Integration of Geological Datasets for Gold Exploration in Nova Scotia

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ABSTRACT: A variety of regional geoscience datasets from Nova Scotia have been co-registered and analyzed using a geographic information system (GIS). The datasets include bedrock and surficial geological maps, airborne geophysical survey data, geochemistry of lake-sediment samples, and mineral occurrence data. A number of line features, including structural lineaments, fold axes and formation contacts, have also been digitized. The GIS uses a quadtree structure, ideally suited to a mixture of polygonal-thematic (e.g., geological maps) and continuous "grey-scale" (e.g., remote sensing, airborne geophysics) raster images. The goal of the study was to create a map showing areas favorable for gold mineralization, based on the distribution of 70 known gold occurrences. Initially, a multi-element geochemical signature was generated using a regression analysis to find the linear combination of geochemical elements that best predict lake catchment basins containing a gold occurrence. A predicted gold occurrence map, based on the geochemistry alone, was produced. A method using Bayes' rule was applied to combine other factors important for gold prediction with the geochemical signature. A unique conditions map shows all those areas where a unique set of overlap between the predictor maps occurs. For each unique condition, an *a posteriori* probability was calculated, resulting in a map depicting probability of gold mineralization. This map confirms that the major known gold districts coincide with areas of high probability. Several new areas of high potential are indicated by the model, although exploration follow-up has not yet been carried out.

INTRODUCTION

A MAJOR ACTIVITY of government geological surveys consists of mapping the composition and structure of the Earth's crust using both traditional field methods and advanced geochemical and geophysical techniques. The integration of such surveys, stored as paper maps and digital datasets for the purposes of mineral resource estimation and exploration, is a task tailor-made for a geographic information system (GIS).

Despite the previous development of excellent software for spatial and statistical analysis of regional geological datasets, e.g., SIMSAG (Chung, 1983), CHARAN (Botbol, 1971), and GIAPP (Fabbri, 1985), mathematical tools for carrying out mineral resource assessments have not been widely adopted. The reasons for this are many, but some important factors have been the difficulty of importing diverse data types into geographically co-registered databases, the lack of good computer graphics, and slow user interaction inherent in many software packages. We believe that with GIS these factors can be overcome to a great extent.

In this paper we describe procedures for integrating geological map data (polygonal, thematic) with structural information (lines), lake-sediment geochemical data (point data associated with multiple attributes), airborne geophysics (raster images), and mineral occurrence data (points). We use both multiple regression analysis and a new method of combining binary map patterns using Bayesian statistics to create a derived map showing areas favorable for gold exploration in part of east mainland Nova Scotia.

SOFTWARE

We employed a quadtree*-based GIS (SPANS) for analyzing regional geological datasets (TYDAC, 1987). [1] SPANS uses a raster data structure with a variable pixel size. Raster images up to a maximum resolution of 2^{15} by 2^{15} pixels can be handled, although normally most SPANS universes* use maps with a quad level* of 10 to 12, i.e., with a size between 2^{10} and 2^{12} (1024 and 4096) pixels. The work described here was carried out on an 80386 PC with 70 mb hard drive, a Number Nine color graphics card, and a color monitor. SPANS will accept a variety of vector and raster data inputs, allows forward and backward transformations from about 20 projections to geographic (1at/long) coordinates, and provides a powerful set of analytical tools for analyzing multiple maps. Because SPANS permits the user to move readily to DOS, other DOS-compatible software (e.g., editors, statistical packages, locally-developed programs) can be executed on mutually shared data files.

GEOLOGY AND MINERALIZATION

The study area (Figure 1) is underlain by three major rock units. The Goldenville and Halifax Formations are Lower Paleozoic quartz wackes and shales, respectively. They are intruded by Middle Devonian granites (Keppie, 1984). Gold occurs in quartz veins, usually confined to the Goldenville Formation. Mining of gold has been carried out intermittently since the mid-19th century, to the present day. About 70 gold occurrences are officially recorded in the study area (McMullin *et al.*, 1986). About 30 of them have known production.

The mechanism of gold mineralization is not well understood. Most of the gold-bearing veins are concordant and occur at or near the crests of folds. The gold occurs within quartz-carbonate veins with associated arsenopyrite and/or pyrrhotite and minor but valuable amounts of galena, chalcopyrite, sphalerite, pyrite, and sometimes scheelite and stibnite. The veins are commonly confined to pyrite- or arsenopyrite-rich black shale horizons, and occur throughout the Goldenville Formation (Kontak and Smith, 1987). In some areas, the gold appears to be related to faults orientated NW-SE (e.g., Bonham-Carter *et al.*, 1985a). Some writers have suggested that mineralization may be related to the Goldenville-Halifax contact (Graves and Zentilli, 1982). Discussion relating to the origins of the deposits are complex, and no consensus has been achieved. Proposals include (a) synsedimentary deposition on the seafloor (b) deposition early in the geological history of the area from metamorphic fluids and multicyclic remobilization of components during deformation and (c) deposition late in the orogenic history from fluids derived either from granitic magmas or other sources deep in the crust.

[1]Some of the SPANS tools and terminology flagged in the text by an asterisk (*), are summarized in a short glossary.

