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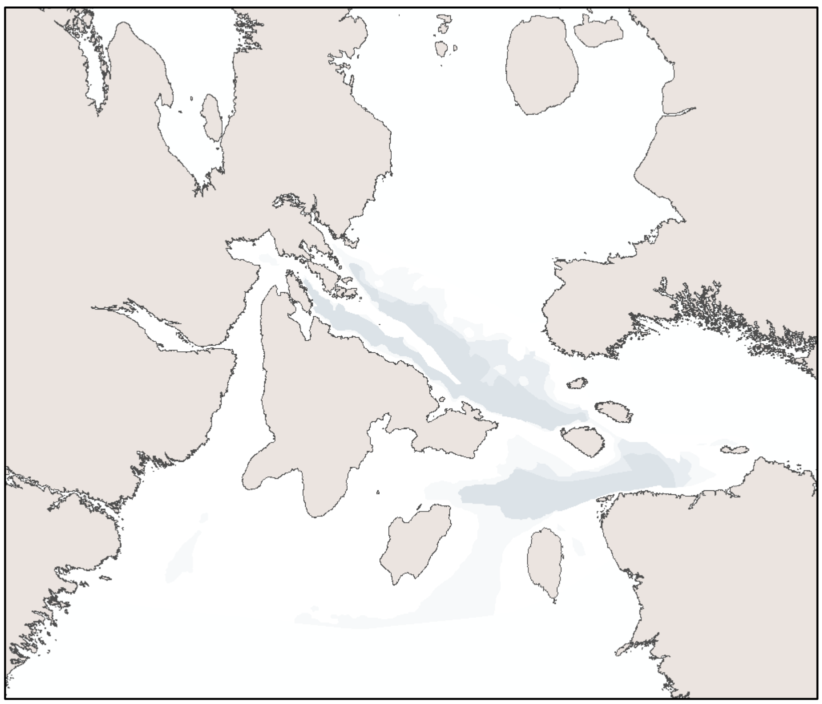
GEOLOGICAL SURVEY OF CANADA
OPEN FILE 9242

Adapting qualitative petroleum resource assessment methods for gas hydrates in ArcGIS®



H.M. King and L.E. Kung

2025

Canada

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Adapting qualitative petroleum resource assessment methods for gas hydrates in ArcGIS®

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TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

Qualitative resource assessments are exploration-level investigations to (1) find areas that warrant further quantitative study and/or (2) provide policy makers, stakeholders, managers, and the general public with easy-to-understand overviews of relative resource distributions. Since the inception of the Marine Conservation Targets (MCT) initiative in 2016, the Geological Survey of Canada (GSC) has produced 11 conventional petroleum resource assessment reports covering over 3,000,000 km^2 (or 53%) of Canada's offshore. These reports have used qualitative resource assessment methods described in Open File 8404 by Lister et. al. (2018) to map conventional petroleum resource potential in offshore areas across Canada (e.g. Figure 1). This method provides consistency, transparency, and repeatability for qualitative resource assessments and can be adapted for any system that is the result of the interplay of independent variables. Some examples of such systems include: gas hydrates, geothermal energy, carbon capture utilization and storage (CCUS), natural hydrogen, wind or wave energy, and even some sediment hosted mineral systems like red bed copper, carbonate-hosted zinc, or lithium brines.

This report describes and illustrates how this qualitative methodology is adapted to the gas hydrates unconventional hydrocarbon system. It is not meant to highlight gas hydrates as an attractive future energy resource, nor to discuss environmental or geohazard-related issues associated with them.

2. GAS HYDRATES: A BRIEF OVERVIEW

Gas hydrates are present in large volumes in permafrost areas in the Arctic as well as on continental shelves and slopes worldwide (e.g. Figure 2, data downloaded courtesy of Waite et. al., 2020). They trap high concentrations of light hydrocarbons inside a frozen cage of water molecules. Their formation and atomic structure are controlled by factors like pressure, temperature, and how much water and gas are available in a reservoir. Depending on the types and volumes of available gases, hydrates can form different physical structures. These structures and their constituent gases affect the location and thickness of what is known as the gas hydrate stability zone, or GHSZ: the range of depths where conditions are favourable for hydrate formation.

2.1 The gas hydrate stability zone (GHSZ)

If sufficient water and natural gases are present, gas hydrates may form and remain stable anywhere within the GHSZ. The GHSZ is often simplified as in Figures 3 and 4, but in reality the GHSZ is represented by a varied geometry that changes both vertically and laterally due to heterogeneous salinity and heat flow values (e.g. Boswell and Collett, 2006). Beneath the stability zone, there is sometimes a layer of free gas. This free gas layer can produce a 'bright spot' on seismic reflection data, known as a bottom simulating reflector (BSR) which can be a helpful indicator of possible gas hydrate presence.

Figure 3 (a) and (b) show simplified stability curves in permafrost and marine settings, respectively (modified from Sloan et. al., 2010; their Fig. 1). Onshore assessments were not part of the MCT initiative and thus all GSC-Calgary qualitative hydrate assessments to-date have been for offshore areas. Various approximations exist for calculating the GHSZ and the curves change depending on the type of gas hydrate present. A full discussion of gas hydrate types and gas composition is beyond the scope of this report. For simplicity and due to limited available information in study areas, the GSC considers 100% methane hydrates for its qualitative assessments. The GSC now uses the stability equation from Sloan (1998) described in Majorowicz and Osadetz (2003) for assessing 100% methane hydrates:

$$T_{100\%\,methane} = 8.9 * \ln(D) - 50.1 \tag{1}$$

where T is the temperature (°C) of 100% methane hydrate stability at depth D (m). Note that a hydrostatic gradient of 10 Mpa/km is assumed for transforming pressure to depth.

2.2 Gas sourcing

Figure 4 shows a generalized formation environment for gas hydrates. Hydrates are commonly sourced either by gas migrating up cracks and faults from underlying conventional (thermogenic) gas accumulations or by in-situ generation of gas by bacteria (biogenic gas). Thermogenic gas is generated from organic matter that is buried deeply (1000s of m) and converted under thermal stress over geological timescales. Most biogenic gas generation occurs in relatively shallow sediments (100s of m below seabed) where bacteria convert organic matter like dead plant or organism materials into natural gases over much shorter timescales than thermogenic accumulations. A third mechanism for gas hydrate sourcing is abiogenic gas and it does not involve organic matter at all. This gas is created in deep mantle processes and subsequently migrates into the crust. At the time of publication, abiogenic gas is regarded as a relatively rare hydrate source and has not been incorporated into a gas hydrates qualitative resource assessment by the GSC.

2.3 Gas hydrates in a resource context

In terms of gas volume, hydrates pack a lot into a small space. At similar temperature and pressure conditions, hydrates trap more than 160 times the volume of gas than the same volume of free-standing gas (e.g. Ruppel, 2011). However, not all gas hydrate accumulations are considered equal when considered from a resource value standpoint. Figure 5 (modified from Boswell and Collett, 2006) shows a gas hydrate resource pyramid. This pyramid separates gas hydrate reservoirs based on abundance, quality, and ease of extraction. In general, more permeable formations have higher saturations of gas hydrates and are also easier to produce (e.g. Beaudoin et al., 2014, Boswell and Collett, 2006, Fig. 5). For this reason, we consider gas hydrate reservoirs to be better if they also would make better conventional reservoirs.

3. QUALITATIVE METHODOLOGY ADAPTATION

The GSC qualitative petroleum resource assessment methodology was designed to be flexible and easily adaptable to other energy systems. Open File 8404 is highly recommended as a resource for anyone undertaking a qualitative resource assessment for the first time or for anyone who would like to see a more in-depth discussion of the concepts discussed below.

Using a conventional petroleum systems approach in gas hydrate resource assessment is not a new concept (e.g. Collett, 1995; Johnson, 2011; Max and Johnson, 2014; Beaudoin et al., 2014). Qualitative gas hydrate assessments often use calculated thickness of the GHSZ as a proxy for relative abundance. Here, we take this several further steps by integrating the chance that there is a gas source available to fill an appropriate reservoir and whether a good reservoir is likely to exist. This results in a relative potential map similar to that for petroleum (Figure 6 – top) that highlights areas of higher gas hydrate saturation potential (Fig 6 - bottom).

The process for creating these maps involves: defining the area of interest and assembling available datasets (§3.1); defining and evaluating individual gas hydrate system elements (§3.2); and combining these elements probabilistically to create a qualitative resource potential map (§3.3). This process is illustrated using a general example and then with a detailed walkthough of the process with a real-world example worked through in ArcGIS (§4).

3.1 Defining area of interest and assembling datasets

The first step in a qualitative resource assessment is defining the Area of Interest (AOI). The AOI could cover a large geographical area for a regional study or could encompass a much smaller study area for a targeted local study.

The accuracy and granularity of a qualitative assessment depends highly on the quantity and quality of available data. Dataset assembly offers value even without further assessment by identifying areas that are data poor or even data void. This can inform scientists when planning research studies, or even raise questions as to why data was previously uncollected in an area and how this relates to data confidence.

3.1.1 Gas hydrates datasets

Valuable datasets to assemble for assessing gas hydrate potential include (but are not limited to):

- Bathymetry, multibeam
- seismic data and interpretation (e.g. structural maps, thickness maps, bottom simulating reflectors (BSRs), facies analysis, etc.)
- well data (e.g. pore water salinity, gas composition, pressure, etc.)
- gas hydrate sample analysis, core samples
- geological maps
- oceanographic data (e.g. salinity, hydrothermal gradient, bottom-water temperatures, etc.)
- geothermal gradient
- hydrostatic pressure gradient
- existing conventional or gas hydrate resource assessments.

It is not necessary to have all the datasets, however the more data available, the more confident the resource assessment will be. Figure 7 shows a schematic of an example dataset accumulation for a gas hydrate qualitative resource assessment.

3.2 Defining system elements and evaluating COS

Chance of success (COS) is the human-assigned probability that something will occur based on assessment of all data available. In the context of a resource assessment for an energy system, the ‘somethings’ we are concerned about are the independent variables that interact to form that system. We refer to those independent variables as systems elements. For example, in a conventional petroleum system the GSC identifies four system elements: source (including timing and migration), reservoir, trap, and seal. For any energy system, these system elements must be identified and evaluated for COS. The combination of all system elements over a given area is called a ‘play’. Each system element in every identified play needs to be evaluated separately.

A successful COS analysis is driven by data confidence: an interplay of the caliber, density, and confirmation of the available data. Caliber is an assessment of the quality of the data, density is the number of data points, and confirmation is the agreement between measured data and your interpretations and observations. The GSC Chance of Success (COS) Scale (Figure 8) is a tool adapted and simplified from the Rose and Associates Matrix (Rose, 2001). This scale assists a team when making COS evaluations by constraining the COS value assignment based on no, low, medium, or high confidence levels. This helps make assessments repeatable, transparent, and as objective as possible.

