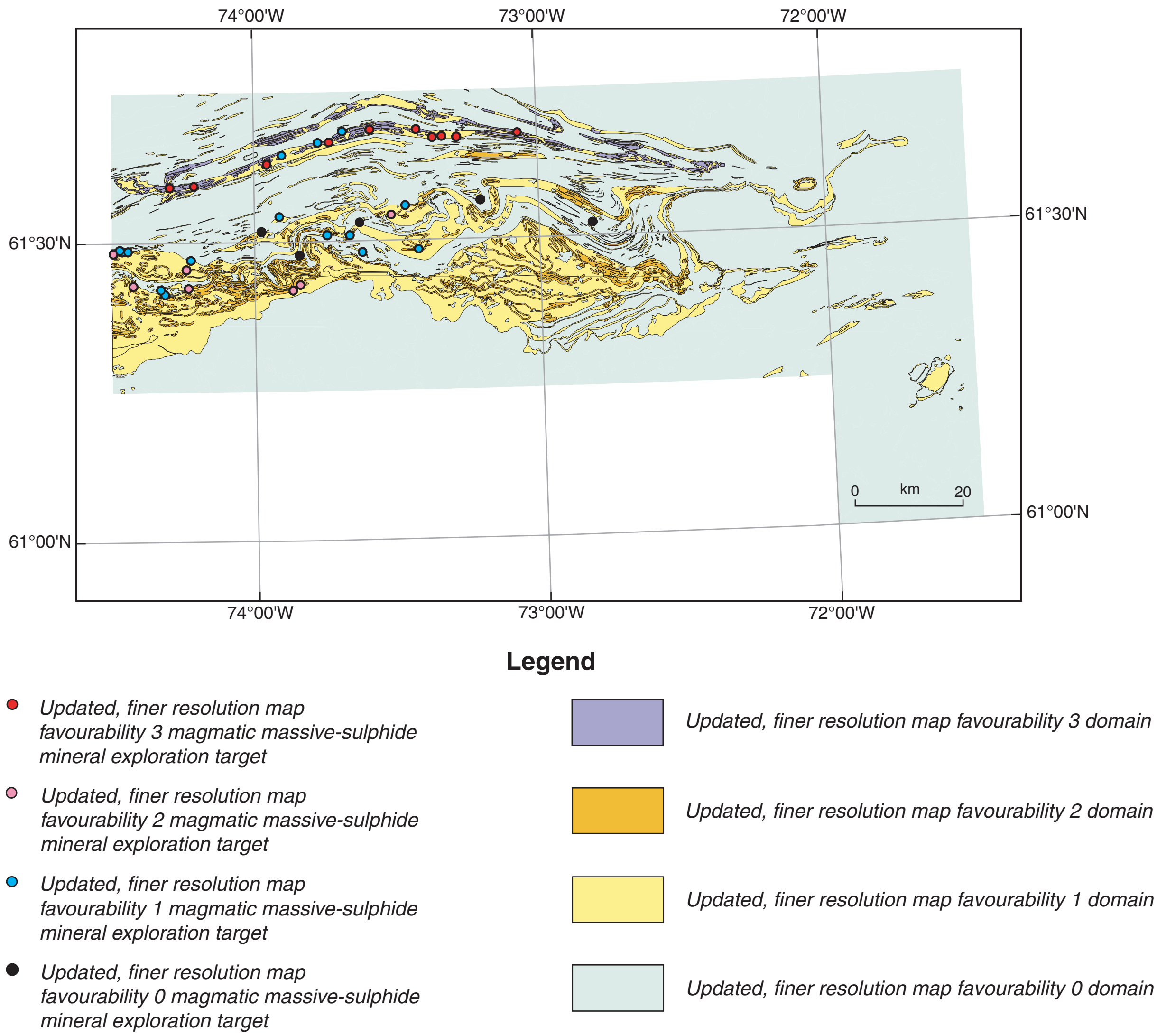


Figure 13. Updated, finer resolution Cape Smith Belt map highlighting magmatic massive-sulphide favourability domains (as defined in Tables 14 and 15) and mineral exploration targets. Hydrographic features (lakes, rivers) are omitted for clarity.

Table 16. Empirical mineral exploration target densities for the favourability domains on the updated, finer resolution Cape Smith Belt map.

Favourability index	Number of 4 km^2 search units contained in the favourability domain	Number of targets	Mineral exploration target density per 4 km^2 (90% confidence interval)
0	1870	5	0.0026 (0.0007–0.0046)
1	410	15	0.0366 (0.0213–0.0518)
2	106	7	0.0662 (0.0264–0.1059)
3	26	10	0.3774 (0.2225–0.5322)

In order to factor in the change of map scale in the present analysis, the delineation of a zone of contact between two units is defined as being 100 m on either side of the contact line for the finer resolution maps and 500 m on either side of the contact line for the coarser resolution maps. Given the use of field systems to capture geological information digitally, and the geographic information system environment that characterizes the map production process from the initial field compilation to the final publication stage for updated maps, a ±100 m buffer for contacts on a 1:50 000 scale map (or a 1:100 000 scale map, *see* below) is thought to be quite realistic.

The expected surface extent of magmatic massive-sulphide exploration targets in the Cape Smith Belt varies between 0.1 km^2 (approximately 300 m x 300 m) and 0.3 km^2 (approximately 550 m x 550 m) (Barnes et al., 1992); however, mineralization within about 800 m is treated as one mineral deposit (Avramtchev, 1982), thus uniquely defining areas between 3.6 km^2 (1900 m x 1900 m) and 4.6 km^2 (2150 m x 2150 m). Consequently, the present authors use 4 km^2 as the search unit area to define a typical magmatic massive-sulphide mineral target in the vicinity of Hudson Strait. The full sample of 37 magmatic massive-sulphide showings and deposits is utilized to derive the empirical exploration target densities for each favourability index within the eastern Cape Smith Belt and populate Tables 16 and 17 for the updated, finer resolution and old, coarser resolution maps, respectively. The target densities in Tables 16 and 17 will appear higher than might be expected since the mineral exploration target densities are calculated with respect to the search unit as defined above and which, for the Cape Smith Belt, has a surface area of 4 km^2.

As can be seen in Table 16, the estimated mineral exploration target density for the updated, finer resolution Cape Smith Belt maps increases with each higher favourability index. Whereas the expected mineral exploration target density for the favourability 2 domain is almost twice that of the expected exploration target density for the favourability 1 domain, the expected target density for the favourability 3 domain is an order of magnitude greater than that of the favourability 2 domain. Likewise, the expected exploration target density for the favourability 1 domain is an order of magnitude greater than that of the favourability 0 domain. Considering the full range, expected exploration target densities for favourability 0 versus favourability 3 domains are distinguished by two orders of magnitude. In contrast, the exploration target density estimates for the old, coarser resolution favourability 3 and 0 domains only differ by one order of magnitude and the expected target densities for favourability 1 and favourability 0 indices are only weakly distinguishable. Compared to the updated, finer resolution map, it is evident that the old, coarser resolution map identifies only a fraction of favourable areas.

South Baffin Island favourability domains and adopted exploration target densities

Four favourability classes were identified for both the finer and coarser resolution maps available for the south Baffin Island area. As was the case for the eastern Cape Smith Belt area, favourability for the south Baffin Island area in this analysis is based upon the likelihood of magmatic massive-sulphide targets being hosted by sulphidic sedimentary rocks, as well as the proximity to key contacts between units:

- Favourability 0 = geology in search unit is not likely to contain an exploration target,
- Favourability 1 = geology in search unit is somewhat favourable for containing an exploration target,
- Favourability 2 = geology in search unit is favourable for containing an exploration target, and
- Favourability 3 = geology in search unit is most favourable for containing an exploration target.

Table 18 lists the diagnostic rock units and/or contacts between units as assigned to each favourability index for the analysis of the old, coarser resolution south Baffin Island geological map $(\theta = \mathrm{OC})$ and Table 19 provides a description of the coding scheme fwhooly cowor individual geological map units.

Table 17. Empirical mineral exploration target densities for the favourability domains on the old, coarser resolution Cape Smith Belt map.

Favourability index	Number of 4 km^2 search units contained in the favourability domain	Number of targets	Mineral exploration target density per 4 km^2 (90% confidence interval)
0	2156	25	0.0116 (0.0078–0.0153)
1	238	9	0.0378 (0.0175–0.0580)
2	11	0	0
3	7	3	0.4138 (0.1129–0.7146)*
* Sample size is not large enough for the confidence interval estimate to be reliable.			