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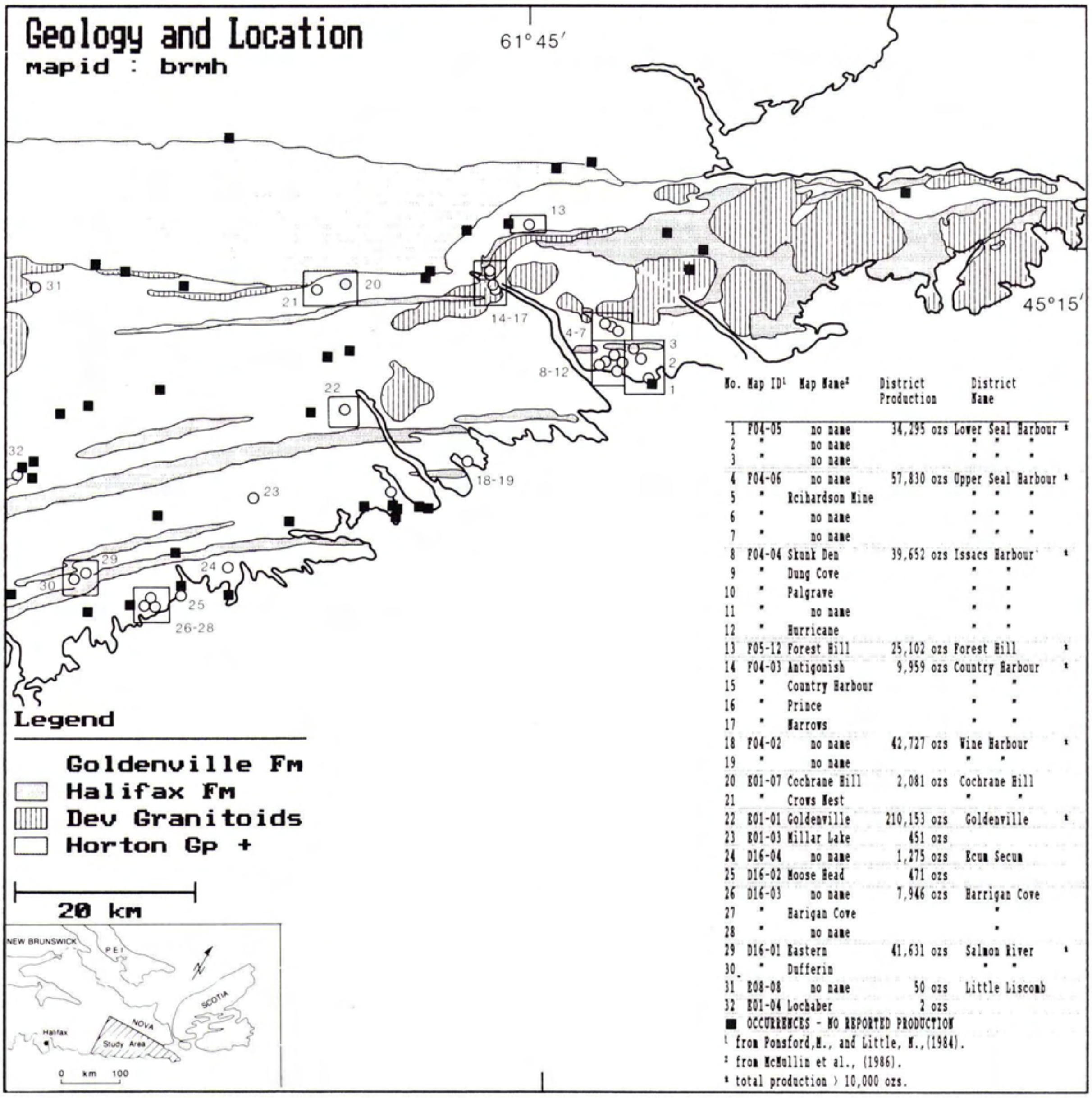

No.	Map ID[1]	Map Name[2]	District Production	District Name	
1	F04-05	no name	34,295 ozs	Lower Seal Harbour	*
2	"	no name		" " "	
3	"	no name		" " "	
4	F04-06	no name	57,830 ozs	Upper Seal Harbour	*
5	"	Rcihardson Mine		" " "	
6	"	no name		" " "	
7	"	no name		" " "	
8	F04-04	Skunk Den	39,652 ozs	Issacs Harbour	*
9	"	Dung Cove		" "	
10	"	Palgrave		" "	
11	"	no name		" "	
12	"	Hurricane		" "	
13	F05-12	Forest Hill	25,102 ozs	Forest Hill	*
14	F04-03	Antigonish	9,959 ozs	Country Harbour	*
15	"	Country Harbour		" "	
16	"	Prince		" "	
17	"	Narrows		" "	
18	F04-02	no name	42,727 ozs	Wine Harbour	*
19	"	no name		" "	
20	E01-07	Cochrane Hill	2,081 ozs	Cochrane Hill	
21	"	Crows Nest		" "	
22	E01-01	Goldenville	210,153 ozs	Goldenville	*
23	E01-03	Millar Lake	451 ozs		
24	D16-04	no name	1,275 ozs	Ecum Secum	
25	D16-02	Moose Head	471 ozs		
26	D16-03	no name	7,946 ozs	Harrigan Cove	
27	"	Harigan Cove		"	
28	"	no name		"	
29	D16-01	Eastern	41,631 ozs	Salmon River	*
30	"	Dufferin		" "	
31	E08-08	no name	50 ozs	Little Liscomb	
32	E01-04	Lochaber	2 ozs		

■ OCCURRENCES - NO REPORTED PRODUCTION
[1] from Ponsford,M., and Little, N.,(1984).
[2] from McMullin et al., (1986).
* total production > 10,000 ozs.