In an area with no data or where there are multiple conflicting pieces of information, a value of 0.5 (or no confidence) would be assigned. In an area with lots of consistent, good quality data, that all points to the same conclusion, the value may begin to approach high confidence at 0.95 or 0.05 depending on whether it was a positive or negative outcome, respectively. A more in-depth explanation of these concepts can be found in Lister et. al. (2018).

3.2.1 Gas hydrate system elements

The GSC elected to use a three-element system for gas hydrates: trap/seal, reservoir, and source (e.g. Fig. 9). Each element is evaluated across the AOI and a chance of success value is mapped according to the COS scale based on data confidence across the area. The following is a summary of each element and examples of indicators of positive COS values.

Trap/Seal: The trap/seal for a hydrate system is geochemical. Hydrates are stable wherever stability conditions exist in a region. The gas hydrate stability curve is calculated using Equation 1 (and/or others) and stability conditions are deduced by using bottom-water temperature, seafloor bathymetry, and geothermal gradient. Indicators for positive trap/seal COS values include: GHSZ thickness - thicker stability zone may increase chance of hydrate deposits; well data or core samples confirming hydrate presence (e.g. Fig. 9a and b). Note that if data were available, seal quality as it relates to current extraction technology could also be considered while assigning COS to trap/seal.

Reservoir: The reservoirs for a hydrate system can include pore space or fractures within formations, sediment displacement within formations, or even free-standing accumulations on the seafloor. The highest hydrate saturations occur in the highest quality reservoirs (i.e. highly permeable sandstones), but the largest volumes of hydrates occur in reservoirs with limited permeability (e.g. Fig. 5). Reservoir quality is considered highest in highly permeable reservoirs that would also make good conventional reservoirs. Indicators for positive reservoir COS values: well data confirming ideal reservoir properties for high-saturation hydrates or confirming hydrate presence and type; core samples; BSRs on seismic reflection data; inferred reservoir quality by environment of deposition or seismic facies interpretation (e.g. Fig. 9c and d).

Source: The source for a hydrate system is a major limiting factor in the formation of hydrates. Gas hydrate sources can be thermogenic (conventional), biogenic (bacterial), or abiogenic (mantle processes), or some combination thereof. When assigning COS values for source, the GSC considers mainly thermogenic sources (migrating from deeper reservoirs and/or source rocks), with consideration of biogenic sources where applicable. Indicators for positive source COS values include: for thermogenic gas – existing resource assessment for underlying source, existing faults to provide migration pathway; biogenic gas – high sedimentation rates; presence of organic matter; well data or core samples confirming gas; inferred source presence due to geologic history (e.g. Figure 9e and f).

3.3 Combined chance of success (CCOS)

Combined chance of success (CCOS) is the overall probability that all system elements in a play will occur together. System elements are assumed to be statistically independent events so CCOS can be calculated by the product of each of the element probabilities. For each identified play, system elements are assessed individually and then combined such that:

$$CCOS_{play} = \prod_{i=1}^{n} COS_i \tag{2}$$

where COS_i is the chance of success for the i^{th} element of a total n systems elements and $CCOS_{play}$ is the combined chance of success (CCOS) for the play.

3.3.1 Gas hydrates CCOS Map: relative saturation potential

The final qualitative hydrate potential map is a result of multiplying the probabilities for the trap/seal, reservoir, and source COS elements to create a CCOS map. Adapting Equation 2 to the gas hydrate system gives the CCOS for gas hydrates gives:

$$CCOS_{Gas\ Hydrates} = COS_{Source} * COS_{Reservoir} * COS_{Trap/Seal} . \tag{3}$$

The gas hydrate saturation potential map contains a singular hydrate play (e.g. Fig. 9g). The map is coloured to highlight areas with higher relative gas saturation potential. This method could be expanded to include stacked plays typically seen in conventional petroleum systems, if necessary.

A note on Technical CCOS (TCCOS) and Stacked TCCOS (STCCOS)

In petroleum systems, plays are often ‘stacked’ on top of each other. To deal with combining these plays together, Lister et al. (2018) created the concept of a Global Scale Factor (GSF) which scales the plays so they are comparable to each other in terms of likelihood of technical success. This factor is assessed for each play and then multiplied with the CCOS to create a Technical CCOS (TCCOS) map. These TCCOS maps are then added together to create Stacked TCCOS (STCCOS) maps, like those seen linked across Canada’s offshore in Figure 1. Note the gas hydrate qualitative assessment does not have stacked assessments, but it is possible to incorporate this in future assessments if required. Any system that is being considered for qualitative assessment should identify whether stacked assessments are required and, if so, implement a method for combining them.

4. ARCGIS® MODELBUILDER WORKFLOW: CONSTRUCTING A RESOURCE POTENTIAL MAP

The qualitative gas hydrates potential map is assembled using an adaptation of the ArcGIS® workflow from Lister et al. (2018). The workflow is summarized in Figure 10 and consists of five steps to produce a resource potential qualitative map: Step A1. Define AOI, Step A2. Create Element, Step A3. Assign COS, Step A4. Combine independent layers into one feature class, and Step A5. Qualitative Hydrate Saturation Potential Map. This method is designed with a procedural structure to facilitate adaptation to other resource potential mapping exercises.

The data required to build a map are highly variable and unique, thus the ability to transform and work with data in a topological, geospatially defined workspace is instrumental in creating a robust map. A mapping software is a key instrument for several reasons: it facilitates the compilation of relevant data, adds the ability to spatially reference data, provides access to a catalog of mathematical tools, and stores relevant metadata in final maps. The final qualitative map is a spatially derived product that represents low to high potential on a 2-dimensional plane.

This section will navigate the ArcGIS® modelbuilder workflow (Fig. 10) using the Southampton Island gas hydrates assessment extracted from the Hudson Bay resource assessment (from Dewing et. al., 2023). This exercise operates in a geodatabase structure; moreover, all emergent data are feature classes. In this ArcGIS® modelbuilder workflow, a feature class is considered to be a polygon feature class.

Step A1. Define AOI

The area of interest is a closed boundary polygon that represents the desired extent of the final resource assessment (e.g. Fig. 11). The extent of the Southampton Island area captures the targeted Mesozoic grabens. These grabens contain clastic sediments and are potentially sourced by Upper Ordovician shales. Given the young age, and shallow reservoir depths; this was considered to be an area of interest in particular for gas hydrates from the Hudson Bay assessment (Dewing et al., 2023).

The AOI starts as a polygon feature class (Fig. 11). A feature class is a geospatial vector data file that is comprised of points, lines, or polygons. The AOI feature class serves as the master data polygon in which the system elements in further steps will be congruent.

Step A2. Create element + A3. Assign COS

Each system element is assigned to a feature class based on the master data polygon created in Step A1 (Figure 12a). In this assessment, there are three system elements and thus three separate feature classes for source, reservoir, and trap/seal. In the Southampton Island AOI, the source was identified as thermogenic gas from Upper Ordovician shales. The better quality reservoir is considered to be located within the Mesozoic graben. There is some limited potential for Mesozoic-Cenozoic sands and muds however, there is glacial thinning and consolidated marine clays. The trap/seal was cut based on a 170, 230, and 250m bathymetric contour. The target contour depths are indicative of potentially unstable to potentially present and stable conditions for gas hydrates to form based on the analysis of hydrate stability curves. Step A2. and A3. aim to integrate the literature review directly into a feature class.

With each system element represented as a single feature class, each feature class is then split using the cut tool based on geographic features and representative data (Figure 12b and c). Each cut forms a group of spatial objects within the feature class, each with their own closed boundary that falls within the defined AOI. Every object within each feature class must have an assigned COS value.

The unique objects, COS values, and description are simultaneously contained in an attribute table (Fig. 13). An attribute table relates the information used to assign a COS value to the feature class. This is referred to as metadata. Relevant fields include: an integer field ("COS_*element*") and a text field (description of spatial object). The user can create as many relevant fields as deemed necessary. When all cuts are complete, a COS value is assessed for each object within the feature class and coloured accordingly (Fig. 12d and e).

It is advised that two planar topology rules must be adhered to at all times. It is essential that object areas do not overlap in one feature class and there must be no gaps between them. Overlapping features would indicate two considered parameters at a specific location. If there are gaps present in the bounded feature class, this essentially states that no such parameters exist at that location. As mentioned in Section 3.3, the method is considering a singular play at this time hence one feature class per system element. This method can be expanded to include more plays and/or system elements, if required.

Step A4. Combine independent layers into one feature class (CCOS)

Once all system element feature classes are complete, the qualitative potential map can be constructed using the 'Union' tool (Fig. 14). The Union tool geometrically calculates the intersection between input features and outputs a new feature class where the intersection is preserved within a planar object. All input attribute tables are preserved and carried over into the union-ed feature class.

To create the final potential map, the source, reservoir, and trap/seal feature class are combined to create a combined elements layer (Fig. 15). The combined elements layer feature class geometrically represents a series of objects that have a difference in value next to its neighbouring objects. Once the 'Combined Elements Layer' is produced, a 'CCOS" field can now be added by using the field calculator and applying Equation 3 (Fig. 16). Querying an object within the combined elements layer shows the CCOS and the COS potential of the source, reservoir, and trap/seal in that region (Fig. 13). Having this metadata preserved in a final map is extremely useful for transparency as well as communication purposes.

Step A5. Qualitative hydrate saturation potential map

The final step applies the qualitative hydrates saturation colourbar to the CCOS field. The CCOS feature class is symbolized attributing the '.lyr' file (Fig. 17) to the CCOS field. A colourbar is a dynamic product with any set colours, number of bins, or evaluation. The colourbar for gas hydrates saturation value is a custom coded colourbar based on bin distribution; and then saved in a layer file. It is a gradational blue colour representing a relative scale from low to high saturation potential. It could be adapted if more data is available or if stacked plays are desired. The final map for Southampton Island indicates a very low to low hydrate saturation potential (Figure 18).

5. DISCUSSION

This report has shown how the qualitative petroleum resource assessment methodology described in Open File 8404 is easily adapted to an unconventional hydrocarbon system. Previous qualitative hydrate assessments usually show the thickness of the GHSZ as a proxy for hydrate potential. The methodology in this report assesses not only if stability conditions exist in an AOI, but also integrates the probability that a gas source exists to feed hydrate formation in a quality reservoir (e.g. Figs. 9 and 15). Furthermore, the resulting gas hydrate saturation potential map has spatial metadata containing all reasoning and references used to assign COS. This makes the final map (and the process used to create it) transparent, repeatable, and easy to update should new information arise.

5.1 Future improvements to gas hydrate assessment

Future improvements on the qualitative gas hydrate methodology could include a more detailed assessment at the reservoir level for higher saturation areas and/or incorporating new data and information as it emerges. If a study area warranted stacked hydrate plays, discussion on how to combine these plays is imperative. A thorough literature review of size and distribution of gas hydrate accumulations worldwide would help answer this question. However, the solution is non-trivial and warrants discussion and experimentation.

