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OPEN FILE 8657**

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and Northwest Territories**

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Abstract

The Mackenzie Trough is a unique geological feature of the Canadian Beaufort Sea connecting the Mackenzie River Delta to the continental slope. This study utilizes geoscientific interpretation methods applied to seismic reflection data acquired on the Beaufort Shelf between 2006 and 2017 to map four seismic markers observed within the shallow subsurface of the Mackenzie Trough; i.e. the base of the Mackenzie Trough and three other seismic markers located between the latter and the seafloor. Seismic interpretation has produced four time-structure maps and five time-isopach maps that contribute to the existing geological framework in this sector of the Beaufort Sea. The results suggest that the actual morphology of the Mackenzie Trough is inherited from its base. During the Quaternary, terrigenous sediment supply related to glacier advance and retreat gradually and partially filled the trough. Thicker Quaternary deposits are found within a broad U-shaped erosional cut located in the center of the Mackenzie Trough. Time-isopach maps reveal that zones of thicker sediment accumulations have shifted during the Quaternary, moving landward between the Pliocene and the Holocene.

Résumé

La fosse du Mackenzie est une particularité géologique de la mer de Beaufort canadienne reliant le delta du fleuve Mackenzie au talus continental. Cette étude utilise des méthodes d'interprétation géoscientifique appliquées aux données de sismique-réflexion acquises sur le plateau continental de la mer de Beaufort entre 2006 et 2017 pour cartographier quatre marqueurs sismiques observés dans la sous-surface peu profonde de la fosse du Mackenzie; c'est-à-dire la base de la fosse du Mackenzie et trois autres marqueurs sismiques situés entre cette dernière et le fond marin. Les pointés sismiques ont permis de construire quatre cartes de profondeur-temps et cinq cartes d'épaisseur-temps afin de fournir un cadre géologique plus détaillé dans ce secteur de la mer de Beaufort. Les résultats suggèrent que la morphologie actuelle de la fosse du Mackenzie est héritée de sa base. Au Quaternaire, les dépôts de sédiments terrigènes liés à l'avancée et au retrait des glaciers ont progressivement et partiellement comblé la fosse. De plus, des dépôts quaternaires plus épais sont localisés dans une large incision en forme de U au centre de la fosse du Mackenzie. Les cartes d'épaisseur-temps ont révélé que des zones d'accumulation sédimentaires plus importantes se sont déplacées vers la côte au cours du Quaternaire, entre le Pliocène et l'Holocène.

Introduction

The Beaufort-Mackenzie Basin (BMB) of the Beaufort Sea is located at the northern limit of the Canadian continental margin bordering both the Yukon and Northwest Territories. Exploration of the BMB dates back to the pioneering work of the Geological Survey of Canada's Operation Porcupine in the 1960s that within 10 years advanced from traditional mapping to subsurface stratigraphic studies (Young et al., 1976). The drilling and geophysical activity by the petroleum industry that followed as well as further work by the Geological Survey of Canada and others has revealed that the BMB results from a complex geological history.

Historical petroleum exploration has shown that the BMB has a unique set of geographical and geological factors to consider (Timco and Frederking, 2009): 1) the BMB is remotely located in an area with sea-ice coverage; 2) the permafrost located onshore extends beneath the Beaufort shelf; and 3) drilling problems related to formation overpressure have been encountered on numerous occasions. Despite these challenges, the BMB remains an area of interest for petroleum development given that new technologies such as Floating Liquid Natural Gas and Ice Breaking Liquid Natural Gas tankers

combined with the reduced and reducing sea ice cover now provides the opportunity for the potential development of offshore natural gas resources in the Arctic (Barr, 2017; Barisic et al., 2018). However, in 2016 the Government of Canada announced that Canadian Arctic waters were indefinitely off limits to new offshore oil and gas licenses, to be re-evaluated every 5 years by a science-based review taking into account marine and climate change science (<https://pm.gc.ca/en/news/backgrounders/2016/12/20/select-actions-being-taken-under-united-states-canada-joint-arctic>).

The Mackenzie Trough is a unique feature of the Canadian Beaufort Sea. It is a major linear bathymetric depression oriented NNW that extends from the modern Mackenzie River Delta to the continental slope measuring over ~150 km in length with a width of ~70 km in water depths ranging from 20 to ~800 m (Figure 1). The Mackenzie Trough is considered to be a young paleo-valley that formed by glacial erosion during the Late Wisconsinan (25 to 10 kyr) that is filled by ~400 m of unconsolidated sediments (Batchelor et al., 2014). Recently, it has received the attention of geoscientists because of its potential to trap sediments that can help constrain climatic and oceanic fluctuations through recent geological times (Batchelor et al. 2013b; Batchelor et al., 2014; Klotsko et al., 2019). This report addresses seismic reflection mapping of four horizons that are observed within the shallow subsurface of the Mackenzie Trough. It provides insights on the geology of this area of the Beaufort Sea and a basis to better understand the occurrence and distribution of subsea permafrost and the potential for marine geohazards. The research forms part of the Public Safety Geoscience and Environmental Geoscience programs within the Geological Survey of Canada.

Data and methods

Two 2-D datasets were available for seismic interpretation (Figure 1): 1) the multi-client BeaufortSpan East Program collected and processed by ION between 2006 and 2011 (<https://www.iongeo.com/data-library/arctic/beaufort-sea/beaufortspan-east/>; Dinkelman et al., 2008), and 2) two high-resolution seismic programs jointly undertaken by the Korea Polar Research Institute (KOPRI), the Geological Survey of Canada (GSC) and the Monterey Bay Aquarium Research Institute (MBARI) in 2014 and 2017 (Jin et al., 2016; Jin et al., 2018), processed by geophysicists from GSC and KOPRI (Riedel et al., 2016; Duchesne et al., 2019a).

Seismic grids were generated for all four interpreted horizons (see description of horizons below). All grids were built using the inverse distance to a power method. This method was selected as the most appropriate given the irregularly and sparse distribution of seismic data across the study area (Shepard, 1968). The inverse distance to a power interpolator applies power weighting at the xyz locations where seismic traces are picked to project interpolated xyz picked values at a grid node location. Weighted values result from a search made from the four direction of a grid node using the input data. Given the irregular seismic line spacing (up to 23 km) in the BMB, horizons were gridded according to a cell size of 500 m. Depending on the spatial distribution of the picks, distance is weighted according to a factor of 2 or 4 and search distance is set between 7.5 km and 30 km. All interpolations are constrained within a surface area corresponding to the maximum lateral extent at which each seismic marker is interpreted. However, because the subsurface is densely sampled along each seismic line (KOPRI/GSC/MBARI trace spacing=6.25 m; BeaufortSpan East trace spacing=12.5 m) compared to seismic lines spacing, grid artifacts are generated. Artifacts are attenuated using a smoothing algorithm derived from a weighted blend between biharmonic and Laplacian functions that are respectively differential and scalar differential operators.

Uncertainty

Maps generated from 2-D seismic data contain an inherent cumulative uncertainty. Sources of error may arise from limitations in seismic line location, acquisition, processing, interpretation and finally gridding. In the BMB, the spatial distribution of seismic data, most specifically wide line spacing is considered the main factor of uncertainty. Although the applied gridding scheme has proven to be robust for sparsely distributed data, interpolated values are estimated and not measured as are soundings made during seismic acquisition. Another source of uncertainty comes from the limited number of wells located within the Mackenzie Trough that restrict the number of seismic-to-well ties. The type of wells (i.e. oil and gas exploration wells) is also a limiting factor, since they do not intended to provide detailed information about the shallow subsurface addressed in this report. Finally, the difference in vertical resolution of the two interpreted seismic datasets is also a potential source of error since it can affect correlation accuracy across both datasets.

Results

Seismic interpretation

Very few exploration wells are located in the Mackenzie Trough area (Figure 1). The Adlartok P-09 well located at the southeast limit of the trough offers the best seismic-to-well log correlation providing an excellent tie for three of the four markers discussed in this report. All horizons are picked automatically using a guiding time window of 0.02 s and stop correlation criteria of 0.05 s. The research strategy included an initial interpretation on the high-resolution dataset that enabled a detailed seismic characterization of the markers and of the sedimentary units that they constrain. The high-resolution dataset was then tied to concomitant ION lines so that high accuracy picks can be “pushed” onto lower resolution data.