Table 20 lists the rock units and contacts allocated to each favourability index for the south Baffin Island updated, finer resolution maps $(\theta = \mathrm{UF})$ and Table 21 explains the related geological coding scheme. The derivative geographic information system favourability maps, resulting from the translation of the map rock units and contacts into their favourability indices for the old, coarser resolution and updated, finer resolution maps for the south Baffin Island area, are shown in Figures 14 and 15. In order to factor in the change of map scale in the present analysis, the delineation of a zone of contact between two units is defined as being 100 m on either side of the contact line for the finer resolution maps and 500 m for the coarser resolution maps. Given the use of field systems to capture geological information digitally, and the geographic information system environment that characterizes the map production process from the initial field compilation to the final publication stage for updated maps, a ± 100 m buffer for contacts on a 1:100 000 scale map (or a 1:50 000 scale map, *see* above) is thought to be quite realistic.

Table 18. Favourability indices for the south Baffin Island old, coarser resolution map (Blackadar, 1967). For the geological contacts in the third column, there are a variety of alternative scenarios represented by the coding scheme. The "or" indicates that the units in the series are substitutable, and the "+" denotes a contact between two series of units. For example in the favourability 3 index, possible contacts between units are 15 and 5, 15 and 6, 15 and 7, and/or 15 and 10.

Favourability index	Units	Contacts
0	All other units	None
1	5, 6, 7, 10, 15	None
2	None	None
3	None	15 + 5 or 6 or 7 or 10

Table 19. Explanation of geological unit coding scheme for the south Baffin Island old, coarser resolution map (Blackadar, 1967) favourability indices.

Geological unit code	Geological unit	Rock type
5	Lake Harbour Group	Sillimanite gneiss and schist
6	Lake Harbour Group	Rusty paragneiss
7	Lake Harbour Group	Garnet-biotite-quartz-feldspar gneiss
10	Lake Harbour Group	Quartzite
15	n/a	Utramafic rocks
n/a = not applicable		

In order to document how the updated, finer resolution map allows for a better definition and resolution of favourability domains when compared to the old, coarser resolution map in the south Baffin Island area, the higher favourability domains on the old, coarser resolution map (favourability indices 1 and 3; Table 18) are overlain on the favourability domains on the updated, finer resolution map (favourability indices 0–3; Table 20) in Figure 16. Juxtaposition of the two sets of favourability domains illustrates the extent of higher favourability (indices 2 and 3) domains on the updated, finer resolution map not captured by a favourable domain on the old, coarser resolution map. Over half of updated, finer resolution map favourability domains (indices 1–3) lie outside the boundaries of the old, coarser resolution map favourability domains (indices 1 and 3).

Table 20. Favourability indices for the updated, finer resolution south Baffin Island maps (St-Onge et al., 1999b). For the geological contacts in the third column, there are a variety of alternative scenarios represented by the coding scheme. The "or" indicates that the units in the series are substitutable, and the "+" denotes a contact between two series of units. For example in the favourability 2 index, possible contacts between units are PLHp and PBBm, PLHp and PLHd, PBBq and PBBm, and/or PBBq and PLHd.

Favourability index	Units	Contacts
0	All other units	None
1	PLHp, PBBq, PBBm, PLHd	None
2	PHLm, PLHu	PLHp or PBBq + PBBm or PLHd
3	None	PLHp + PLHm or PLHu

Table 21. Explanation of geological unit coding scheme for the updated, finer resolution Baffin Island map favourability indices (St-Onge et al., 1999b).

Geological unit code	Geological unit	Rock type
PLHp	Lake Harbour Group	Dominantly psammite, semipelite, quartzite, minor marble, calc-silicate rocks
PBBq	Blanford Bay Assemblage	Feldspathic quartzite, pelite, semipelite
PBBm	Blanford Bay Assemblage	Metaperidotite, metagabbro, metapyroxenite
PLHd	Lake Harbour Group	Metaleucodiorite, metatonalite
PLHm	Lake Harbour Group	Metagabbro, amphibolite
PLHu	Lake Harbour Group	Metaperidotite, metapyroxenite, metadunite

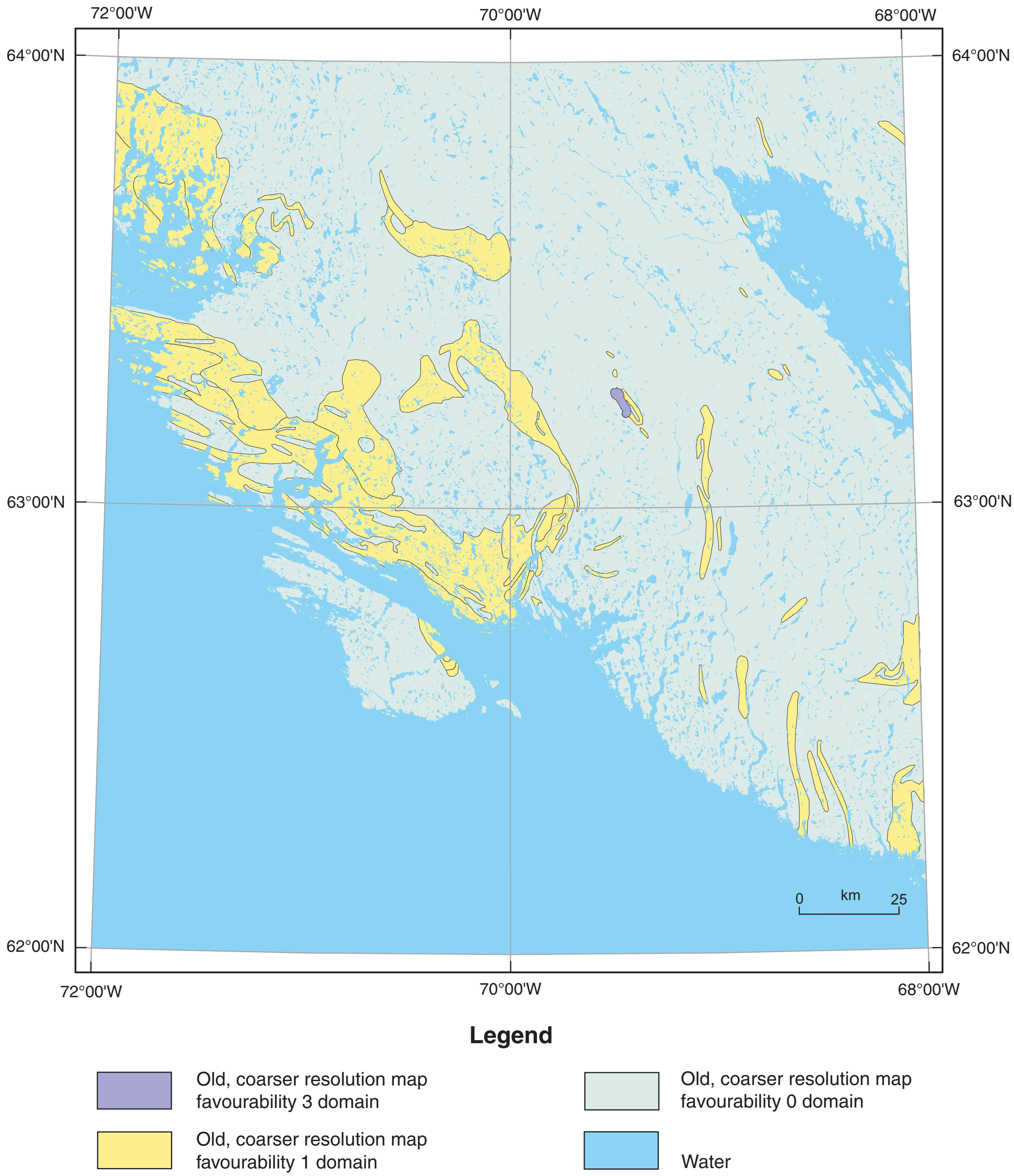


Figure 14. Old, coarser resolution south Baffin Island map highlighting magmatic massive-sulphide favourability domains (as defined in Tables 18 and 19).