5.2 Adapting this methodology to other energy systems

Some energy systems that could be adapted to this methodology include, but are not limited to: natural methane emissions, naturally-occurring hydrogen, geothermal energy, wind or wave energy, or underground carbon storage, as well as some sediment-hosted mineral systems like lithium, redbed copper or sediment hosted lead-zinc. Depending on the energy system, the approach may be more straightforward like the hydrate system (i.e. one play), or the system may be more complex and requiring the stacked play method used in conventional petroleum assessment (e.g. Lister et. al., 2018). In this case, it is imperative to discuss the best way to combine these plays in a way that makes sense to the system. For a different system, different system elements might be considered other than the source, reservoir, trap, seal combination that is typical for conventional petroleum. The key is to identify variables that are independent of each other and can therefore be combined probabilistically to obtain the overall system chance of success given by Equation 1. When assigning probabilities, it is essential to capture data confidence by effectively using the GSC COS Scale (or another similar tool).

5.3 Communicating results with colourbars

A qualitative map is a high-level visual overview of resource potential designed to be used as a communication tool for a wide audience. As such, choosing a colourbar for displaying results is arguably one of the most important steps in any qualitative resource assessment process. In the original GSC methodology, a green to red 'stoplight' colour bar (e.g. Fig 6 – top) was used to show high to low petroleum potential, respectively. However, for gas hydrates, a gradational blue colourbar was used to show increasing hydrate saturation potential at a relative scale (e.g. Fig. 18). It is important to consider what message you are trying to convey to your audience. For example, a green to red map might suggest higher confidence that some areas are higher potential (green) compared to others which are lower potential (red). Conversely, a graded single colour can convey more uncertainty. This is an important point of discussion in emerging energies where not as much information exists about successful resource extraction. Best practice is to choose a colourbar that represents the most objective approximation of the inherently subjective results that are obtained during a qualitative resource assessment.

6. CONCLUSIONS

Qualitative resource assessments are useful investigation and communication tools that can be adapted to many systems. As illustrated in this report, the gas hydrate system is a simple modification and serves as a good example of an extension of the methodology for an unconventional petroleum system.

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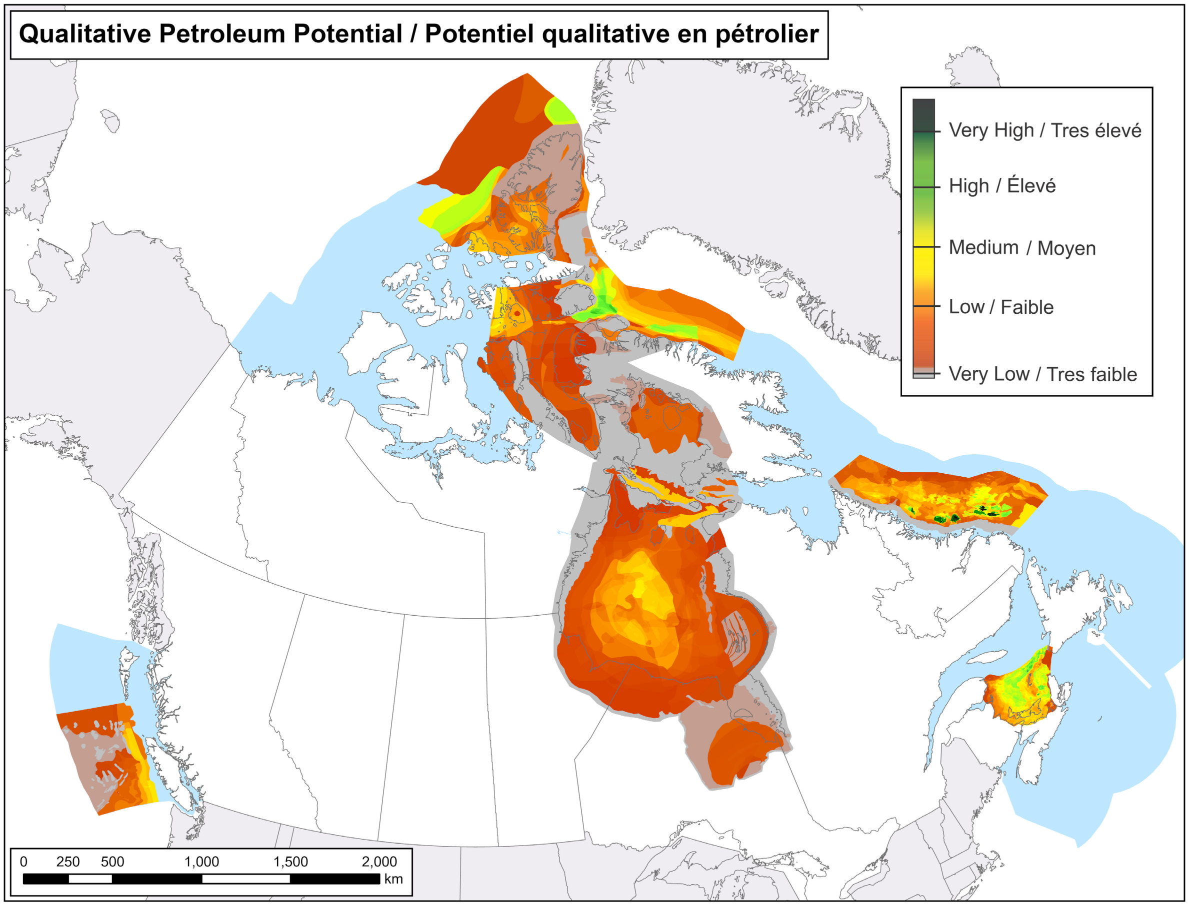

Figure 1. Qualitative petroleum resource potential map of Canada

This map displays 11 qualitative hydrocarbon petroleum potential resource assessments conducted by the MCT team since 2016 to present. Resource assessments are presented with a very low (grey-red) to very high (dark green) potential qualitative scale. Qualitative assessments can give large scale snapshots of resource potential to be used as communication tools or as first steps in more detailed, quantitative assessments of high potential areas.

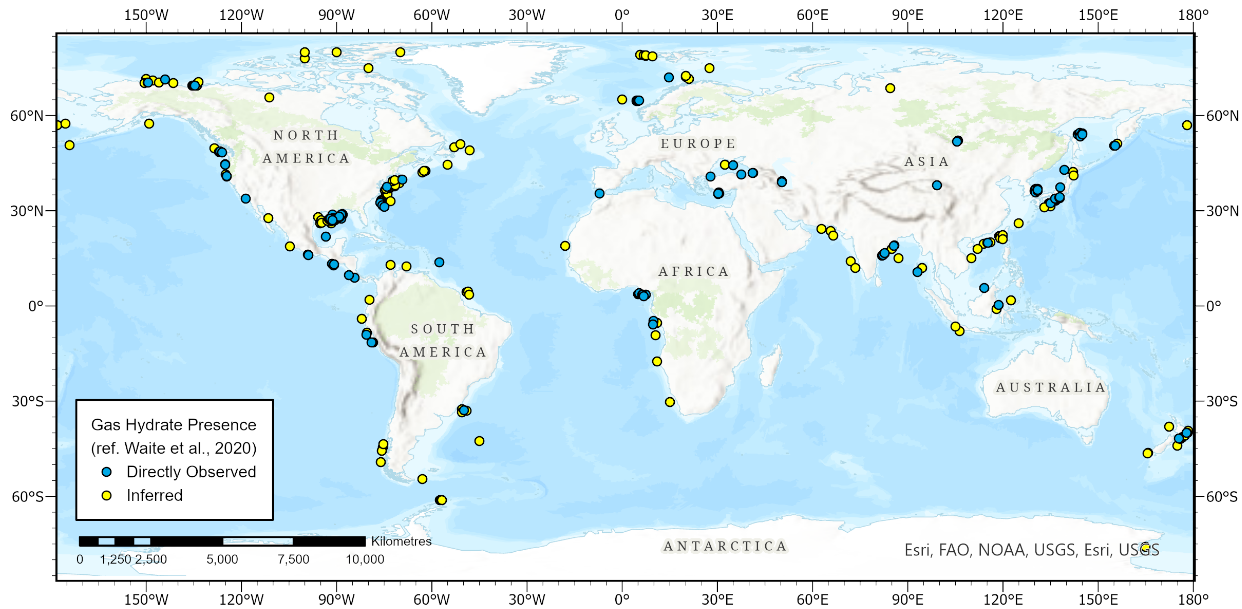

Figure 2. Worldwide gas hydrate presence based on data downloaded from the USGS

Gas hydrates are present around the world offshore on continental slopes and onshore in arctic regions in permafrost zones. Locations of directly observed and inferred gas hydrates and shown with blue and yellow circles, respectively. Inferred hydrate occurrence is based on seismic data interpretation and/or well logs. Map created from a publicly available dataset published by the United States Geological Survey (Waite et al., 2020).

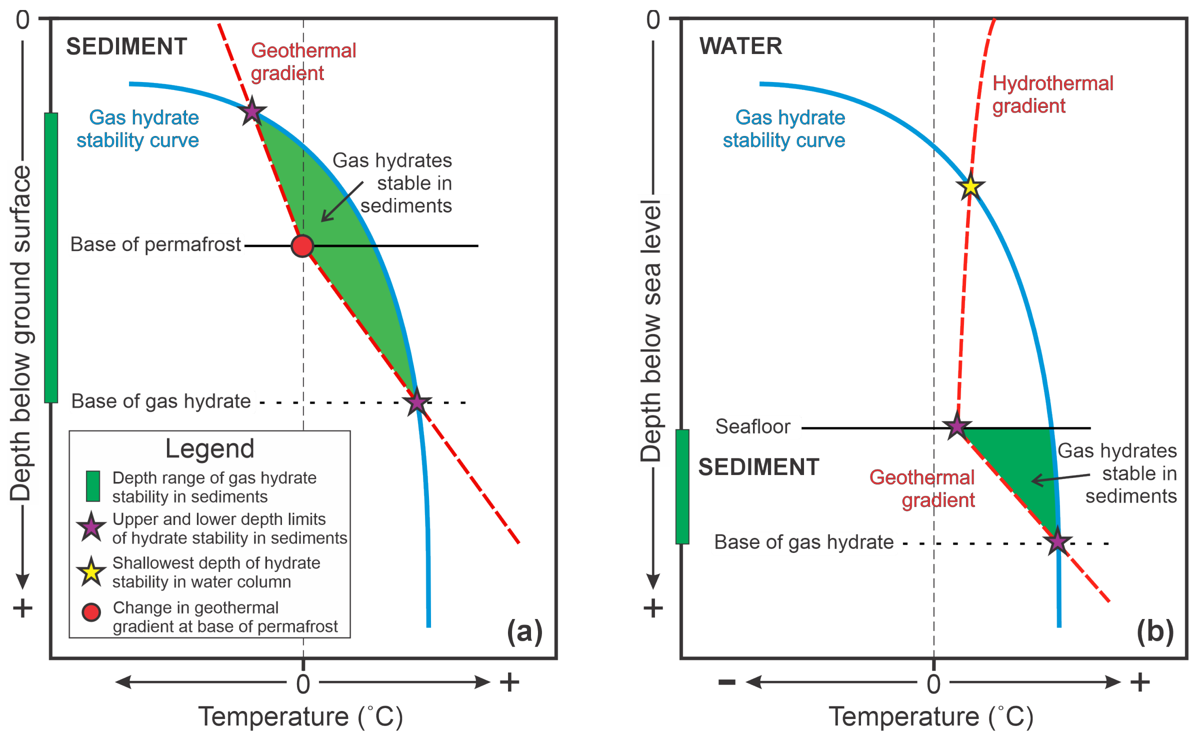

Figure 3. Schematic illustrating gas hydrate stability curves in (a) onshore permafrost and (b) marine settings

