New mineral potential mapping methodology for Yukon: Case studies from the Beaver River and Dawson regional land use planning areas

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Abstract

Territory-wide mineral potential mapping in Yukon was last conducted 18 years ago. An updated suite of maps for land use planning is, therefore, necessary. Yukon Geological Survey has developed a new GIS-based mapping process for this purpose. Industry-based applications using the new method will be developed going forward.

The approach makes use of mineral system components that potentially contribute to metal accumulations in an area. The method is a hybrid between a classic data-driven probabilistic approach and an expert-driven fuzzy logic approach. It is non-specific in terms of commodity and/or deposit type–however, the claim and assessment report footprint data that are integral to the mapping process capture these important components.

The procedure makes use of block modeling techniques where each block is assigned a prospectivity and (bedrock mapping) confidence score. Calculations are based on the presence or absence of categorical features within unit cells, and the scores represent the posterior favourability of each cell. Evidential layers are weighted according to buffer distance and/or through the application of knowledge-based factors. Lithology classes are factored using a multiclass weights-of-evidence approach.

Mineral potential and confidence scores are converted to either a 1, 2 or 3 according to a defined mathematical schema. The values are then combined–blocks with scores of 1:1 have the lowest mineral potential/lowest confidence whereas blocks with scores of 3:3 have the highest mineral potential/highest confidence. Nine possible combinations exist. Mineral potential maps containing measures of both potential and confidence are generated based on the cumulative contrast values.

Areas cut by major structures along which significant displacement has occurred need to be evaluated separately, and then stitched back together at the end of the assessment process. Concurrently, the mineral potential data need to be levelled to account for prospectivity differences across the structure concerned.

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Introduction

After a five-year hiatus, the Yukon Government is getting back into land use planning. The Beaver River watershed and Dawson regional land use plans (BRLUP and DRLUP, respectively; Fig. 1) are currently underway. The BRLUP was initiated in response to a proposal from ATAC Resources for the construction of an all-season, single-lane tote road from the existing Hanson Lakes road to the Tiger deposit located on the Rau property. The original completion date for the BRLUP was March 31, 2020; however, the date has been pushed back to November 2020.

Land use planning for the Dawson region commenced in 2011 but was suspended in 2014. During this time, the commission consulted on, and drew up, a comprehensive resource assessment report, generated a number of plan alternatives, and commenced work on a draft land use plan. Planning recommenced in early 2019 with the establishment of a new commission. The (revised) terms of reference of the reconstituted commission call for the completion of a Recommended Plan by March 2021 and a Final Recommended Plan by September 2021.

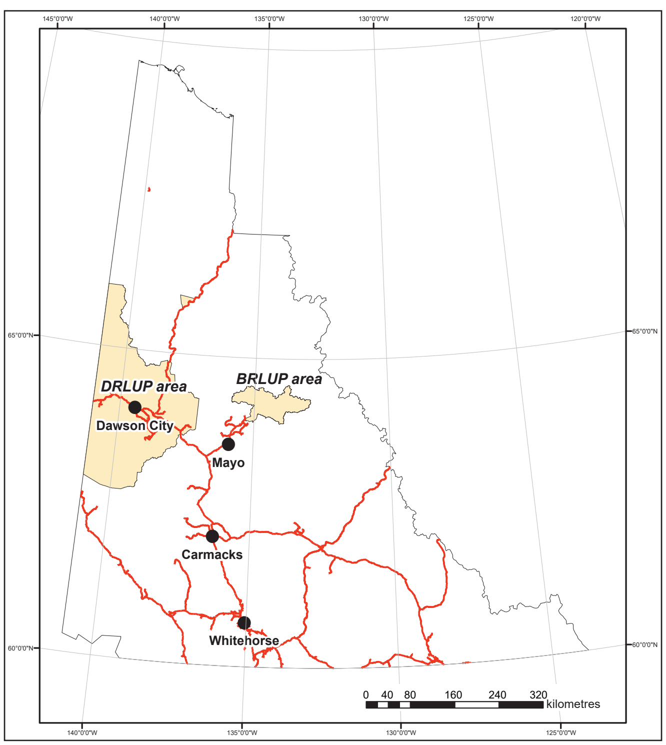

Figure 1. *Map of Yukon illustrating the boundaries of the BRLUP and DRLUP areas.*

Mineral potential mapping in Yukon

Previous mapping

Territory-wide mineral potential mapping for Yukon was last carried out over the period 1999 to 2001 (Bradshaw and VanRanden, 2003). The mapping was conducted using a quantitative method for prediction of undiscovered deposits developed by the United States Geological Survey (USGS) and first described by Singer (1993). Popularly known as the "three-part method for quantitative mineral resource assessment", it is based on mineral deposit models described by Cox and Singer (1986) and their probability of being hosted in a particular geological environment. To better accord with the metallogenic setting of the southern Canadian Cordillera (Lefebure and Ray, 1995; Lefebure and Hoy, 1996) the mineral deposit models used for the Yukon assessment were modified and added to by the British Columbia Geological Survey. To ensure all deposits in the territory were incorporated (Fonseca and Bradshaw, 2005) further modifications were made to the deposit models for the Yukon assessments.

Systems-based mineral potential mapping

Earlier mineral potential maps are now considered dated given advances in both Yukon Geological Survey (YGS) work and industry exploration. An updated suite of maps is, therefore, necessary for land use planning in the territory to ensure decisions are based on the most current data available, particularly in respect of the pending BRLUP and DRLUP. Furthermore, to be effective, design of the mineral potential maps should resonate with land use planning stakeholders. This is important as overly complicated representations of mineral potential data, or maps that do not appear spatially logical to land use planners, may not gain the necessary traction in the land use planning process.

Mineral potential maps of the territory should:

1. Be simple, easy to understand and easy to relate to.
2. Minimize subjective input to the extent possible.
3. Be based primarily on actual rather than hypothesized data. In practice, this means moving

away from the three-part, deposit model-based method where the primary inputs are subjective estimations of mineral occurrence probability. Mineral potential mapping for land use planning should, in any event, not focus on deposit models as their predictive power is limited at larger scales (McCuaig and Hronsky, 2014), as required by land use planners. Deposit models focus on features at the deposit scale with the deposit model approach ascribing equal probability to the presence of deposits of all possible sizes in a geologically favorable tract. Additionally, the evidence suggests that larger mineral deposits tend to be discovered first with later discoveries being smaller in size (Ellefsen, 2019). According to Ellefsen, such "size biased" sampling may have "adversely affected the resource predictions of previous U.S. Geological Survey assessments that were conducted with the three-part method". There are other potential problems with using deposit types for mineral potential mapping:
   a. missing deposits or generating "false positives" given too strict a focus on the analogue;
   b. the ongoing generation of additional model variations for the same commodity as new deposits in different settings are discovered; and
   c. the inability of deposit models to distinguish large and/or high quality occurrences from small and/or low quality ones (McCuaig and Hronsky, 2014).
4. Differentiate between mineral potential categories in a clear, transparent, and mathematically defined manner.
5. Contain mathematically defined measure(s) of confidence in relation to the mineral potential categories in order to facilitate land use planning decisions.
6. Be presented as a single map to avoid confusion.

To this end, YGS has developed a generalized mineral system approach to prospectivity mapping for land use planning. The process is based on actual data, and while the amount, quality and vintage of data in different parts of Yukon varies, the fundamental principles utilized in prospectivity mapping going forward will remain the same to ensure uniformity and consistency of output.

The generalized mineral system approach adopted by YGS makes use of mineral system components that may contribute to the development of metal accumulations in an area, in this case the area in which land use planning activities are taking place. Although conceptually similar to the mineral systems-based exploration targeting approach advocated by McCuaig and Hronsky (2014), the YGS method has been explicitly designed to accommodate land use planners in the territory. It is non-specific in terms of commodity (suite) and/or deposit type continuums, hence the generalized designation. These important components are fully captured, however, in the Placer/Quartz claim and assessment report footprint data that is integral to the mapping process. YGS has embarked on the process to develop the method such that the focus shifts to private sector applications. Commodity suite and deposit type continuums, together with newly developed features, will form an important component of these applications.

Wyborn *et al.* (1994), in a seminal paper, defined mineral systems as "all geological factors that control the generation and preservation of mineral deposits, and stress the processes that are involved in mobilizing ore components from a source, transporting and accumulating them in a more concentrated form and then preserving them throughout the subsequent geological history". The authors list the important controlling geological factors as sources of mineralizing fluids and transporting ligands, sources of metals, fluid migration pathways, energy sources and thermal gradients, focusing mechanisms (mechanical/structural), and precipitation mechanisms (chemical/physical).

Mineral potential mapping for land use planning in Yukon makes use of the above factors and incorporates additional criteria relevant to the prospectivity of the area concerned:

1. the occurrence and spatial distribution of known mineral deposits/mineralization;
2. aeromagnetic geophysical data;
3. claim data (Placer and Quartz, current and historical), the rationale being that resource companies stake ground deemed, after careful study, to be prospective for the minerals being sought. Companies also take practical (*i.e.*, economic) and political (*i.e.*, prevailing and probable future sentiment around commodity type) considerations into account when staking ground;

4. assessment report footprints, in order to highlight areas lying within claim boundaries that are considered more prospective than the claim as a whole; and
5. stream sediment sample data, the rationale being that watersheds upstream of anomalous sample data are potentially prospective for the metal(s) concerned.

