Depth to Basement and Thickness of Unconsolidated Sediments for the Western United States—Initial Estimates for Layers of the U.S. Geological Survey National Crustal Model

Open-File Report 2018–1115

U.S. Department of the Interior
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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Density	
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)

Depth to Basement and Thickness of Unconsolidated Sediments for the Western United States—Initial Estimates for Layers of the U.S. Geological Survey National Crustal Model

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Abstract

We present numeric grids containing estimates of the thickness of unconsolidated sediments and depth to the pre-Cenozoic basement for the western United States. Values for these grids were combined and integrated from previous studies or derived directly from gravity analyses. The grids are provided with 1-kilometer grid-node spacing in ScienceBase (https://www.sciencebase.gov). These layers may be updated as results from new studies become available.

Introduction

The U.S. Geological Survey (USGS) is currently (2018) developing a National Crustal Model (Boyd and Shah, 2018) to assist with earthquake hazard risk assessment by supporting estimates of ground shaking in response to an earthquake. The period-dependent intensity and duration of shaking depend upon the three-dimensional seismic velocity, seismic attenuation, and density distribution of an area, which in turn are governed to a large degree by rock type. For example, ground composed of poorly consolidated sediments typically experiences greater shaking intensity than ground composed of bedrock such as granite or sandstone. Additionally, ground shaking within sedimentary basins may be of greater duration and amplitude relative to locations outside of basins. In order to estimate the three-dimensional geophysical structure, knowledge of surface and subsurface geologic variations is needed. Geological data and models from various sources are thus being compiled to determine geophysical property variations over the conterminous United States, with 1-kilometer (km) grid-node spacing.

Two quantities describing vertical dimensions of key geologic layers provide a spatial framework for describing three-dimensional geophysical structure: (1) the thickness of unconsolidated sediments (which may also be considered as the depth to bedrock) and (2) the depth to basement. The dimensions of these layers determine where strong impedance contrasts are likely to occur and are therefore important for seismic hazard assessment. Estimates of these quantities also play important roles in other fields such as water resources, mineral and energy resources, and three-dimensional geologic mapping.

Models of these quantities for the western conterminous United States, with 1-km grid-node spacing, are presented here. The grid values have mostly been combined and integrated from previous published models, which typically cover smaller areas. These published grids were derived using various methods including seismic reflection, well data, gravity, and magnetic surveys; many include a component of interpretation. We also used gravity data to generate new estimates in some areas where previous models were not available.

Large areas of the grids are based on models derived from quantities such as topography or gravity data, and there are likely to be deviations from the actual values being estimated; some deviations may be large. Additionally, there can be unusual "edge effects" where estimates from different sources are merged. The grids are thus intended as approximations over a broad scale; studies that require more precise estimates should include additional data such as well logs, seismic reflection, or other data available at local scales. Efforts to develop improved models of unconsolidated sediment thickness and depth to basement at various scales are ongoing within the scientific community. A goal of the National Crustal Model is to continue to update layer grids as new models become available.

Thickness of Unconsolidated Sediments

The surficial layer of unconsolidated sediments can generally be thought of as sedimentary deposits that have not yet lithified into sedimentary rock. In some areas, unconsolidated sediments lie directly over igneous or metamorphic rock, so describing their thickness is straightforward. In other areas, the sediments may gradually become more indurated with depth, so a distinct boundary between sediments and sedimentary rock is more difficult to define. One approach is to define unconsolidated sediments according to age, as this can provide a consistent definition in all locales. A recent study covering the conterminous United States (Pelletier and others, 2016) defined unconsolidated sediments as those of Miocene age or younger; this definition is similar to that used for other hydrologic studies (for example, Gutentag and others, 1984).