The gas hydrate stability zone (GHSZ) is extracted from the intersection points of the geothermal and hydrothermal gradients with the phase boundary for gas hydrates (i.e. highlighted green area in figures). Note that onshore, hydrates are stable both above and below the base of permafrost and offshore, they can be stable within the water column itself up to a certain depth (yellow star in (b). Water column occurrences of hydrates are commonly seen as mounds on the seafloor, but further up in the water column, hydrate encrusted bubbles can form. Figure modified from Sloan et. al. (2010).

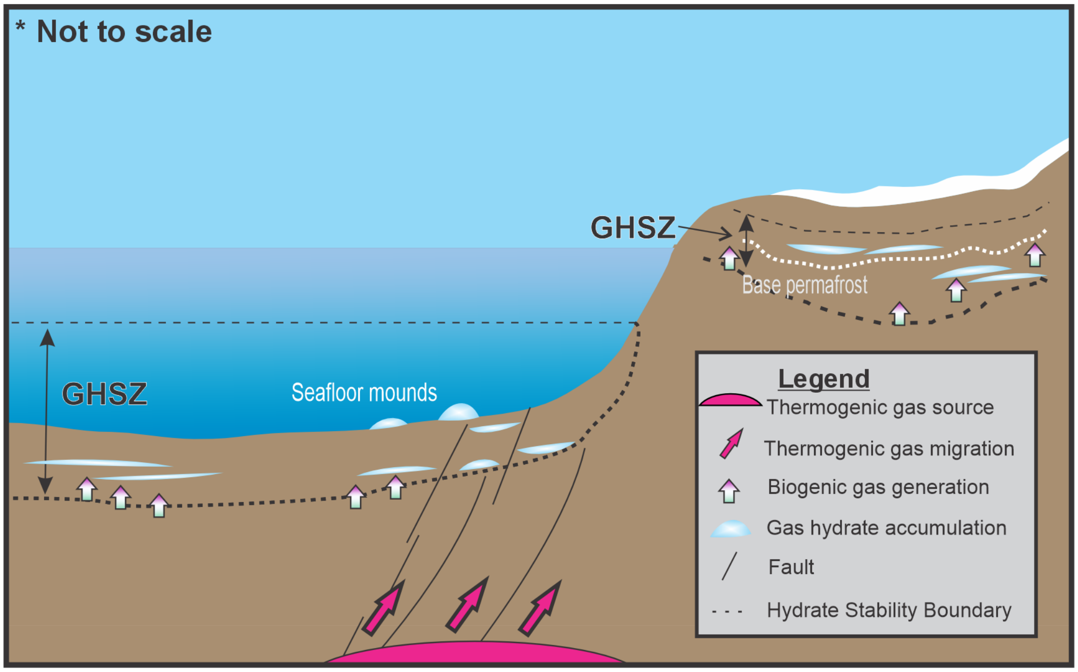

Figure 4. Schematic illustrating gas hydrate stability environments and gas sourcing

Gas hydrates exist in limited conditions onshore and offshore. Onshore, hydrates can be stable above and below the base of permafrost. Offshore, hydrates can be stable within the water column (e.g. seafloor mounds) and into relatively shallow sediments. Gas hydrates are commonly sourced by thermogenic gas migration from underlying reservoirs or by in situ biogenic gas generation. GHSZ = Gas hydrate stability zone. Note this figure is not to scale. Note a section of this 'seismic interpretation cross section' figure is used in Figure 7 as part of an example dataset used to illustrate the qualitative resource assessment process for gas hydrates (Fig. 9).

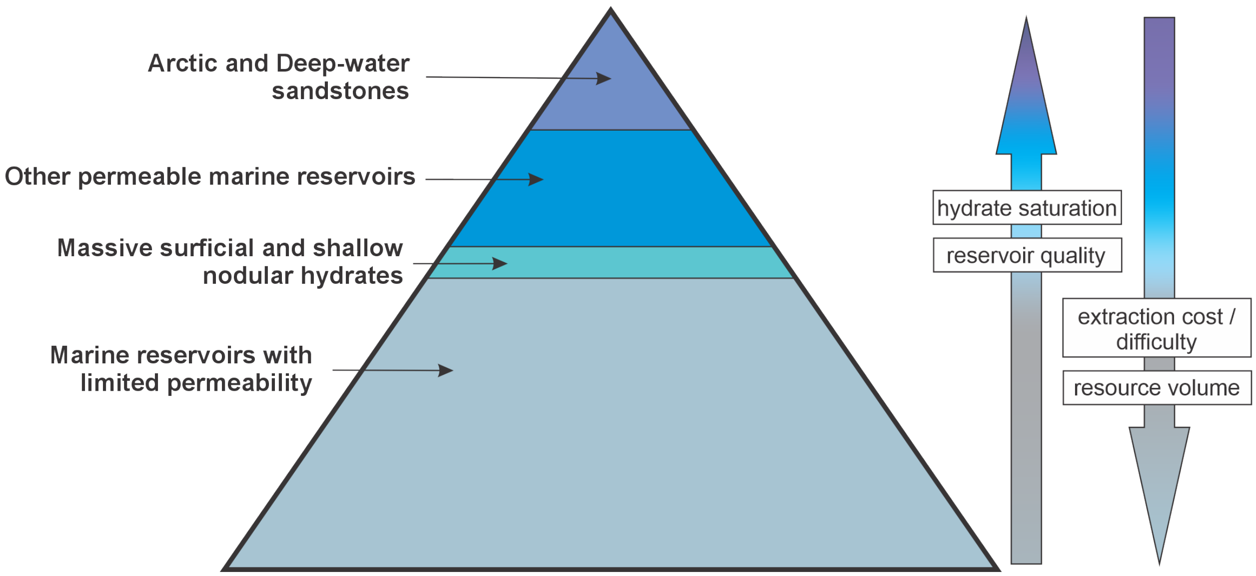

Figure 5. Gas hydrate resource pyramid

Modified from Boswell and Collett (2006). Most gas hydrate accumulations are not good candidates for extraction with current technologies. When assigning COS to hydrate reservoirs, higher values were given to sandstone reservoirs. Note the original pyramid separates onshore Arctic and deep marine sandstones due to accessibility concerns (closer proximity to existing infrastructure classified into higher quality deposits). The GSC does not factor in existing infrastructure and considers all good quality sandstones reservoirs to be of equal value on a resource potential scale.

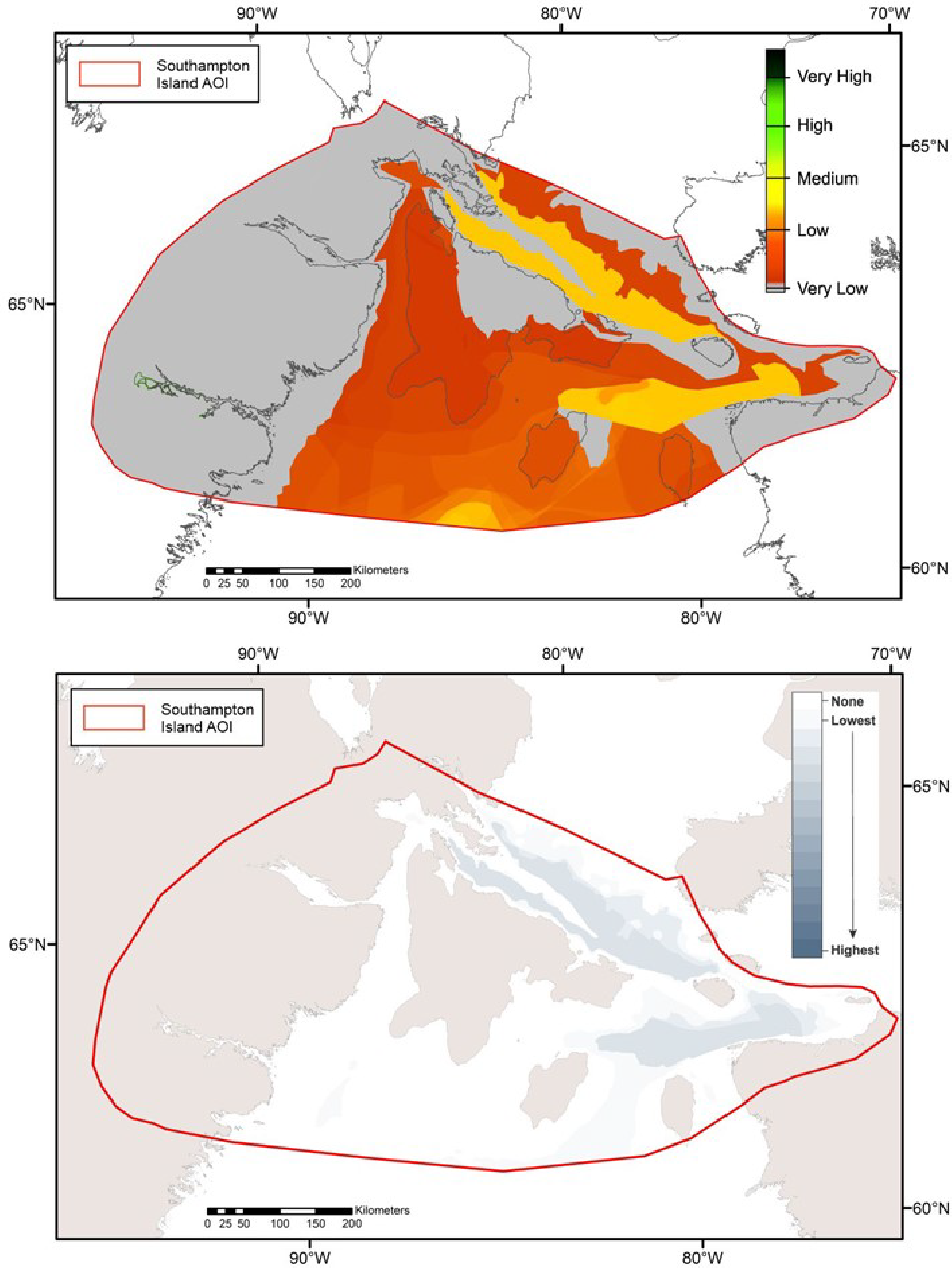

Figure 6. Qualitative potential maps

Top. Qualitative Petroleum Potential Map modified from Dewing et al., 2023. Areas of higher potential in the Mesozoic grabens are in shades of yellow north and southeast of Southampton Island AOI. Red border shows the AOI. Bottom. Gas hydrate saturation potential map for Southampton Island from low (light blue) to high (dark blue) qualitative potential.