The assessments use geophysical data, in the form of airborne magnetics, primarily implicitly–in the sense that other inputs, (faults, folds, bedrock contacts) are based on/corroborated by this information. The airborne magnetic data however, is used explicitly to assess the possible extent of the influence of plutonic intrusions on surrounding rocks.

New mapping principles employed by YGS

Mineral potential maps have been completed for the BRLUP and DRLUP areas using ArcGIS. The maps are based on quantifiable, spatially referenced categorical features buffered and/or weight-factored as required using a knowledge-based approach. The process is iterative in nature and relies on existing rather than hypothetical data.

The procedure makes use of block modeling techniques where each block (unit cell) is assigned a prospectivity score and, separately, a confidence score. Scores are calculated based on the presence or absence of categorical features within unit cells and represent the posterior favourability of each unit cell relative to other unit cells. The posterior favourability refers to mineral potential and confidence scores after all evidence has been taken into account. Evidential layers are weighted according to buffer distance and/or through the application of knowledge-based factors. Lithology classes are an exception–these features are factored using a multiclass weights-of-evidence (WofE) approach with known mineral deposits used as training points.

The process thus differs to pure data-driven mineral prospectivity mapping, where known mineral deposits are used to establish the relative importance each input (evidential) layer plays in the outcome. In data-driven mapping, the "weight" of each input layer is established using the spatial relationship between mineral deposits, referred to as the training population or data set, and evidential map features. Mineral potential maps generated by YGS, on the other hand, are based on cumulative contrast values (*i.e.*, the relative, between-block, prospectivity and confidence score totals).

The method is somewhat of a hybrid between a classic data-driven probabilistic WofE approach (which uses a binary value assessment, *i.e.*, 0/1) and an expert-driven fuzzy logic approach, the latter providing the advantage of allowing the user to assign a membership value anywhere between 0 and 1 (*i.e.*, 0, 0.01, 0.02,...0.98, 0.99, 1) for any predictive input parameter. This also allows for the integration of continuous data where, for example, the weighted importance of 'buffer' distance from a certain feature may be expressed in numerical terms.

While some similarities exist between data/knowledge-driven mapping methodologies and the mineral potential assessment process adopted by YGS, the YGS approach differs in a number of key respects and has been designed to fulfil a different function. The process does not rely, in contrast to standard WofE mapping, on training data, which may be lacking in less well-mapped/explored areas. A second important advantage is that the process is independent of the number of parameters (categorical features) entered. Parameters may vary from one (in theory) to as many as might be deemed relevant by the user. The resulting output is fundamentally useful irrespective of the number of parameters used; standard mineral prospectivity mapping methodologies can also generate output from just one or two predictor maps, although the results from such an exercise tend to be inaccurate and of limited use. A third difference relates to practicality and ease of use, and the fact that the method is dynamic–*i.e.*, new/revised/updated spatial data can be input as soon as it becomes available and the mineral potential map updated at short notice. Finally, the method itself does not require the generation of complex models or processing steps, and as such can be used by anyone with a moderate understanding of GIS software. However, expert knowledge is required to generate meaningful outcomes and this input is integral to the entire process.

Factors and buffers are an important fuzzy logic (*i.e.*, non-Boolean) component of the mineral potential mapping process. The choice of buffer distance in the case of point, line (and less commonly polygonal) data, and the selection of weighting factors in the case of polygonal data, is critical to a successful outcome. Expert input is key in this respect.

New mapping methodology

Mineral potential and confidence

The YGS has a detailed procedure for determining mineral potential. The steps involved are laid out in order below. Several of the steps are iterative, and some of the inputs, while adequate, are known to be imperfect–notably with regard to confidence. This aspect will be improved on in future maps.

1. All available geological information pertaining to the area of interest (AOI) is captured in a standard GIS environment either as polygons (e.g., favorable host lithology, zones of hydrothermal alteration, watersheds), polylines (e.g., thrusts, faults, fold axes) or points (e.g., mineral deposits). As noted above, the procedure is independent of the amount of geological information available. However, quality of information is critical and data, as it pertains to mineral systems, is considered key.
2. The AOI includes the assessment area itself (*i.e.*, the BRLUP and DRLUP areas) plus a zone around it that may have a bearing on the mineral potential within the planning area. An exception occurs when planning boundaries are coincident with Yukon borders, an example being the western margin of the DRLUP area that marks the boundary between Yukon and Alaska.
3. The AOI is then subdivided into blocks of equal size using an ArcGIS fishnet overlay–a 2 by 2 km polygon grid was used in the BRLUP and DRLUP areas (Fig. 2). The grid forms the basis for the computational process so it is important that grid dimensions are neither too large (will cause excessive smoothing of the mineral potential scores) or too small (results in very long computational times without meaningful enhancements to the overall mineral potential profile of the AOI). The underlying logic to the gridding process is a follows:
   a. if the AOI is encompassed by a single grid square, then the mineral potential of the AOI will be represented by a single score (the overall or average mineral potential) and the entire area will be, for example, highly prospective, moderately prospective, etc. Such a map would be of no use to land use planners, as they must be able to distinguish between areas of differing mineral potential to be able to make decisions;
   b. subdividing the AOI into four grid squares, for example, has no effect on the overall mineral potential, but results in contrasting scores for each of the four blocks. While there is a non-linear relationship between the four mineral potential scores, the overall score remains static; and

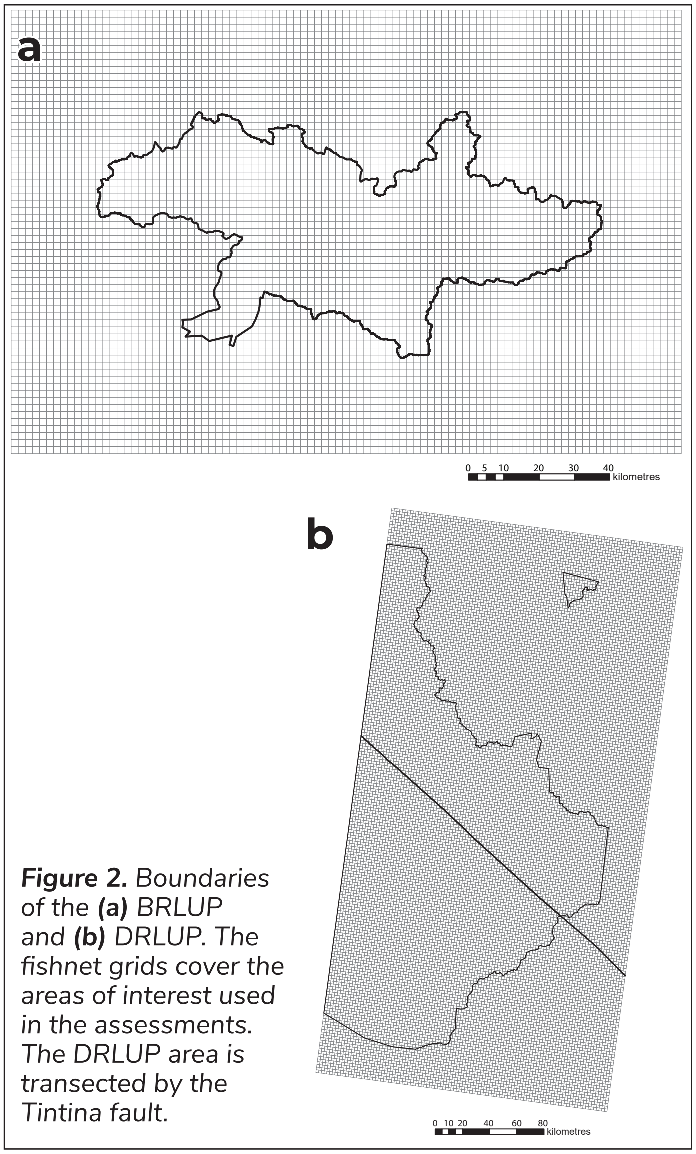

Figure 2. *Boundaries of the **(a)** BRLUP and **(b)** DRLUP. The fishnet grids cover the areas of interest used in the assessments. The DRLUP area is transected by the Tintina fault.*

c. continued subdivision of the AOI into smaller and smaller grid squares results initially in more detailed and practically useful prospectivity scores. However, once the block size drops below a certain threshold, prospectivity scores in areas of similar potential start to repeat themselves as the contrast between the data elements informing those scores becomes less pronounced.

Different grid sizes were applied to the Beaver River watershed to assess the impact of cell size variation on prospectivity score maxima and the average number of categorical elements used to calculate block potential. The following grid sizes were applied: 8 × 8 km, 7 × 7 km, 6 × 6 km, 5 × 5 km, 4 × 4 km, 3 × 3 km, 2 × 2 km, 1 × 1 km, 500 × 500 m and 250 × 250 m. The following metrics were used to quantify the impact:

a. the ratio of the highest block score to the lowest for each grid size; and
b. the between grid differences of the average of the number of elements used to calculate each cell's prospectivity score divided by that cell's block score.

Figure 3 depicts the outcome.