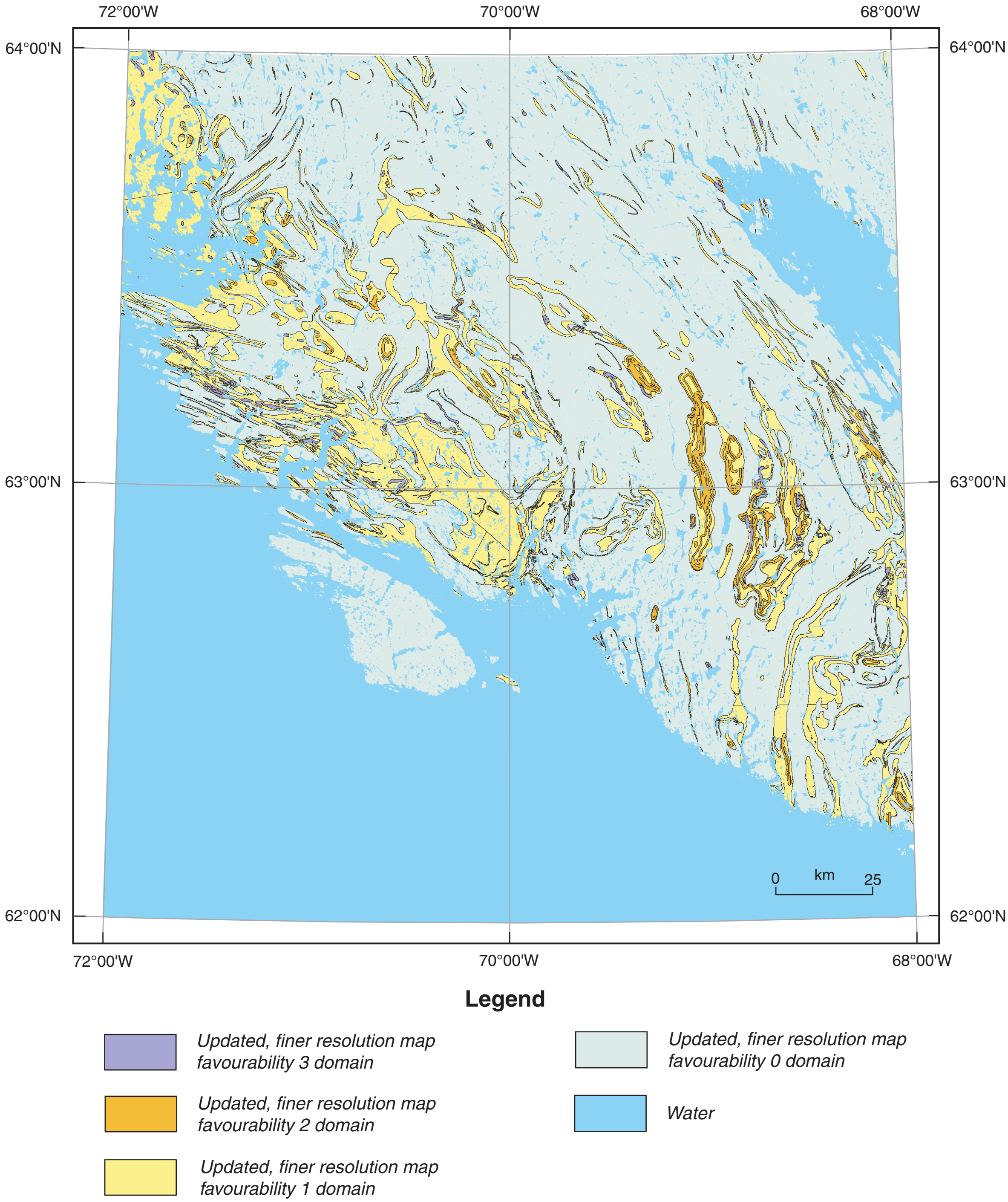


Figure 15. Updated, finer resolution south Baffin Island map highlighting magmatic massive-sulphide favourability domains (as defined in Tables 20 and 21).

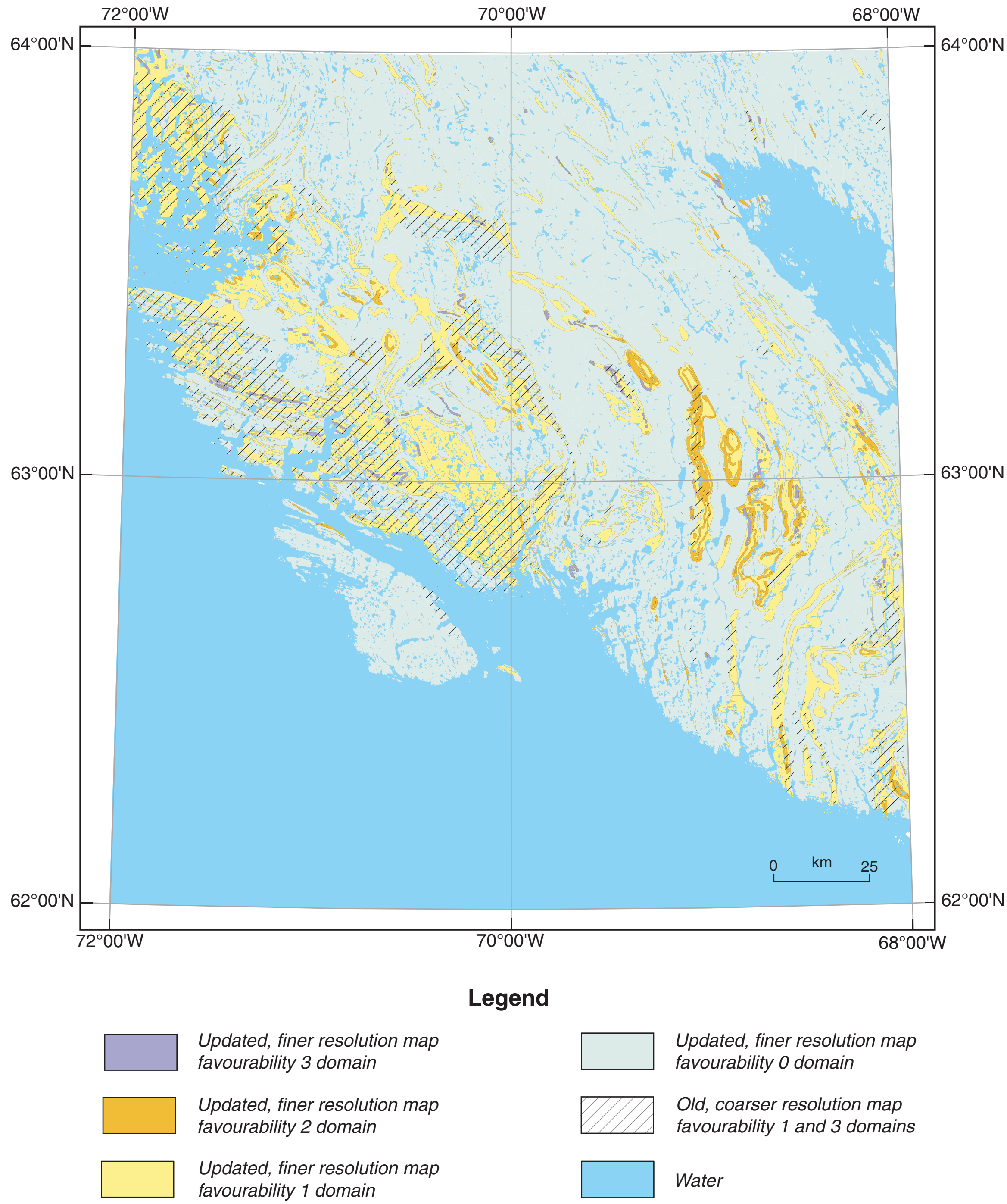


Figure 16. South Baffin Island old, coarser resolution favourability map overlain onto updated, finer resolution favourability map.

Table 22. South Baffin Island updated, finer resolution map search statistics using the Cape Smith Belt updated, finer resolution map mineral exploration target densities.

South Baffin Island favourability index	Number of south Baffin Island 4 km^2 search units	Expected target density per 4 km^2 (extrapolated from Cape Smith Belt analysis)	Expected number of south Baffin Island mineral exploration targets
0	6885	0.0026	19
1	1514	0.0366	55
2	121	0.0662	8
3	40	0.3774	15

Table 23. South Baffin Island old, coarser resolution map search statistics using the Cape Smith Belt old, coarser resolution map mineral exploration target densities.