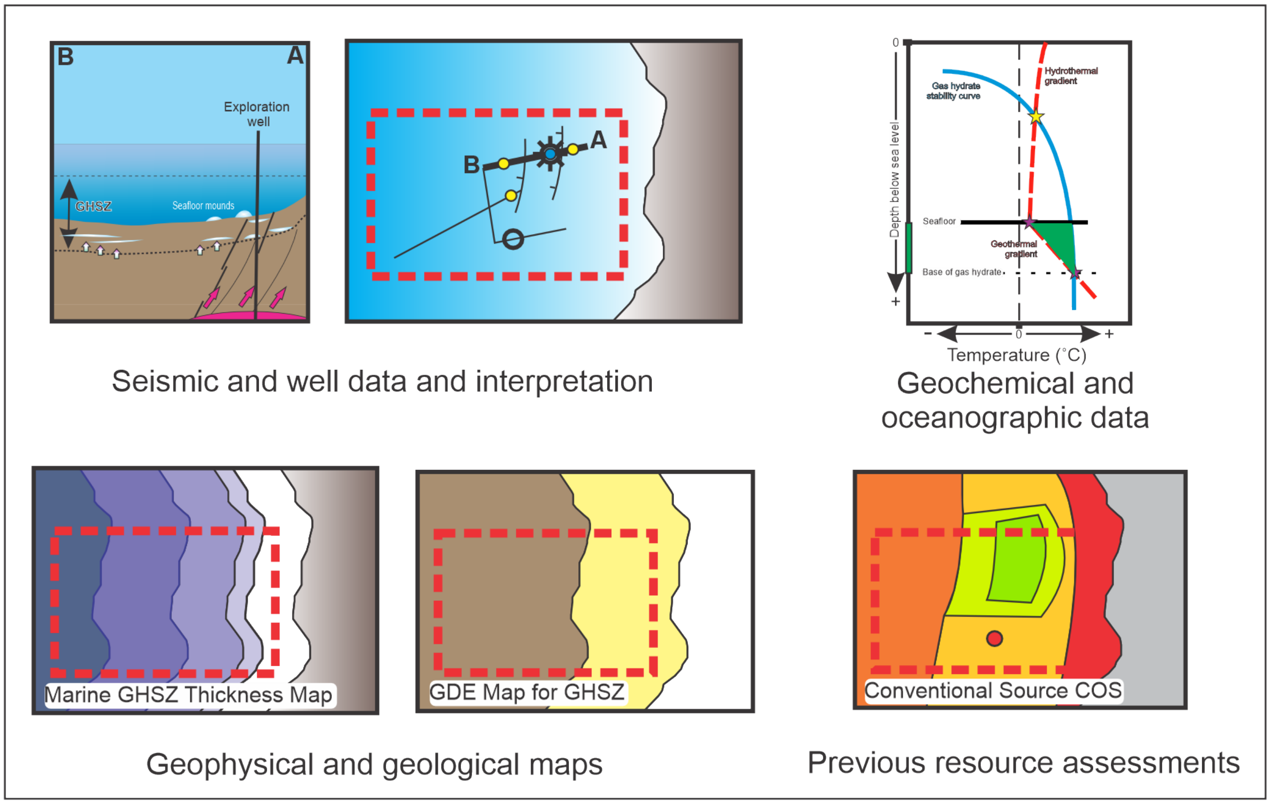

Figure 7. GIS datasets for gas hydrates

The accumulation of relevant datasets is a key first step in performing a qualitative resource assessment. It is necessary to visualize and understand the spatial overlap and interplay of different data. These schematic datasets are used in Figure 9 as a high-level example of how COS might be assigned during an assessment. In this example, the data available includes (from left to right, and top to bottom) seismic and well data interpretation, gas hydrate phase stability curves, interpreted or calculated geophysical and geological maps (marine GHSZ thickness map and a gross depositional environment (GDE) map for the stability zone), as well as a map from a previous conventional resource assessment. See Figure 9 for COS assessment and the resulting CCOS (gas hydrate saturation) map for this 'dataset'.

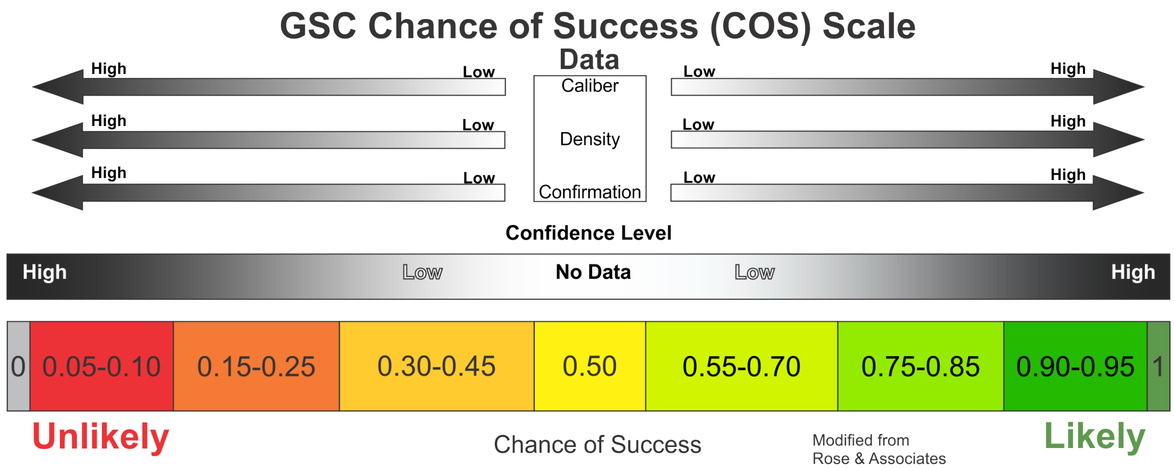

Figure 8. COS scale from Lister et al, 2018 (their Fig. 1)

Data confidence COS scale used to assess petroleum system elements (modified from Rose, 2001, p. 38). As data calibre, density or confirmation increase, the COS can move to the unlikely (0) or likely (1) ends of the scale depending on whether data confirm or refute the presence of the system element. If an area is data void, or if there is conflicting information from available data, a value of 0.5 (or no confidence) is assigned.

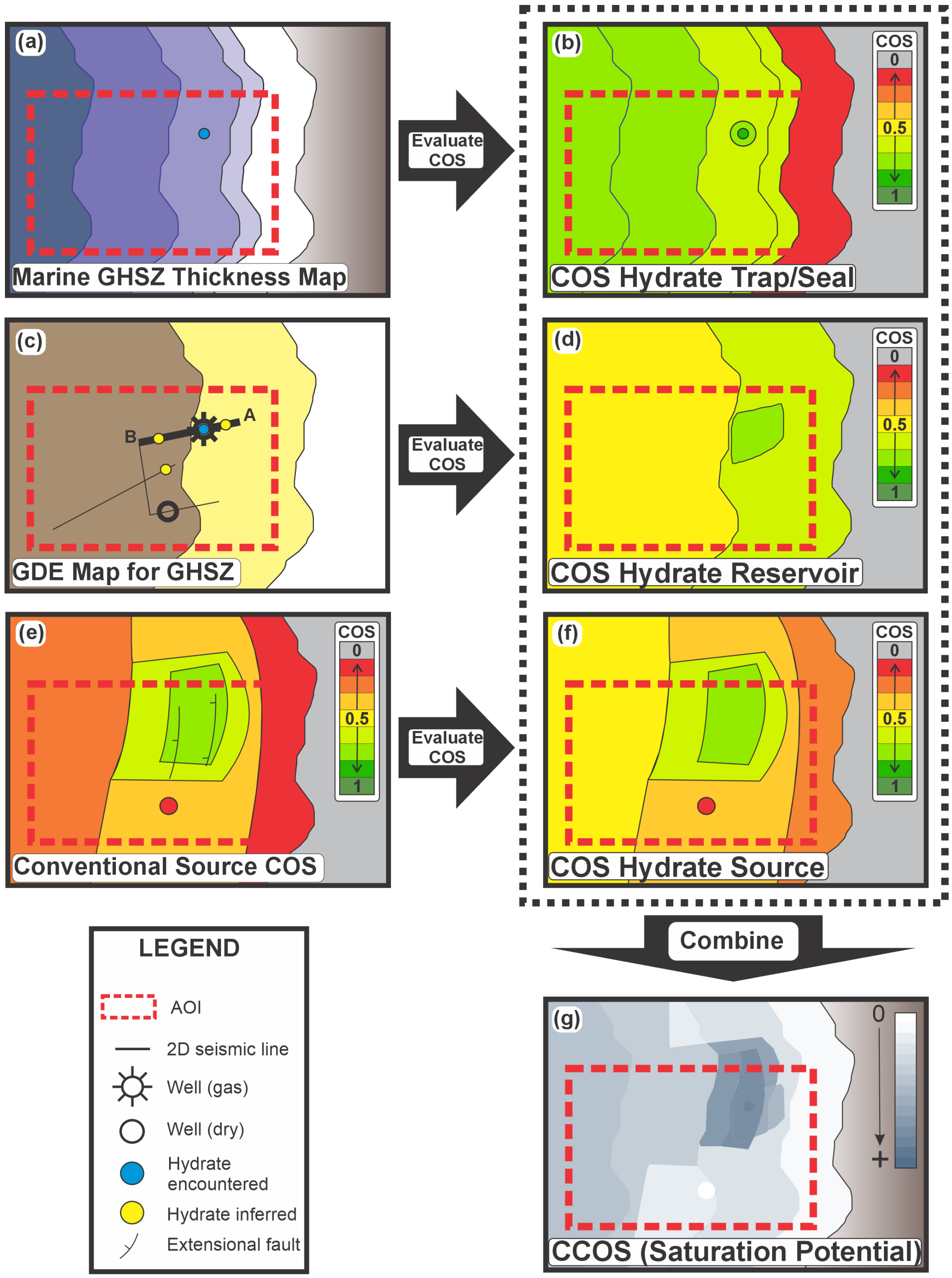

Figure 9. Evaluating COS elements for gas hydrates to create a saturation potential map

A high-level gas hydrate qualitative resource assessment illustrating spatial assignment of COS values by evaluating the relevant available data for each system element (a: trap/seal, c: reservoir, and e: source) then spatially assigning COS values according to data confidence (b, d, and f). The COS elements are then combined using Eq. 3 and the resulting CCOS map (g) is coloured based on a relative saturation scale to highlight areas of higher hydrate saturation potential (darker blues).