The BeaufortSpan East dataset is also available in depth. However, the anchor dataset (i.e. KOPRI/GSC/MBARI) was processed in time. Although, the current work benefited from review of previous publications that utilized the BeaufortSpan East dataset made in the depth domain (Batchelor et al., 2013a; Batchelor et al., 2013b), datasets and interpretations have been kept in the time domain. This choice was made since the complexity of the velocity structure of the shallow subsurface posed challenges not only for processing but also for converting the datasets to the depth domain. With the exception of the deepest marker, this approach considers different markers than the previous studies. The deepest seismic marker is a high amplitude negative polarity reflection that truncates underlying parallel to sub-parallel reflections of various amplitudes (Figure 2). This unconformity is interpreted in the literature as the base of the Mackenzie Trough (Batchelor et al., 2013a; Batchelor et al., 2013b). At the Adlartok P-09 well, geological and geophysical logs allow interpretation of high velocity <100m thick that suggest the occurrence of a buried permafrost layer just above the unconformity (Duchesne et al., 2019b). The seismic event represented by the unconformity corresponds to a sharp decrease in compressional-wave (P-wave) velocity, explaining the negative polarity of this reflection (Figure 3). The horizon interpreted directly above the marker indicating the base of the Mackenzie Trough has the weakest distribution of those interpreted. Quaternary seismic marker 3 (QSM-3) corresponds to a high amplitude undulating reflection that is observed in an elongated depression sitting at the base of the Mackenzie Trough. It is not intersected by well P-09. This event has been picked on the negative polarity of the seismic traces because this marker is easier to follow across the Mackenzie Trough using this polarity (Figure 3). This marker is also correlative to the apexes of small hyperbolae evident on both datasets. A marker with similar characteristics as QSM-3 has been interpreted as the top of an early Quaternary till deposit solely on its reflection character in Batchelor et al. (2013a). The other two markers interpreted above QSM-3 are more widespread. Quaternary seismic marker 2 (QSM-2) is a high to medium amplitude reflection that has an undulated morphology near the edges of the trough before

flattening out near the central and shallower parts. This marker is easily followed using the peak of the reflection. At Adlartok P-09 it is correlative to an increase in P-wave velocity. The shallowest horizon presented in this report is Quaternary seismic marker 1 (QSM-1). Near the outer limits of the Mackenzie Trough it almost directly lies on top of QSM-2 (Figure 2). Compared to QSM-2, QSM-1 has a wavy morphology near the limits of the trough flattening out near its central and shallower portions. Finally, the seafloor reflection was also picked but only for time-interval computations that are discussed in subsequent sections.

Seismic grids

Time-structure maps were generated for all seismic markers discussed above and time-isopach maps for time-intervals computed between the base of the Mackenzie Trough and the seafloor. The time-interval between QSM-3 and QSM-2 is not directly computed since the former is spatially restricted to the center of the trough representing 15 % of the surface area of the study region, as opposed to the latter that covers most (62 %) of the region. To overcome this spatial restriction, the base of the Mackenzie Trough and QSM-3 are merged together into a single surface to compute a time-interval for QSM-2.

Base of the Mackenzie Trough

Along its long axis, the time-structure map of the base of the Mackenzie Trough shows time-depths ranging from 0.160 s to 1.32 s that are respectively observed over portions of the map that are the nearest and the farthest from the shoreline (Figure 4). The base of the Mackenzie Trough gently dips seaward. The main feature of the trough is a broad U-shaped erosional cut spanning ~50 km that incises up to 0.25 s several into the surrounding Plio-Pleistocene and older sediments. This strikingly narrow and linear u-shaped feature is oriented along the main trough axis. It is filled with sediments displaying high amplitude and chaotic reflections. This geological feature is defined between the mid-shelf and the base of the continental slope. Its width (~15 km) remains constant across the continental shelf and slope until it reaches the basin floor where it widens considerably (>40 km). This paleovalley is asymmetric with steepest slopes observed on the west flank compared to its opposite flank. The Mackenzie Trough is filled by Quaternary sediments up to a time-thickness of 0.5 s with the depocenter located mid-slope hosted in a paleovalley having a length of 29 km and width of 10 km (Figure 5). The thinnest Quaternary deposits are found off the Yukon shelf, where it varies between 0.05 and 0.160 s.

Quaternary Seismic Marker 3

Time-structure map of QSM-3 shows it is restricted to the overdeepened valley described above (Figure 6). This marker is imaged at times increasing seaward from 0.5 s to 1.2 s. Compared to the base of the Mackenzie Trough, it possesses a rugose surface. Its time-thickness reaches 0.23 s within the distal portion of the trough. The depocenter spreads over a distance of ~40 km with time-thicknesses rapidly increasing from 0.095 s to 0.175 s over the first 10 km from the coastline (Figure 7). The seaward end of the QSM-3 depocenter is located ~7 km beyond the depocenter illustrated by the total Quaternary time-thickness map (Figure 5).

Quaternary Seismic Marker 2

QSM-2 is widespread over the study area and imaged at time-depths ranging between 0.25 s and 0.92 s (Figure 8). This marker smoothly dips seaward following the broad morphology of the base of the Mackenzie Trough with slightly steeper slopes located on the west side of the study area. Along the continental shelf, off the coast of the Northwest Territories, QSM-2 is mostly flat and identified between 0.325 s and 0.362 s. QSM-2 time-thickness significantly increases seaward along the Mackenzie Trough from 0.02 s in the portion of the grid that is the closest to the shoreline, to almost 0.3 s in a depocenter located at the base of the continental slope (Figure 9). Across the Mackenzie Trough, the time-thickness is relatively constant although greater accumulations are observed along the west flank of the trough.

Quaternary Seismic Marker 1

QSM-1 entirely covers the study area and is imaged between 0.16 s and 1.3 s (Figure 10). This surface gently dips seaward. Across the shelf break, on the flanks of the Mackenzie Trough, steeper slopes are observed. Sediments in between QSM-1 and the seafloor have time-thicknesses ranging from 0.01 s to 0.2 s (Figure 11). The most important time-thicknesses comprised between 0.13 s to 0.163 s are found over a 25 km wide N-S trending corridor on the shelf.

Discussion and conclusion

The present morphology of the Mackenzie Trough is inherited from its basal surface. The seismic markers presented in this report are traced over a significant lateral extent within the subsurface of the Mackenzie Trough. They most likely document a change in the acoustic properties that are tied to variations in the Quaternary depositional history. The three seismic markers mapped above the base of the Mackenzie Trough suggest they are related to depositional events; QM-3 tops a unit restricted to a u-shaped valley found in the central portion of the Mackenzie Trough, onlapping its base, whereas the morphology of QM-2 and QM-1 grossly mimic the morphology of the base of the Mackenzie Trough with both markers topping units overlying each other. The Quaternary time-thickness map reveals that thicker accumulations of sediments are observed where accommodation space was available, i.e. within the U-shaped portion of the base of the Mackenzie Trough. Nevertheless, the computation of time-interval maps between each marker reveals that zones of thicker sediment accumulation have shifted during the Quaternary. Indeed, time-thickness grids suggest that, between the Pliocene and the Holocene, depocenters have moved landward. However, beneath QM-2 thicker sediment accumulations are locally observed along the western flank of the Mackenzie Trough and the base of the continental slope. The position of those accumulations and the chaotic seismic reflection pattern they possess could suppose subglacial till deposits that formed sometimes between the Pliocene and the Late Pleistocene (Batchelor et al., 2013b). Moreover, they are correlative to the westernmost ice stream proposed by Margold et al. (2018) that drained within the Mackenzie Trough reaching the foot of the continental slope.

