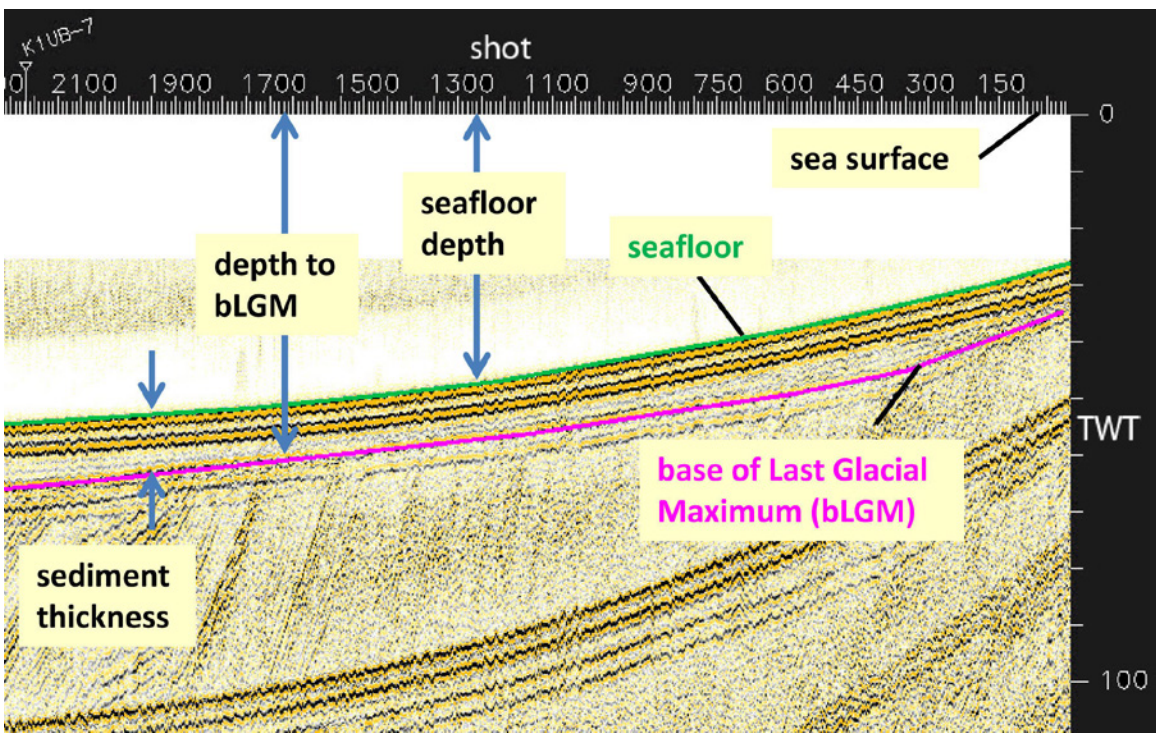
Modeling of Depth to Base of Last Glacial Maximum and Seafloor Sediment Thickness for the California State Waters Map Series, Eastern Santa Barbara Channel, California

By Florence L. Wong, Eleyne L. Phillips, Samuel Y. Johnson, and Ray W. Sliter



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Cover: Seismic-reflection profile with interpreted horizons of seafloor (green) and base of Last Glacial Maximum (bLGM, magenta). See Figure 2 caption.

Contents

Figures

Tables

Conversion Factors and Datum

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
mile, nautical (nmi)	1.852	kilometer (km)

SI to Inch/Pound

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
meter per second (m/s)	3.281	foot per second (ft/s)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
square kilometer (km^2)	0.3861	square mile (mi^2)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
millisecond (msec)	0.001	second

Datum

The World Geodetic System (WGS) 84 is the reference coordinate system used by the Global Positioning System.

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Abstract

Models of the depth to the base of Last Glacial Maximum and sediment thickness over the base of Last Glacial Maximum for the eastern Santa Barbara Channel are a key part of the maps of shallow subsurface geology and structure for offshore Refugio to Hueneme Canyon, California, in the California State Waters Map Series. A satisfactory interpolation of the two datasets that accounted for regional geologic structure was developed using geographic information systems modeling and graphics software tools. Regional sediment volumes were determined from the model. Source data files suitable for geographic information systems mapping applications are provided.

Introduction

The California State Waters Map Series in the eastern Santa Barbara Channel is a series of thematic maps covering the offshore area between Refugio and Hueneme Canyon, California (fig. 1). The thematic maps of shallow subsurface geology and structure include maps of depth to the base of the Last Glacial Maximum (bLGM), and the thickness of the uppermost Pleistocene and Holocene sediments deposited over the bLGM. We describe the derivation of these two map layers and the calculation of footprint area, thickness, and volume of the deposits, and provide results of these calculations for the whole area and for structural subareas (Johnson and others, 2012a, 2012b). We also provide data files of the original thickness and depth measurements.

Methods

Digitizing Reflection Surfaces

Single-channel seismic-reflection profiles from surveys Z-3-07-SC and S-7-08-SC conducted by the U.S. Geological Survey in 2007 and 2008, respectively, were imported into SeisWorks® 3D software for interpretation (fig. 1; U.S. Geological Survey 2007, 2008; Johnson and others, 2012a). Reflection surfaces representing the seafloor and the bLGM were digitized in two-way travel time (TWT) milliseconds (msec; fig. 2. Sediment thickness was calculated as the difference between the seafloor and bLGM travel times. Before exporting from SeisWorks®, seafloor depths were corrected with a water column velocity of 1,500 m/s (depth = TWT msec/2 × 1,500 m/s) and sediment thickness with a sediment velocity of 1,600 m/s (thickness = TWT msec/2 × 1,600 m/s). The depth to the bLGM is the sum of the corrected seafloor depth and corrected sediment thickness (fig. 2).

The sediment thickness and depth to bLGM were exported with UTM 11 coordinates as text files with approximately 925,000 points each. The data points are spaced 1 m apart along track (the shot interval of the seismic-reflection data systems) and are spaced 1–2 km apart cross track (fig. 3).

Thickness data were converted to ArcGIS point format with the following original attributes plus latitude and longitude (converted from X_UTM1184 and Y_UTM1184) and a corrected thickness:

X_UTM1184 – x coordinate in UTM Zone 11 coordinate system, datum WGS84
Y_UTM1184 – y coordinate in UTM Zone 11 coordinate system, datum WGS84
THK_M0 – thickness in meters as exported from SeisWorks®
LONG84 – longitude, datum WGS84
LAT84 – latitude, datum WGS84
THK_M – adjusted thickness, where any value <= 0.1 m is changed to 0.1 m

Depth to bLGM data have the following original attributes plus latitude and longitude (converted from X_UTM1184 and Y_UTM1184):

X_UTM1184 – x coordinate in UTM Zone 11 coordinate system, datum WGS84
Y_UTM1184 – y coordinate in UTM Zone 11 coordinate system, datum WGS84
LONG84 – longitude, datum WGS84
LAT84 – latitude, datum WGS84
BSM_M – depth in meters to base of Last Glacial Maximum

Surface Generation

Many interpolation or gridding methods are available for calculating a continuous surface from point data. If, as is the case here, the data area includes discontinuous geologic and physiographic features (faults and canyons), the data need to be modified for these features before or during the calculation. In this section, we describe adjustments to the sediment thickness data and several approaches to a satisfactory regional sediment thickness, from which the depth to bLGM was then calculated.