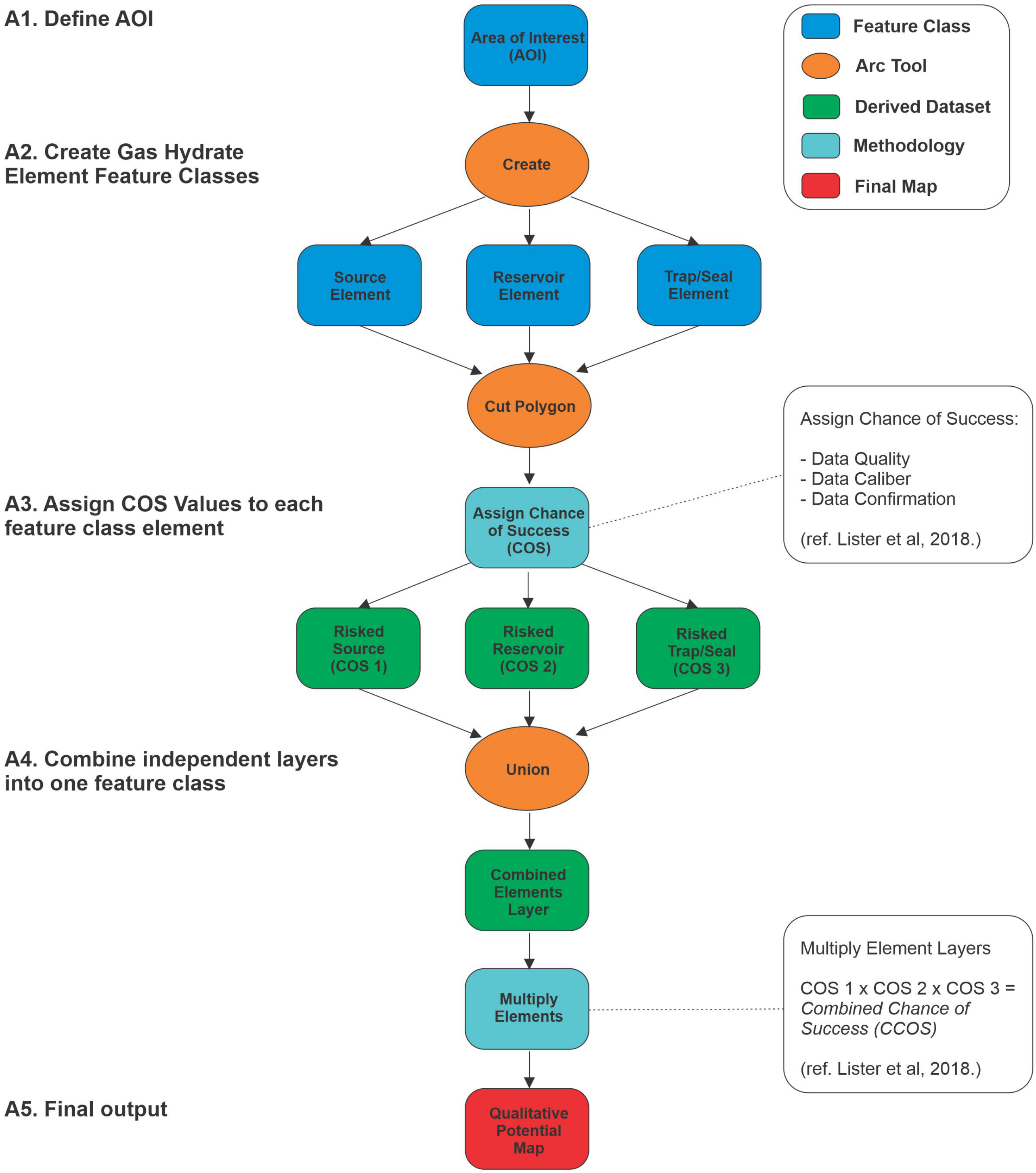

Figure 10. ArcGIS® modelbuilder workflow

The qualitative gas hydrates potential map is generated through the ArcGIS® modelbuilder workflow consisting of 5 steps (A1 to A5). The workflow begins with a creation of a user defined geodatabase and feature classes (blue element), utilization of pre-defined set of Arc Tools (orange element), qualitative assessment of elements (teal element), output of derived dataset (green element), and computed final qualitative potential map (red element).

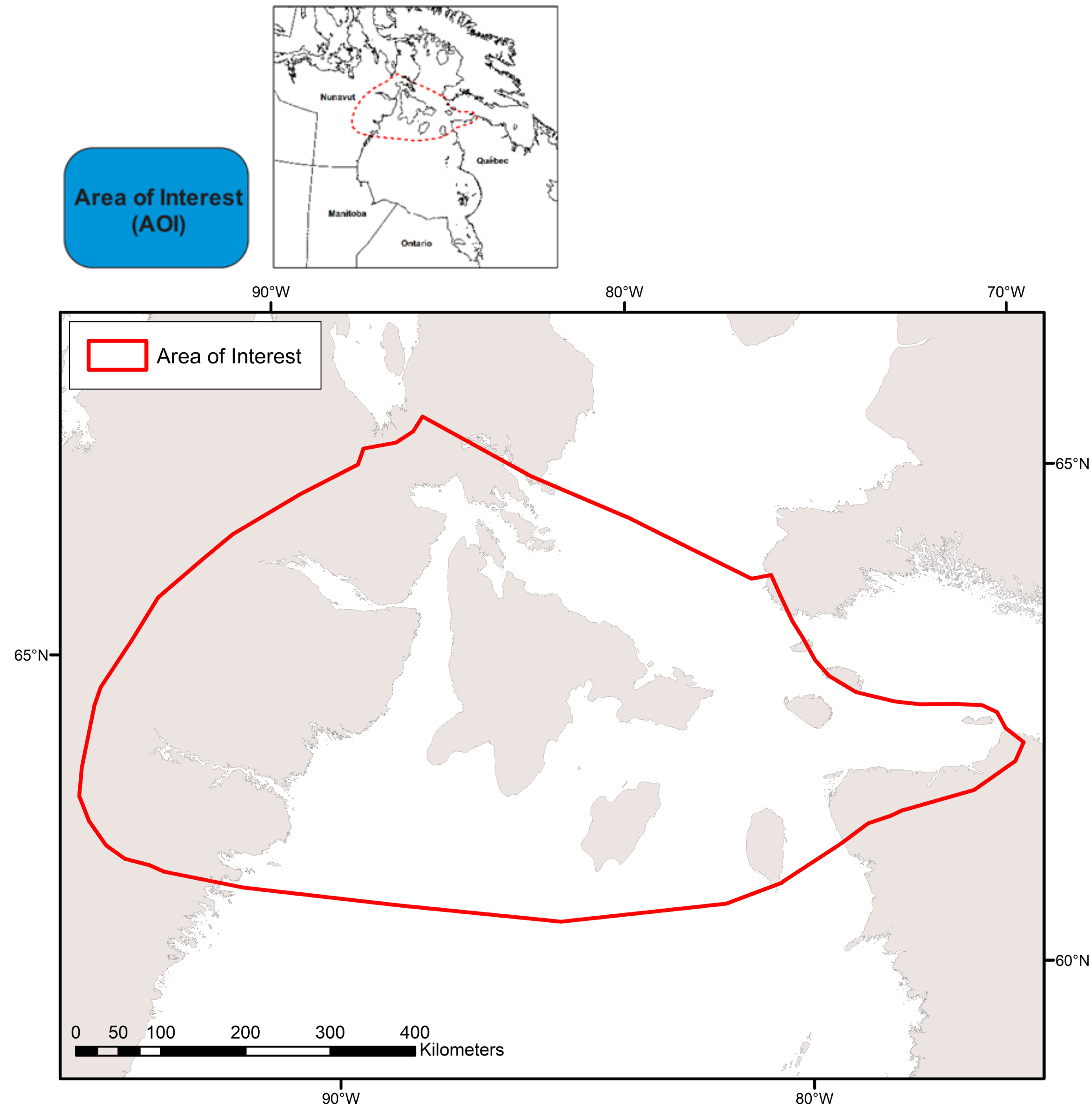

Figure 11. Step A1. Define AOI

The AOI represents the extent of the study area for the qualitative gas hydrates potential map. The area of interest is typically geologically constrained, however there is no size limit. The area of interest is defined by a polygon feature class. The red outline illustrates the Southampton Island AOI.