FIG. 1. Location map, showing area in S.E. mainland of Nova Scotia (inset), and the principal geological units and gold occurrences, from Wright *et al.* (1988). Thirty-two of the largest occurrences are shown as open circles, flagged by number, and listed to show map sheet number, production, and name. Solid squares show minor occurrences. Large open rectangles indicate major gold-producing districts.

In this paper, GIS is used to examine empirically the spatial relationship of the following factors to known gold occurrences: multi-element lake sediment geochemistry, lithology, distance to formation contacts, and distance to anticlinal fold axes. A probabilistic model is then developed for predicting gold mineralization using these empirical relationships.

DATA INPUTS

The data input to the GIS were very diverse (Table 1). The bedrock and surficial geology maps were raster-scanned using an Optronics 4040 at Canada Lands Data Systems (CLDS) (Bonham-Carter *et al.*, 1985b). Manuscript preparation involved tracing closed polygon boundaries on to a stable base, using a 0.006-inch black line. Identifying numbers were assigned to each polygon, tagged by hand-digitizing, and used as pointers to an associated attribute file. Output from the CLDS system consisted of an arc-node vector file, subsequently converted to a raster format (Steneker and Bonham-Carter, 1988). Geochemical data on lake sediment samples from about 550 sites were obtained as a samples × variables ASCII file, containing analyses for 16 chemical elements for each sample. The catchment area or basin surrounding each sampled lake was taken as the zone of influence of the sample. A map of catchment basins, one per sample, was drawn using a topographic map and raster-scanned as above. Again, each polygon number was used as a pointer to the associated sample record in the attribute file (Wright *et al.*, 1988).

Fold axes and structural lineaments were table-digitized. The same method was used to enter the locations of roads and towns for reference purposes.

TABLE 1. SOURCES AND TYPES OF VECTOR AND RASTER INPUT DATA.

Name of Map	Type	Digital Capture	Attributes
Bedrock geology	Polygonal, thematic	Raster-scanning of polygon boundaries[2]	Map units
Surficial geology[1]	Polygonal, thematic	Raster-scanning of polygon boundaries[2]	Map units
Lake catchment basins	Polygonal, thematic	Raster-scanning of polygon boundaries[2]	Lake sediment samples, 16 geochemical elements
Fold axes	Lines	Table digitizing[3]	Anticlines, synclines, age.
Lineaments, faults	Lines	Table digitizing[3]	Length, orientation
Airborne radiometrics[1]	Raster, grey scale	Gridded from digital flight line data[4]	K, eTh, eU, plus ratios
Airborne magnetics[1]	Raster, grey scale	Gridded from digital flight line data[4]	Total field, vertical gradient
Landsat MSS[1]	Raster, grey scale	Computer compatible tapes[5]	4 spectral bands
Mineral occurrences	Points	Digital database[6]	Elements, status
Roads[1]	Lines	Table digitized[3]	Major, minor
Towns, cities[1]	Points	Table digitized[3]	Size

[1]not directly used for gold prediction in this study
[2]by Canada Lands Data Systems, Environment Canada
[3]Gentian digitizing table, using TYDIG (part of SPANS system)
[4]Gridding by geophysical personnel, Geological Survey of Canada
[5]Purchased from Canada Centre for Remote Sensing
[6]CANMINDEX, National mineral occurrence database, Geological Survey of Canada

Airborne geophysical images were imported in an 8-bit raster format by downloading from a VAX mainframe. Each image (UTM projection) was geo-referenced using the southwest corner in UTM coordinates and image dimensions in metres. A Landsat MSS image was geometrically corrected on a micro-based image analysis system (EASIPACE software developed by Perceptron Incorporated) to a UTM base and imported to SPANS by a similar route.

Finally, point data defining the locations of gold occurrences were downloaded from CANMINDEX, a mineral occurrence database maintained at the Geological Survey of Canada (Picklyk *et al.*, 1978), updated with data from McMullin *et al.* (1986).

MAP CREATION

Maps in the quadtree structure were created for each of the polygonal-thematic inputs (e.g., geology) and grey-scale raster inputs (e.g., Landsat). A title and legend was created for each map by using a text-editor to add entries to ASCII dictionary files. Screen images were saved in a browse* file for future reference. Re-display of browse file images is virtually instantaneous, and files could be re-ordered for demonstrations.

It was possible to superimpose any point or line file as vectors on to any image for display purposes. Vector files could also be converted into quadtree maps by creating corridors or buffer zones around lines. This is particularly important for geological problems, where "distance to" linear features is often significant in studies of mineralization. For example, 20 corridors were spaced at 0.25-km intervals (0 to 5 km) around anticlinal axes, thereby creating a map showing distance to these structures. As will be shown below, a significant proportion of gold occurrences lie close to fold axes, and this corridor map is important for modeling gold mineralization. In addition, corridor maps showing distance to northwest trending lineaments, distance to the granite contact, and distance to the Halifax-Goldenville contact were prepared, using the same corridor-generating routine, permitting an analysis of gold occurrences in relation to these linear features.