Bedrock exposures from the map of seafloor geology (Ritchie and others, 2012) were used to define points of zero thickness (fig. 4). Before adding these points to the dataset, any original SeisWorks® value (THK_M0) less than 0.1 m was changed to 0.1 m (THK_M) to allow the bedrock points to be the authoritative zero values. Data points were excluded over Hueneme

Canyon, where data were too sparse to adequately image the highly variable changes in sediment thickness in the canyon (Ritchie and others, 2012).

As gridding operations usually produce results that fill a rectangular window or otherwise spill beyond the available data extent, a clip mask or polygon was constructed to limit the final grid to the available data and to the geographic limits of the map series. A mask can be manually sketched around the data or extracted from geographic elements, which was our method. The seaward boundary of the mask is defined by the 3-nmi limit for the State of California. The inner limit was constructed from the intersection of a 100-m buffer of the coastline and a 200-m buffer around the input dataset. The canyon areas also were omitted (fig. 5).

The first sediment thickness grid interpolated from the SeisWorks® point data was processed with the ArcGIS TopoToRaster tool (Esri, 2011), an interpolator designed for topographic surfaces that often serves well for other types of continuous fields. Figure 6*A* displays the results from applying TopoToRaster on the data before the bedrock data were added (zero-thickness areas are patchy). Figure 6*B* displays the same calculation after zero-thickness points from bedrock areas were added. This grid provides a rapid overview, but retains some patchiness from along-track data variations.

The Red Mountain, Pitas Point, and Oak Ridge faults displace parts of the seafloor sediment in this area (Johnson and others, 2012b). TopoToRaster does not have an option to include the effect of faults or other topologic breaklines (fig. 7*A*), so we next tried the triangular irregular network (TIN) tool (Esri, 2011). TIN calculations can ingest data points or contours, exclude unwanted features, and accommodate breaklines (fig. 8). The TIN results showed some breakline (fault) influence, but did not show as sharp a change across the faults as were evident in seismic-reflection profiles (figs. 7*B*-7*C*; Johnson and others, 2012a).

From the earlier TopoToRaster grid, isopachs (thickness contours) at 0.1, 2, 4, 7 m, and then at 5 m intervals from 10 m to the maximum thickness (55 m) were extracted. These contours were edited and additional contours were digitized in Adobe© Illustrator to better represent the effect of local faults and other geologic structures and to remove gridding artifacts. The edited contours alone were gridded by TopoToRaster, using the following parameters. All but the grid cell size are default values.

```
ITERATIONS 50
ROUGHNESS_PENALTY 0.00000000000
DISCRETE_ERROR_FACTOR 0.50000000000
VERTICAL_STANDARD_ERROR 0.00000000000
TOLERANCES 0.50000000000 0.10000000000
ZLIMITS 0.00000000000
CELL_SIZE 50.00000000000
MARGIN 0
```

This calculation failed to portray the substantial change in sediment thickness caused by the uplift associated with the Oak Ridge fault zone (fig. 7*C*; Johnson and others, 2012a, 2012b; Ritchie and others, 2012). The most satisfactory approach to accommodate the fault was to generate two separate grids–one to the north of the fault and one to the south (fig. 9)–and then mosaic the two into one (fig. 7*D*). This interpolation is used in the final maps of shallow subsurface geology and structure (fig. 10*A*; Johnson and others, 2012b).

Initially, the depth to the base of Last Glacial Maximum also was calculated from the points exported from SeisWorks®. Instead of repeating the sediment thickness adjustments on the bLGM data, the final depth to bLGM was calculated by subtracting the modified sediment thickness data from the seafloor depth as determined by multibeam bathymetry (fig. 10*B*; Kvitek and others, 2012). At the 50-m resolution of the gridding, the mean difference between the along-track seafloor depths digitized in SeisWorks® and the multibeam bathymetry was 0.6 m, with a standard deviation of 5 m, an acceptable uncertainty for the depth of the bLGM (table 1).

Table 1. Comparison of grid statistics for the depth to seafloor from multibeam bathymetry data and depth to seafloor as digitized from SeisWorks®.

[m, meter]

	Minimum (m)	Maximum (m)	Mean (m)	Standard deviation (m)
Depth to seafloor (multibeam)	-290	-2	-40	25
Depth to seafloor (SeisWorks®)	-270	-7	-40	25
Difference: multibeam – SeisWorks®	-17	55	0.6	4.7

Regional Areas and Volumes

Area, mean sediment thickness, and sediment volume were calculated for regions bound by major faults (Oak Ridge fault, Pitas Point fault, and the Red Mountain fault) and Hueneme Canyon (fig. 11). The volume of each column of sediment under a grid cell can be determined by multiplying the area of the grid cell and the sediment thickness. The ArcGIS “zonal statistics as table” tool generates, for each polygon of interest, cell (pixel) count, area, minimum value, maximum value, range, mean, standard deviation, and sum. We use the zonal sum (sediment thickness of all cells in a zone) and the final grid cell size (50 m) to calculate volume = ZONALSUM * 2500.

Results

The thickness of the uppermost Pleistocene to Holocene sediments in the State waters of the eastern Santa Barbara Channel has a mean value of 15 m and a maximum thickness of 57 m (table 2). This thickness is not evenly distributed across the region, but thinner northwest of the Red Mountain fault and thicker southeast of that feature (fig. 10*A*; table 3; Johnson and others, 2012b). The depth to the bLGM or bedrock in the area has a mean value of 56 m. Excluding the submarine Hueneme Canyon, the value deepens from 12 m to a maximum of 190 m within the 3-nmi limit. The total volume of sediment in the study area is about 9.6 km^3, distributed over five domains, the largest of which lies between the Oak Ridge fault and Hueneme Canyon (table 3; Johnson and others, 2012b).

Table 2. Grid statistics for sediment thickness and depth to base of Last Glacial Maximum for entire area of study.

[m, meter]

	Minimum (m)	Maximum (m)	Mean (m)	Standard deviation (m)
sediment thickness (m)	0	57	15	16
depth to bLGM: multibeam seafloor – sediment thickness	-190	-12	-56	21

Table 3. Area, mean sediment thickness, and sediment volume for regional sediment-thickness domains (see fig. 11).