To estimate the thickness of unconsolidated sediments, we used the model of combined sediment and soil thickness derived by Pelletier and others (2016) as a starting grid. For that model, surface geologic data and topographic analyses were combined to determine whether an area was likely to experience net erosion (highland hillslopes) or net sediment accumulation (lowland areas and highland valleys). The latter generally represents younger basins and river valleys. Within these divisions, they combined additional topographic analyses and well data to estimate the thickness of unconsolidated sediments (fig. 1). Pelletier and others (2016) acknowledge, however, that the methods do not work well in glaciated areas or in areas where sediments are likely to be greater than 50 meters (m) thick, and thus they capped the sediment thickness at 50 m in all areas. This cap can be a substantial underestimate in various places, especially in sedimentary basins.

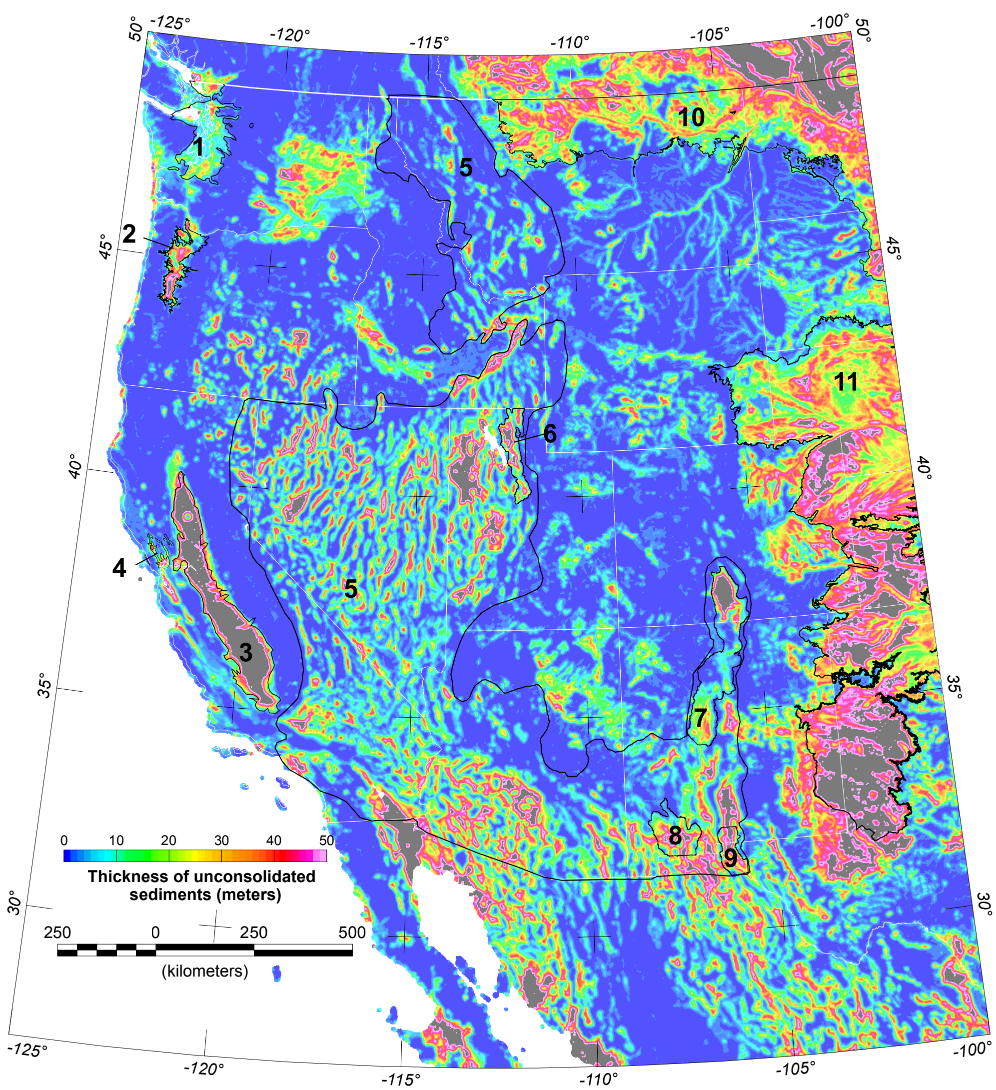


Figure 1. Thickness of unconsolidated sediments modeled by Pelletier and others (2016), with areas assigned a maximum value of 50 meters shaded in gray. For these areas, the actual thickness is likely to be greater. Polygons show bounds of regional models that were merged with the Pelletier and others (2016) model—1, Puget Sound; 2, Portland and Willamette Basins; 3, Central Valley of California; 4, northern San Francisco Bay; 5, Basin and Range; 6, Salt Lake Valley; 7, San Luis and Albuquerque Basins; 8, Mimbres Basin; 9, Hueco Bolson; 10, glacial deposits east of the Rocky Mountains; 11, High Plains sediments. White lines represent State boundaries.

Alternative sediment thickness estimates are required in locales where bedrock is likely to be deeper than 50 m. We thus incorporated local estimates of sediment thickness based on other methods, mostly from previous studies. These estimates (summarized in table 1 and shown in figure 2) include forearc basins, rift basins, and areas with high amounts of glacial and eolian deposits. In many of those areas, the local models and the Pelletier and others (2016) model are merged smoothly (such as the High Plains), but in some areas there are sharp contrasts between the different models (such as California's Central Valley and the San Luis and Albuquerque Basins). Potential future versions of this layer would include reassessment in these areas using additional data constraints. For some of the smaller (usually a few kilometers wide) areas such as fluvial valleys where Pelletier and others (2016) capped sediment thicknesses at 50 m, estimates from other studies were not available. We estimated the sediment thickness in these areas by first removing values of 50 m from the grid and then fitting a smoothly varying surface to those areas. The surface was determined by finding a minimum curvature surface that matches grid values less than 50 m. This approach essentially ensures smooth topographic slopes for the sediment-thickness grid over these valleys and small basins.