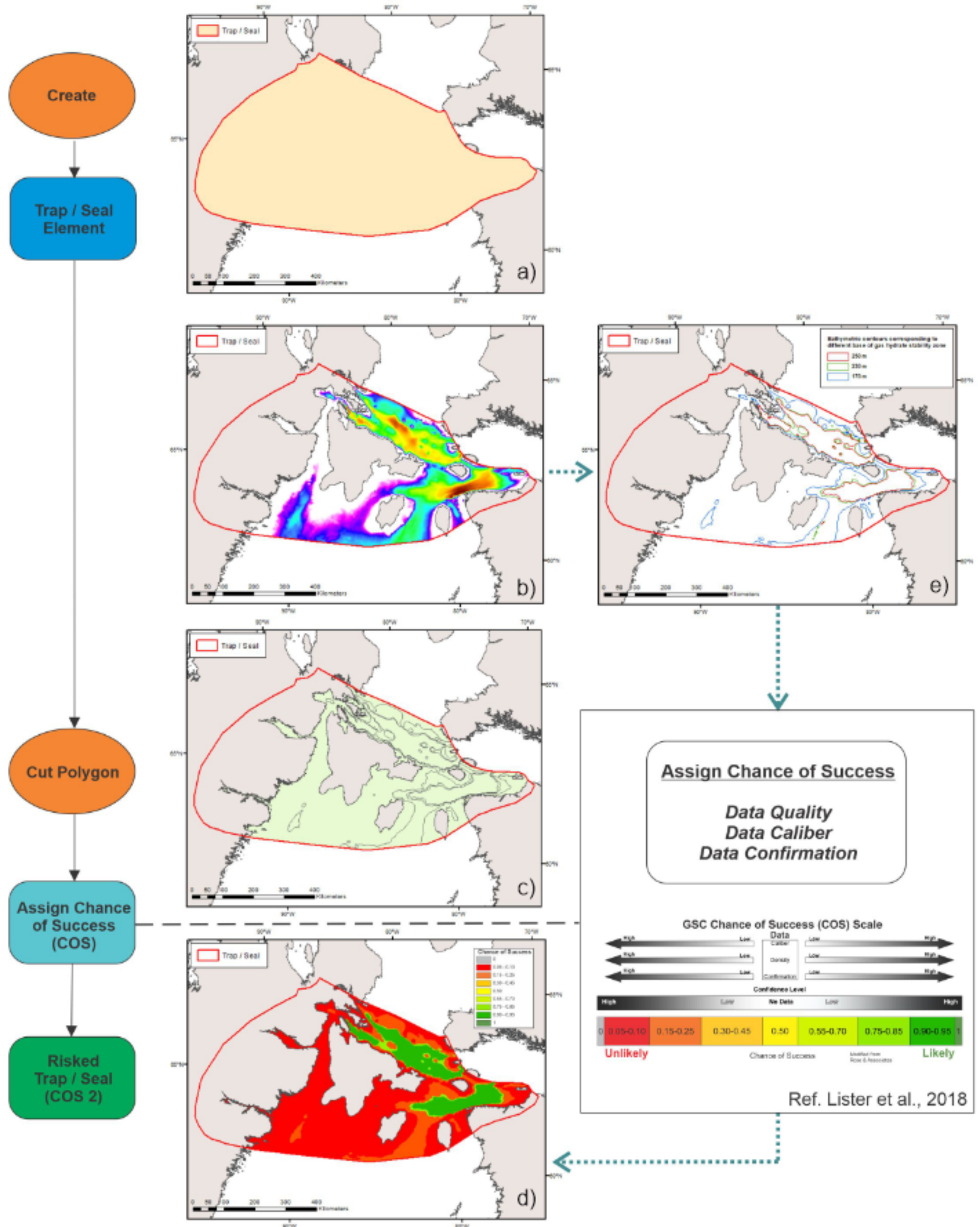

Figure 12. Step A2. Create element + A3. Assign chance of success

This workflow further breaks down Step A2. And A3. and the process in evaluation and assigning chance of success to gas hydrates elements. In step A2, using the feature class from A1, create a unique polygon feature class for each play element: source, reservoir, and trap/seal. Each feature class is then divided using the “Cut” tool based on relevant data sources to the element that is being divided. In this workflow, the “trap/seal” element is cut based on bathymetric contours corresponding to different base of calculated stability zone (170m, 230m, and 250m). The “cut” feature class will then be assigned a “Chance of Success” value based on the geological property in relation to the element being risked in the “Attribute Table” (Figure 13).

Table

TrapSeal_GasHydrate

Shape *	COS_Trap	TrapSeal_Description
Polygon	0.95	250. Stability conditions exist at seafloor for all curves.
Polygon	0.95	250. Stability conditions exist at seafloor for all curves.
Polygon	0.95	250. Stability conditions exist at seafloor for all curves.
Polygon	0.75	230-250. Stability conditions exist in wedge below seafloor for Lewin et al. curve and Sloan 1998. Majorowicz and Osadetz, 2003.
Polygon	0.75	230-250. Stability conditions exist in wedge below seafloor for Lewin et al. curve and Sloan 1998. Majorowicz and Osadetz, 2003.
Polygon	0.75	230-250. Stability conditions exist in wedge below seafloor for Lewin et al. curve and Sloan 1998. Majorowicz and Osadetz, 2003.
Polygon	0.75	230-250. Stability conditions exist in wedge below seafloor for Lewin et al. curve and Sloan 1998. Majorowicz and Osadetz, 2003.
Polygon	0.75	230-250. Stability conditions exist in wedge below seafloor for Lewin et al. curve and Sloan 1998. Majorowicz and Osadetz, 2003.
Polygon	0.75	230-250. Stability conditions exist in wedge below seafloor for Lewin et al. curve and Sloan 1998. Majorowicz and Osadetz, 2003.
Polygon	0.75	230-250. Stability conditions exist in wedge below seafloor for Lewin et al. curve and Sloan 1998. Majorowicz and Osadetz, 2003.
Polygon	0.25	170-230. Stability conditions exist in wedge below seafloor for Lewin et al. curve. Majorowicz and Osadetz, 2001.
Polygon	0.25	170-230. Stability conditions exist in wedge below seafloor for Lewin et al. curve. Majorowicz and Osadetz, 2001.
Polygon	0.25	170-230. Stability conditions exist in wedge below seafloor for Lewin et al. curve. Majorowicz and Osadetz, 2001.
Polygon	0.25	170-230. Stability conditions exist in wedge below seafloor for Lewin et al. curve. Majorowicz and Osadetz, 2001.
Polygon	0.25	170-230. Stability conditions exist in wedge below seafloor for Lewin et al. curve. Majorowicz and Osadetz, 2001.
Polygon	0.25	170-230. Stability conditions exist in wedge below seafloor for Lewin et al. curve. Majorowicz and Osadetz, 2001.
Polygon	0.25	170-230. Stability conditions exist in wedge below seafloor for Lewin et al. curve. Majorowicz and Osadetz, 2001.
Polygon	0.25	170-230. Stability conditions exist in wedge below seafloor for Lewin et al. curve. Majorowicz and Osadetz, 2001.
Polygon	0.25	170-230. Stability conditions exist in wedge below seafloor for Lewin et al. curve. Majorowicz and Osadetz, 2001.
Polygon	0.25	170-230. Stability conditions exist in wedge below seafloor for Lewin et al. curve. Majorowicz and Osadetz, 2001.
Polygon	0.05	Marine hydrate stability conditions do not exist.
Polygon	0.05	Marine hydrate stability conditions do not exist.
Polygon	0.05	Marine hydrate stability conditions do not exist.
Polygon	0.05	Marine hydrate stability conditions do not exist.
Polygon	0.05	Marine hydrate stability conditions do not exist.
Polygon	0.05	Marine hydrate stability conditions do not exist.
Polygon	0.05	Marine hydrate stability conditions do not exist.

Figure 13. Step A3. Assign chance of success

Each polygon feature class is cut based on compiled geological resources and a differing chance of success value. The assigned chance of success value is based on the risk matrix published in Lister et al. (2018). This is an attribute table in ArcGIS® from the Trap/Seal COS feature class. The table summarizes each cut that has been made based on COS value and relevant data.

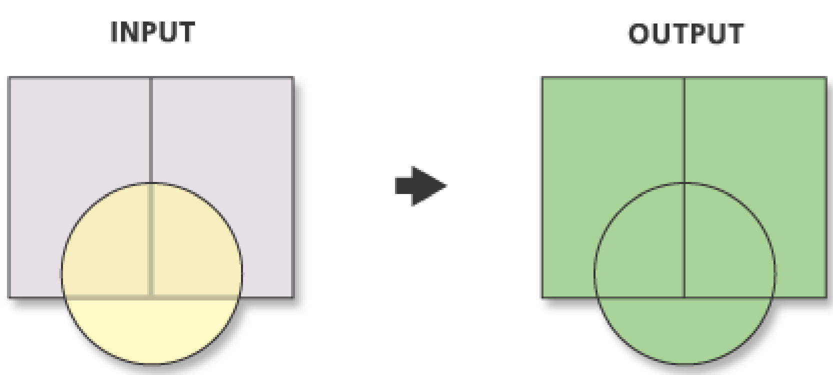

Figure 14. Union Analysis tool

The Union tool creates a new object for when an intersection of *n* objects occurs (ref. ArcGIS® Pro Documentation, https://pro.arcgis.com/en/pro-app/latest/tool-reference/analysis/union.htm).

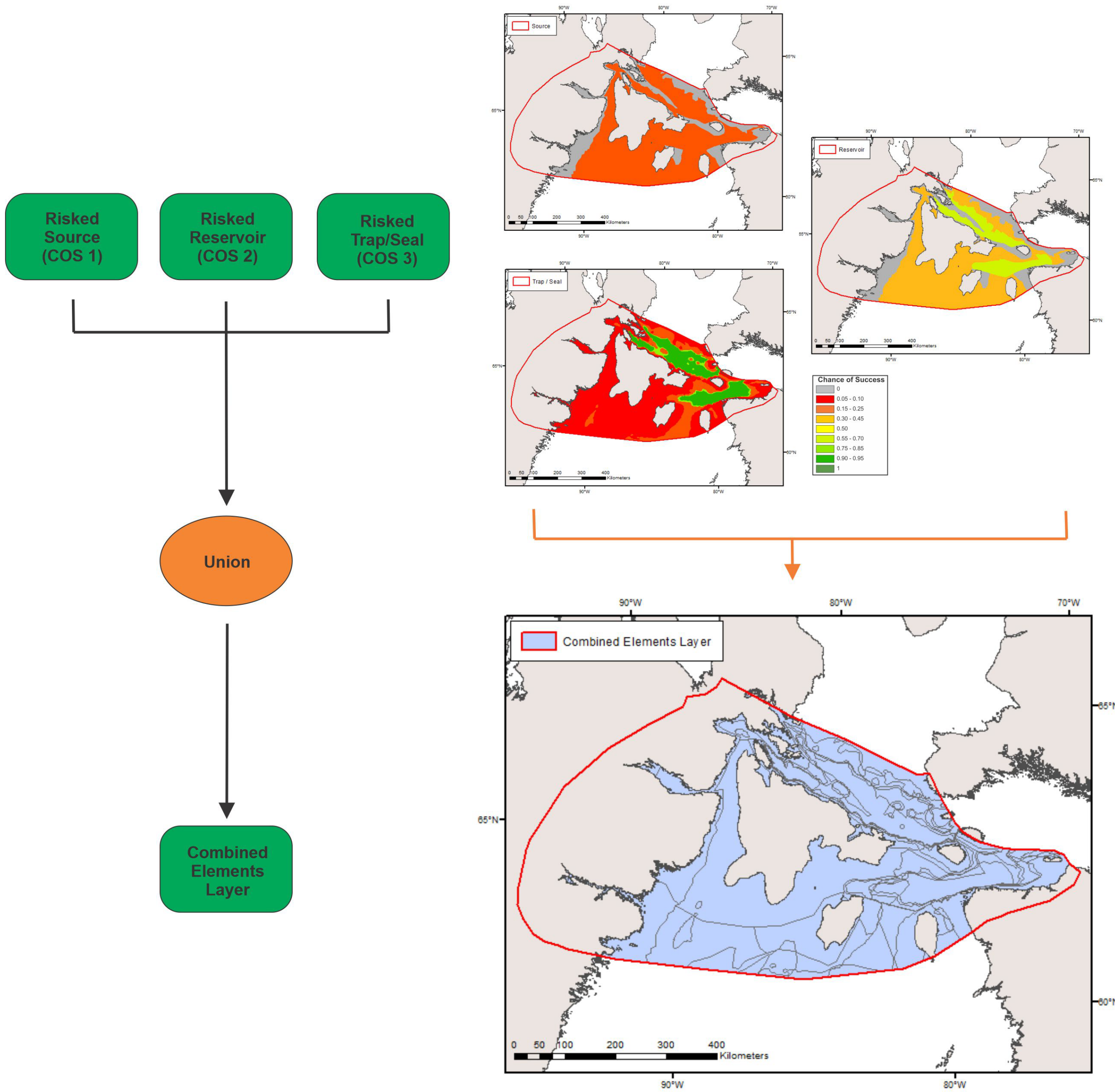

Figure 15. Step A4. Combine independent layers into one feature class

From step A2. and A3., the source, reservoir, trap/seal are combined using the Union tool. The Union tool creates a new feature class polygon based on an intersection of n inputs (Equation 3). In the Southampton Island case, n=3.