For block score ratios, there is a natural break in values at a grid size of 3 km, at which point the ratios increase markedly. The scores level out again, at a significantly higher level, at a grid size of 1 km. For the average of the number of elements divided by the block potential metric there is a natural break at a grid size of 2 km with values appearing to level out below 1 km. Based on these metrics, a 2 × 2 km grid size was chosen. It is suggested, however, that a 1 × 1 km grid might be more applicable for smaller-scale industry-sector targeting purposes. In any event, grid sizes below 1 km require excessive computational times making their use impractical from both a land use planning and targeting perspective.

4. Data are simplified to facilitate the assessments. For example, for the BRLUP area, bedrock geology was "dissolved" into similar lithologic/stratigraphic units, and unnamed, but clearly contiguous, fault segments were extrapolated, where necessary, into major (named) faults so that these structures were continuous. For the Dawson region, rock types were simplified and grouped based on rock class and subclass (the "Rock_CLASS" and "ROCK_SUBCL" fields, respectively, in the bedrock geology ArcGIS table; Table 1).

5. All point and line data are buffered to varying degrees in line with standard mineral potential mapping procedures (e.g., Porwal, 2006; Harris, *et al.*, 2001; Schmitt, 2010). This is important because while this data is effectively dimensionless

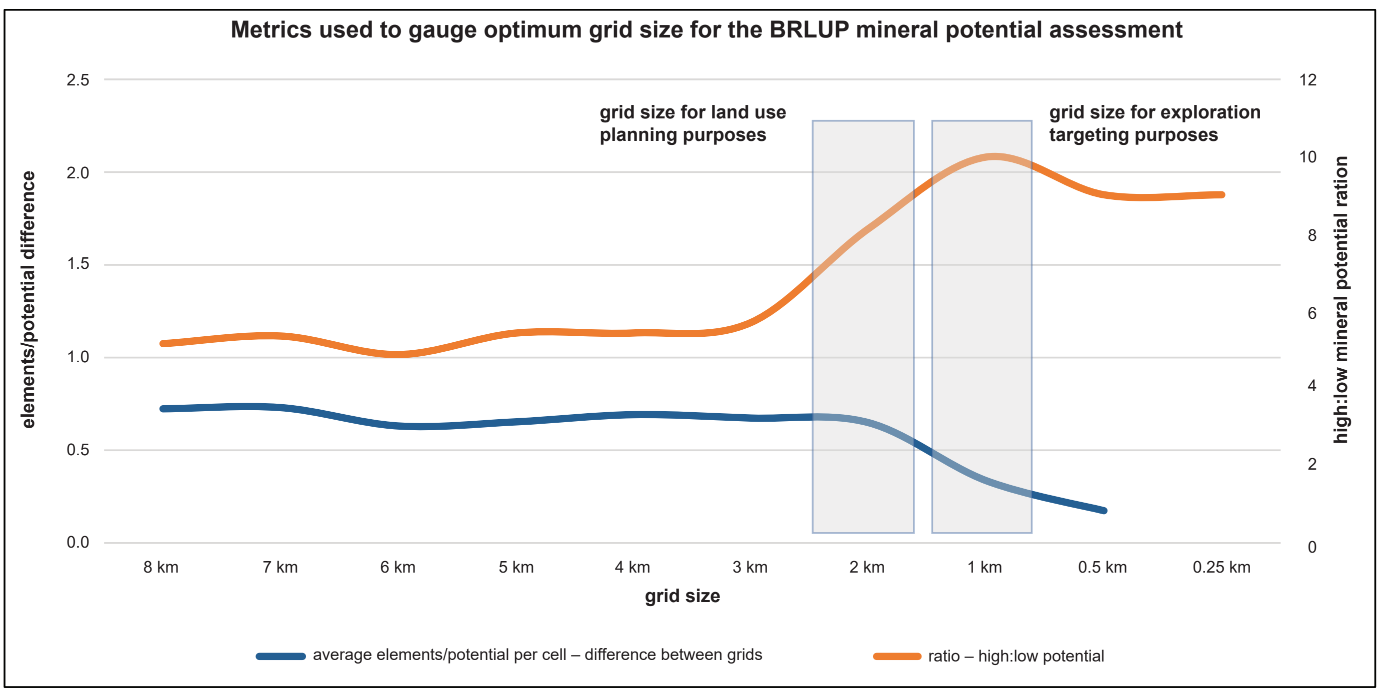

Figure 3. *Graph illustrating the ratio of the highest/lowest block scores for each grid size, and the between grid differences of the average of the number of elements used to calculate each cell's mineral potential score divided by that cell's score.*

Table 1. *Simplified bedrock geology for the BRLUP* ***(top)*** *and DRLUP* ***(bottom)*** *areas.*

Stratigraphic/lithologic simplification	Rock unit(s)
Cretaceous granite intrusions	LKM?, mKM
Phanerozoic volcanic/plutonic rocks	CSM, TrG
Phanerozoic sandstone/siltstone	TrJ, ImCS, PCB
Phanerozoic limestone/dolostone	CDB, CH, DB, DG, ICI, ICS, OSK, PJC, uCT
Phanerozoic shale ± other seds	CPMC, CT, DME, ICG, ODR
Proterozoic sandstone/shale/limestone	PCH
Proterozoic diorite/gabbro	mPH
Proterozoic black shale	IPQ, uPFI, uPS
Proterozoic siltstone/conglomerate	uPCI, uPP, uPR
Proterozoic limestone/dolostone	IPG, uPB, uPG, uPH, uPHC, uPN, uPRi

Rock class	Rock subclass
Sedimentary	Clastic
	Carbonate
	Clastic/carbonate
	Clastic/carbonate/chert
Volcanic	Hydrothermal
	Felsic/intermediate
	Mafic/ultramafic
Plutonic	Felsic/intermediate
	Intermediate/mafic
	Mafic/ultramafic
Metamorphic	Carbonate
	Clastic
	Mixed igneous/sedimentary
	Volcanic felsic/intermediate
	Volcanic mafic/ultramafic
	Plutonic felsic/intermediate
	Plutonic mafic/ultramafic

it has a strong influence on potential mineralization in 3D-space. The extent of buffering depends on the perceived mineral system "weight" of the data element concerned. For example, in the case of mineral deposits, the buffer distance is based on deposit status (Table 2). Once completed, all point and line data are represented as polygons, the relative size of each class feature component being a function of its perceived importance vis-à-vis the mineral system concept.

6. Factors are applied to polygonal data if deemed necessary to account for the perceived "weight" of the various class feature components relative to mineral systems generally (in certain instances) and critically, to each other. For example, for the Beaver River area, lithology/stratigraphic bedrock geology "packages" were weighted (factored) downwards or upwards depending on, among other things, their perceived favorability for mineralization, possible source of metals, heat engines, etc. For the Dawson region, rock subclasses were assigned a factor using a multiclass WofE approach, with known mineral occurrences used as training data. A unit cell size of 4 km^2 was used, equivalent to the fishnet grid size, with each deposit assumed to occupy one cell.

   Calculation of quantities used to estimate the WofE were as follows:

   a. Number of cells in the AOI occupied and not occupied by a deposit.
   b. Number of cells occupied and not occupied by each rock subclass.
   c. Number of cells within each rock subclass occupied and not occupied by a deposit.
   d. Number of cells outside each rock subclass occupied and not occupied by a deposit.

   W^+ and W^- pairs for each class feature (*i.e.*, rock subclass) were estimated using Bayes' theorem (*e.g.*, Harris, *et al.*, 2001; Porwal, 2006). For each class feature, positive weights indicate that more deposits are associated with the class than simply due to chance, with the inverse applying to negative weights (Raines, *et al.*, 2000).

   Contrast values, *i.e.*, $W^+ - W^-$, were calculated for each class feature. This metric provides an overall measure of the spatial association between the rock subclass and mineral deposits. The contrast values were converted to a standardized normal distribution and factors were determined based on the deviation of the normalized contrast value from the mean (ranging from 1.5 for deviations greater than +2 standard deviations (StDev) to 0.5 for deviations less than −2StDev; Table 2).