South Baffin Island favourability index	Number of south Baffin Island 4 km^2 search units	Expected target density per 4 km^2 (extrapolated from Cape Smith Belt analysis)	Expected number of south Baffin Island mineral exploration targets
0	7141	0.0116	83
1	1414	0.0378	53
2	0	0	0
3	4	0.4138	1–2

As previously outlined, the equivalence of the lithological context for magmatic massive-sulphide mineralization in the Cape Smith Belt and the south Baffin Island areas (St-Onge et al., 1999a), as well as the equivalence in geological knowledge as contained in updated map information for both areas (St-Onge and Lucas, 1990; St-Onge et al., 1999b), allows the present authors to apply information on mineral exploration target densities derived from the extensively explored Cape Smith Belt area to the frontier south Baffin Island area where such information is not yet available. Consequently, the empirical mineral exploration target densities and statistics derived for the various Cape Smith Belt favourability domains (Table 16, 17) are adopted for the south Baffin Island analysis and are presented in Tables 22 and 23. The number of search units contained in each south Baffin Island favourability domain is calculated and utilized to yield the estimate of expected number of targets per favourability domain shown in Tables 22 and 23. As can be noted in Table 17, the Cape Smith Belt analysis did not provide an estimate for the mineral exploration target density for favourability 2 domains on the old, coarser resolution map; however, this was of no consequence for the present analysis, as the assignment of favourability domains to the old, coarser resolution map for south Baffin Island does not yield favourability 2 domains (Table 18).

The updated, finer resolution map and the old, coarser resolution map do not predict the same expected number of mineral exploration targets for the area as a whole (sum of the fourth column in Tables 22 and 23). The predictions would have been consistent if the same proportions of each favourable domain on the coarse resolution and finer resolution Cape Smith Belt maps had been preserved on the south Baffin Island maps. The main source of the discrepancy is that relatively less favourable 2 and 3 land is prescribed on the updated, finer resolution south Baffin Island map than its Cape Smith Belt counterpart, producing a relatively lower estimate of targets for the south Baffin Island updated, finer resolution map. In addition, the south Baffin Island coarser resolution map represents a disproportionate amount of favourability 1 domain land, that is partially compensated for by relatively less favourability 3 domain land, but still results in a relatively higher estimate of targets for the south Baffin Island coarser resolution map. Despite the greater number of total targets predicted by the old, coarser resolution south Baffin Island map, the updated, finer resolution south Baffin Island map promises to locate more targets within favourability domains 1 to 3 than does the old, coarser resolution map within favourability domains 1 and 3.

Mineral exploration efficiency and productivity of south Baffin Island maps

Tables 24 and 25 present the results of the authors' first two models that minimize mineral exploration search unit examinations (maximizing exploration efficiency) for given numbers of exploration targets, and maximize mineral exploration productivity for given numbers of search unit examinations for the various south Baffin Island maps. Figure 17 summarizes the results across the continuum of possible exploration outcomes.

Table 24. Solution to minimizing the search unit examinations utilizing updated, finer resolution and old, coarser resolution maps for south Baffin Island. Label OC3 denotes the exploration campaign that examines favourability 3 domains on the old, coarser resolution map; OC31 denotes the exploration campaign that examines favourability 3 and 1 domains on the old, coarser resolution map; OC310 denotes the exploration campaign that examines favourability 3, 1, and 0 domains on the old, coarser resolution map; UF3 denotes the exploration campaign that examines favourability 3 domains on the updated, finer resolution map; UF32 denotes the exploration campaign that examines favourability 3 and 2 domains on the updated, finer resolution map; and UF321 denotes the exploration campaign that examines favourability 3, 2, and 1 domains on the updated, finer resolution map.

Expected target potential, *t*	Updated, finer resolution map campaign: expected number of searches	Old, coarser resolution map campaign: expected number of searches
15	UF3: 40	$OC3_q$: 357
23	UF32: 161	$OC3_q$:569
55	$UF32_q$: 1033	OC31: 1418
78	UF321: 1675	$OC310_q$: 3395
Subscript q denotes that a fraction of the lowest favorability class is explored.		

Results for model 1: minimizing the search area

Table 24 presents the results of minimizing the number of search unit examinations to yield a selected expected target potential, *t*, by applying model 1 to the south Baffin Island area. By systematically searching selections of successively higher to lower favourability domains as defined by the updated, finer resolution map and the old, coarser resolution map, the number of search units required in each case can be calculated and compared for the two maps of different ages and scales.

As can be seen in Table 24, the number of search unit examinations needed using the old, coarser resolution map ranges from 1.4 times to 9 times greater than the expected number of search unit examinations needed using the updated, finer resolution map. The larger ratio occurs when the favourability 3 domain is searched on the updated, finer resolution map compared to searching the favourability 3 domain and a fraction of the favourability 1 domain on the old, coarser resolution map. The smaller ratio occurs when both maps are used to explore all favourable domains. When the old, coarser resolution map runs out of favourable domains, the old map search has to continue into the favourability 0 domain in order to reach the stated expected target potential, thus significantly increasing the ratio of old map to updated map search unit examinations.

Results for model 2: maximizing the mineral target potential

Table 25. Solution to maximizing the target potential, using the updated, finer resolution and the old, coarser resolution maps for south Baffin Island. Label OC3 denotes the exploration campaign that examines favourability 3 domains on the old, coarser resolution map; OC31 denotes the exploration campaign that examines favourability 3 and 1 domains on the old, coarser resolution map; OC310 denotes the exploration campaign that examines favourability 3, 1, and 0 domains on the old, coarser resolution map; UF3 denotes the exploration campaign that examines favourability 3 domains on the updated, finer resolution map; UF32 denotes the exploration campaign that examines favourability 3 and 2 domains on the updated, finer resolution map; and UF321 denotes the exploration campaign that examines favourability 3, 2, and 1 domains on the updated, finer resolution map.

Number of searches, *s*	Updated, finer resolution map campaign: expected number of targets	Old, coarser resolution map campaign: expected number of targets
40	UF3: 15	$OC3_q$: 3
161	UF32: 23	$OC3_q$: 8
1418	$UF32_q$: 69	OC31: 55
1675	UF321: 78	$OC310_q$: 58
Subscript q denotes that a fraction of the lowest favorability class is explored.		

Exploring a fixed number of search areas, *s*, on both the old, coarser resolution map and the updated, finer resolution map yields different expected numbers of targets, as per Table 25.

The expected target discovery for a fixed number of search unit examinations (a measure of productivity) using the updated, finer resolution map ranges from 1.25 times to 5 times more than the results using the old, coarser resolution map (Table 25). The larger ratio occurs for 40 search unit examinations when the updated, finer resolution map favourability 3 domain is examined and the old, coarser resolution map favourability 3 and a fraction of the favourability 1 domain are examined (Table 25). The smaller ratio occurs when favourability domains 1–3 are searched on both maps (the number of search units equal 1418 and 1675 in Table 25). These conditions for the biggest and smallest differences (in terms of ratios of expected results) between the two maps mirror those observed for the first model.

The two maps are compared in terms of exploration efficiency and productivity across all optimal exploration outcomes involving favourability domains 3, 2, and 1 in Figure 17. Since the optimal solution to models 1 and 2 explores the highest favourability areas first, the slope of the line segments for a map containing geology that is interpreted to have more than one favourable domain (e.g. the line for the updated, finer resolution map on Fig. 17) progressively decreases. The decreasing positive slope of the updated, finer resolution map exploration campaign exhibits its increasing expected target discovery at the expense of efficiency, when expanding the search into lower favourability domains. The horizontal distance between the graphed lines on Figure 17 represents the number of additional search unit examinations required by the older, coarser resolution map to yield the same expected number of targets as the updated, finer resolution map (and is a measure of the relative efficiency of the different maps). The vertical distance between the graphed lines on Figure 17 shows the additional expected number of targets for the same search effort across the maps (and is a measure of the comparative productivity of the different maps). When all favourable domains are examined on both maps the analysis projects that the updated, finer resolution map enables a 40% increase in the number of targets found and a 27% reduction in search effort relative to the old, coarser resolution map exploration outcome.

South Baffin Island exploration economic model

In the Flin Flon Belt case study, exploration campaigns were plotted against a target density, a risk constraint, and an isobenefit curve. The development of a budget constraint for mineral exploration in the south Baffin Island area is the point of departure from the preceding Flin Flon Belt analysis. The derivation of the constraints for the south Baffin Island economic model is explained below, followed by analysis of exploration campaign feasibility and preference.