[km^2, square kilometer, km^3, cubic kilometer, m, meter]

Regional sediment-thickness domains	Area (km^2)	Mean sediment thickness (m)	Sediment volume (km^3)
(1) Refugio Beach to northern strand of Red Mountain fault zone	357	4	1.27
(2) Northern strand of Red Mountain fault zone to Pitas Point fault	68	18	1.20
(3) Pitas Point fault to Oak Ridge fault	70	39	2.74
(4) Oak Ridge fault to Hueneme Canyon	75	39	2.90
(5) South of Hueneme Canyon	54	28	1.53

Summary

Several GIS and graphic techniques were combined to produce continuous grids of sediment thickness and accompanying depth to the bLGM. Each stage of the calculations was evaluated for consistency with the various datasets that informed the interpretation. With a variety of tools available, the determination of which tool to use for the individual steps and how to minimize data manipulation artifacts was integral to the creation of the final product. Files in ArcGIS format of the final grids of sediment thickness and depth to bLGM will be compiled in the database accompanying the California State Waters Project. The SeisWorks® point data from which the grids were calculated are provided with this report as separate files (sbsedthkpt.zip and sbsedbsmpt.zip).

Acknowledgments

This report was greatly improved by reviews from Amy Foxgrover and Pete Dartnell, both USGS.

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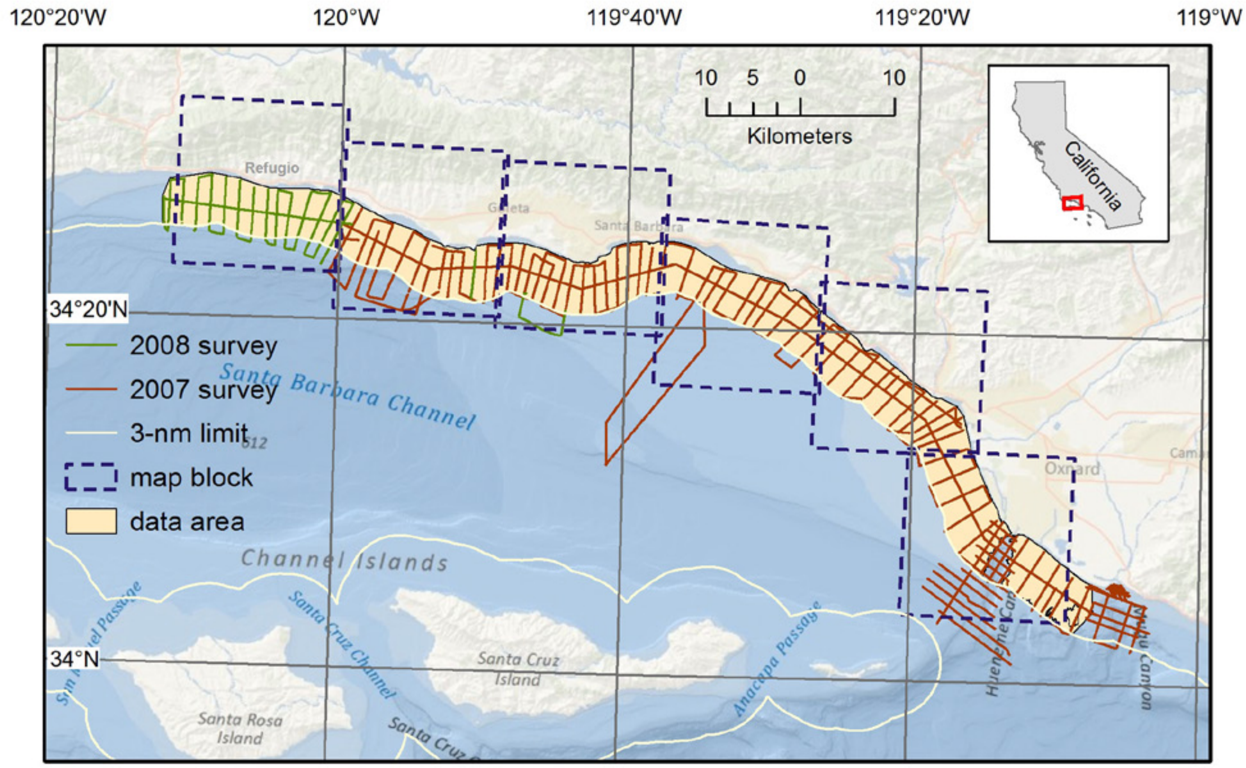
U.S. Geological Survey, 2008, USGS CMG S-7-08-SC Metadata: accessed June 25, 2012, at *http://walrus.wr.usgs.gov/infobank/s/s708sc/html/s-7-08-sc.meta.html*.

Appendix

Compressed GIS files of data points for depth to base of Last Glacial Maximum and sediment thickness used in calculations described in this report are available from *http://pubs.usgs.gov/of/2012/1161/*.



Basemap: http://services.arcgisonline.com/arcgis/services/Ocean_Basemap accessed 17-Jul-2012.

Figure 1. Map of Santa Barbara Channel, California. Map blocks are outlines of quadrangles defined for the California State Waters Map Series. The data area for this report spans the shelf from Refugio to southeast of Hueneme Canyon. Seismic-reflection data were collected by the U.S. Geological Survey in 2007 and 2008 along the displayed tracklines. The 3-nautical mile limit is the seaward boundary of the State waters.