Table 2. *Class elements, factors and buffers used in the BRLUP and DRLUP mineral potential assessments.*

Dawson region

	Rock subclasses*		Factor	Buffer	Rationale
north of Tintina fault	Felsic to intermediate, igneous plutonic rocks of Jurassic age and younger		1	4000 m	Estimate of potential influence of intrusion away from contact from aeromagnetic surveys.
	Sedimentary	Carbonate	0.9	none	Using a multiclass WofE approach (see text for explanation), factors determined as follows:
					StDev > 2.0 = 1.5
		Clastic	0.8		1.5 < StDev ≤ 2.0 = 1.4
		Clastic/carbonate	0.8		1.0 < StDev ≤ 1.5 = 1.3
		Clastic/carbonate/chert	0.9		0.5 < StDev ≤ 1.0 = 1.2
	Volcanic	Hydrothermal	1.3		0.0 < StDev ≤ 0.5 = 1.1
		Felsic/intermediate	0.6		-0.5 < StDev ≤ 0.0 = 0.9
		Mafic/ultramafic	0.9		-1.0 < StDev ≤ -0.5 = 0.8
	Plutonic	Felsic/intermediate	1.3		-1.5 < StDev ≤ -1.0 = 0.7
		Intermediate/mafic	1.3		-2.0 < StDev ≤ -1.5 = 0.6
		Mafic/ultramafic	1.2		-2.0 > StDev = 0.5
south of Tintina fault	Felsic to intermediate, igneous plutonic rocks of Jurassic age and younger		1	4000 m	Estimate of potential influence of intrusion away from contact from aeromagnetic surveys.
	Sedimentary	Clastic	1.1	none	Using a multiclass WofE approach (see text for explanation), factors determined as follows:
	Volcanic	Felsic/intermediate	0.8		StDev > 2.0 = 1.5
		Mafic/ultramafic	0.9		1.5 < StDev ≤ 2.0 = 1.4
	Plutonic	Felsic/intermediate	1.1		1.0 < StDev ≤ 1.5 = 1.3
		Mafic/ultramafic	0.9		0.5 < StDev ≤ 1.0 = 1.2
	Metamorphic	Carbonate	0.7	none	0.0 < StDev ≤ 0.5 = 1.1
		Clastic	0.9		-0.5 < StDev ≤ 0.0 = 0.9
		Mixed igneous/sedimentary	1.4		-1.0 < StDev ≤ -0.5 = 0.8
		Volcanic felsic/intermediate	0.9		-1.5 < StDev ≤ -1.0 = 0.7
		Volcanic mafic/ultramafic	1.1		-2.0 < StDev ≤ -1.5 = 0.6
		Plutonic felsic/intermediate	0.8		-2.0 > StDev = 0.5
		Plutonic mafic/ultramafic	1.4		

Beaver river watershed

Stratigraphy/lithology	Factor	Buffer	Rationale
Cretaceous granite intrusions	1	5000 m	Width of Rau intrusive contact aureole as mapped.
Phanerozoic volcanic/plutonic rocks	1.1	None	Estimated relative importance to mineralizing process (observational/knowledge-based).
Phanerozoic sandstone/siltstone	0.5		
Phanerozoic limestone/dolostone	1.5		
Phanerozoic shale ± other seds	1.3		
Proterozoic sandstone/shale/limestone	1		
Proterozoic diorite/gabbro	1.1		
Proterozoic black shale	1.3		
Proterozoic siltstone/conglomerate	0.3		
Proterozoic limestone/dolostone	1.5		

Beaver River watershed and Dawson region

Deposit type	Buffer	Rationale
Past producer/producer	2000 m	Estimated relative importance of categorical features
Deposit	1000 m	
Anomaly/drilled prospect/prospect	500 m	
Showing	250 m	
Staked – no work recorded/Unknown	100 m	

Beaver River watershed and Dawson region

Fault category	Buffer	Rationale
Tintina	2000 m	Estimated relative importance of categorical features
Major	1000 m	
Minor	500 m	

Beaver River watershed

Fold category	Buffer	Rationale
Major	500 m	Estimated relative importance of categorical features
Minor	250 m	

Beaver River watershed

	Claim category	Factor	Buffer	Rationale
placer claims not material to assessment	Historic Quartz and Placer claims	0.5	None	Previously staked, not re-staked.
	Current Quartz and Placer claims	0.75		Not upgraded to higher class.
	Current Quartz and Placer claims – Class 3	1		Prospective.
	Current Quartz and Placer claims – Class 4	1.5		Highly prospective.
	Current Quart claims – Class 5	2		Potentially economic.
	Assessment report footprints (dissolved)	1		Superimposed on current/historical claims.

Dawson region

	Claim category	Factor	Buffer	Rationale
placer: claims highly material to assessment, factors increased accordingly	Historic Placer claims	1	None	Previously staked, not re-staked.
	Current Placer claims (incl. mineral lease and lake)	1.5		Not upgraded to higher class.
	Current Placer claims – Class 3	2		Prospective.
	Current Placer claims – Class 4	2.5		Highly prospective.
	Assessment report footprints (dissolved)	1		Superimposed on claims.
quartz: numerous advanced projects, factors increased accordingly	Historic Quartz claims	1		Previously staked, not re-staked.
	Current Quartz claims (incl. mineral lease)	1		Not upgraded to higher class.
	Current Quartz claims – Class 2	1.25		Known to be prospective.
	Current Quartz claims – Class 3	1.5		Known to be significantly prospective.
	Current Quartz claims – Class 4	1.75		Known to be highly prospective.
	Current Quart claims – Class 5	2		Potentially economic.
	Assessment report footprints (dissolved)	1		Superimposed on current/historical claims.

Stream sediment geochemistry

	Commodity	Factor	Buffer	Rationale
Beaver River watershed	Ag	1	None	Upstream watershed polygons cover anomalous area, no factor or buffer required. Thresholds calculated at 2 StDev's.
	Au			
	Cu			
	Pb			
	Zn			
	W			
Dawson region	Ag	1	None	Upstream watershed polygons cover anomalous area, no factor or buffer required. Thresholds calculated graphically using histograms, resultant threshold percentiles for Ag, Au, Cu, Mo, Ni, Pb, W and Zn = 98, 96, 98, 97, 98, 98, 97 and 97, respectively. Re-assayed data used for area south of the Tintina fault; re-assayed plus original assay data used for area north of the Tintina fault (latter used where re-assayed data not available). For the original assays, instrumental neutron activation "INA" data used when available (superior detection limits). Watershed polygons not available for extreme northwest portion of DRLUP area.
	Au			
	Cu			
	Mo			
	Ni			
	Pb			
	W			
	Zn			

Dawson region

Placer potential	Factor	Buffer	Rationale
Probability 5	5	500 m	From Placer Gold Potential Map (J Bond), estimated relative significance of probability categories.
Probability 4	4	400 m	
Probability 3	3	200 m	
Probability 2	2	100 m	
Probability 1	1	50 m	

The application of factors to bedrock geology is an important component of the mineral potential assessment process. For example, while many mineral deposits may be structurally hosted, or spatially associated with structures, lithology plays a critical role in determining whether the structures will be mineralized, notably in terms of competency and/or chemical reactiveness of the host. The Keno Hill silver district serves to illustrate this point. While the silver mineralization is clearly structurally hosted, there is a marked spatial association with quartzite rocks of the Keno Hill Quartzite Formation. A multiclass bedrock WofE estimation for this area would ascribe positive factors to these rocks as expected (and required).

In addition to applying bedrock factors, felsic to intermediate, mainly Cretaceous and younger, igneous plutonic rocks in the Dawson and Beaver River areas were buffered to account for the potential influence of these intrusive rocks on mineralization in surrounding rocks–in terms of both fluid supply and source of metals. Intrusive rocks in the Beaver River area were buffered by 5,000 m in line with the mapped extent of the contact aureole around the Rau intrusive. In the Dawson region, Jurassic and younger intrusive rocks were buffered by 4,000 m, based on an assessment of the aeromagnetic geophysical data available for the area.

7. The area of each fishnet grid square occupied by each class element polygon (using the “intersect” function in ArcGIS) is then calculated. This process takes the buffers, but not the factors, into account. Multiple instances of the same class feature occurring within a single grid square are captured separately (*i.e.*, as separate records)–*e.g.*, different mineral deposit status types. In addition, intersections between same-class polygons within a grid square (*e.g.*, mineral “showings”) give rise to new polygons, which are captured as separate records. This “reinforcement” process is a required outcome as it takes into account the cumulative effect of the clustering of discrete, closely spaced categorical features within unit cells. For example, if two mineral “deposits” occupy the same grid square, their buffered areas will likely intersect. This will give rise to four records within the intersect table:
   a. the buffered area of the first deposit minus the intersection with the second deposit;
   b. the buffered area of the second deposit minus the intersection with the first deposit; and
   c. the area of the intersection between deposits one and two (with one of the records relating to deposit one, and the other to deposit two).
8. The proportion of each grid square occupied by each class feature polygon is then calculated. This is done by dividing the area occupied by each class element polygon by the grid area (4 km^2 in the case of the Beaver River and Dawson region areas) and multiplying the outcome by the class feature factor, if relevant–*i.e.*, when the factor is either greater or lesser than one.
9. The various attribute tables are then dissolved for simplification purposes if need be, keeping, at minimum, the grid square (fishnet) IDs, the class feature names, and the calculated proportion fields.
10. The dissolved tables are then merged into a single table. Each record in the merged table, which will consist of tens to hundreds of thousands of records, contains, among other things, the proportion data for each polygon class feature present in each grid square.
11. The various class feature proportions within each grid cell are then summed using the summary statistics function in ArcGIS. The StDev of class feature proportions within each grid cell is calculated at the same time–this parameter allows for the calculation of block standard errors (StErr) which are a potentially useful confidence and block selection metric. A summary statistics table is generated with the output constrained against the fishnet polygon IDs. The resultant table contains one record for each fishnet polygon (grid square) with each record containing the sum (and StDev) of the class feature proportions within each square. The process is shown schematically in Figure 4.
12. The summary statistics table is then joined to the original fishnet polygon attribute table and a preliminary mineral potential map is created showing the fishnet polygons coloured according to the sum of the proportions calculated for each grid square (with warmer colours corresponding to higher values, etc.). The warmer colours, therefore, represent the prospective portions of the mineral potential map (and so on), and the output provides a first-pass overview of the mineral potential of the AOI as a whole. This map is used for initial verification purposes (figs. 5 and 6).
13. Mineral potential confidence is then assessed. Two measures are used for this purpose, namely