South Baffin Island economic model constraints

Figure 18 illustrates the target density, risk, and budget constraints utilized for the south Baffin Island economic model. Since this area is a frontier region in terms of mineral exploration, the authors assume that mineral explorers will demand to be well assured about the likelihood of success of locating a minimum number of targets to justify the set-up costs of going into a new region. For example, the authors assume the risk criterion for an exploration campaign will require a probability of 0.95 of finding at least 10 targets, although later the minimum number of targets are allowed to vary. The target density constraint is set at $E = 0.02$ and again is later varied to show its influence on feasible and preferred exploration campaigns.

At the time of this study, mineral exploration of the south Baffin Island region was very recent and of a reconnaissance nature (as stated in the 'Introduction', south Baffin Island could be considered devoid of any previous history of significant mineral exploration or mining). Consequently, the costs associated with a full-scale exploration campaign were not publicly known. To populate the budget constraint, the authors describe a hypothetical four-year exploration campaign below with the expert knowledge of Natural Resources Canada (D.J. Scott, pers. comm., 2000). This campaign assumes that exploration is being conducted in a so-called greenfield or frontier region of Baffin Island, Nunavut.

Year 1: acquire 800 000 ha for CAN$750 000.

- Phase 1: staking and ground acquisition based on an interpretation of the mineral potential associated with geological elements and units as documented on newly released government maps.

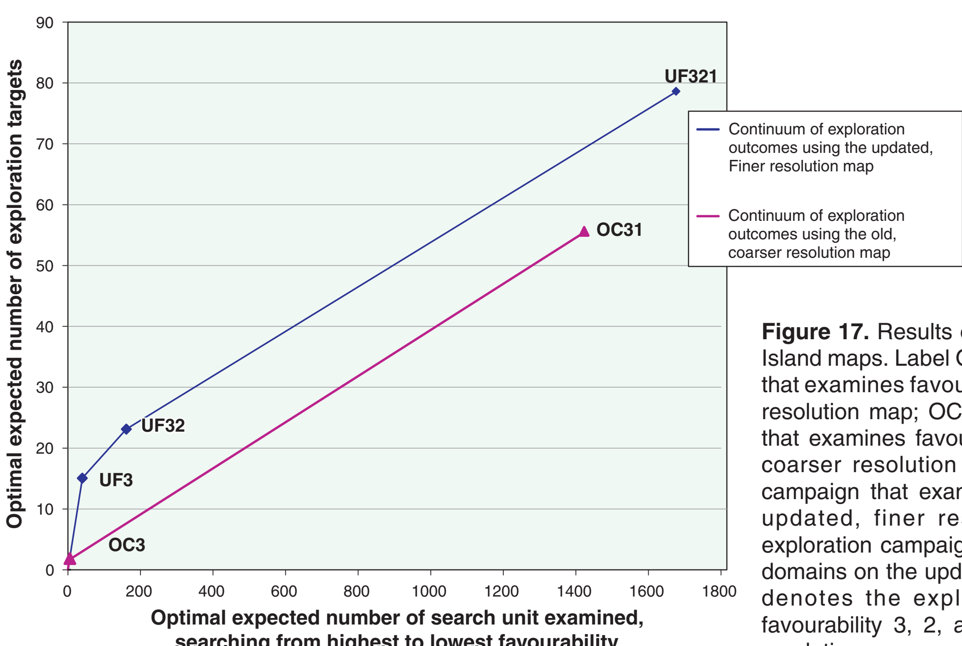


Figure 17. Results of models 1 and 2 for the south Baffin Island maps. Label OC3 denotes the exploration campaign that examines favourability 3 domains on the old, coarser resolution map; OC31 denotes the exploration campaign that examines favourability 3 and 1 domains on the old, coarser resolution map; UF3 denotes the exploration campaign that examines favourability 3 domains on the updated, finer resolution map; UF32 denotes the exploration campaign that examines favourability 3 and 2 domains on the updated, finer resolution map; and UF321 denotes the exploration campaign that examines favourability 3, 2, and 1 domains on the updated, finer resolution map.

- Phase 2: reconnaissance geology plus geochemical sampling, leading to prioritization for geophysical surveys (ground and airborne magnetic and electromagnetic surveys).
- Phase 3: geophysical surveys leading to identification of drill targets. Phase 3 leads to the prioritization of 15 anomalies for drill testing. Refine area to 60% of original land position.

Year 2: commence drilling on geophysical targets.

- Using newly released government maps, repeat phases 1–3 of year 1.
- Identify 15 additional drill targets for testing.
- Refine land position to 20% of original area.

Year 3: continue drilling on geophysical targets

- Drill year 2 anomalies and define at least one anomalous intersection from year 1 or year 2.
- Repeat phases 2 and 3 from year 1, but without additional government map information.
- Identify 10 new drill targets for testing in year 4. Refine land position to 10% of original area.

Based upon these activities, the exploration project budget would be approximately CAN$10.5 million with the specific exploration investment being variable with respect to both search area examined and mineral targets identified. Search-area–dependent exploration costs (e.g. ground acquisition, geological reconnaissance, geochemical sampling, ground and airborne magnetic testing, and electromagnetic surveys) were extracted from the above budget and determined to be CAN$572/$km^2$ or CAN$2288/search unit of 4 km^2. The assumed expected investment required to explore a target (follow-through drill testing) is CAN$147 875/target. These numbers are used to produce the budget constraint in Figure 18.

Analysis of south Baffin Island exploration campaigns

Figure 18 also provides the context to discuss the various constraints faced by the mineral exploration geologist. Exploration campaigns that explore all or nothing of a favourability domain in descending order are described in Table 26 and plotted in Figure 17. By definition, favourability domains characterized by higher target densities require fewer searches to find a minimum number of targets, and consequently, to achieve target exploration success; however, for a 0.95 probability of success and minimum number of 10 targets, the risk criterion (red line on Fig. 18) eliminates the old, coarser resolution map favourability 3 domain (OC3) as a stand-alone campaign, despite its high target density, due to the small number of search units defined within that favourability domain. In fact, the old, coarser resolution map favourability 3 exploration campaign does not satisfy the risk criterion requiring a probability of 0.95 of finding at least one target.

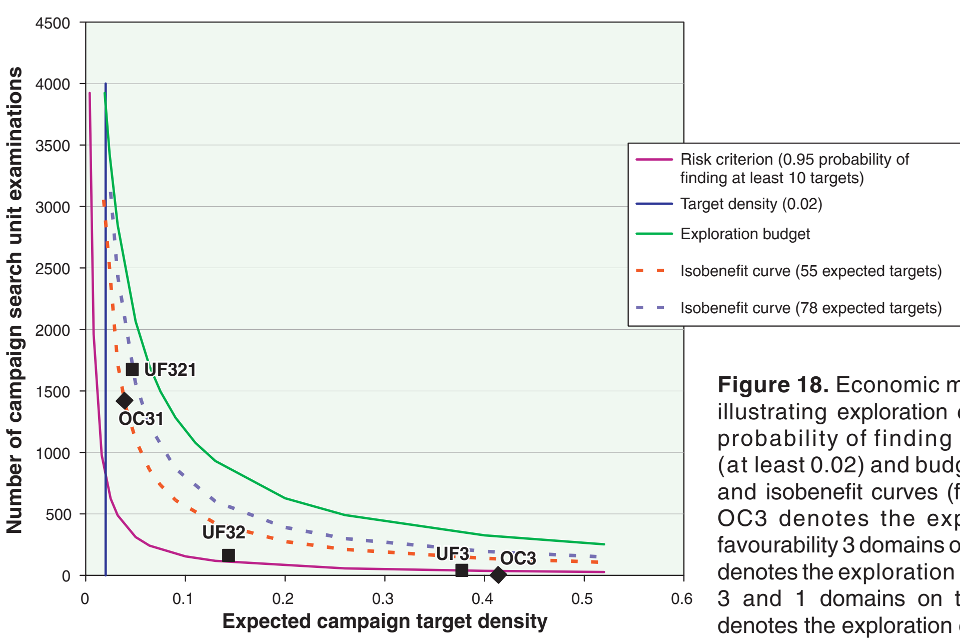


Figure 18. Economic model for the south Baffin Island maps illustrating exploration campaigns in the context of risk (0.95 probability of finding at least 10 targets), target density (at least 0.02) and budget (described in the text) constraints, and isobenefit curves (for 55 and 78 expected targets). Label OC3 denotes the exploration campaign that examines favourability 3 domains on the old, coarser resolution map; OC31 denotes the exploration campaign that examines favourability 3 and 1 domains on the old, coarser resolution map; UF3 denotes the exploration campaign that examines favourability 3 domains on the updated, finer resolution map; UF32 denotes the exploration campaign that examines favourability 3 and 2 domains on the updated, finer resolution map; and UF321 denotes the exploration campaign that examines favourability 3, 2, and 1 domains on the updated, finer resolution map.