DATA ANALYSIS

INTRODUCTION

Although gold exploration has been carried out in Nova Scotia for over 100 years, the 70 gold "occurrences" represent only the discovered gold resources of the study area. The purpose of spatial data integration was to make a map which would predict the location of new deposits. The new map was based on those factors that are associated with the location of known gold occurrences.

The predictive strategy for mapping areas favorable for gold mineralization involved two stages. In the first stage, the multi-element geochemical data (16 elements) were combined into a single new variable. As we show below, this variable represents the prediction that gold mineralization occurs using known gold occurrences as a dependent variable. Each lake sediment sample is assumed to exhibit a geochemical response representative of the rocks and mineralized zones occurring in the catchment area of the sampled lake. Regression was used to combine the geochemical variables into a weighted sum that best predicts whether a basin contains a known occurrence. The resulting map of predicted gold occurrences may be useful for locating new deposits from the geochemistry alone, but it can only help in those areas covered by the sampled catchment basins. There are several other factors observable throughout the region that may be useful guides to gold mineralization. These are combined with the geochemical evidence in the second stage.

Recent work by Agterberg (in press) has provided a new method for combining map patterns using Bayesian statistics. The simplest kind of map for this exercise is one which shows only the presence or absence of a single theme — a binary pattern. Although the method is not confined to binary maps, most geologists tend to think of predictor variables that are either "anomalous" or "background," so the thresholding of maps into binary form is appealing. For example, "background" levels of a geochemical element cover a concentration range believed to be associated with the particular rocks and soils of the area; "anomalous" levels would be above this range, and might be due to mineralization or other processes. Each binary map is associated with positive and negative weights, depending upon whether or not the pattern is present. Such weights are more easily interpreted than regression coefficients. The weights are determined using the locations of known deposits, so it is assumed that sufficient exploration has been carried out to make reliable estimates of the coefficients. The final product from the second stage is a new predicted gold map that should reflect the locations of known mineralization, as well as provide new target areas.

Multi-Element Geochemical Signature

Determining the multi-element geochemical signature that best predicts those lake catchment basins containing known gold occurrences (Wright *et al.*, 1988) involved adding a new attribute column to the lake sediment file indicating whether each lake basin contains a gold occurrence (score = 1) or not (score = 0). In practice this was achieved using the SPANS point result* option, thereby attaching the lake sediment basin number to the gold point file, and using this information to update the geochemical attribute file. This modified file was then entered into SYSTAT, a DOS-compatible statistical package to carry out regression analysis as illustrated below.

Let Y be a binary variable denoting presence/absence of a gold occurrence. Let X_j, $j = 1, 2, \ldots, 16$, be the concentration values of the 16 geochemical elements, log transformed to stabilize the variance. Then let

$$\hat{Y}_j = b_o + \sum_{j=1}^{16} b_j X_{ij}$$

be the predicted gold occurrence at the *i*th catchment basin, where the coefficients, *b* are determined by ordinary least-squares regression. In practice, this was carried out by a stepwise method, reducing the number of variables and coefficients requiring interpretation.

These regression coefficients represent a multi-element geochemical signature for predicting gold mineralization. A new column for predicted gold occurrence, $\hat{Y}$, was added to the lake sediment attribute table. This new attribute column was converted to a map based on the catchment basins, subdividing the range of predicted values into discrete classes. This step was carried out using the SPANS modeling language, written in a special ASCII file ("equation.inp")* reserved for this purpose.

Binary Map Analysis

In order to combine other factors with the geochemical signature, the second stage of the analysis employs the new method described by Agterberg (in press) for modeling conditional probabilities. This method is more convenient to use than multiple regression for several reasons. First, it avoids the requirement to subdivide the region into cells, each cell associated with an attribute list (e.g., geochemical elements, "distance to" measures, presence/absence of mineralization, and rock type). In order to capture the geometrical information about "distance to" linear features adequately, a very large number of small sampling cells must be created, and this is undesirable because of the resulting large attribute file and degree of spatial autocorrelation present in such a dataset. Secondly, the binary map method is better able to cope with the problem of missing data. For example, the lake catchment basins do not cover the whole study area, whereas the other maps (rock types, "distance to" maps) occur ubiquitously. Using regression, one must either assume mean values for those missing observations, or simply omit those regions with incomplete data.

The equations for the map pattern analysis are as follows. Let P_{prior} be the *a priori* probability of a gold deposit occurring within a small area of arbitrary but known size (e.g., 1 km²). The *a priori* odds are then defined by

$$O_{prior} = P_{prior} / (1 - P_{prior}).$$

The *a posteriori* odds can be expressed as

$$O_{post} = \exp\left\{\ln\left(O_{prior} + \sum_{j=1}^{m} W_j^k\right\}\right.,$$

$$\text{where } W_j^k = \left\{\begin{array}{l} W_j^+ \text{ if pattern } j \text{ is present,} \\ W_j^- \textit{ if pattern } j \text{ is not present,} \\ \emptyset \text{ if pattern } j \text{ is unknown,} \end{array}\right\}$$

and the *a posteriori* probability of a gold deposit occurring is

$$P_{post} = O_{post} / (1 + O_{post}).$$

The weights for the *j*th pattern are determined from

$$W_j^+ = \ln\{p(j|d) / p(j|\bar{d})\} \text{ and}$$

$$W_j^- = \ln\{p(\bar{j}|d) / p(\bar{j}|\bar{d})\}$$

The conditional probability terms are calculated from

$$p(j|d) = A_{dj} / A_{dt},$$

$$p(j|\bar{d}) = (A_j - A_{dj}) / (A_t - A_{dt}),$$

$$p(\bar{j}|d) = (A_{dt} - A_{dj}) / A_{dt}, \text{ and}$$

$$p(\bar{j}|\bar{d}) = (A_t - A_j - A_{dt} + A_{dj}) / (A_t - A_{dt})$$

where

A_{dt} = number of 1 km² units containing a deposit in the total study area,
A_{dj} = number of 1 km² units containing a deposit in pattern j,
A_j = area of pattern j, km², and
A_t = total study area, km².