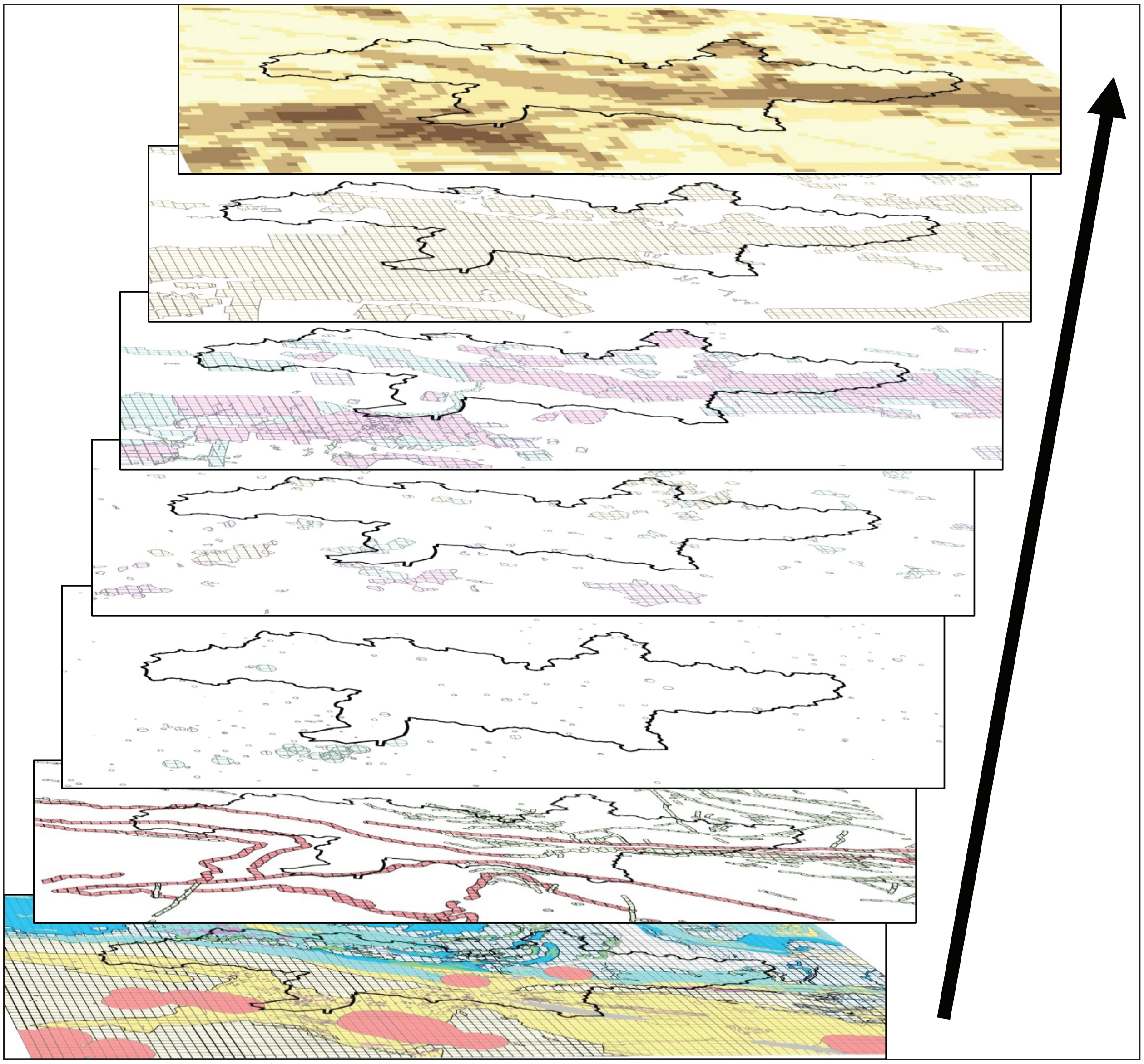

Figure 4. *Schematic representation of layers (simplified for presentation purposes) used to produce the Beaver River mineral potential map. More than 30 layers were used to produce the Beaver River map, while 92 were used to produce the Dawson Regional map.*

bedrock mapping confidence and block StErr. The bedrock mapping confidence metric is considered more appropriate for mineral potential maps for land use planning purposes, whereas both metrics are useful for maps produced for exploration targeting (*i.e.*, for industry use). Confidence metrics are required in order to distinguish between, well-mapped areas that might be deemed highly prospective from poorly mapped areas that might also be rated as highly prospective.

Bedrock mapping "confidence" for Yukon has been assessed based on the amount of mapping undertaken in an area and scores, ranging from one to six, assigned (with six being ascribed to the highest confidence areas and one to the least):

1 = unknown or poorly defined at any level (Supergroup/Group/Formation/ Member);
2 = mapped to the Supergroup level only;
3 = mapped to the Group level;
4 = mapped to the Formation level;
5 = mapped to the Member level; and
6 = mapped in sufficient detail to confirm and confine a mineralized horizon, either at the Member or Facies level.

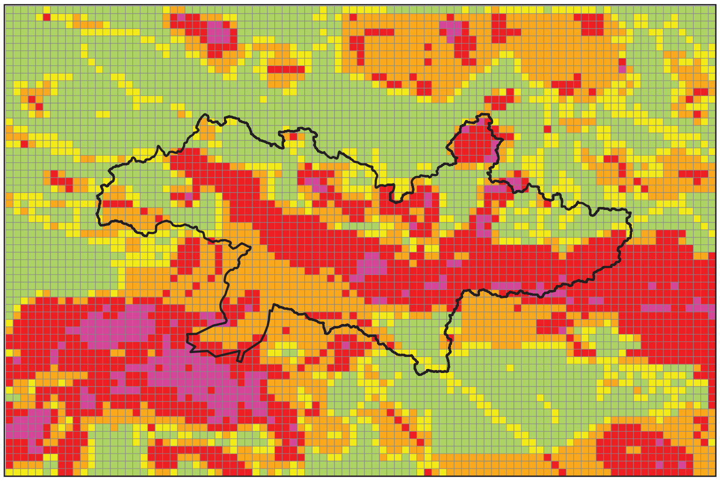

Figure 5. Preliminary, fishnet-based, mineral potential map (excluding measures of confidence) for the BRLUP area of interest. ArcGIS-ascribed Jenks Natural Breaks used.

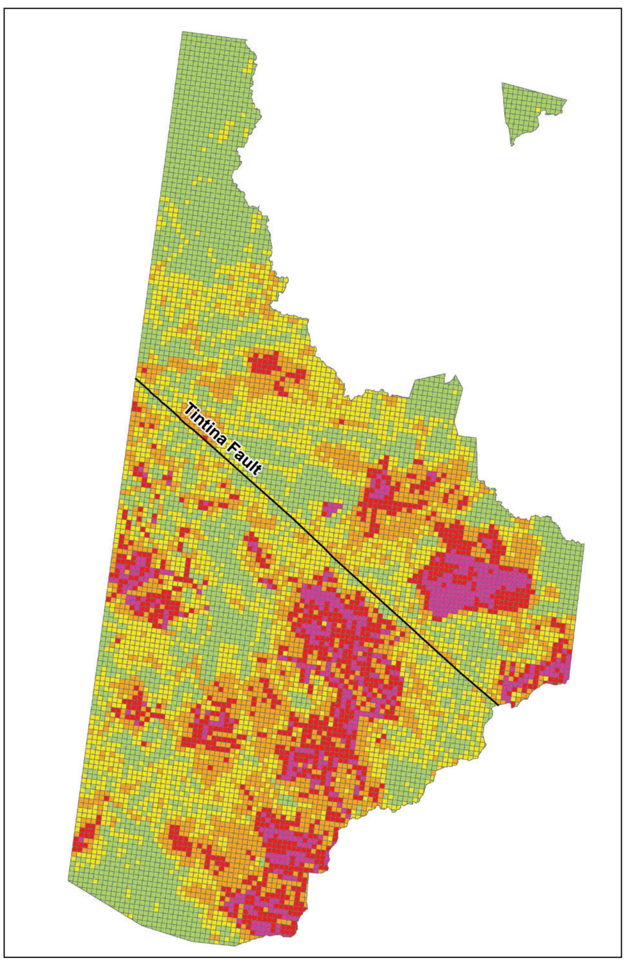

Figure 6. Preliminary, fishnet-based, mineral potential map (excluding measures of confidence) for the DRLUP area of interest. ArcGIS-ascribed Jenks Natural Breaks used.

For plutonic rocks, the following "confidence" schema has been introduced:
   1 = undated, no geochemical data;
   2 = undated, geochemical data;
   3 = other dating method, no geochemical data;
   4 = other dating method, geochemical data;
   5 = zircon dating, no geochemical data; and
   6 = zircon dating, geochemical data.

14. The procedure used to apportion the bedrock mapping confidence values to grid scores follows that described above–*i.e.*, the confidence scores for each rock unit within the AOI are incorporated into the fishnet grid using ArcGIS's intersect function and the proportions calculated accordingly (Fig. 7). No factors or buffers are used. The fishnet-based output for the Beaver River AOI is depicted in Figure 8, with the warmer colours representing areas of higher bedrock mapping confidence etc., as per the aforementioned methodology.