The seismostratigraphic sub-division of Batchelor et. al. (2013b) has strong similarities with this study. However, the maps presented in this report benefited from rigorous velocity/depth considerations, thorough gridding methods and parameters analyses in addition to a high-resolution interpretation input coming from the KOPRI/GSC/MBARI dataset. Finally, this report has aimed to provide some background information to build a more detailed geological framework that will be used to better understand the occurrence and distribution of subsea permafrost and to assess geohazards in the Mackenzie Trough area. Upcoming work will focus on the integration of other datasets such as multibeam bathymetry, subbottom profiling, shallow coring, water column imaging and sampling as well as geochemical analyses. This geoscientific data integration will allow to better circumscribe sources of geological hazards for the coastal communities and infrastructures and consequent environmental effects of subsea permafrost degradation on marine ecosystems.

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Figures

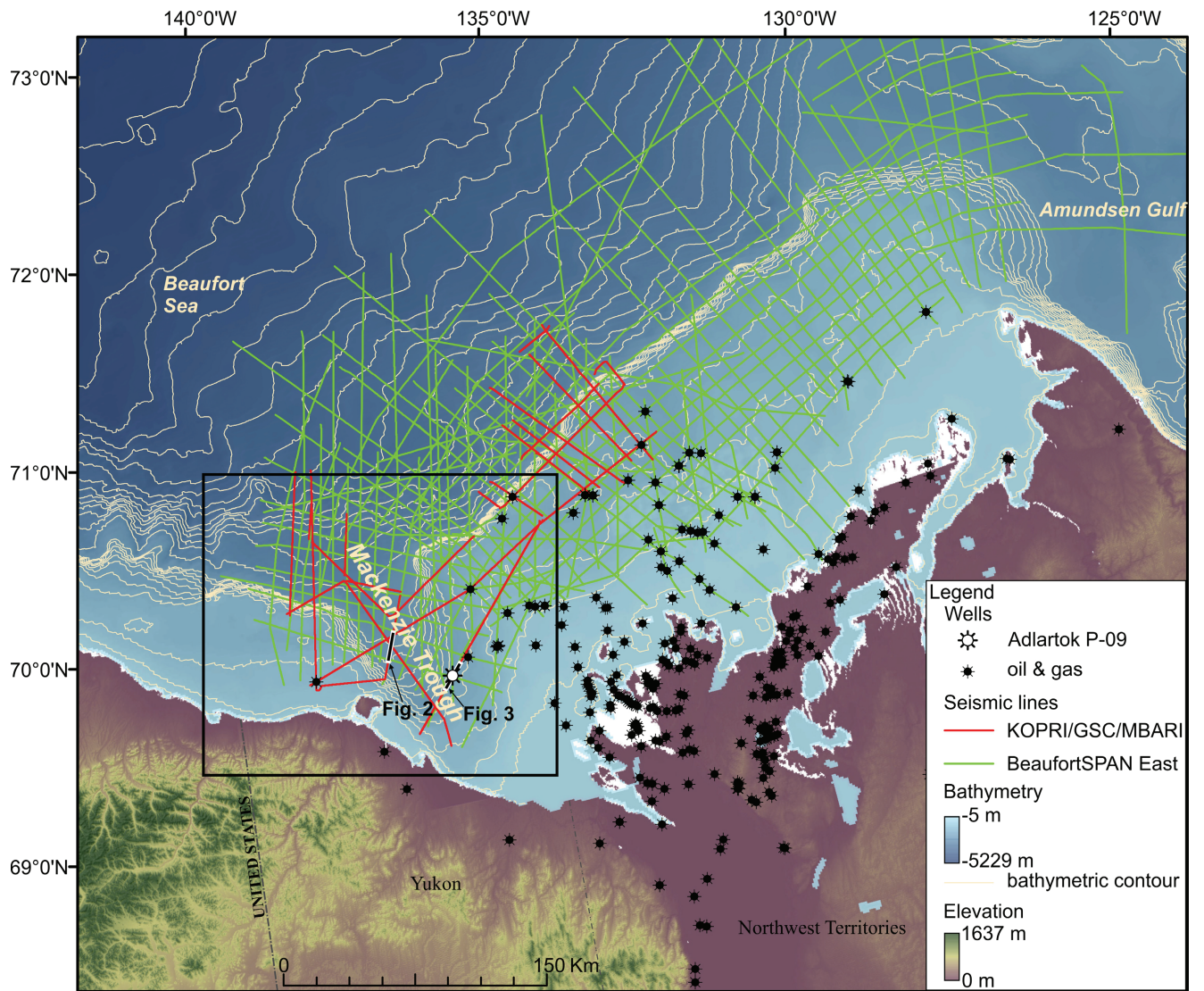


Figure 1. Location map of the study area. The black box indicates the Mackenzie Trough area where time-structure and time-isopach maps were generated. Seismic sections displayed on figures 2 and 3 are also indicated.