The *a priori* probability P_{prior} can be estimated as A_{dt}/A_t. Bayes' rule assumes that the patterns are conditionally independent. This will not always be the case, and a general test for conditional independence can be made by comparing the predicted versus observed number of deposits, as described by Agterberg *et al.* (in press).

In order to determine the optimum cutoffs for classifying patterns into binary presence/absence (absence reflects "not present" as opposed to unknown), the weights W^+ and W^- can be calculated for a succession of cutoffs and, under normal conditions, the maximum value of $(W^+ - W^-)$ gives the cutoff at which the predictive power of the resulting pattern is maximized.

The numerical area calculations were made in SPANS using "area analysis"* of the map in question and a "point result"* of the map by the gold deposit point file. Weights for each pattern were computed using an external program. The final map showing *a posteriori* probabilities was calculated using the SPANS modeling language, after creating a "unique conditions"* map. This map consists of the set of unique polygons, each one defined as that area with a unique overlap of the binary patterns being modeled. Finally, the *a posteriori* probability map can be displayed. A "point select"* is useful to show which patterns are actually present for each gold occurrence, and the associated *a posteriori* probability value.

RESULTS

Figure 2a shows a map of the geochemical signature ($\hat{Y}$) obtained using the regression coefficients in Table 2 and thresh-