For the Basin and Range region, gravity modeling was used to estimate sediment thickness within the numerous smaller basins associated with Cenozoic extension. We employed the separation approach of Jachens and Moring (1990), which uses an iterative algorithm to separate gravity anomalies caused by lower density sedimentary fill from those caused by density variations within the surrounding rock. The basin-fill gravity anomalies are then used to solve for the thickness of the fill layer, assuming a prescribed layered density structure. The approach is discussed in more detail in the section "Notes for Specific Areas."

For some areas, such as eastern Washington (which has hundreds of meters of eolian sediment) and larger basins of New Mexico and Colorado (including the San Juan, Denver, and Raton Basins), our model is especially generalized, and the sediment thickness is likely to be underestimated. Updated sediment-thickness estimates will be incorporated into the model as additional data or models become available.

Table 1. Regional models used in the thickness of unconsolidated sediments layer.

[Area indexes used in figures 1 and 2]

Area index	Location	Model source	Method
1	Puget Sound, Washington	Eungard (2014)	Mixed
2	Portland, and Willamette Basins, Oregon	Conlon and others (2005)	Wells
3	Central Valley, California	Williamson and others (1989)	Wells
4	Northern San Francisco Bay, California	Modified from Langenheim and others (2010)	Gravity
5	Basin and Range: Arizona, California, Idaho, Montana, Nevada, New Mexico, and Utah	This study	Gravity
6	Salt Lake Valley, Utah	Radkins and others (1989)	Mixed
7	San Luis and Albuquerque Basins, Colorado and New Mexico	Keller and others (1984), Grauch and Connell (2013)	Gravity, wells
8	Mimbres Basin, New Mexico and Texas	Heywood (2002)	Gravity, wells
9	Hueco Bolson, New Mexico and Texas	Heywood and Yager (2002)	Gravity, wells
10	Glacial deposits east of the Rocky Mountains: Montana, North Dakota, and South Dakota	Soller and Garrity (2018)	Mixed
11	High Plains: Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas	Gutentag and others (1984), Cedarstrand and Becker (1998), Houston and others (2013)	Mixed
12	Offshore areas in San Francisco Bay, the Columbia River, and Puget Sound	Whittaker and others (2013)	Mixed