Claim and assessment report footprint data

Claim and assessment report footprint data represent an important store of intellectual capital and form an important component of the mineral potential mapping process. Companies and private individuals that stake claims do so on the basis of the perceived prospectivity for the commodities of interest to them. Staking is only done after considerable research and after due consideration of the practicalities concerned.

For example, consider a bulk tonnage commodity (e.g., an iron deposit) in an area with little to no infrastructure, or an "out-of-favor" commodity within the context of the prevailing political climate (e.g., coal or uranium). The mineral occurrences will reflect positively on the mineral potential map before claim data are taken into account. However, companies interested in these commodities will think twice before staking ground in this area as the likelihood of a return on investment, at any stage of the exploration/development phase, would be very low. Even if a company does elect to stake, the likelihood of upgrading claims to Class 3 or 4 status is even more improbable given the significant expense that would need to be committed to the program and the minimal return on investment that could reasonably be expected to accrue. Incorporating claim data in the mineral potential assessment would, therefore, downgrade the mineral potential of the area

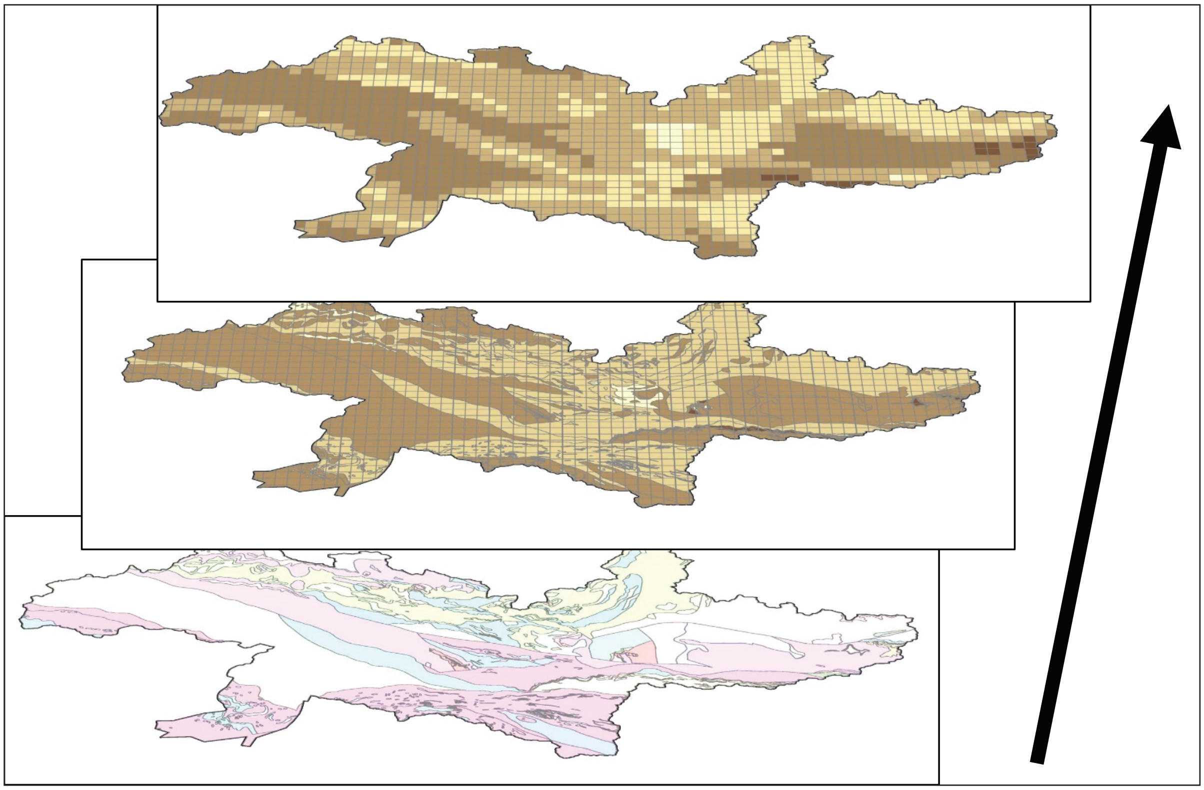

Figure 7. Schematic representation of layers used to produce the bedrock confidence map for the Beaver River watershed and Dawson Regional mineral potential maps (simplified for presentation purposes).

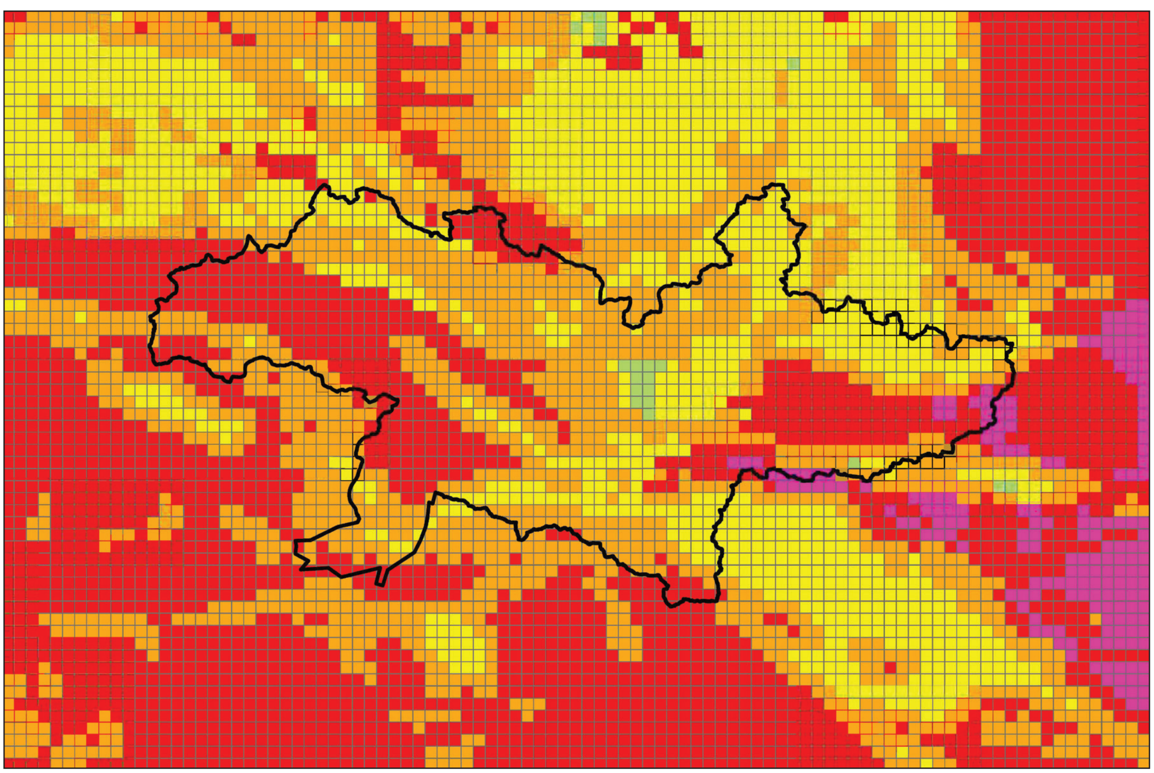

Figure 8. Preliminary, fishnet-based, bedrock confidence map (excluding measures of mineral potential) for the BRLUP area of interest.

encompassed by, in this example, the iron/uranium/coal mineralization, as the area would either not be staked, or contain no upgraded claims.

In contrast, claim data covering precious metal mineral deposits would have the opposite effect, reinforcing areas previously determined to be prospective using other data.

Obviating the edge effect

The assessment process for a mineral potential map ideally needs to include the actual assessment area plus a zone around it (*i.e.*, the AOI) for two reasons:

1. Areas of high (or low) mineral potential immediately adjacent to the assessment area influences the potential of the area itself. For example, the Keno area immediately southwest of the BRLUP is exceptionally prospective based on a number of factors. Cretaceous granite intrusions in this area, while lying outside the BRLUP, have a direct and materially positive impact on the prospectivity of the BRLUP and must, therefore, be taken into account when determining the area's mineral potential; and
2. Clipping the assessment area (prior to calculation of the final mineral potential and confidence scores) truncates the grid squares along the margin of the area. Polygon proportions in these marginal blocks will be reduced by the degree of truncation and the blocks will not, therefore, accurately reflect potential and confidence around the margins of the area. For example, a polygon occupying 100% of a block which has been truncated by 50% will be ascribed a proportion of 0.5, rather than 1. For that reason, assessment areas are clipped only right at the end of the assessment process, rather than at the beginning of, or during, the process.

Processing the mineral potential and confidence data

The mineral potential and bedrock mapping confidence data are clipped to the planning area itself and then exported to Excel for processing. The exported data contain, as a minimum, the summed proportions of the mineral potential categorical features for each fishnet square, and the bedrock confidence data for each fishnet square (expressed as a weighted average score when two or more confidence values are present in a square). The StDev for each fishnet square may also be exported, should the StErr be used as a measure of confidence.