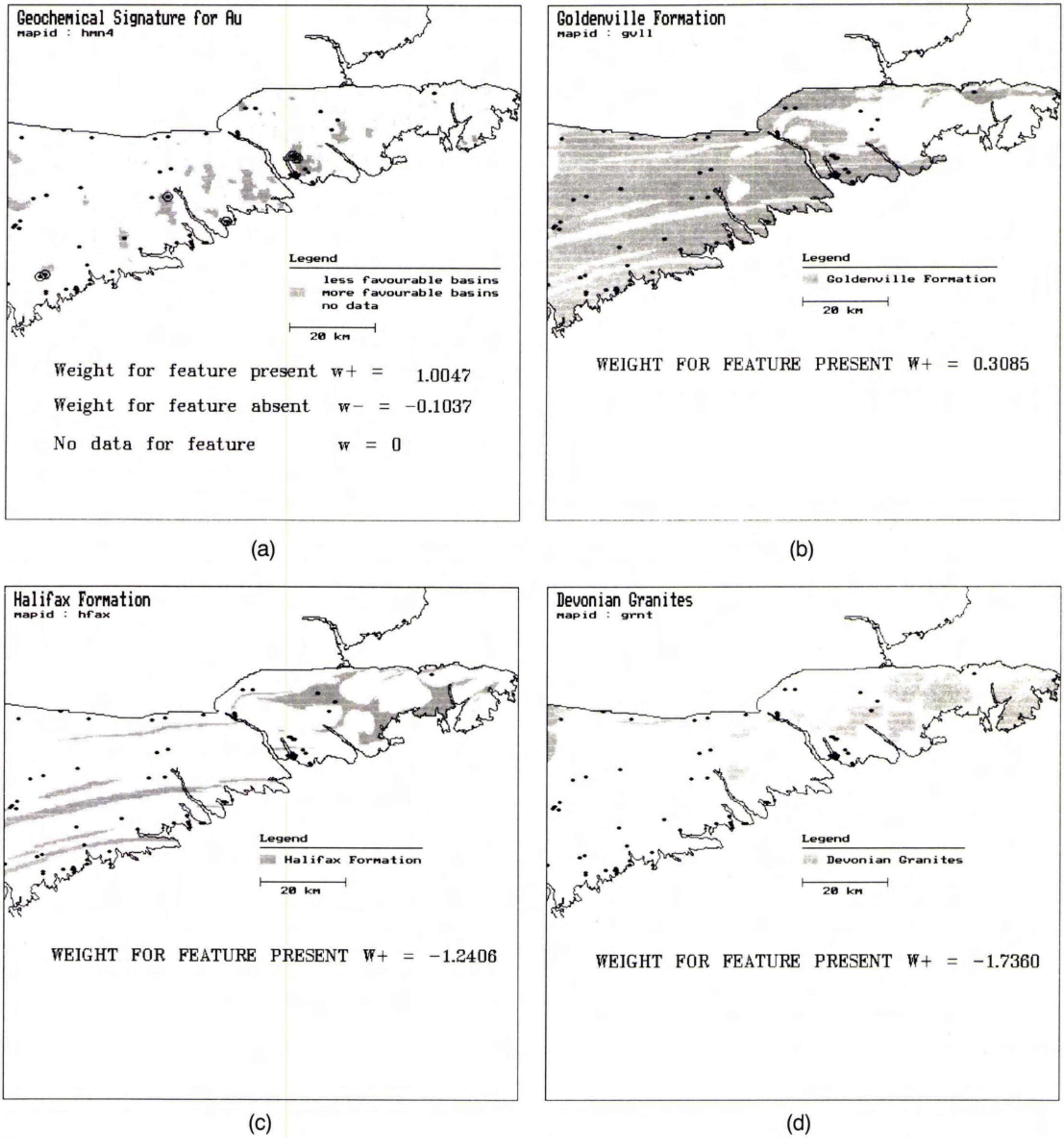

FIG. 2. Map patterns used to predict gold (Au) occurrences. Black dots show locations of known gold occurrences. (a) Geochemical signature. Note that, outside the catchment basins, the signature is unknown. (b) Goldenville Formation. (c) Halifax Formation. (d) Devonian Granites.

olded to a binary pattern. Several cutoff thresholds were tried, as discussed in Agterberg *et al.* (in press), to maximize ($W^+ - W^-$). The coastline, fault contact, and limit of lake catchment areas were displayed as vector overlays.

Figures 2b, 2c, and 2d show the mapped areas of the three bedrock units. These three patterns are mutually exclusive, and together cover the whole study area. As a consequence, no W^- weights were used, as shown in Table 3, although it is to be noted that the W^+ weights can actually be negative.

Figure 3 shows four different types of corridor map patterns. In each case, successive corridors were created around a vector feature, at intervals of 0.25 km out to 5 km. Optimal cutoffs

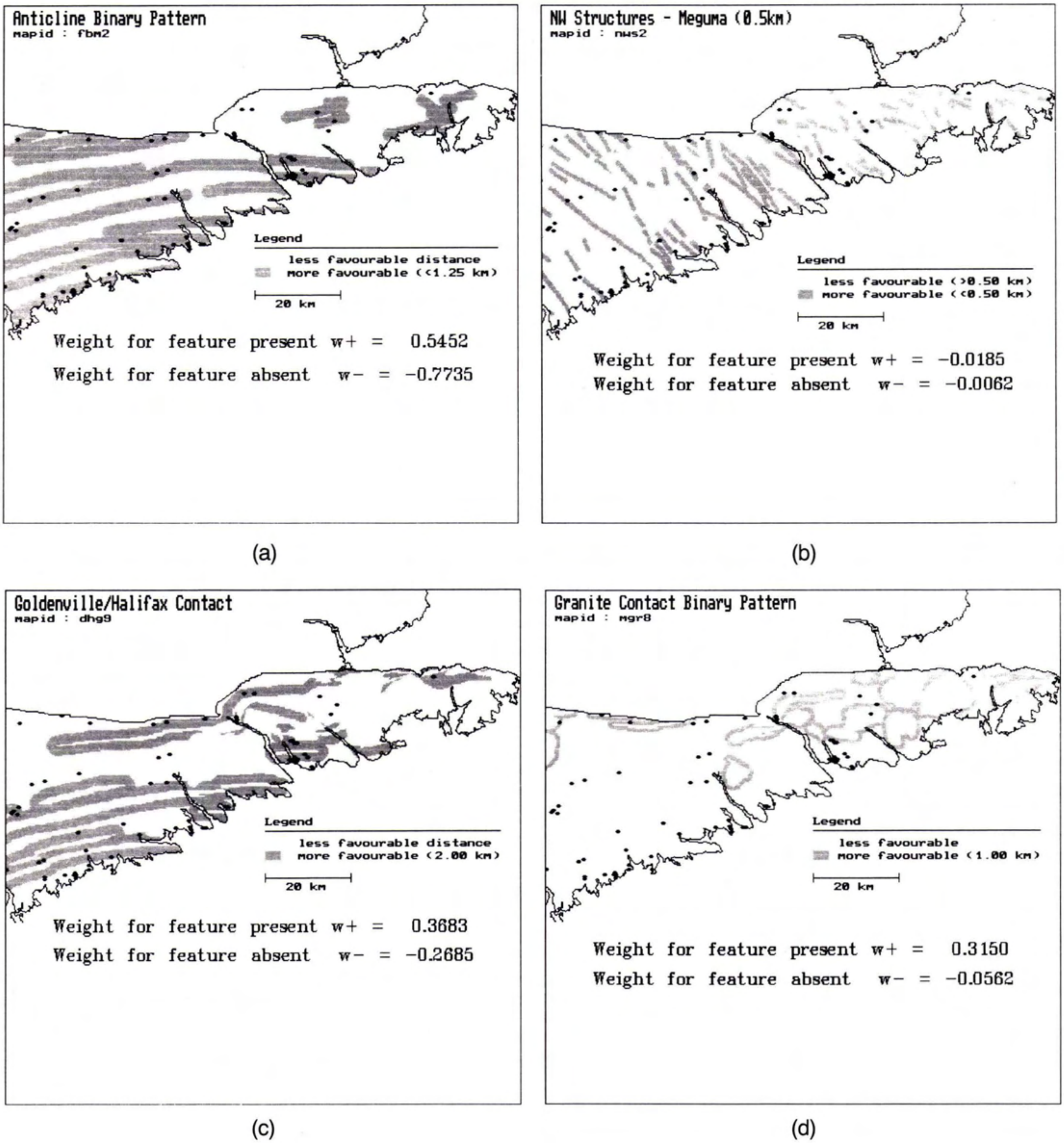

FIG. 3. Map patterns used to predict gold occurrences, based on corridor neighborhoods round a linear feature. Black dots show locations of known gold occurrences. (a) Anticline axes with corridors. (b) N.W. lineaments with corridors. (c) Goldenville-Halifax contact with corridors. (d) Granite contact with corridors.