Table 26. Number of search units examined, target density, and expected number of targets for exploration campaigns derived from the south Baffin Island maps. Label OC3 denotes the exploration campaign that examines favourability 3 domains on the old, coarser resolution map; OC31 denotes the exploration campaign that examines favourability 3 and 1 domains on the old, coarser resolution map; UF3 denotes the exploration campaign that examines favourability 3 domains on the updated, finer resolution map; UF32 denotes the exploration campaign that examines favourability 3 and 2 domains on the updated, finer resolution map; and UF321 denotes the exploration campaign that examines favourability 3, 2, and 1 domains on the updated, finer resolution map.

Exploration campaign	Number of search units	Campaign target density per 4 km^2	Expected number of targets
Old, coarser resolution map			
OC3	4	0.414	1–2
OC31	1418	0.039	53
Updated, finer resolution			
UF3	40	0.377	15
UF32	161	0.143	23
UF321	1676	0.047	78

If the campaign target density constraint (blue line on Fig. 18) is moved to the right (effectively requiring the successful identification of a greater number of expected exploration targets per area searched) the constraint becomes more difficult to satisfy and first eliminates the exploration campaign based on the old, coarser resolution map and focused on favourability 3 and 1 domains (OC31). A further movement of the campaign target density makes the exploration campaign based on the updated, finer resolution map and focused on favourability 3, 2, and 1 domains (UF321) unattractive to the exploration investor. It is the first exploration campaign based on the updated map depicted to become infeasible; however, the updated, finer resolution map offers alternative, more focused exploration options that remain attractive and satisfy higher campaign target density requirements. For example, exploration campaigns based on the updated, finer resolution map and focused on favourability 3 domains (UF3) or favourability 3 and 2 domains (UF32) would be the more preferred feasible option with respect to target density; but the UF3 and UF32 campaigns cover more limited areas such that they are the second and third campaigns to get culled by the risk constraint if the minimum number of targets and/or the probability of finding the minimum number of targets are increased. The UF321 exploration campaign is the most resilient option in terms of more demanding risk constraints.

A continuum of exploration campaigns exists between the campaigns plotted in Figure 18 that partially explore the lowest favourability domain of the campaign. It can be shown that the continuum of exploration campaign options provided by the coarser resolution map always lies beneath those of the updated, finer resolution map, displaying consistently the greater sensitivity of old, coarser resolution map campaigns to the risk and target density constraints.

If budget constraint is the determining factor (green line on Fig. 18) then the exploration campaigns based on the finer resolution map will be cut into before those based on the old, coarser resolution map; however, exploration campaigns based on the finer resolution map will still reap more benefits (find more targets) than campaigns based on the alternative old, coarser resolution map. For the constraints depicted in Figure 18, the UF321 exploration campaign provides the greatest expected benefit of 78 expected targets versus 55 expected targets from the OC31 exploration campaign.

Preferred solution

Leaving the budget constraint aside, the authors studied the effects of the campaign target density and risk constraints on the viability of exploration campaigns suggested by maps of different age and resolution. The authors sought a range of exploration outcomes to illustrate the decision criteria-dependent value of an updated, finer resolution map. Towards this goal the economic model (equation 3) is employed with an additional simplifying constraint that binds the decision variables to search all or nothing of a favourability domain:

$$x_f^\theta(x_f^\theta - n_f^\theta) = 0$$

Table 27 reports the results of the simplified economic model regarding the number of search unit examinations and the required investment for each selected possible optimal exploration campaign. Two exploration campaigns UF3 and UF32 are suggested by the updated, finer resolution map for higher values of *E* (minimum campaign target density) and lower values of *t* (minimum expected number of exploration targets assured with 0.95 probability) in the south Baffin Island area. Since there is no feasible, old, coarser resolution map campaign for the conditions satisfied by these campaigns, the updated, finer resolution map generates CAN$2.3 million and CAN$3.7 million exploration investment, respectively, whereas the old, coarser resolution map is not expected to attract any exploration investment at all.

In the fourth row of Table 27 the conditions are such that, again, the old map does not stimulate investment whereas the exploration campaign based on the updated, finer resolution map and focusing on favourability 1, 2, and 3 domains (UF321) satisfies the constraints. This set of decision-making criteria highlight the capacity of the updated, finer resolution map stimulating as much as CAN$15 million in exploration investment (that would not have occurred without publication of the updated, finer resolution map).

As shown in the third row of Table 27, for one set of determining conditions investigated (expected number of exploration targets ≤ 44 and minimum campaign target density ≤ 0.038) the old, coarser resolution map is able to stimulate investment with a campaign based on favourability domains 3 and 1 (OC31). For

Table 27. Optimal exploration and investment solutions to the simplified constrained optimization economic model for the south Baffin Island area with respect to t and E keeping the budget constraint constant. x_f^θ is the optimal number of search units examined in favourability domain f on map θ for the ranges of target density and minimum targets required by the risk constraint.

Determining conditions	Finer resolution map, optimal exploration campaign	Coarser resolution map, optimal exploration campaign	Expected updated, finer resolution map exploration investment (million $CAN)	Expected old, coarser resolution map exploration investment (million $CAN)
$t \leq 10$ $.144 \leq E \leq .377$	UF3 with $x_3^U = 40$ $x_2^U = x_1^U = 0$	$x_3^O = x_1^O = 0$	2.3	0
$t \leq 16$ $.039 \leq E \leq .143$	UF32 with $x_3^U = 40$ $x_2^U = 121$ $x_1^U = 0$	$x_3^O = x_1^O = 0$	3.7	0
$t \leq 44$ $E \leq .038$	UF321 with $x_3^U = 40$ $x_2^U = 121$ $x_1^U = 1514$	OC31 with $x_1^O = 1414$ $x_3^O = 4$	15.2	11.3
$45 \leq t \leq 65$ $E \leq .038$ OR $t \leq 65$ $.039 \leq E \leq .047$	UF321 with $x_3^U = 40$ $x_2^U = 121$ $x_1^U = 1514$	$x_3^O = x_1^O = 0$	15.2	0

the same conditions, the UF321 campaign based on the updated, finer resolution map stimulates an additional four million dollars of investment. For all other determining conditions investigated, the old, coarser resolution map does not stimulate investment (either because t or E is too high).

The promise of success and the expected efficiency of an exploration campaign focused on the favourability 3 domain of the updated, finer resolution map (UF3) is unmatched — inviting prospectors to a new region, backed up with more potential from finer resolution, favourability 2 and 1 domains. In contrast, exploration of the favourability 3 domain on the old, coarser resolution map (OC3) is risky and indicates few targets (i.e. Fig. 18). The mineral exploration target densities of the favourability 1 area on the old, coarser resolution map would not seem impressive enough to vie for frontier competition (Table 27). This has historically been the case.

Figure 19 is a graph of the difference between the two last columns of Table 27 showing the differential investment advantage provided by the updated, finer resolution map information for four alternative exploration campaign outcomes. When favourability 3, 2, and 1 domains based on the updated, finer resolution map are explored (campaign UF321) and the coarser resolution map is not used, the payoff from the producing the updated, finer resolution map is the greatest. Additionally, the results shown on Figure 19 illustrate that it is difficult to calculate a single value of information without knowing the specific decision context and understanding how the information affects a decision.

Estimated net economic value of the updated, finer resolution maps for south Baffin Island

Application of equation 10 yields the estimated economic value of the updated, finer resolution map in terms of exploration investment; in the simplest terms, the authors assume that the net value of the updated maps to society is the difference between the expected exploration investment stimulated by the updated maps and the public sector's cost of producing the maps such that there are dollar-for-dollar benefits to society from exploration investments.

There are both fixed (capital) costs and variable (operating) costs in a public bedrock geological mapping campaign. In general, as the location of the mapping effort moves northward geographically, costs increase dramatically due to the scarcer transportation infrastructure and the harsher climatic conditions. The list of cost sources, however, is fairly straightforward. These can be listed as follows: salaries, operating costs (including food, lodging, transportation, materials), contracted surveys (e.g. geophysical surveys), laboratory expenses (e.g. geochemistry, geochronology), data acquisition (e.g. topographic base maps, remotely sensed imagery), and geographic information system development and map production.