The mineral potential and StErr (if used) confidence data are assessed for skewness. If the skewness is <–1 or >1 (*i.e.*, highly skewed) the data are transformed to reduce the distortion. For mineral potential, a log-transformation is suitable. Log-transformations for StErr data are not suitable given that StErr values of zero occur and log 0 is undefined. Consequently, a square root transformation is applied to StErr values for highly skewed data. Note that negatively skewed data must first be converted to positively skewed data prior to transforming by way of a reflection. The data can then be back-transformed for further processing if need be (or simply assessed as is in reverse).

The transformed mineral potential and StErr data are then converted to standardized normal distributions, each with a mean of zero and a StDev of one. The normalized scores for the mineral potential and StErr metrics are then assigned values of 1, 2 or 3:

1. Scores falling below a StDev of –1 are assigned a value of 1 (encompassing approximately 16% of the data, designated "Moderately prospective" in the final mineral potential map);
2. Scores falling between a StDev of –1 and +0.5 are assigned a value of 2 (approximately 53% of the data, designated "Significantly prospective" in the final mineral potential map); and
3. Scores falling above a StDev of +0.5 are assigned a value of 3 (approximately 31% of the data, designated "Highly prospective" in the final mineral potential map).

The weighted average scores for the bedrock mapping confidence metric are assigned values of 1, 2 or 3:

1. Block values ≤2.6665 (*i.e.*, lower third of values) are assigned a value of 1;
2. 2.6665 < Block values ≤4.3335 (middle third of values) receive a score of 2; and
3. 4.3335 < Block values (upper third of values) receive a score of 3.

The result is the conversion of mineral potential and confidence scores to either a 1, 2 or 3 according to a defined mathematical schema. The scores are then combined such that fishnet blocks with scores of 1:1, for example, have the lowest mineral potential and the lowest confidence whereas blocks with scores of 3:3 have the highest mineral potential and the highest confidence. Combining the revised prospectivity and confidence scores will, therefore, give rise to (up to) nine possible combinations ranging from 3:3 (most potential, highest confidence) to 1:1 (least potential, lowest confidence). The combined scores are best understood when viewed graphically (Fig. 9).

The data, together with the associated scores, are imported from Excel into ArcGIS and joined to the fishnet attribute table. Two contour maps are then constructed using the normalized mineral potential scores and the confidence scores (*i.e.*, the 1, 2, 3 values). Three ArcGIS functions are implemented:

1. polygon to raster using a cell size of 250 m and the proportion and confidence as the value fields, respectively;
2. focal statistics, which calculates for each raster input cell location a statistic of the values within a specified neighborhood around it thereby helping to smooth the final contours (circle neighborhood, radius = 20 (raster pixels); and
3. contour, to create contours from the focal statistics raster grid (contour type = "CONTOUR_POLYGON"). A contour interval of 0.6667 and a base contour of 1 are selected. The process is shown schematically in Figure 10.

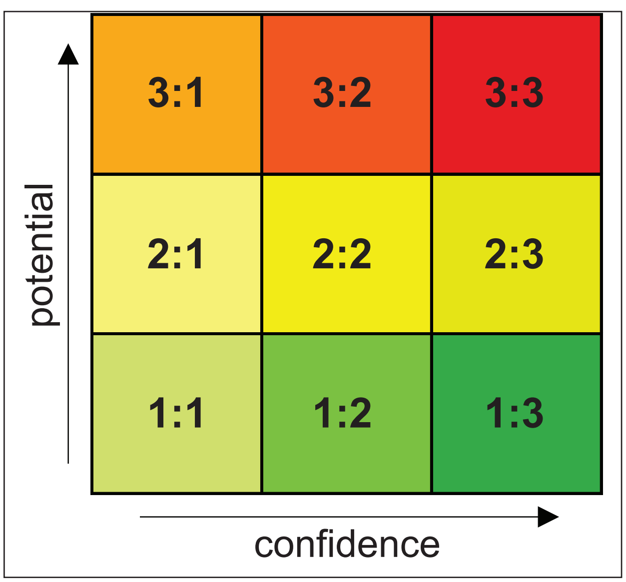

Figure 9. *Graphic representation of colour-coded mineral potential/confidence scores as used in YGS mineral potential maps. The colours are incorporated into the final map and the mineral potential and confidence metrics interpreted accordingly.*

The potential and confidence contour maps are then combined using the "union" function in ArcGIS. The result is a single map divided into polygons based on the different combinations of the mineral potential/confidence scores–*i.e.*, 3:3, 3:2, 3:1, 2:3, 2:2, 2:1, 1:3, 1:2, and 1:1. The polygons are coloured according to Figure 9 to produce a combined mineral potential/confidence map for land use planning purposes.

Levelling mineral potential data across major structures

Areas cut by major structures along which significant displacement has occurred need to be evaluated separately, and then stitched back together at the end of the assessment process. Concurrently, the mineral potential data need to be levelled to account for prospectivity differences across the structure concerned.

The DRLUP area serves as a case in point. The AOI is cut by the Tintina fault (Fig. 6) along which 430 km of displacement has taken place (Israel, et *al.*, 2019). Rocks of the Selwyn basin (Ancestral North America) to the north are juxtaposed against rocks of the Yukon-Tanana terrane (Intermontane) to the south. Assessing mineral potential across the fault is neither logical nor feasible and hence the two terranes need to be evaluated separately.

Mineral potential scores for the DRLUP area shows that the Yukon-Tanana terrane is, on average, 2.066 times more prospective than the area north of the Tintina fault. This difference needs to be captured in the final mineral potential map for the Dawson region by levelling the data across the Tintina fault so that the mineral potential of the two terranes is correctly reflected when viewed holistically. The following process was used to achieve this:

1. The area under a standardized normal distribution curve below a StDev of -1 was divided by the difference in average mineral potential between the rocks of the Selwyn Basin and the Yukon-Tanana terrane–*i.e.*, 15.87/2.066 = 7.68%.

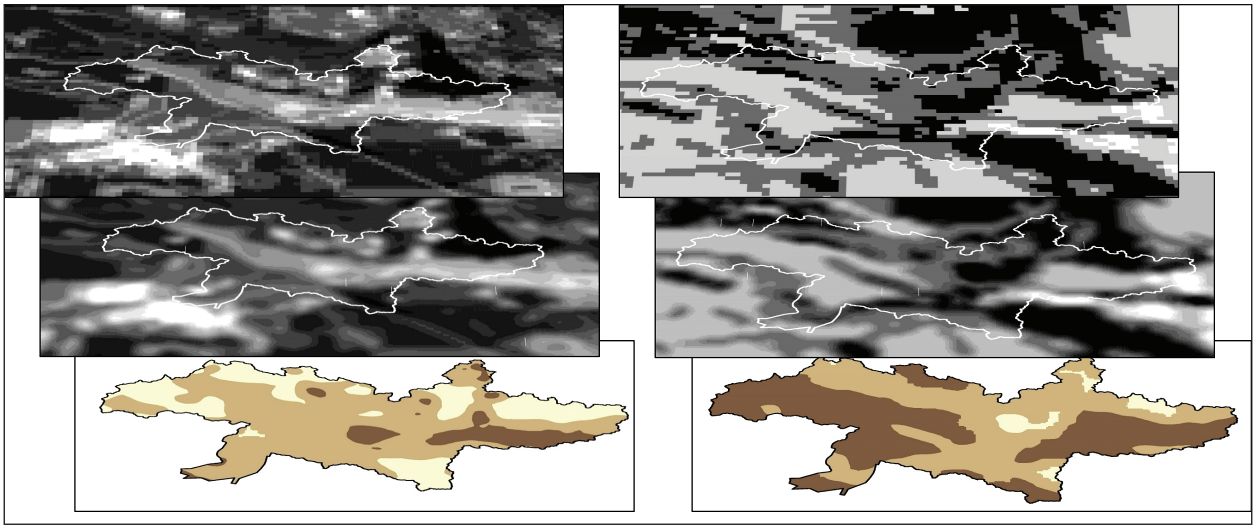

Figure 10. *Schematic representation of layers used to produce the bedrock confidence map for the Beaver River watershed and Dawson Regional mineral potential maps.*

2. For the Selwyn basin component: a mineral potential of 1 was ascribed to the area falling under the normal curve of 23.55% (*i.e.*, 15.78 + 7.68, which corresponds to a StDev = -0.72);
3. For the Yukon-Tanana terrane: a mineral potential of 1 was ascribed to the area falling under the normal curve of 8.19% (*i.e.*, 15.78 - 7.68, which corresponds to a StDev = -1.39);
4. For the Selwyn basin for mineral potential scores of 2 and 3: the areas under the normal curve were reduced by 3.84% (*i.e.*, 7.68/2) to 49.44% and 27.01%, respectively, and the StDev dividing the two areas determined–StDev = 0.61; and
5. For the Yukon-Tanana terrane for mineral potential scores of 2 and 3: the areas under the normal curve were increased by 3.84% (*i.e.*, 7.68/2) to 57.12% and 34.69%, respectively, and the StDev dividing the two areas determined–StDev = 0.39.

For the Selwyn basin component, mineral potential values therefore were apportioned as follows:

1. Scores falling below a StDev of -0.72 = 1;
2. Scores falling between a StDev of -0.72 and 0.61 = 2; and
3. Scores falling above a StDev of 0.61 = 3.