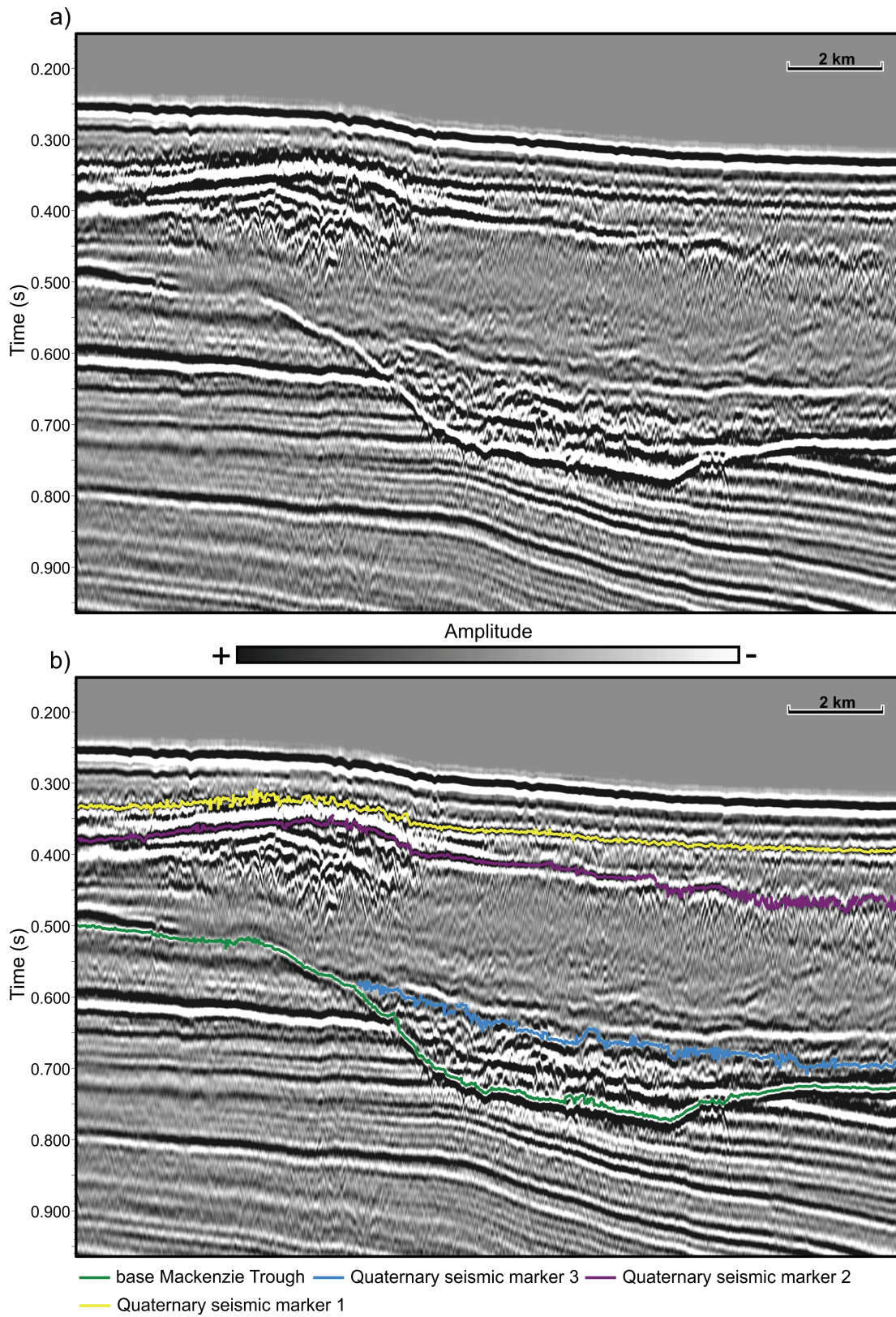
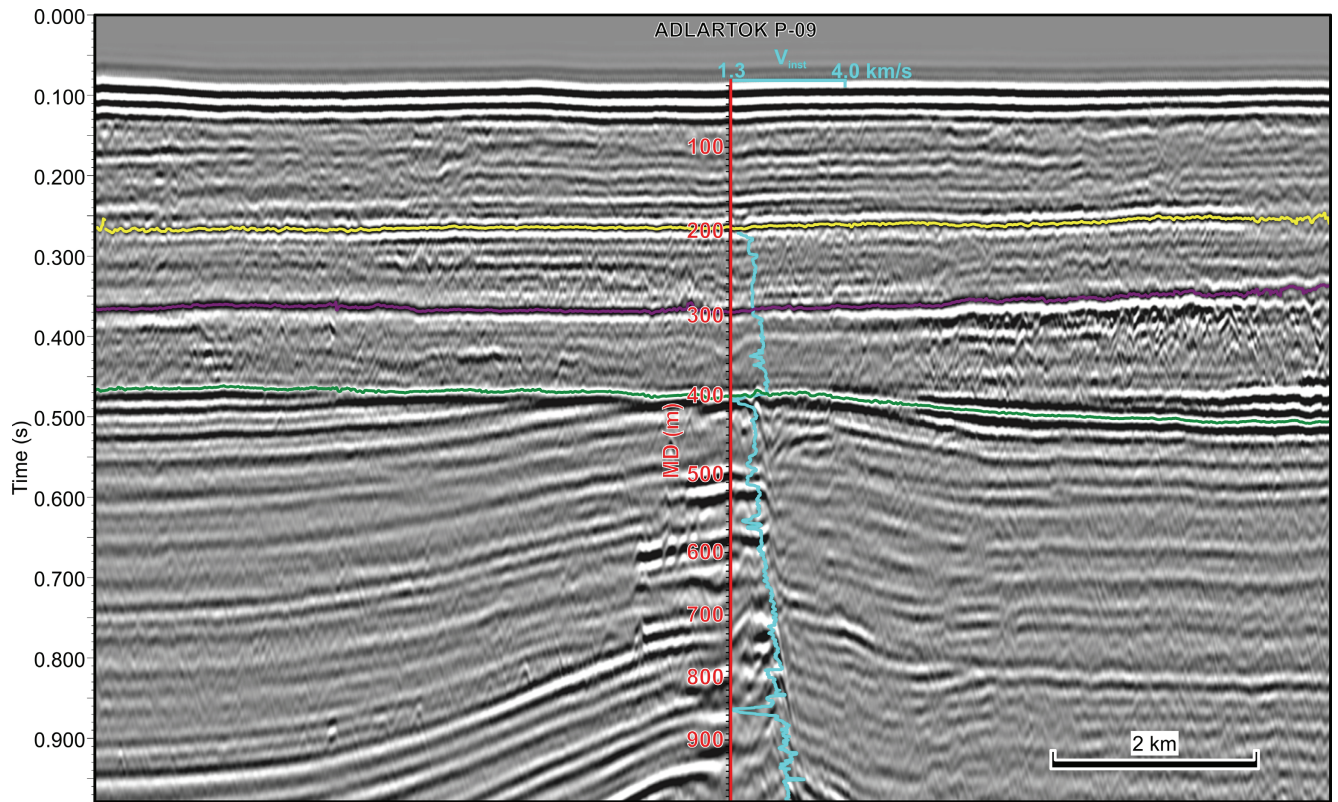


Figure 2. a) Uninterpreted and b) interpreted high-resolution seismic section collected in the Mackenzie Trough. See Figure 1 for location.



— base Mackenzie Trough — Quaternary seismic marker 2 — Quaternary seismic marker 1

Figure 3. Adlartok P-09 well with tie to a high-resolution seismic line. The cyan curve is the instantaneous P-wave velocity log calculated from sonic well logging. See Figure 1 for location.

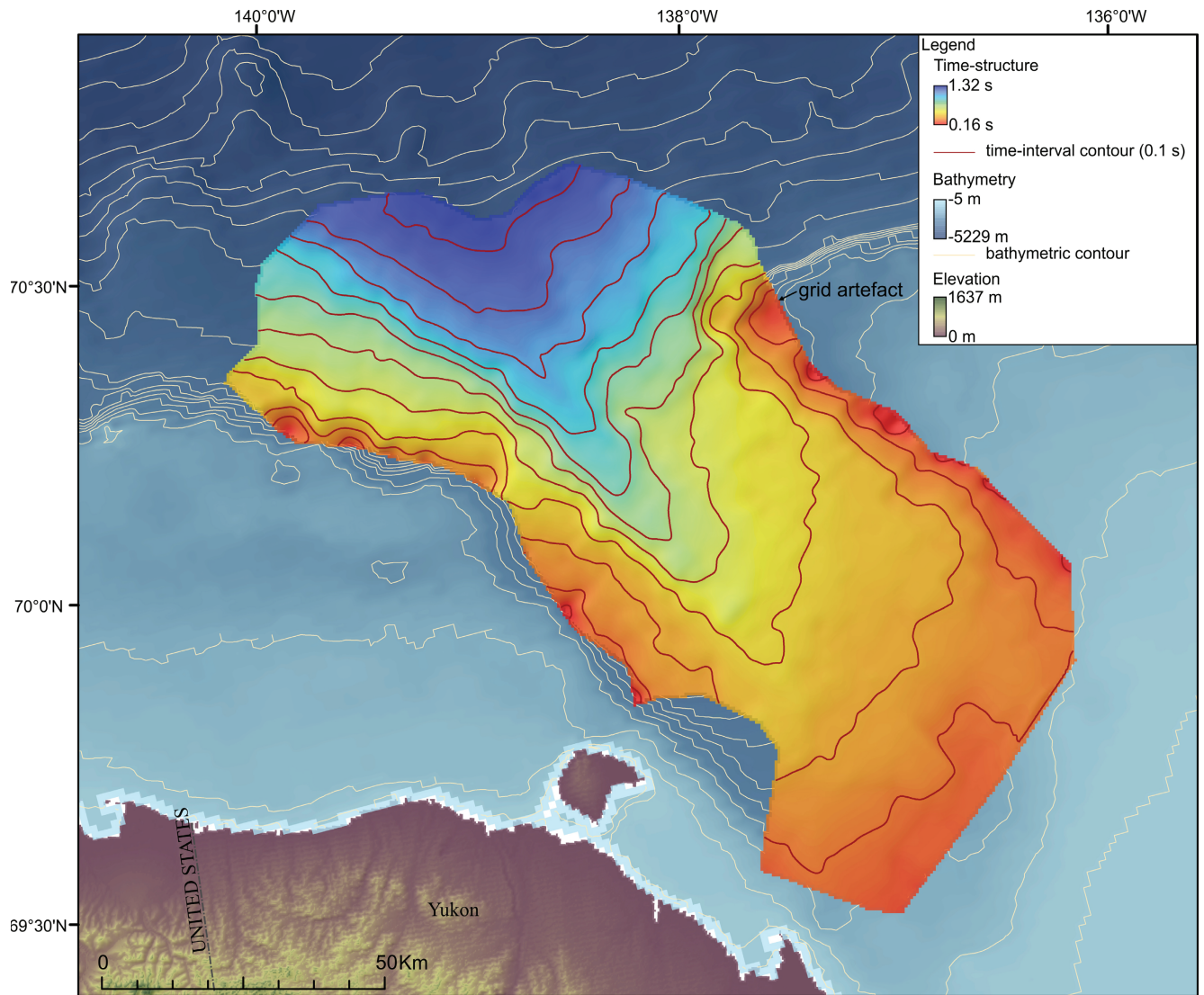


Figure 4. Time-structure map of the base of the Mackenzie Trough seismic marker. See Figure 1 for location.