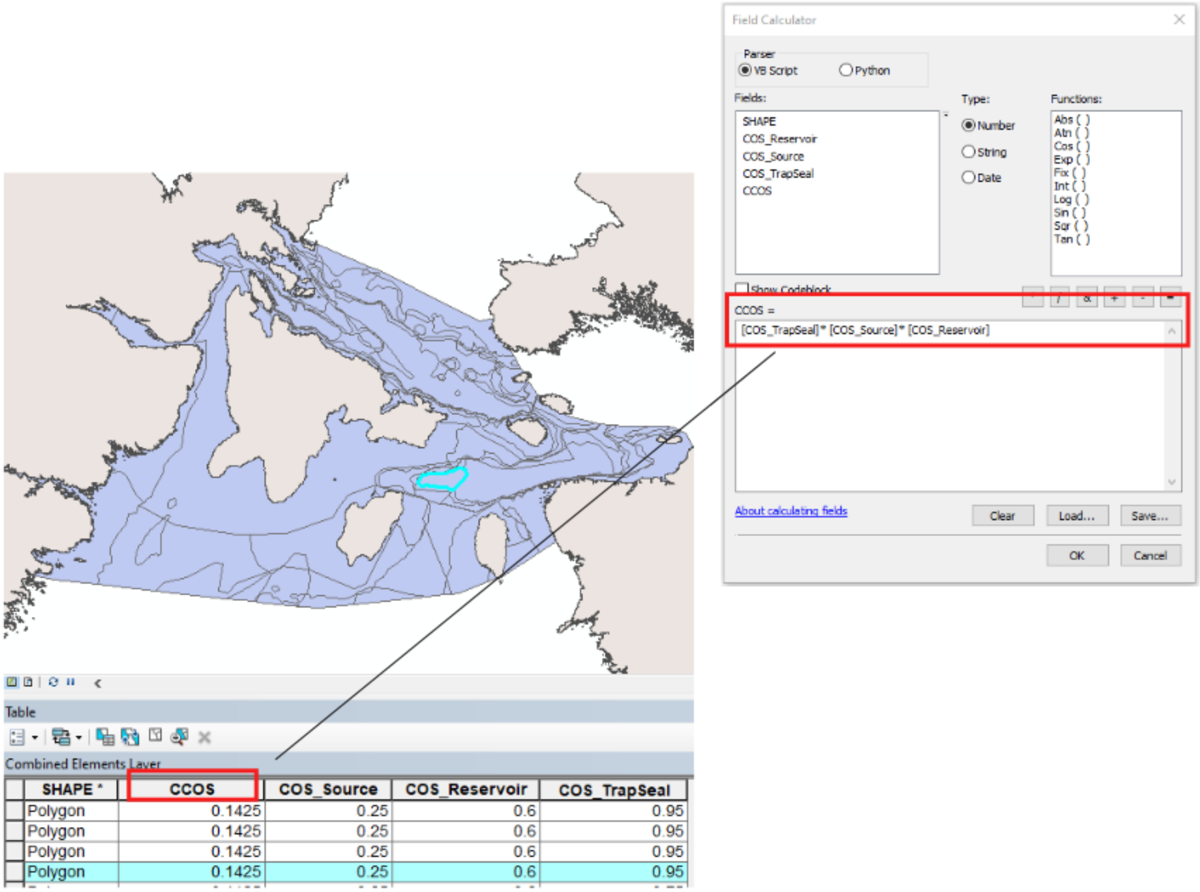

Figure 16. Create CCOS field and calculate CCOS value

Left. Create “CCOS” field in the feature class attribute table highlighted in red. Right. Utilizing the raster calculator, calculate CCOS using equation 3 and fill the appropriate field.

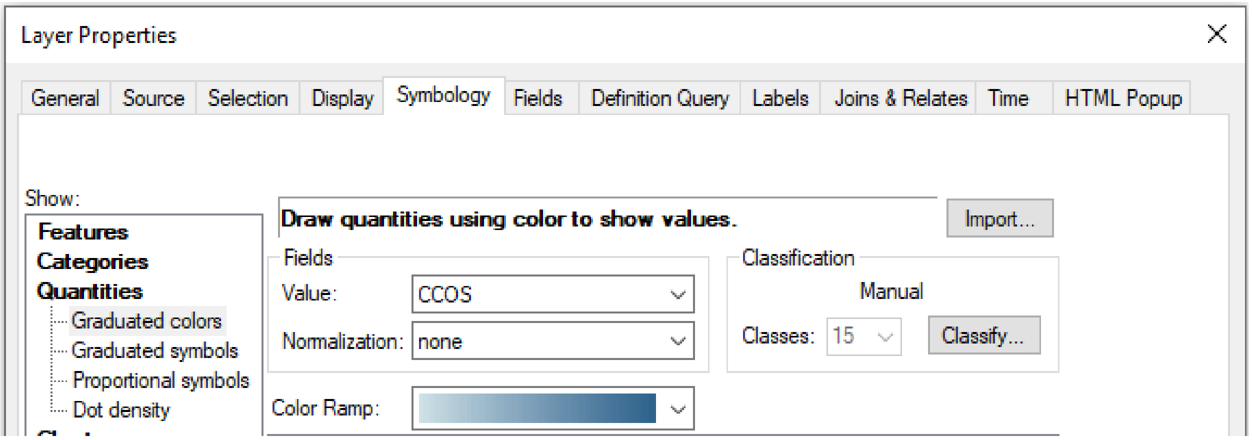

Figure 17. Applying gas hydrates saturation colourbar

Using the 'Layer Properties" tool, apply custom colour coded CCOS colourbar to the CCOS field in the attribute table. A gradational blue colour was chosen to reflect the relative uncertainty in gas hydrate saturation potential.

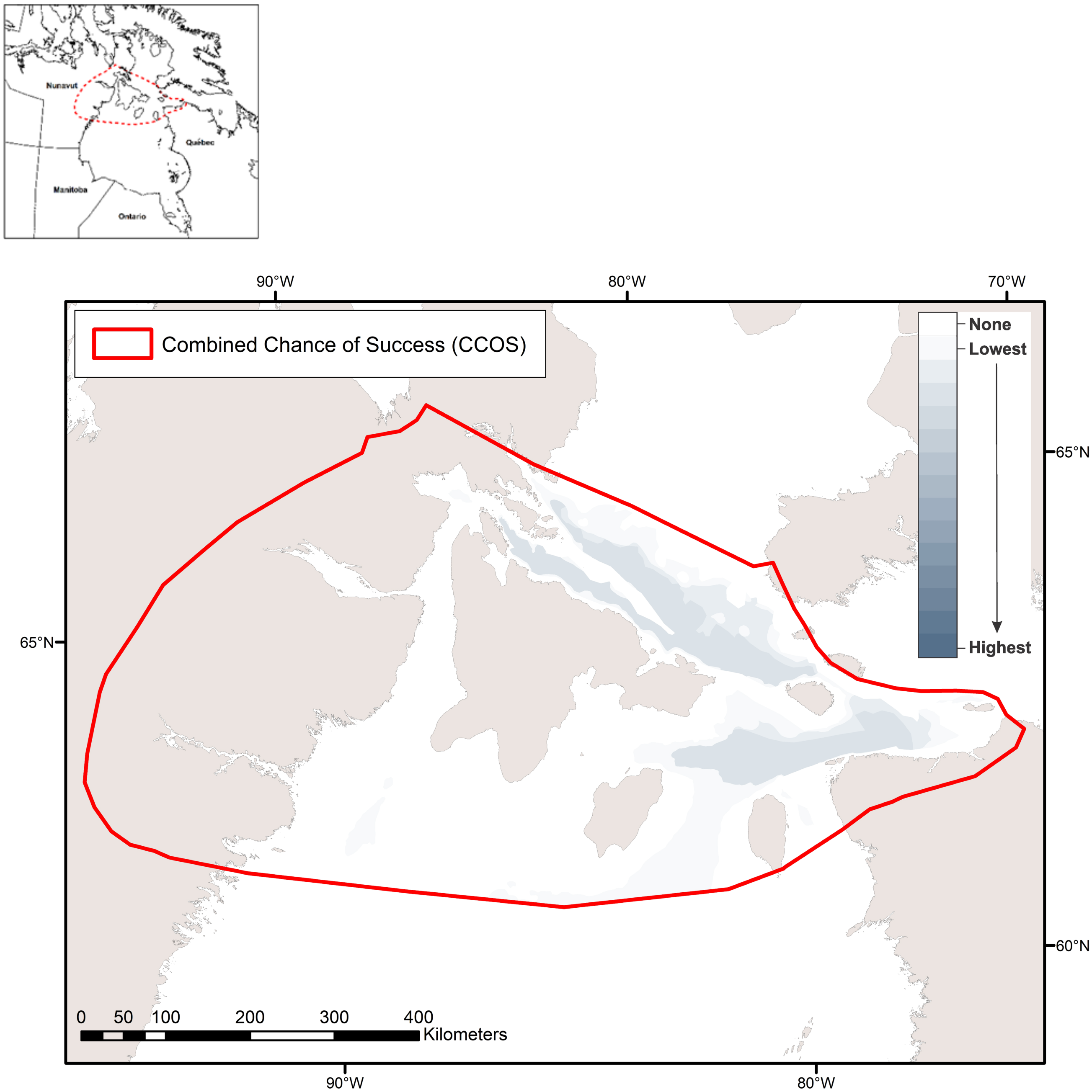

Figure 18. Step A5. Qualitative methane hydrates CCOS (hydrate saturation potential)

This map represents the probabilistic 'roll-up' of the gas hydrates with a low to high saturation potential colourbar. The final qualitative map indicates a very low to low hydrate saturation potential for the Southampton Island AOI. Note that when choosing a colourbar for an energy system, it is important to consider what message is being conveyed. For systems where there is already a robust assessment history, a colourbar that is red to green (i.e. 'low potential' to 'high potential', like in the petroleum resource assessment seen in Fig. 7 - top) might work; however, for systems where there is more uncertainty (like gas hydrates), a gradational monocolour bar might be more appropriate.