The total map production costs (including all relevant sources listed above) for the updated, finer resolution map for the south Baffin Island area were provided by the mapping agency involved. The GSC provided the cost of making the updated, finer resolution map as CAN$1.86 million over a three-year period (M.R. St-Onge, unpub. data, 2000).

Figure 19 shows that the expected additional exploration investments for all four mineral exploration campaigns investigated and based on the updated, finer resolution map, exceed the CAN $1.86 million cost of producing the updated, finer resolution map. The final specific value of the updated map depends on its use in the mineral exploration campaign, the extent of the campaign, and whether or not the original old, coarser resolution map offered exploration-stimulating information. The net value of the updated, finer resolution map thus range from CAN$0.42 million up to CAN$13.35 million (depending on the exploration campaign implemented; Table 26), when the costs associated with producing the new map are compared to the potential exploration investments stimulated by the release of the map in the public domain. In other words, the south Baffin Island case study demonstrates that the stimulated private-sector exploration investment can exceed the original government expenditure by as much as a factor of eight.

DISCUSSION

A range of discussion topics is covered in this section. The authors recognize the role of geoscientific information in a broader context and identify applications of the methodology used. Some extensions to the work are considered that included shadowing favourability polygons and switching the economic model constraints with the objective.

Geoscientific information and mineral exploration investment

The authors are aware that the contribution of geoscientific information to the mineral exploration investment decision is not the only information available and applied to the search effort, and that such a decision is complicated by national legislation and policies, political stability and infrastructure, and

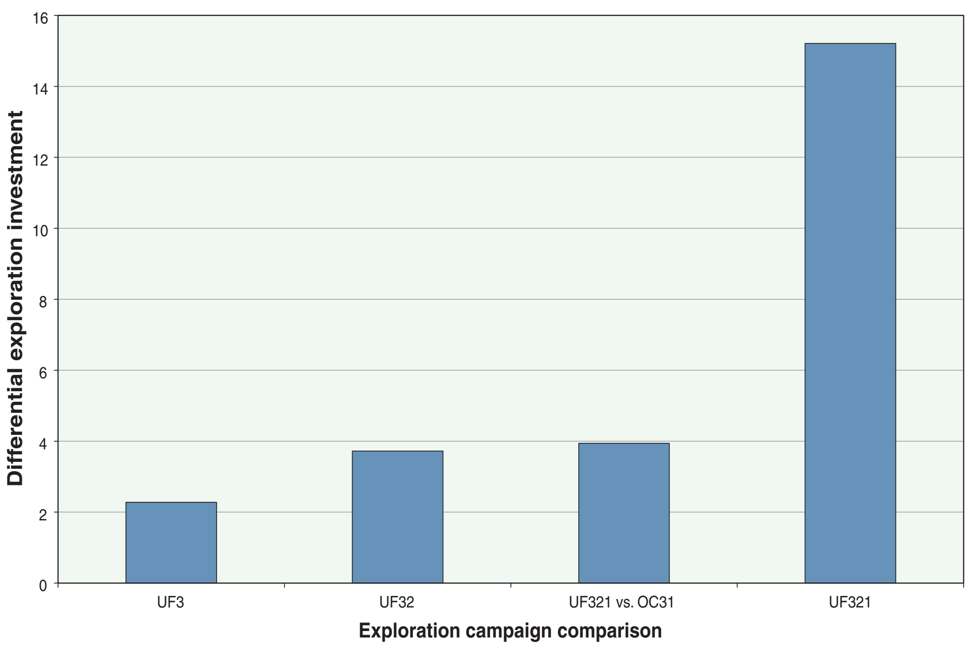


Figure 19. Investment advantage of the south Baffin Island updated, finer resolution map relative to that stimulated by the old, coarser resolution map. Label OC31 denotes the exploration campaign that examines favourability 3 and 1 domains on the old, coarser resolution map; UF3 denotes the exploration campaign that examines favourability 3 domains on the updated, finer resolution map; UF32 denotes the exploration campaign that examines favourability 3 and 2 domains on the updated, finer resolution map; and UF321 denotes the exploration campaign that examines favourability 3, 2, and 1 domains on the updated, finer resolution map.

global market trends. Neither do the authors intend to imply that exploration decisions are based solely on available public geological map information as companies will have their own sources of ancillary data, expertise, and in some cases specific field data. Overall it remains difficult to assess a relationship between geoscience information and exploration investment given that the potential relationship is often blurred by lags between publication of information and exploration activities. Others, including Scott et al. (2002) and Bhagwat and Ipe (2000) surveyed users to estimate the utility of geological information in hindsight. The challenge of this time-consuming approach lies in the framing of surveys and questions to elicit unbiased results (Mitchell and Carson, 1989; OXERA, 1999). To complement other efforts, the present authors took a different approach that seeks to relate the quantity and quality of information to decision making. Specifically in this study, the authors examined the influence that geological map information could have on exploration investment decisions as a means to indicate potential benefits of publicly funded geological map information to society via mineral exploration industry expenditures.

Assessments of the economic stimulus provided by updated, finer resolution maps are conservative in that the benefits of the updated information are restricted to the next step of the exploration phase in terms of stimulating investment. The models herein do not incorporate grade and tonnage considerations or the ultimate value of an economical discovery that results from investment in an exploration campaign based on information contained in newly released bedrock maps. Quite obviously the discovery and development of an economic deposit would multiply by several orders of magnitude the value of the geological information contained in an updated map utilized by industry for the discovery.

The actual exploration investment depends on the number of search units explored and the number of targets located, which, in turn depend on the disparity between the target densities explorers use to choose their exploration strategy and the actual densities they find in the field. As previously noted, very little information is available about the variability of target densities.

Applications of this work

This work contributes to private and public decision-making. The authors have defined and estimated measures of efficiency, productivity, risk, cost, and effectiveness. This contribution addresses a need identified in the literature by Lord et al. (2001) that

> "The industry needs more robust and quantitative methodologies for measuring exploration effectiveness, and for informing management, investors, and shareholders of exploration risk, reward, value and progress to discovery".

In the public arena, an application of the methodology developed in this paper could assess how much better updated geological map information needs to be to justify the expense of providing it. A government not only supplies basic information in the form of a geological map, which can stimulate potentially profitable exploration as documented here, but in addition the map information could also highlight how inviting an area might be by publishing the authors' type of analysis. Additionally, viewing the government as an honest broker, it supplies geological data not only to the mineral exploration industry, but also to society as a whole, thus enabling more informed public decision making for planning and development with respect to social, economic, and environmental issues, and improving scientific knowledge (Nielsen, 2004).

Shadowing geological information for inaccuracies

Because the accuracy of favourability domain boundaries depends on the accuracy of the geological rock unit boundaries, analysis (that is not presented in detail here) was carried out that shadowed favourability polygons by a buffer of size related to the map resolution. The use of shadowing to compensate for inaccuracies reduced target density estimates due to the increase in area of nonzero favourability domains, but did not change the nature of the results.

Alternative economic model formulations

In the economic model used (model 3), it is assumed that the decision maker is primarily interested in maximizing the number of targets located with the condition that efficiency, risk, and budget constraints are satisfied. If the decision maker were primarily concerned with maximizing efficiency, minimizing risk, or minimizing cost, the relevant constraint would be switched with the effectiveness objective.

If the decision maker maximizes exploration efficiency subject to the same constraint set for the economic model except that the effectiveness constraint replaces the efficiency constraint, the form of the optimal solution will be the same: the higher favourability domains will be searched until the effectiveness or risk constraint is reached. Minimizing search area and maximizing the expected number of targets (models 1 and 2, respectively) are a subset of this problem in that they maximize efficiency subject to an effectiveness constraint (Fig. 20).

In another model, the decision maker could minimize risk (maximize the probability of finding at least a certain number of targets) subject to the same constraint set for the economic model except that the effectiveness constraint replaces the risk constraint. In this model, the outcome will depend on whether or not increasing the number of campaign searches compensates for the decreasing campaign target density as the search is expanded from higher to lower favourability domains. An examination of the data in the authors' case studies reveals that the expansion of the campaign search area dominates the decrease in campaign target density, such that risk decreases as the search is expanded until either the efficiency or budget constraint is reached.