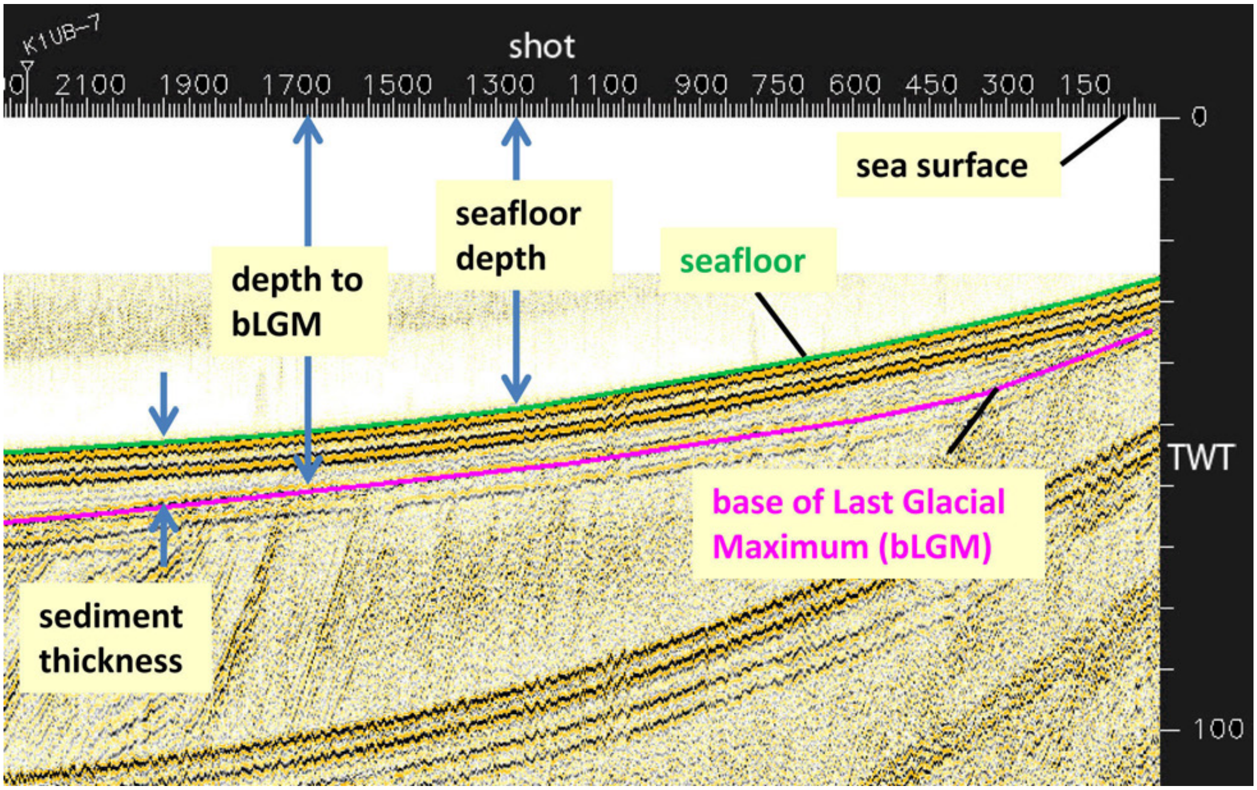


Figure 2. SeisWorks® display of a seismic-reflection profile with interpreted horizons of seafloor (green) and base of Last Glacial Maximum (bLGM, magenta). Depth to seafloor, depth to bLGM, and sediment thickness (all in two-way travel time (TWT)) are available for export. The horizontal scale marks seismic shot value; the vertical scale is in TWT (msec). At the right edge of the profile, the seafloor horizon is approximately 25 msec (or 0.025 m)/2 × 1,500 m/s = 18.75 m; the sediment thickness is approximately 10 msec (or 0.010 s)/2 x 1,600 m/s = 8.0 m. The depth to bLGM = 18.8 + 8.0 = 53.5 m.

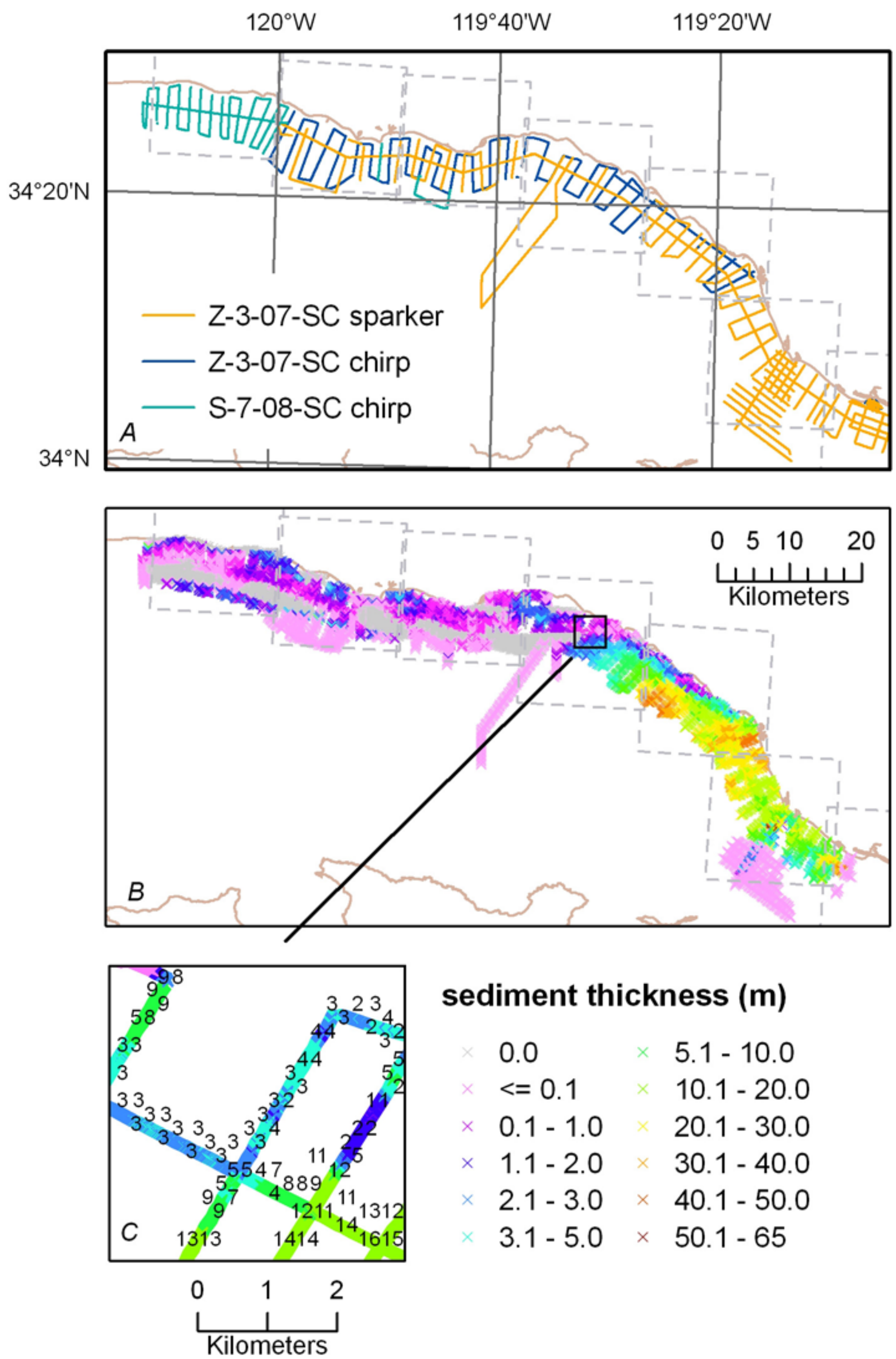


Figure 3. (A) Seismic-reflection tracklines color-coded by survey identification. (B) Points color-coded by sediment thickness values as originally exported from SeisWorks®. (C) Enlargement of a subwindow of points. Density of data causes “x” symbols on maps to blur together.