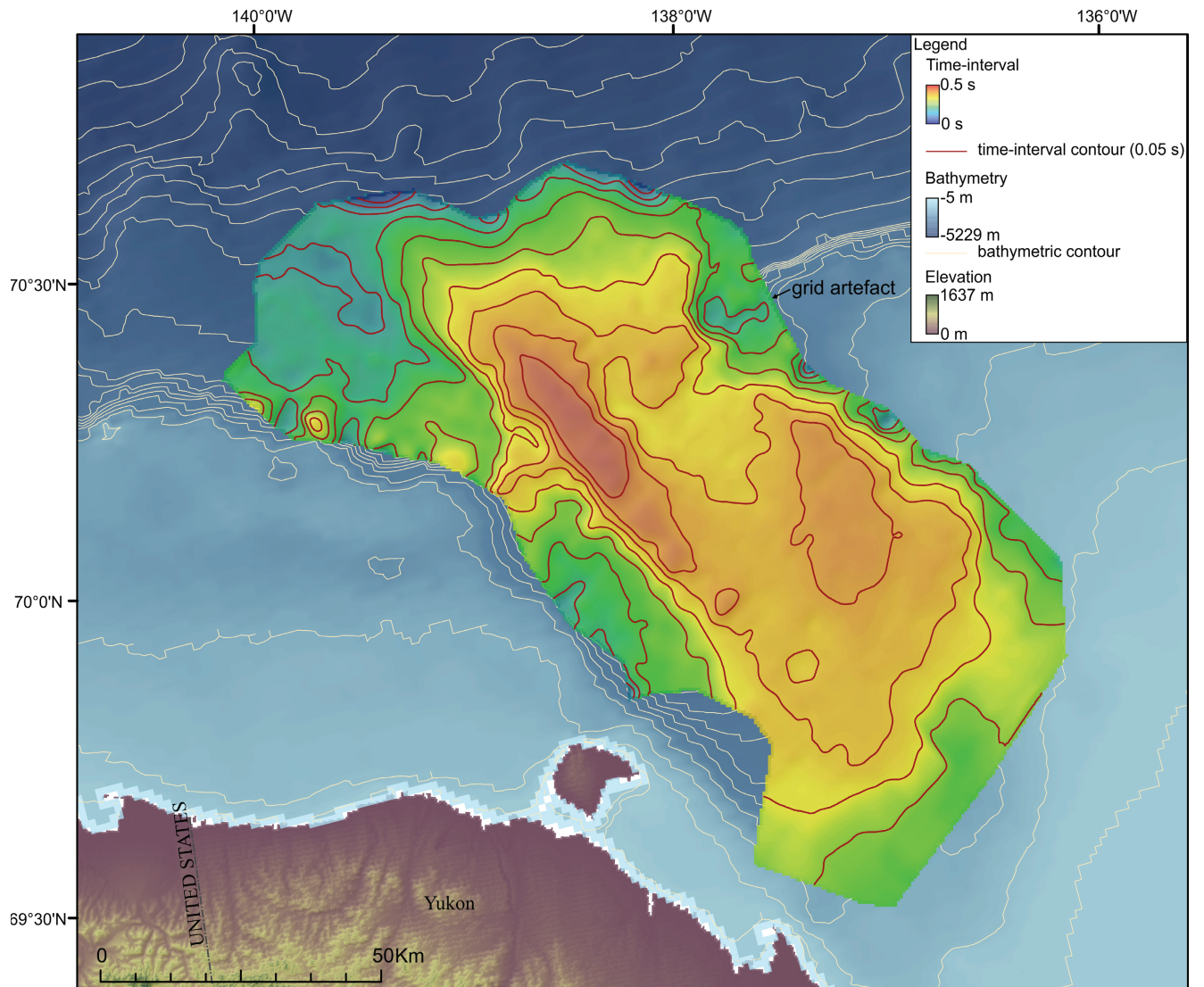


Figure 5. Time-isopach map of Quaternary sediments (Base of the Mackenzie Trough marker – seafloor reflection). See Figure 1 for location.

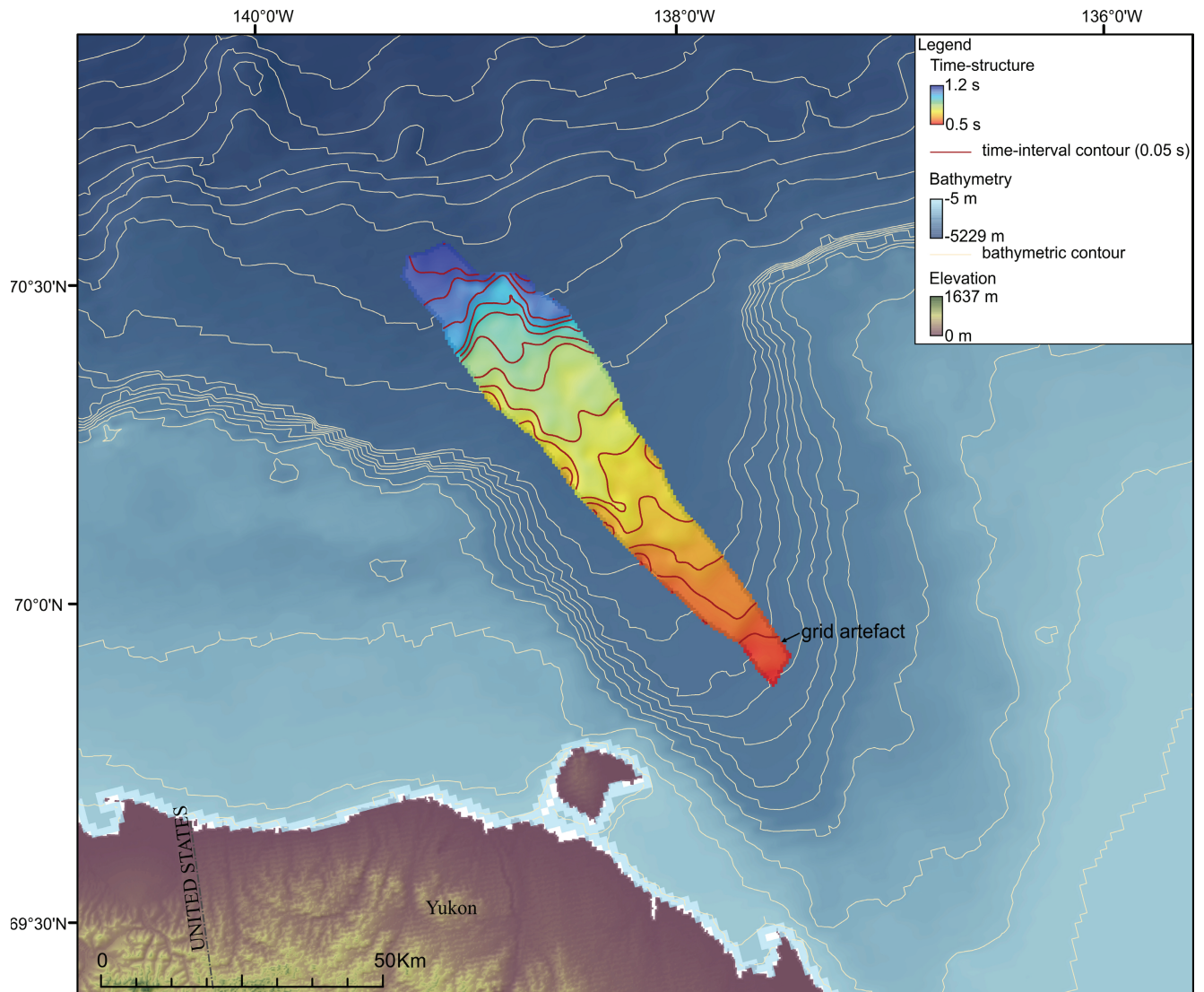


Figure 6. Time-structure map of Quaternary seismic marker 3 (QSM-3). See Figure 1 for location.