(Table 3) were calculated by finding the distance at which ($W^+ - W^-$) was maximized, as shown in Agterberg *et al.* (in press).

Finally, the map of P_{post} was generated (Figure 4). The program was set up with interactive prompts so that several alternatives could be tried experimentally, omitting one or more maps to evaluate the robustness of the results to changes in the assumptions of the model.

From the weights in Table 3, it is clear that the presence of

TABLE 2. REGRESSION COEFFICIENTS[1] AND THEIR STANDARD ERRORS GIVING THE MULTI-ELEMENT GEOCHEMICAL SIGNATURE THAT BEST PREDICTS GOLD DEPOSITS.

Element	b	S.E.b
Au	0.196	0.021
As	0.009	0.009
W	0.037	0.029
Sb	0.005	0.022
Constant	0.128	0.024

[1]Stepwise regression was used resulting in the selection of four out of the original 16 elements, from Wright *et al.* (1988).

TABLE 3. WEIGHTS FOR MODELING POSTERIOR PROBABILITY OF A GOLD DEPOSIT OCCURRING IN A 1 KM^2 AREA

Map Pattern	W^+	W^-
N.W. Lineaments	−0.0185	−0.0062
Anticline axes	0.5452	−0.7735
Geochemical Signature	1.0047	−0.1037
Goldenville-Halifax Contact	0.3683	−0.2685
Granite Contact	0.3419	−0.0562
Bedrock geology[1]		
Halifax Formation	−0.2406	–
Goldenville Formation	0.3085	–
Granite	−1.7360	–

[1]A ternary pattern where units are mutually exclusive, and no negative weights are used.

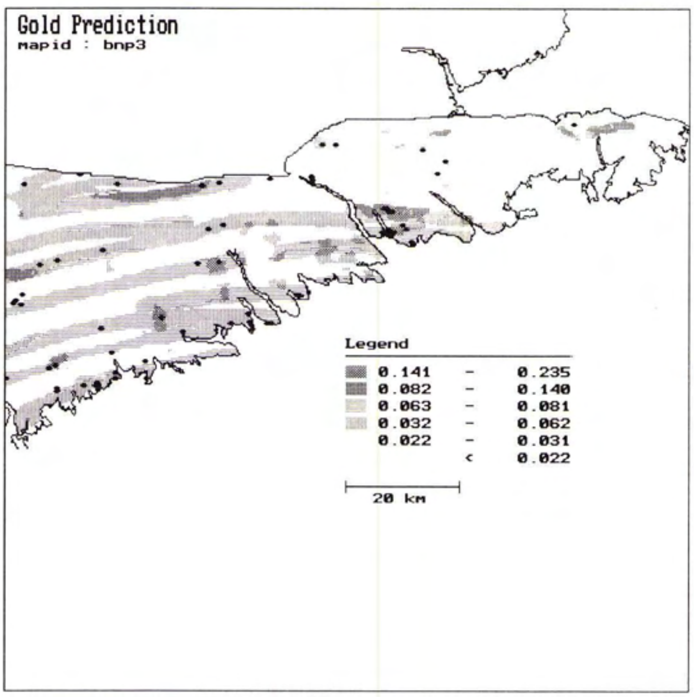

FIG. 4. Map of *a posteriori* probability of a gold deposit occurring in a 1 km^2 area. Black dots show locations of known gold occurrences.

granite strongly downweights the probability of gold mineralization, whereas the presence of the favorable geochemical signature and proximity to anticlinal axes are strong positive factors. The presence of the Goldenville Formation, particularly where in close proximity to the Halifax contact, is moderately favorable. The proximity to granite and proximity to northwest lineaments have little effect on the probability map, at least in the study area.

DISCUSSION

This study could have been carried out using a mix of existing computer programs for image analysis and statistical analysis. However, the advantages of using a GIS were

- relative ease of importing diverse map inputs, and creating a co-registered database;
- ability to move between GIS and other DOS-compatible software packages;
- interactive graphics capability, with windowing, map overlays, and vector overlays permitting experimentation not previously practical;
- integration of corridor generation, unique conditions mapping, area analysis, and modeling; and
- the browse feature, which is very useful for keeping track of both the development and final stages in a data integration project.

CONCLUSIONS

Spatial data integration for mineral resource assessment and exploration using digital databases is greatly facilitated using a GIS in association with other software. Advanced GIS packages may provide breakthroughs which will bridge the gap between the traditional manual overlay approach and mathematical methods using multivariate statistics and image analysis. The method of combining map patterns using Bayesian statistics is practical and intuitively appealing because it is closer to the "seat-of-the-pants" approach of the exploration geologist than are statistical regression methods. In the Nova Scotia example, the map showing probability of gold mineralization indicates several areas of favorable mineral potential, with no known occurrences. Although the predicted gold map is useful itself, the real benefit of this study for an assessment of gold potential in Nova Scotia would derive from geologists performing their own integration experiments, given the database and the GIS with which to manipulate the data.