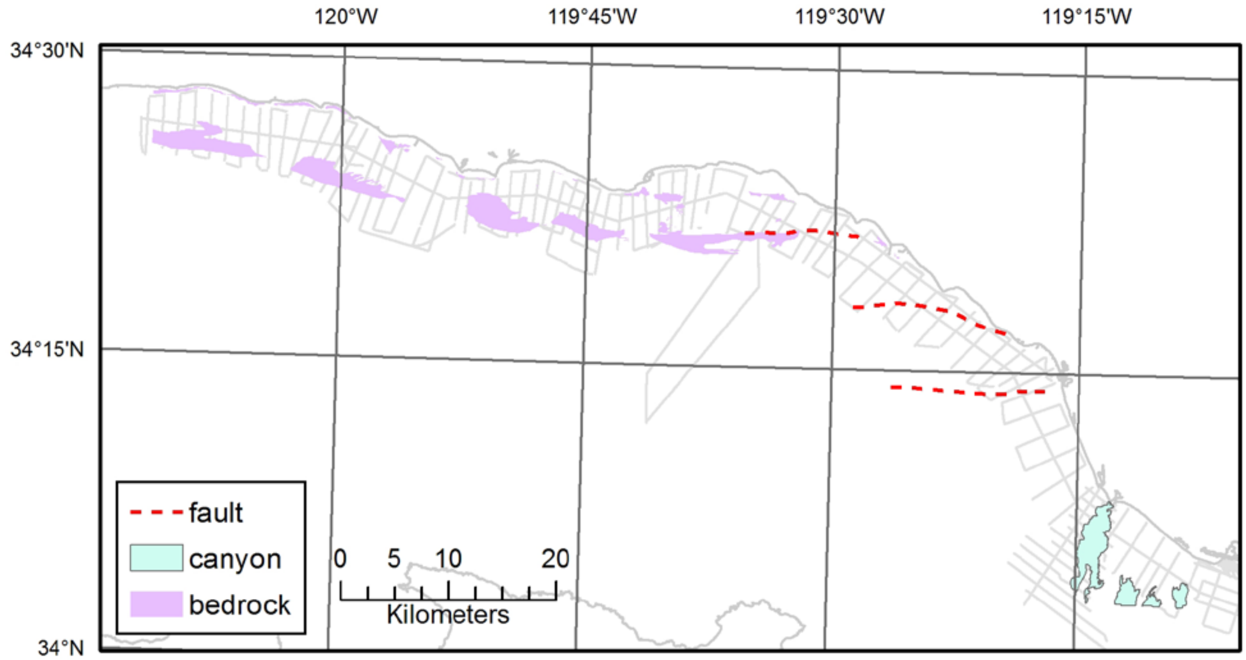


Figure 4. Modifications to sediment thickness data. Areas mapped as bedrock exposures are interpreted as having zero thickness. Canyon polygons are areas for which thickness data points are excluded before gridding. Faults are to be treated as breaklines, disrupting the continuity of the gridding where they occur. RM, Red Mountain fault; PP, Pitas Point fault; OR, Oak Ridge fault.

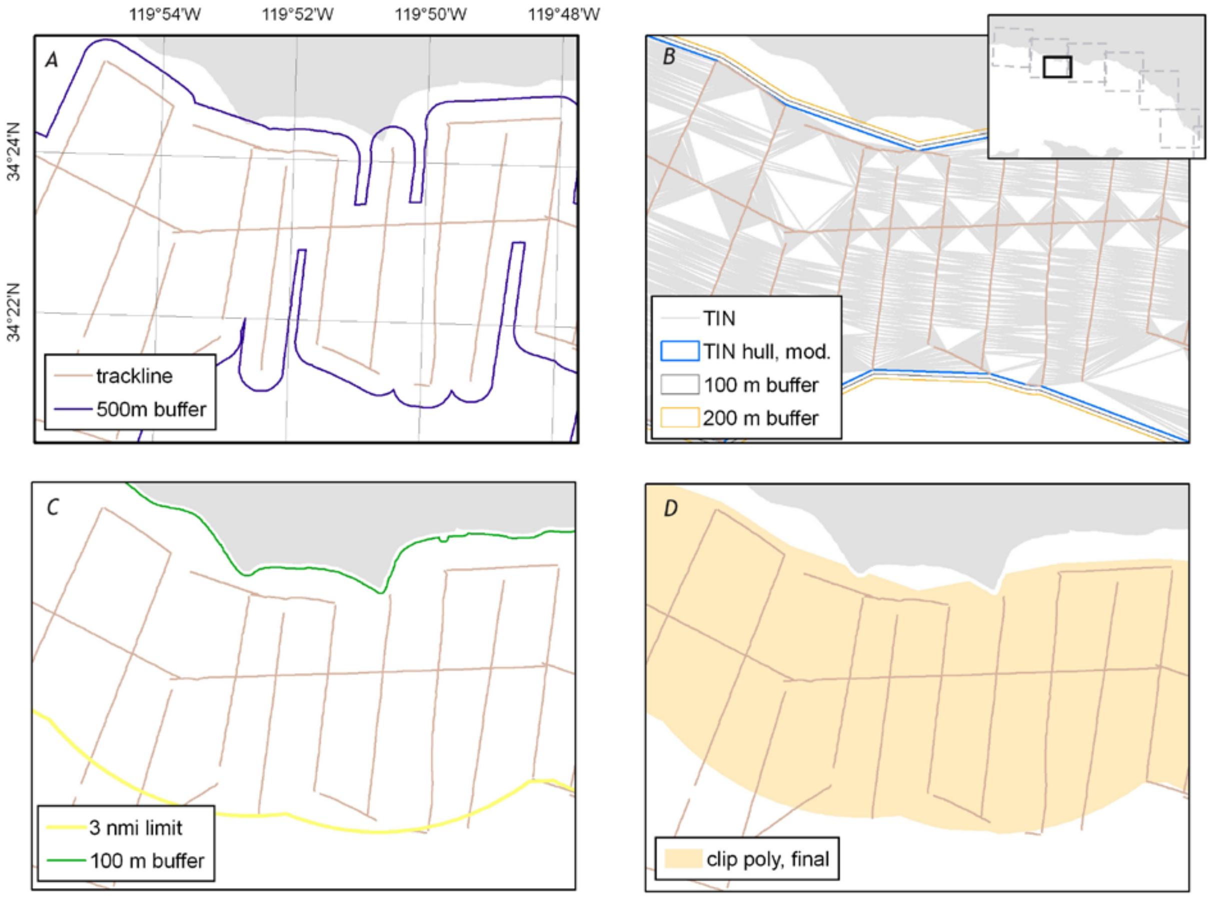


Figure 5. Candidates for data clipping mask. (A) 500-m buffer around tracklines was not used because it excludes useable data areas (deep incursions between tracklines). (B) An enclosing polygon (hull) is extracted from a triangular irregular network (TIN) constructed from the sediment thickness points. The hull is buffered with 100-m and 200-m margins; the 200-m margin was used. (C) For the landward limit, a 100-m buffer is applied to the coastline. The seaward boundary is the 3-nmi limit line. (D) The final clipping mask consists of pieces of the 200-m TIN buffer, 100-m coast buffer, 3-nmi limit, and excludes areas within the canyon outlines in the southeast.