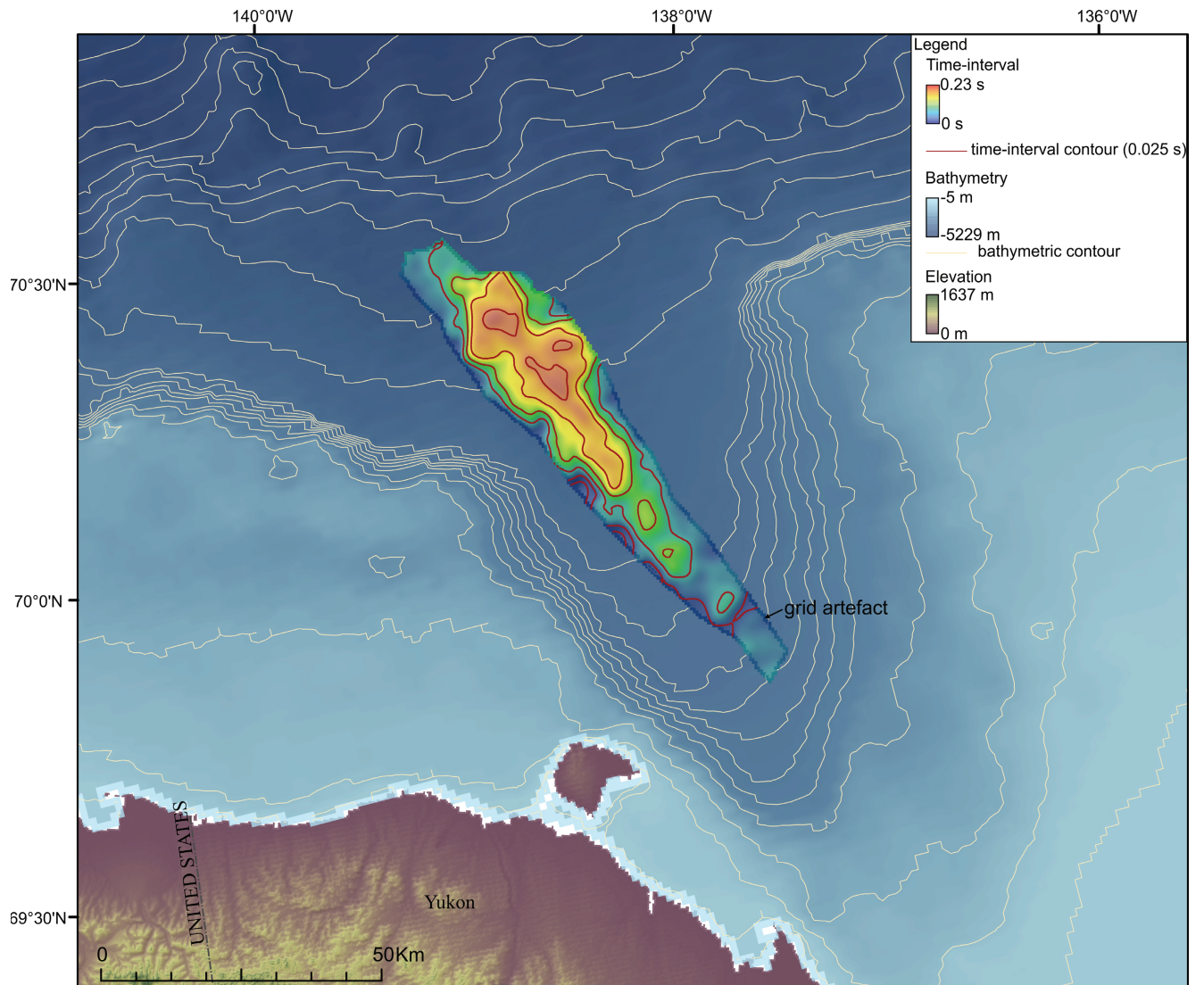


Figure 7. Time-isopach map of the sediments included between the base of the Mackenzie Trough seismic marker and Quaternary seismic marker 3 (QSM-3). See Figure 1 for location.

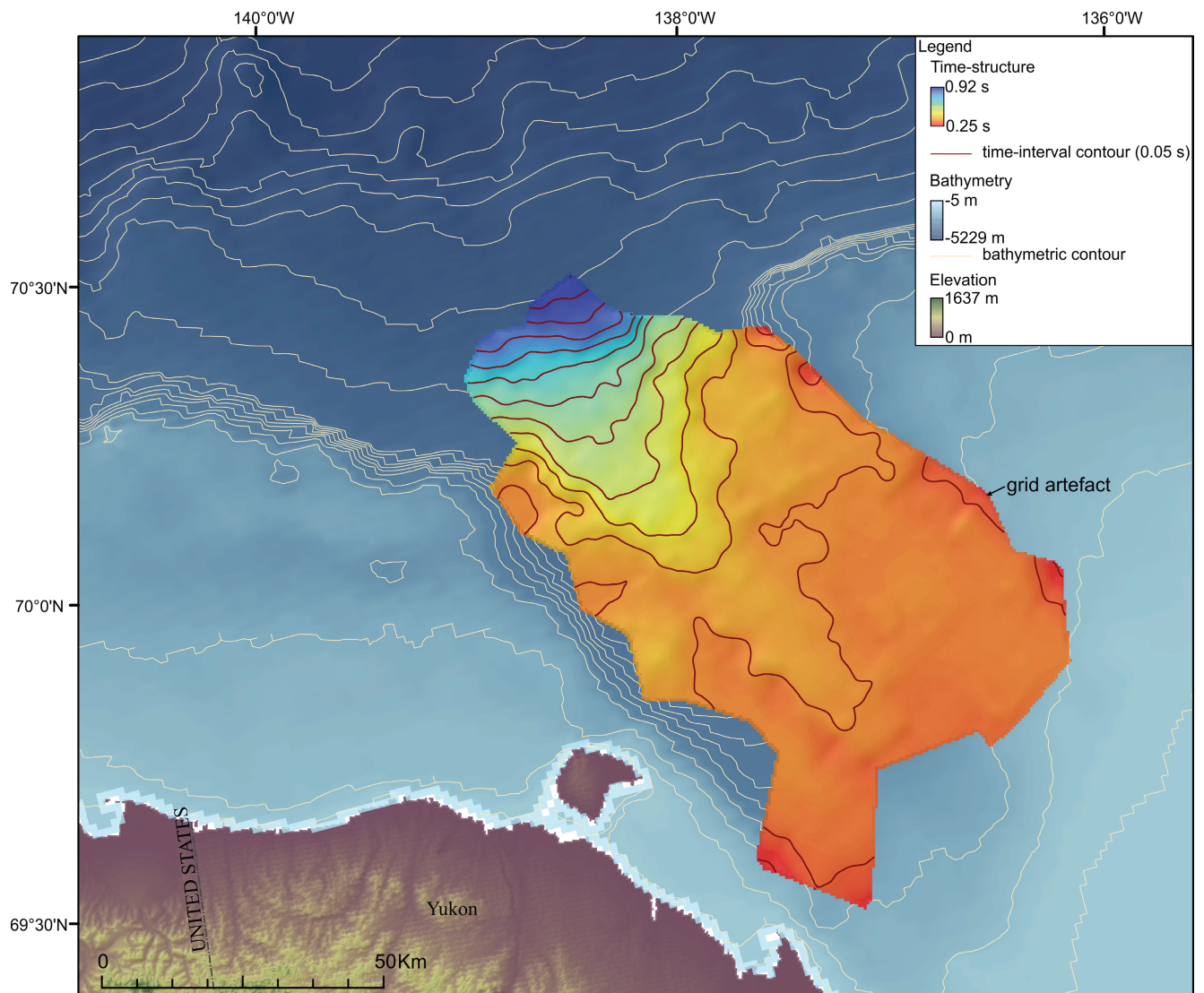


Figure 8. Time-structure map of Quaternary seismic marker 2 (QSM-2). See Figure 1 for location.