If the decision maker minimizes the money spent subject to the same constraint set for the economic model except that the effectiveness constraint replaces the budget constraint, then the optimal solution will again be to search the highest favourability domains first until the effectiveness and risk constraints are satisfied. The optimal solution is the campaign that finds just enough targets most efficiently to satisfy these constraints, since there are costs related to the number of search units examined and the number of targets found.

In all of these models, the rational decision maker would search the highest favourability domains first (Table 28). Furthermore, the decision maker would always use the most up-to-date and most detailed map information for exploration to maximize his return on investment.

Other improvements

Further refinement of the analysis could embrace other techniques to identify the key geological and mineralization associations (e.g. Nielson, 2004), in addition to utilizing expert opinion as the present authors have done, or to expand the perspective to three-dimensional information. Exploration is a three-dimensional process and experience says most areas that are well explored are not well explored in three dimensions (G. Raines, pers. comm., 2005).

The benefits could also capture broader implications of updated information such as the outcome of disturbing less of the environment. A map that better delineates exploration areas suggests less damage to the environment on a regional scale relative to mineral exploration success.

Table 28. The return on investment, south Baffin Island area (the number of expected targets per million dollars spent). Label OC31 denotes the exploration campaign that examines favourability 3 and 1 domains on the old, coarser resolution map; UF3 denotes the exploration campaign that examines favourability 3 domains on the updated, finer resolution map; UF32 denotes the exploration campaign that examines favourability 3 and 2 domains on the updated, finer resolution map; and UF321 denotes the exploration campaign that examines favourability 3, 2, and 1 domains on the updated, finer resolution map.

Exploration campaign	Expected targets/million dollars
UF3	6.6
UF32	6.2
UF321	5.1
OC31	4.7

CONCLUSIONS

The development of a model of mineral exploration investment decisions contains many assumptions. Whereas the model is a simplification of actual investment and risk preferences, the results are intuitively appealing as a representation of the economic incentives. That is, they represent a behavioural approach to exploration decisions. The authors demonstrate that updated geological information, as contained in maps, can extend the area of exploration interest by assigning more land to the favourable domains (as in the Cape Smith Belt and south Baffin Island case studies) or significantly narrow the search to increase the target density (as in the Flin Flon Belt case study). Either way, exploration risk is reduced and exploration campaign efficiency, productivity, and effectiveness increased, and consequently updated, finer resolution map information is more likely to attract exploration

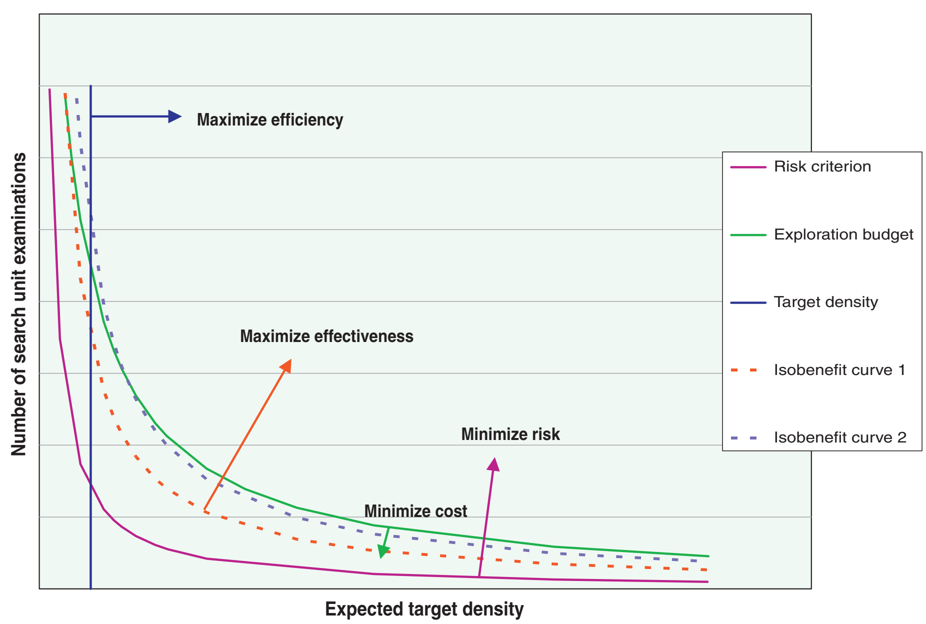


Figure 20. Exploration preference, feasibility, and constraints.

investment to the region than old, coarser resolution map information. This explains why explorationists will preferentially invest in jurisdictions with updated public geoscience information. The south Baffin Island case study demonstrates that the stimulated private sector exploration investment can exceed the original government expenditure by as much as a factor of eight.

In summary, this study resulted in an innovative methodology for estimating the value of bedrock geological maps within the context of mineral exploration. This methodology can be applied to other circumstances such as environmental assessments and land-use decisions, highlighting both the utility of the model and the value of the geological map information as a public good. The two case studies validated the model and demonstrated the potential economic benefits of the updated geological maps.

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Appendix A

GIS method to delineate contacts

The method to find razor sharp ('unshadowed') contacts for rock unit A and rock unit B is as follows, the implication being that the unit boundaries are shown with complete accuracy on the geological map:

- Select by location the polygons of rock unit A touching a polygon of rock unit B.
- Apply a 100 m (for a 1:50 000 scale map) or 500 m (for a 1:250 000 scale map) buffer around the polygons of unit A selected in step 1.
- Select by location the polygons of rock unit B touching a polygon of rock unit A.
- Apply a 100 m (for a 1:50 000 scale map) or 500 m (for a 1:250 000 scale map) buffer around the polygons of unit B selected in step 3.
- Take the intersection of steps 2 and 4.

Appendix B

Kuhn-Tucker conditions (Avriel, 1976) for the optimal solution to model 3

$$x_f \geq 0 \forall f$$

$$y_i \geq 0 \forall i$$

$$n_f^\theta - x_f \geq 0 \forall f$$

$$-E + \frac{1}{\sum_{f=0}^{F_\theta} x_f} \sum_{f=0}^{F_\theta} x_f \hat{p}_f^\theta \geq 0$$

$$M - I_s \sum_{f=0}^{F_\theta} x_f - I_t \sum_{f=0}^{F_\theta} x_f \hat{p}_f^\theta \geq 0$$

$$1 - P - (1 - \frac{1}{\sum_{f=0}^{F_\theta} x_f} \sum_{f=0}^{F_\theta} x_f \hat{p}_f^\theta)^{\sum_{f=0}^{F_\theta} x_f} \geq 0$$

$$y_s (n_f^\theta - x_f) = 0 \forall f$$

$$y_e (E - \frac{1}{\sum_{f=0}^{F_\theta} x_f} \sum_{f=0}^{F_\theta} x_f \hat{p}_f^\theta) = 0$$

$$y_b (M - I_s \sum_{f=0}^{F_\theta} x_f + I_t \sum_{f=0}^{F_\theta} x_f \hat{p}_f^\theta) = 0$$

$$y_r (1 - P - (1 - \frac{1}{\sum_{f=0}^{F_\theta} x_f} \sum_{f=0}^{F_\theta} x_f \hat{p}_f^\theta)^{\sum_{f=0}^{F_\theta} x_f}) = 0$$

$$\hat{p}_f^\theta - y_{s_f} + \frac{y_e}{\sum_{f=0}^{F_\theta} x_f} (\hat{p}_f^\theta - \frac{1}{\sum_{f=0}^{F_\theta} x_f} \sum_{f=0}^{F_\theta} x_f \hat{p}_f^\theta) + y_b (-I_s - I_t \hat{p}_f^\theta) +$$

$$y_r (\sum_{f=0}^{F_\theta} x_f (\frac{1}{\sum_{f=0}^{F_\theta} x_f} \sum_{f=0}^{F_\theta} x_f \hat{p}_f^\theta)^{\sum_{f=0}^{F_\theta} x_f - 1} (\frac{1}{\sum_{f=0}^{F_\theta} x_f} (\hat{p}_f^\theta - \frac{1}{\sum_{f=0}^{F_\theta} x_f} \sum_{f=0}^{F_\theta} x_f \hat{p}_f^\theta)) +$$

$$(\frac{1}{\sum_{f=0}^{F_\theta} x_f} \sum_{f=0}^{F_\theta} x_f \hat{p}_f^\theta)^{\sum_{f=0}^{F_\theta} x_f} \text{In} \frac{1}{\sum_{f=0}^{F_\theta} x_f} \sum_{f=0}^{F_\theta} x_f \hat{p}_f^\theta) \geq 0 \forall f$$

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