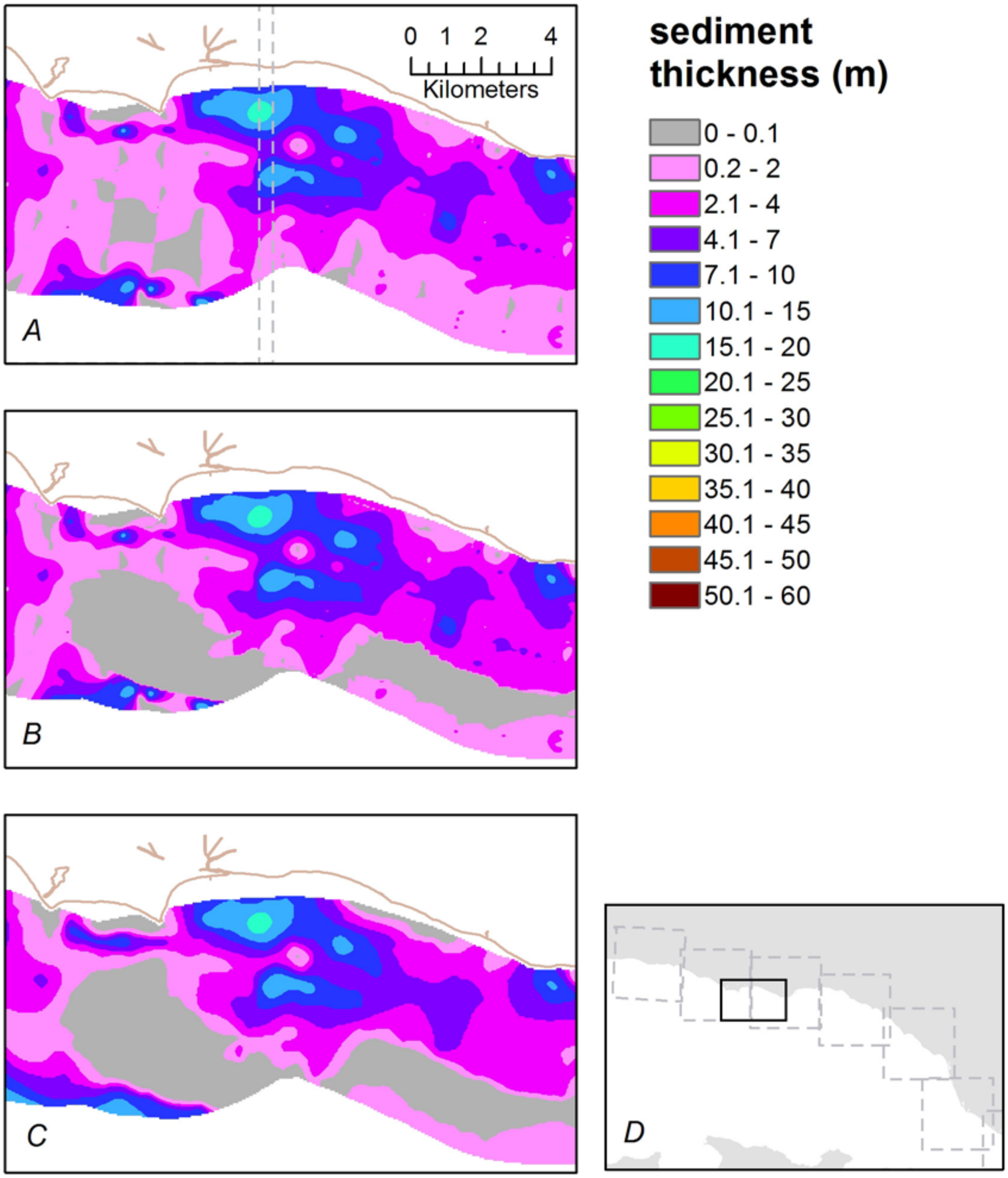


Figure 6. (*A*) Grid result from applying TopoToRaster to collection of points. (*B*) Grid calculation includes bedrock points (thickness = 0). (*C*) Final grid calculated from edited isopachs. (*D*) Location map.