For the Yukon-Tanana terrane, mineral potential values were apportioned as follows:

1. Scores falling below a StDev of -1.39 = 1;
2. Scores falling between a StDev of -1.39 and 0.39 = 2; and
3. Scores falling above a StDev of 0.39 = 3.

Fair copy output

The final mineral potential/confidence maps for the Beaver River watershed and Dawson region are depicted in Figs. 11 and 12. Note that the BRLUP mineral potential map contains eight combinations of prospectivity/confidence scores, rather than the maximum of nine. There is no 1:3 category (*i.e.*, lowest potential/highest confidence), meaning that there are no areas on the BRLUP map that we can be very sure are not prospective.

With respect to the Dawson region, the relatively higher mineral potential of the Yukon-Tanana terrane south of the Tintina fault is clearly reflected in the overall mineral potential map.

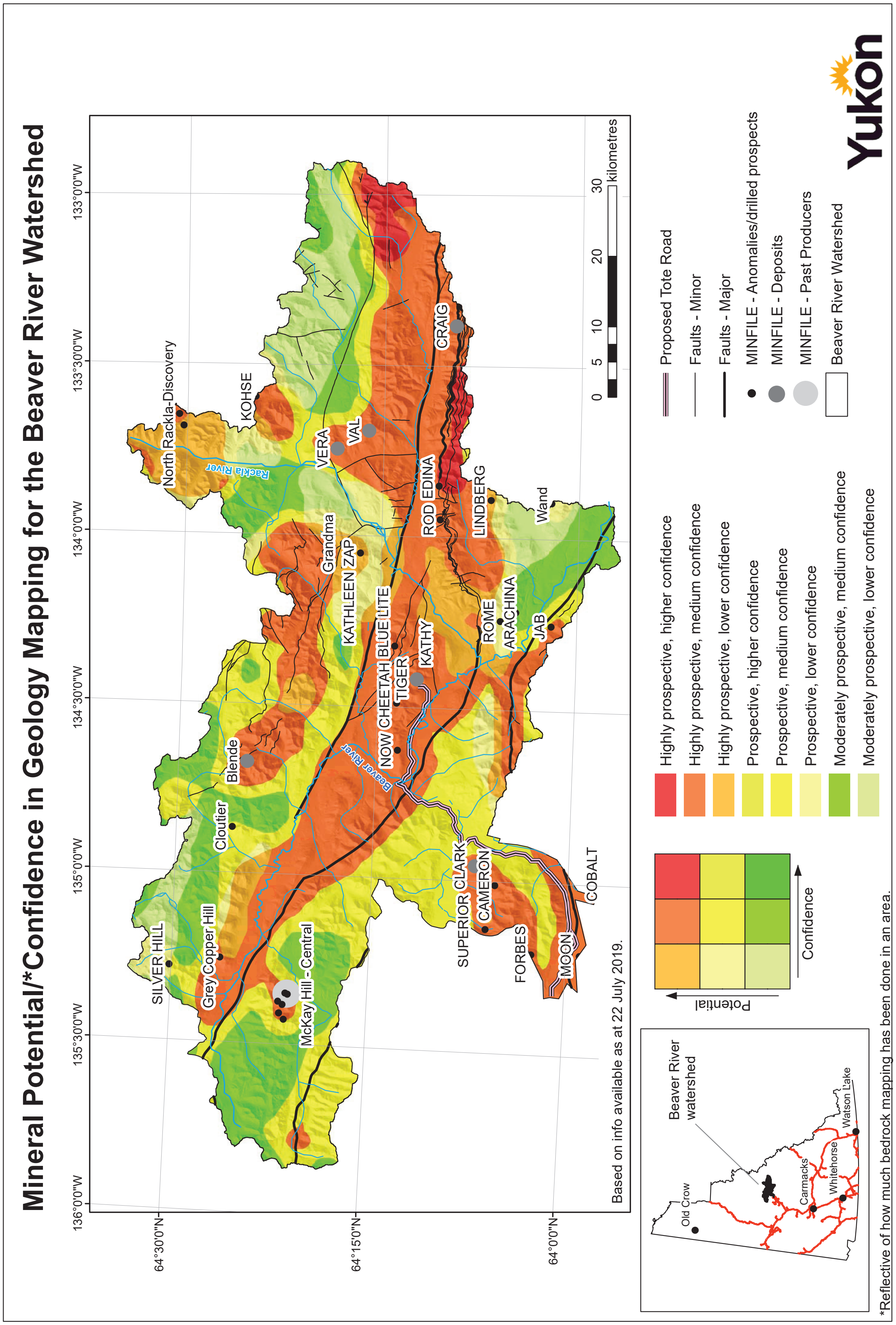

Figure 11. *Mineral potential versus geology mapping confidence map for the BRLUP area.*

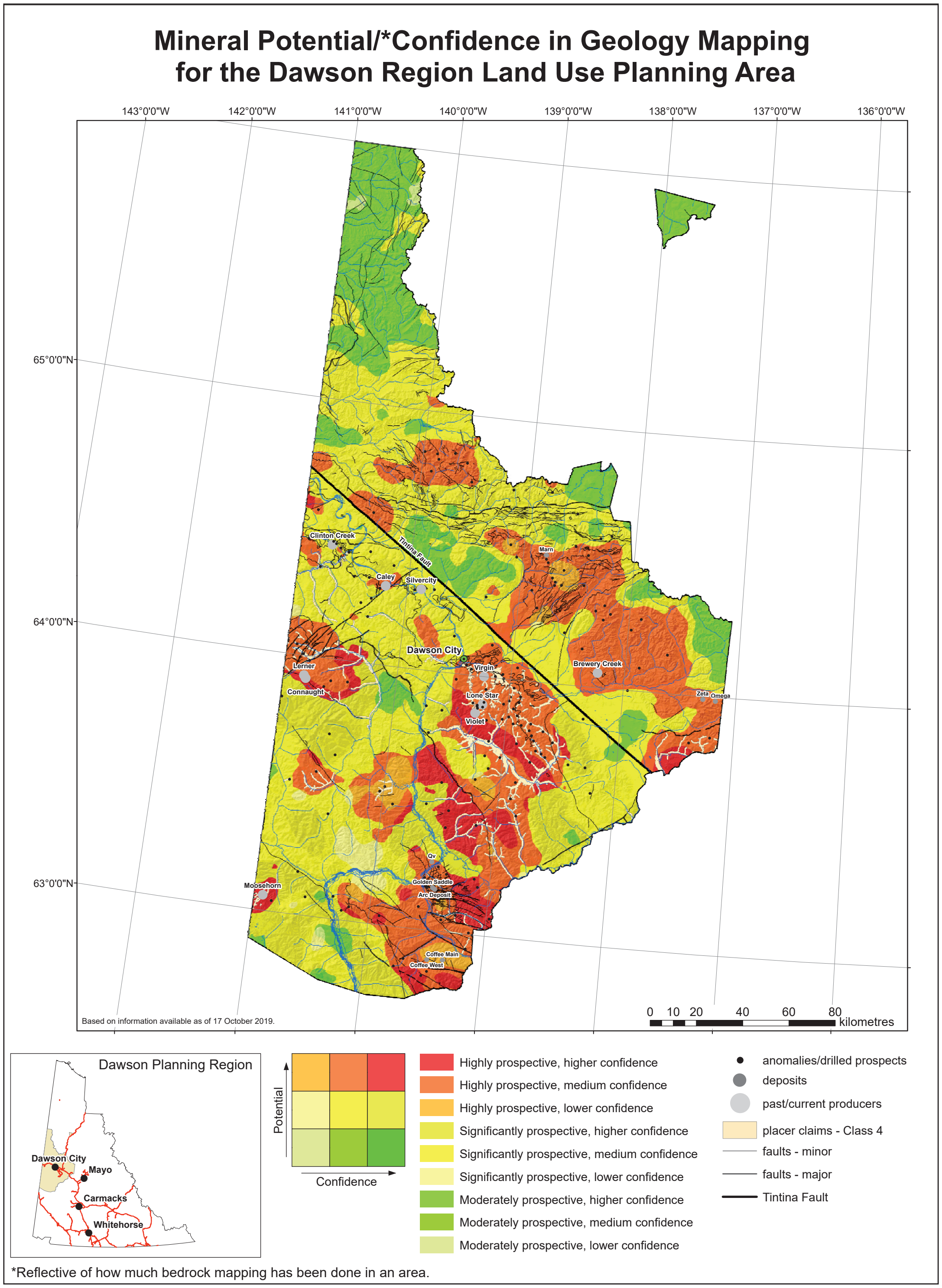

Figure 12. *Mineral potential versus geology mapping confidence map for the DRLUP area.*

Conclusion

Mineral potential maps for land use planning in Yukon will be generated using the process described above. Maps developed for the Beaver River watershed and Dawson region have been well received by land use planners as:

1. they are simple to use and easily understandable, helping with decision-making;
2. they are based on hard data;
3. they are presented as a single map containing all relevant mineral potential data, rather than as separate maps highlighting individual items;
4. uncertainty is built in to the process; and
5. they offer up areas for removal from exploration that minimize impacts on future economic opportunities.

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