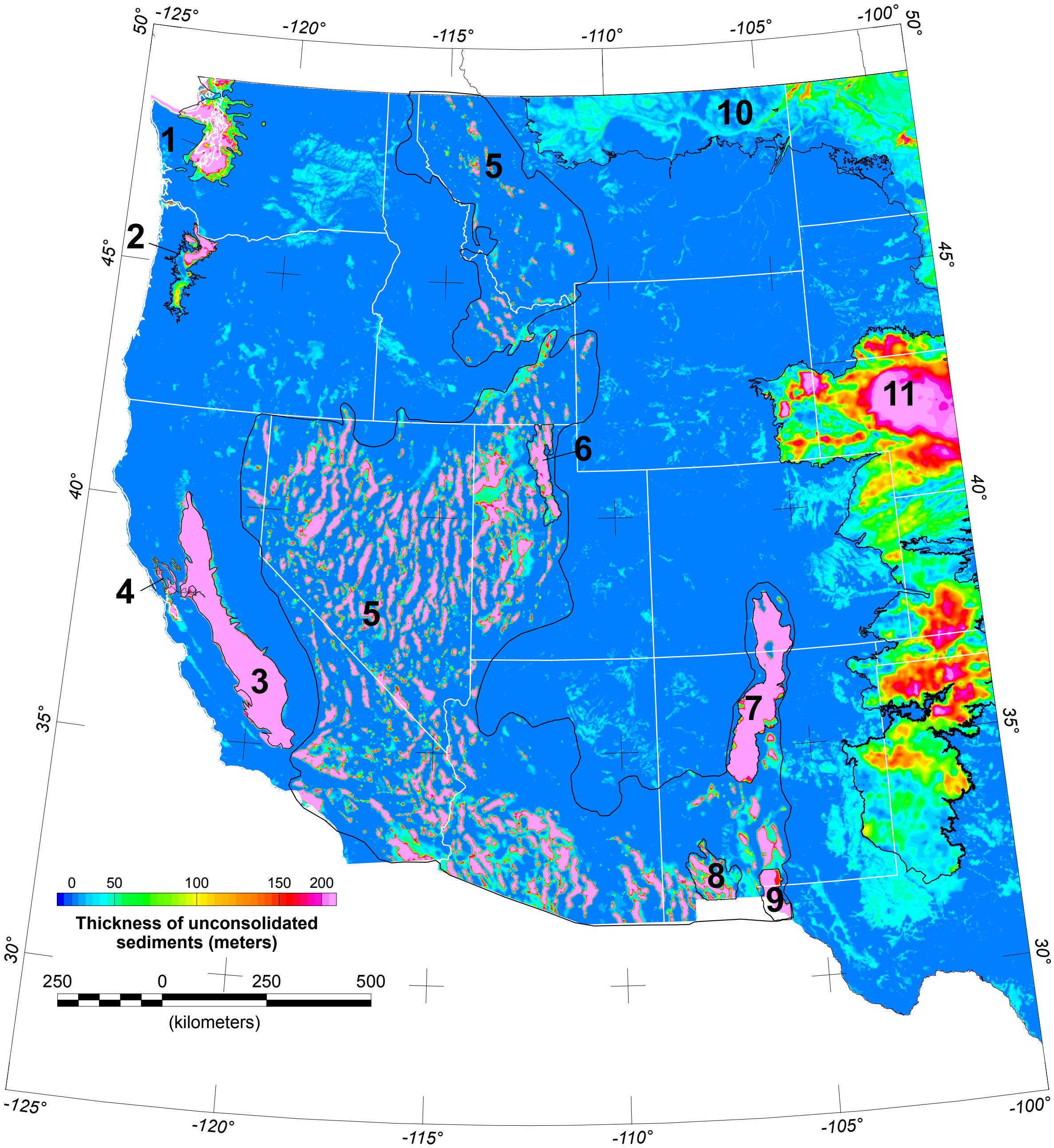


Figure 2. Thickness of unconsolidated sediments combined from Pelletier and others (2016) and regional models. Note that the color scale is different than that used in figure 1. Polygons show bounds of regional models—1, Puget Sound; 2, Portland and Willamette Basins; 3, Central Valley of California; 4, northern San Francisco Bay; 5, Basin and Range; 6, Salt Lake Valley; 7, San Luis and Albuquerque Basins; 8, Mimbres Basin; 9, Hueco Bolson; 10, glacial deposits east of the Rocky Mountains; 11, High Plains. White lines represent State boundaries.

Depth to Basement

The depth to basement (sometimes referred to as the depth to crystalline basement) is typically defined as the depth to the top surface of igneous or metamorphic rocks; rocks above this depth are either sediments or sedimentary rocks. Impedance contrasts are often observed at the interface between these rock types. To provide consistency over different regions, it is helpful to describe the basement rocks in terms of their geologic age. This approach is most directly achieved in the North American midcontinent, where the Great Unconformity distinguishes Precambrian basement from sedimentary cover (Marshak and others, 2017, and references therein). However, challenges arise in the western United States because tectonic processes have created significant local variations in the elevation of this surface (Marshak and others, 2017). Precambrian rocks crop out as far west as California, but there is limited information regarding their broader distribution. Furthermore, Cenozoic tectonic events have generated more recently formed basins. Numerous studies of basement elevation in areas west of the Rocky Mountains thus concern the thickness of overlying Cenozoic sedimentary rock.

Early published maps of sedimentary rock thickness or depth to basement for the conterminous United States were provided by Frezon and others (1983) and Exxon Production Research Company (1985). These maps combined public and proprietary data, and data sources were not provided. Nonetheless, these maps provide a rare quantitative estimate of depth to basement over the conterminous United States. The maps are very similar and may have been derived from the same datasets. Mooney and Kaban (2010) combined the Frezon and others (1983) map with other studies over California's Central Valley and the State of Nevada to provide an updated grid (fig. 3*A*). Additional published data over the midcontinent (between the Rocky Mountains and Appalachian Mountains) were later compiled by Marshak and others (2017), who provided an update for the depth to Precambrian basement within that region (fig. 3*B*).