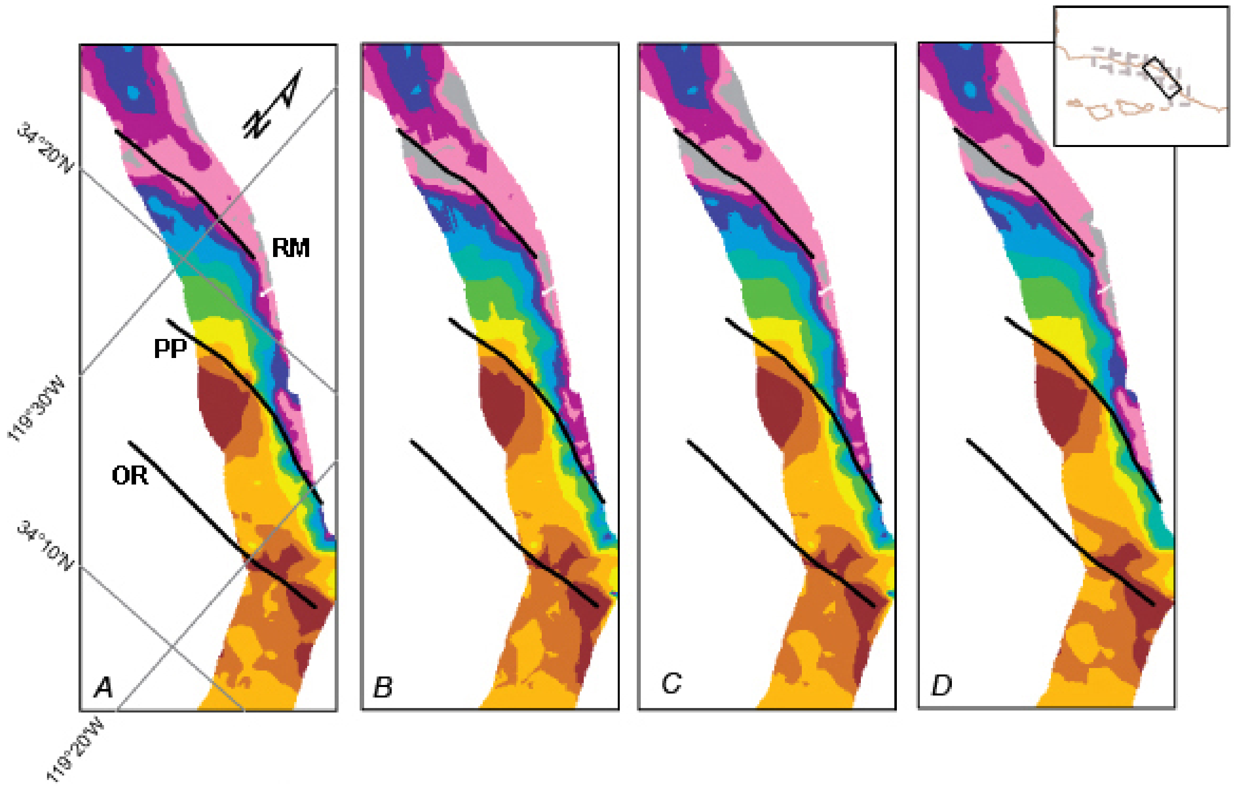


Figure 7. Faults (topologic breaklines) that disrupt seafloor sediment, as mapped from seismic-reflection profiles. North to south: RM, Red Mountain fault; PP, Pitas Point fault; OR, Oak Ridge fault. (A) Thickness interpolated with TopoToRaster, which has no option for breaklines. (*B*) Thickness interpolated by triangular irregular network (TIN) without breaklines. Result is similar to *A*. (*C*) Thickness TIN model calculated with breaklines, exhibits slight accommodation for Pitas Point fault (middle fault). (*D)* Final map interpolated from manually edited lines of equal thickness.

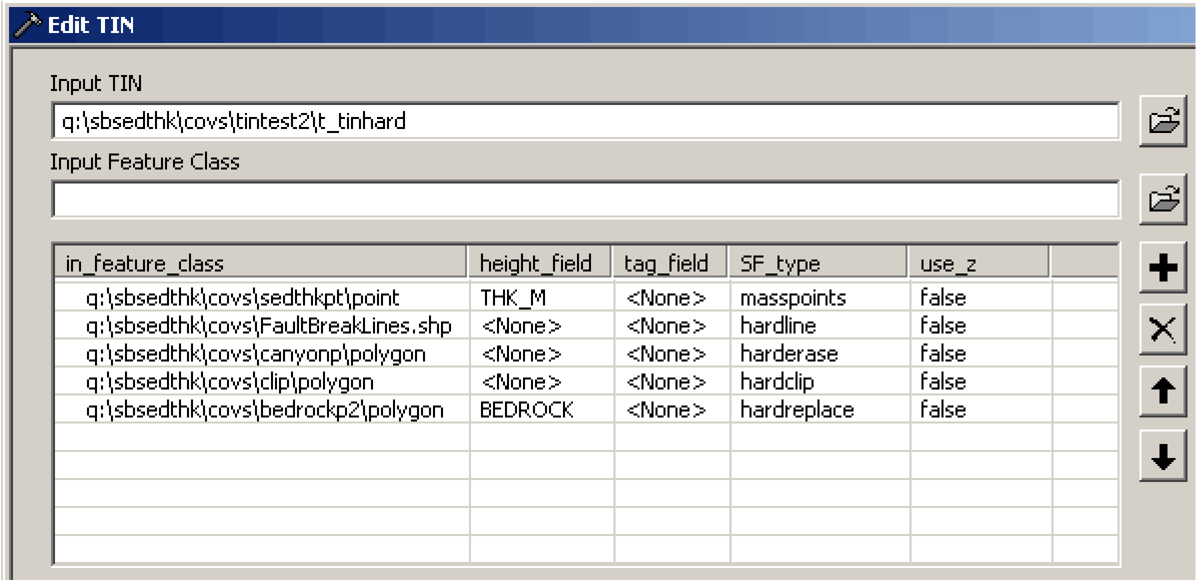


Figure 8. Input data for TIN calculation. SF_type (surface feature type) determines how data layers are treated in construction of the TIN. Interpolation takes in all points (masspoints), replaces bedrock with zero thickness (hardreplace), recognizes faults (hardline), omits canyons (harderase), and is confined to a clip polygon (hardclip).

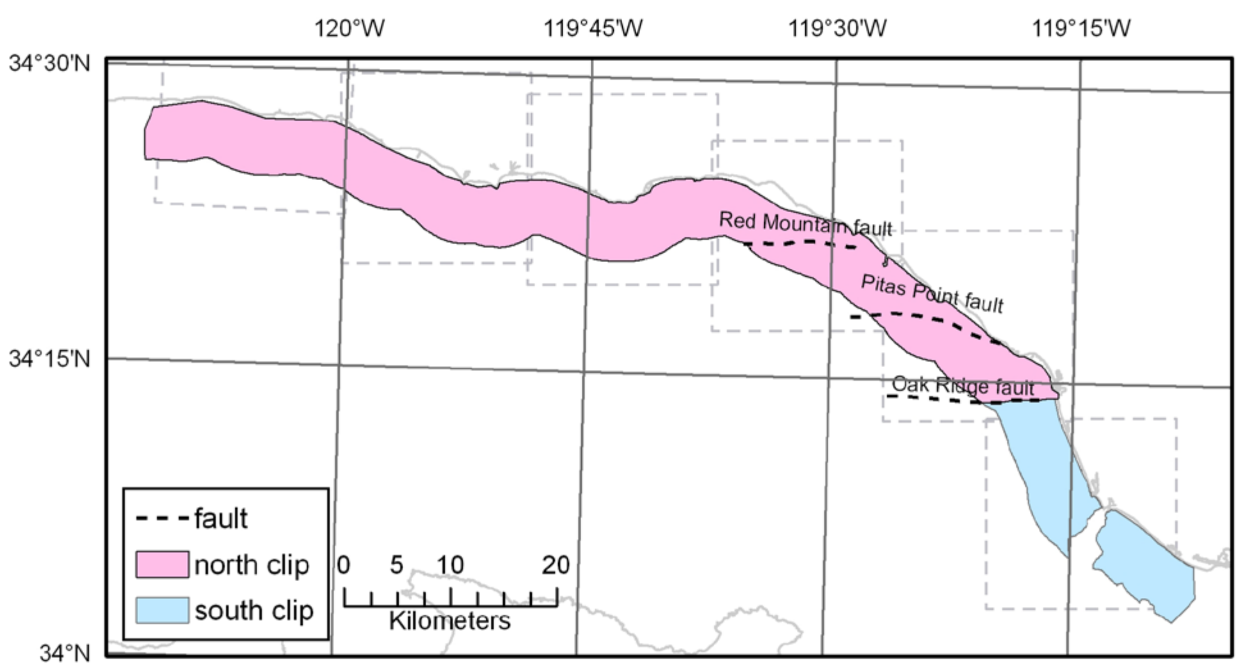


Figure 9. Northern (pink) and southern (blue) extents, separated by the Oak Ridge fault, were separately gridded and then mosaicked.