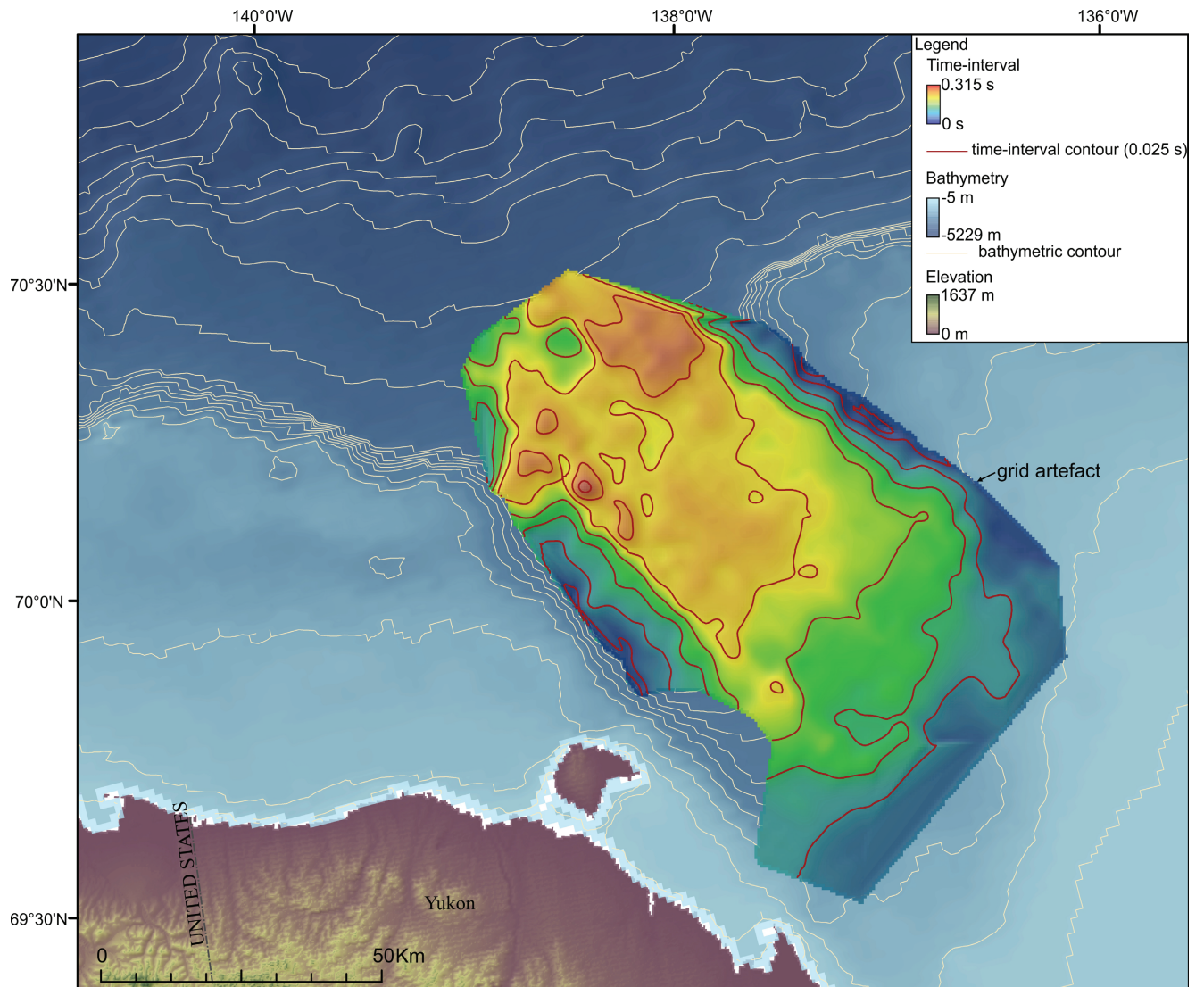


Figure 9. Time-isopach map of the sediments included between the base of the Mackenzie Trough seismic, Quaternary seismic marker 3 (QSM-3) and Quaternary seismic marker 2 (QSM-2) (Base of the Mackenzie Trough marker + Quaternary seismic marker 3) – Quaternary seismic marker 2). See Figure 1 for location.

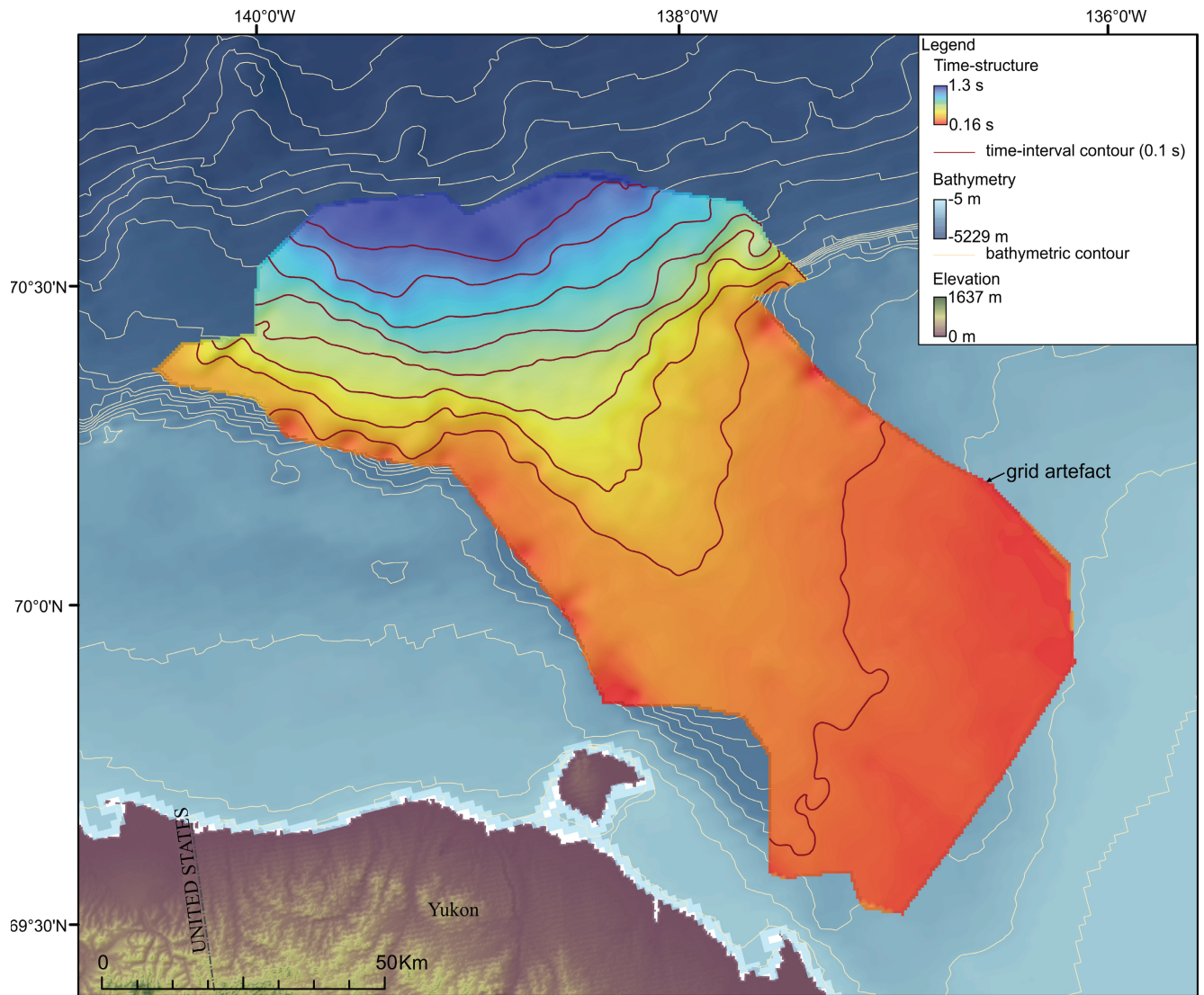


Figure 10. Time-structure map of Quaternary seismic marker 1 (QSM-1). See Figure 1 for location.