A forthcoming paper (Agterberg *et al.*, in press) discusses the problem of estimating uncertainty of the probability estimates, and using a goodness-of-fit test for the assumption of conditional independence. Uncertainty is due to many factors, but two important sources of error are associated with the estimates of the weighting factors, and with the incomplete coverage of one or more data layers.

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GLOSSARY OF SPANS TERMS

Area Analysis - An operation which produces a table of areas for each map class. Two-map area analysis produces a two-way table of areas of class overlaps.

Browse File - A directory of screen images saved in compact form directly from the graphics board. Can be re-ordered and re-displayed quickly.

Equation.inp - Text file containing statements to control modeling and classification of maps. Created by the operator using a text editor.

Potential Mapping - A series of functions used for interpolation of point data.

Point Result - Used in conjunction with a statement in Equation.inp, this operation adds one or more attribute columns to a point file, indicating the attribute value of one or more maps at point locations.

Point Sample - Operation to generate new set of points on a grid with a pre-set spacing. Points may be confined to selected themes. Used in conjunction with point result to "resample" a series of maps on a regular grid and produce an attribute file.

Quad level - Defines the pixel resolution of a specific map layer. The minimum pixel size in metres is determined by dividing the width of the universe in metres by 2 raised to a power equal to the quad level. Usually in the range of 9 to 12; must be ≤ 15.

Quadtree - A raster data structure that uses a variable pixel size, depending on the spatial homogeneity of the image. Efficient for data compression of thematic maps, and allows for fast search of the database with Morton coordinates — a referencing system that uses quad level and quad position.

Unique Conditions - An operation which produces a map where the polygons are defined by the overlap combinations of up to 15 selected input maps. Used for modeling operations.

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Forthcoming Articles

F. J. Ahern and *J. Sirois*, Reflectance Enhancements for the Thematic Mapper: An Efficient Way to Produce Images of Consistently High Quality.

Michael H. Brill and *James R. Williamson*, Multi-Sensor DLT Intersection for SAR and Optical Images.

Christopher W. Brown, *Daniel L. Civco*, and *William C. Kennard*, Adaptation of a Hand-Held Radiometer for Measuring Upwelling Radiance in the Aquatic Environment.

Jack Bryant, On Displaying Multispectral Imagery.

Pat S. Chavez, Jr., Use of the Variable Gain Settings on SPOT.

Pat S. Chavez, Jr. and *Jo Ann Bowell*, Comparison of the Spectral Information Content of Landsat Thematic Mapper and SPOT for Three Different Sites in the Phoenix, Arizona Region.

Pat S. Chavez, Jr., and *Andrew Yaw Kwarteng*, Extracting Spectral Contrast in Landsat Thematic Mapper Image Data Using Selective Principal Component Analysis.

Liping Di and *Donald C. Rundquist*, Color-Composite Image Generation on an Eight-Bit Graphics Workstation.

S. A. Drury and *G. A. Hunt*, Remote Sensing of Laterized Archaean Greenstone Terrain: Marshall Pool Area, Northeastern Yilgarn Block, Western Australia.

Thomas D. Frank, Mapping Dominant Vegetation Communities in the Colorado Rocky Mountain Front Range with Landsat Thematic Mapper and Digital Terrain Data.

Tuomas Häme and *Markku Rantasuo*, Shuttered Camera — Aerial Color Video Imaging in the Visible and Near Infrared.

James A. Henry, *Steven E. Dicks*, *Organ F. Wetterqvist*, and *Stephen J. Roguski*, Comparison of Satellite, Ground-Based, and Modeling Techniques for Analyzing the Urban Heat Island.

Susanne Hummer-Miller, A Digital Mosaicking Algorithm Allowing for an Irregular Join "Line."

Larry R. G. Martin, Accuracy Assessment of Landsat-Based Visual Change Detection Methods Applied to the Rural-Urban Fringe.

Peter A. Murtha and *Raoul J. Wiart*, Cluster Analysis of Pine Crown Foliage Patterns Aid Identification of Mountain Pine Battle Current-Attack.

Paul G. Pilon, *Philip J. Howarth*, *Ronald A. Bullock*, and *Peter O. Adeniyi*, An Enhanced Classification Approach to Change Detection in Semi-Arid Environments.

Scott M. Rae, Alternative Methods of Determining the Orientation of a Stellar Camera (Bausch & Lomb Graduate Award).

Urho A. Rauhala, Compiler Positioning System: An Array Algebra Formulation of Digital Photogrammetry.

Urho A. Rauhala, *Don Davis*, and *Ken Baker*, Automated DTM Validation and Progressive Sampling Algorithm of Finite Element Array Relaxation.

Yang Shiren, *Li Li*, and *Gao Peng*, Two-Dimensional Seam-Point Searching in Digital Image Mosaicking.

J. Sneddon and *T. A. Lutze*, Close-Range Photogrammetric Measurement of Erosion in Coarse-Grained Soils.

E. Lynn Usery and *R. Welch*, A Raster Approach to Topographic Map Revision.

H. D. Williamson, The Discrimination of Irrigated Orchard and Vine Crops Using Remotely Sensed Data.

James R. Williamson and *Michael H. Brill*, Dominant Geometry Combinations of Two- and Three-Point Perspective in Close-Range Applications.