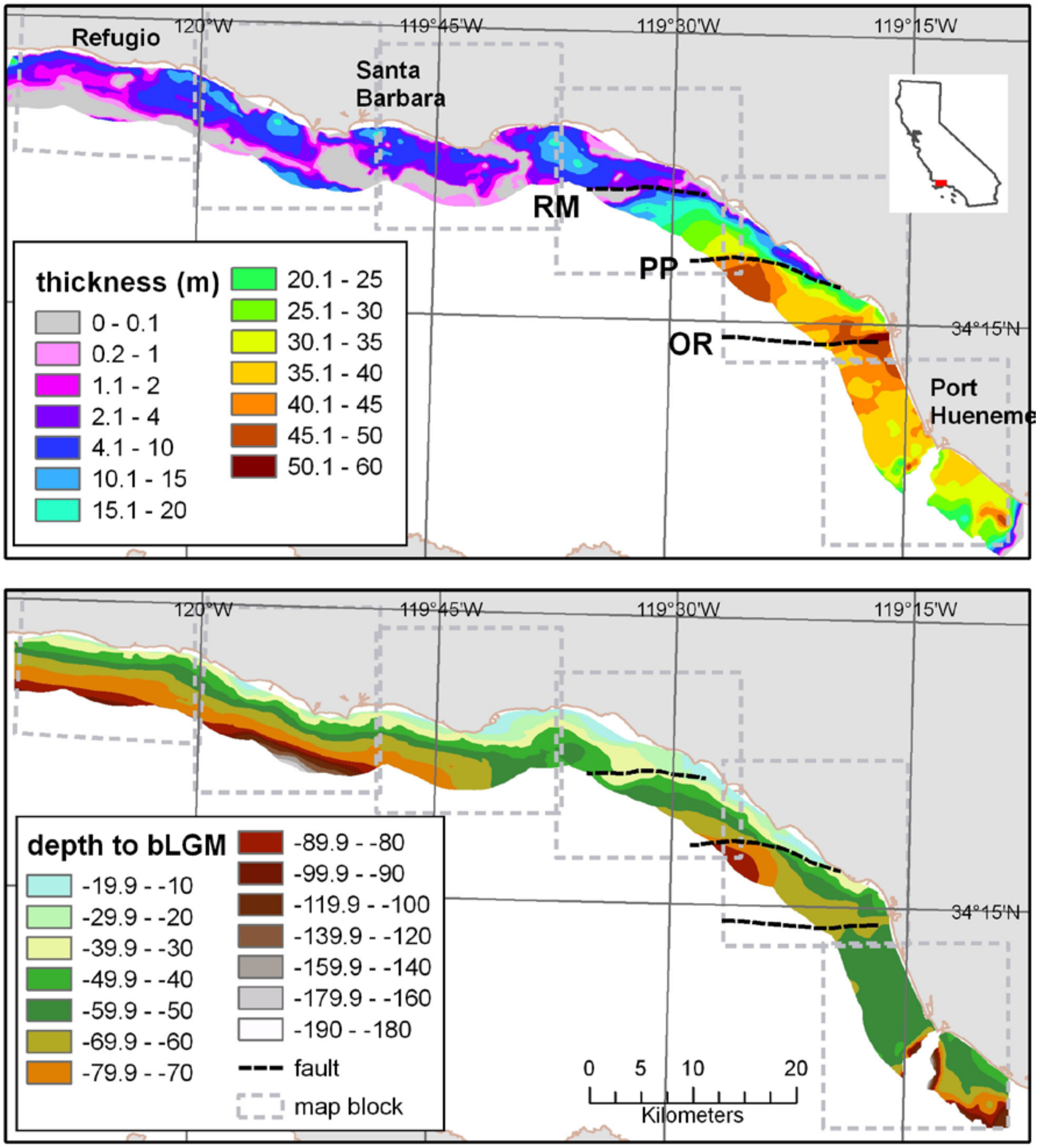


Figure 10. Final grids of (A) sediment thickness, and (B) depth to base of the Last Glacial Maximum for offshore eastern Santa Barbara Channel. RM, Red Mountain fault; PP, Pitas Point fault; OR, Oak Ridge fault.

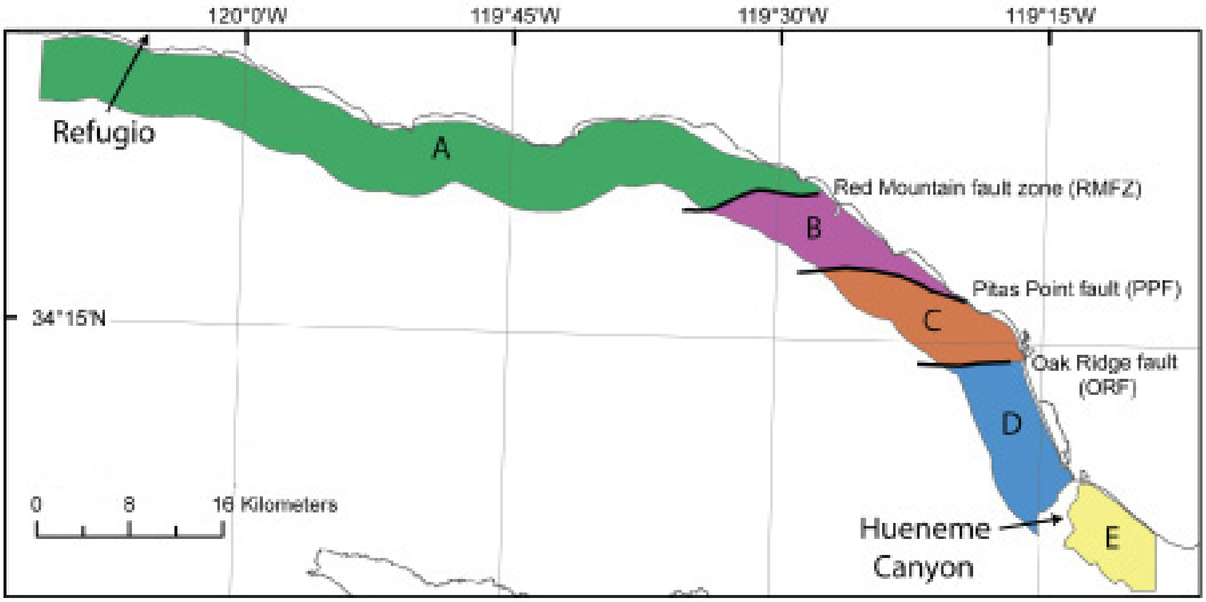


Figure 11. Regional extents for sediment volume calculations. Region A (green) extends from the western extent of the data (offshore of Refugio) to the southern strand of the Red Mountain fault zone (RMFZ). Region B (pink) extends from RMFZ to the Pitas Point fault (PPF). Region C (brown) extends from PPF to the Oak Ridge fault (ORF). Region D (blue) extends from ORF to Hueneme Canyon. Region E (yellow) comprises the remainder of the data, on the eastern side of Hueneme Canyon. Faults are shown in heavy black lines.