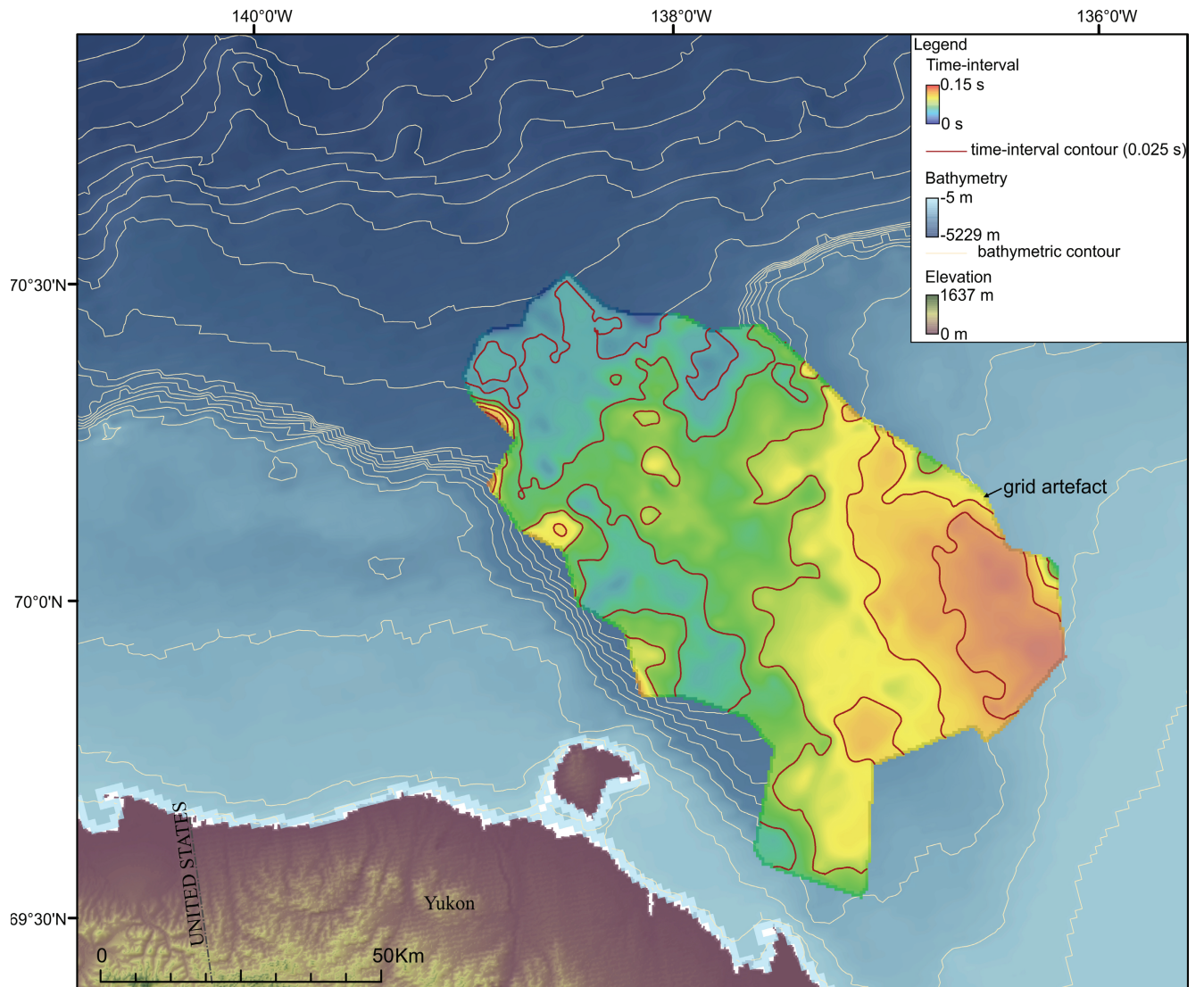


Figure 11. Time-isopach map of the sediments included between Quaternary seismic marker 2 (QSM-2) and Quaternary seismic marker 1 (QSM-1) (Quaternary seismic marker 2 – Quaternary seismic marker 1). See Figure 1 for location.

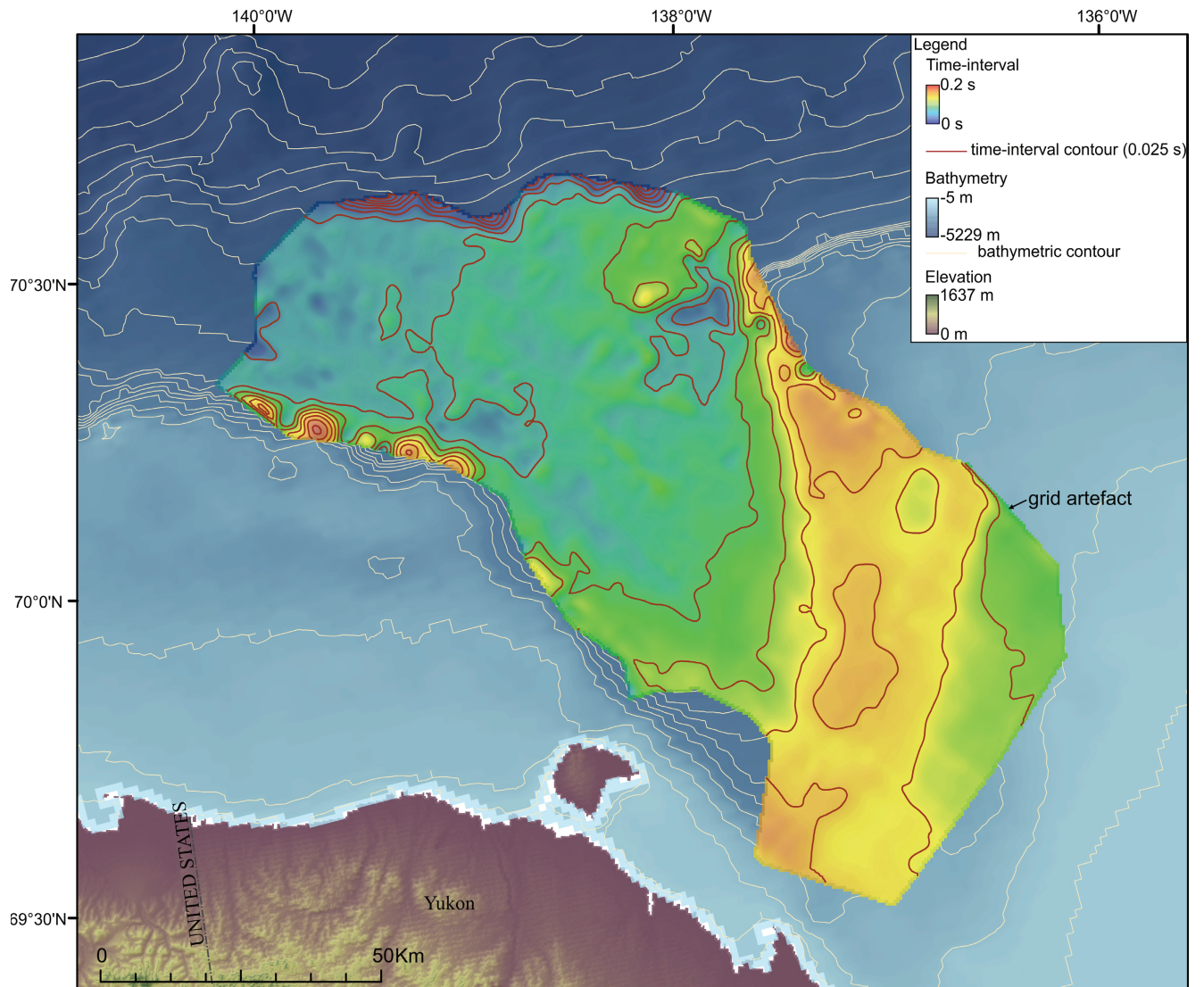


Figure 12. Time-isopach map of the sediments included between Quaternary seismic marker 1 (QSM-1) and the seafloor reflection (Quaternary seismic marker 1 – seafloor reflection). See Figure 1 for location.