For the western United States, we considered the depth to Mesozoic basement but cropped the resulting grid to the east along a boundary that approximates the extent of the Basin and Range Province to the south and areas with similar deformation to the north (fig. 4). We used the grid derived by Mooney and Kaban (2010) as a base map and incorporated previous local models for deeper valleys, summarized in table 2. In some areas, however, sediments or sedimentary rocks are present at the surface but the depth to basement given by Mooney and Kaban (2010) is zero, and alternative models were not available. We thus adjusted the depth to basement so that it is at least as deep as the depth to bedrock at each grid node. In some areas, Miocene or younger sediments unconformably lie over older crystalline rock, so this adjustment may be a good approximation, but in others, that is not the case, and the depth to basement is underestimated. One example might be in eastern Washington and parts of Oregon, where there are thick layers of sedimentary rocks beneath Miocene lava flows (Saltus, 1993). For areas farther east, the depth to Precambrian basement compiled by Marshak and others (2017) is used in the National Crustal Model.

The use of basement depth for estimation of geophysical characteristics such as density or velocity presents several challenges. One issue is that, for very deep basins, the definition of basement can be ambiguous because deep sedimentary rocks may experience low-grade metamorphism. In these cases, the depth to basement is usually considered to be the depth to igneous or metamorphic rock that existed prior to sedimentary deposition, but the differences in velocity and density between the basement and overlying metasedimentary rock may be small. Another issue that may arise is the presence of carbonate rocks, which may also be similar in density and velocity to igneous or metamorphic basement rocks. In these situations, consideration of the lithology of the corresponding layers is required.

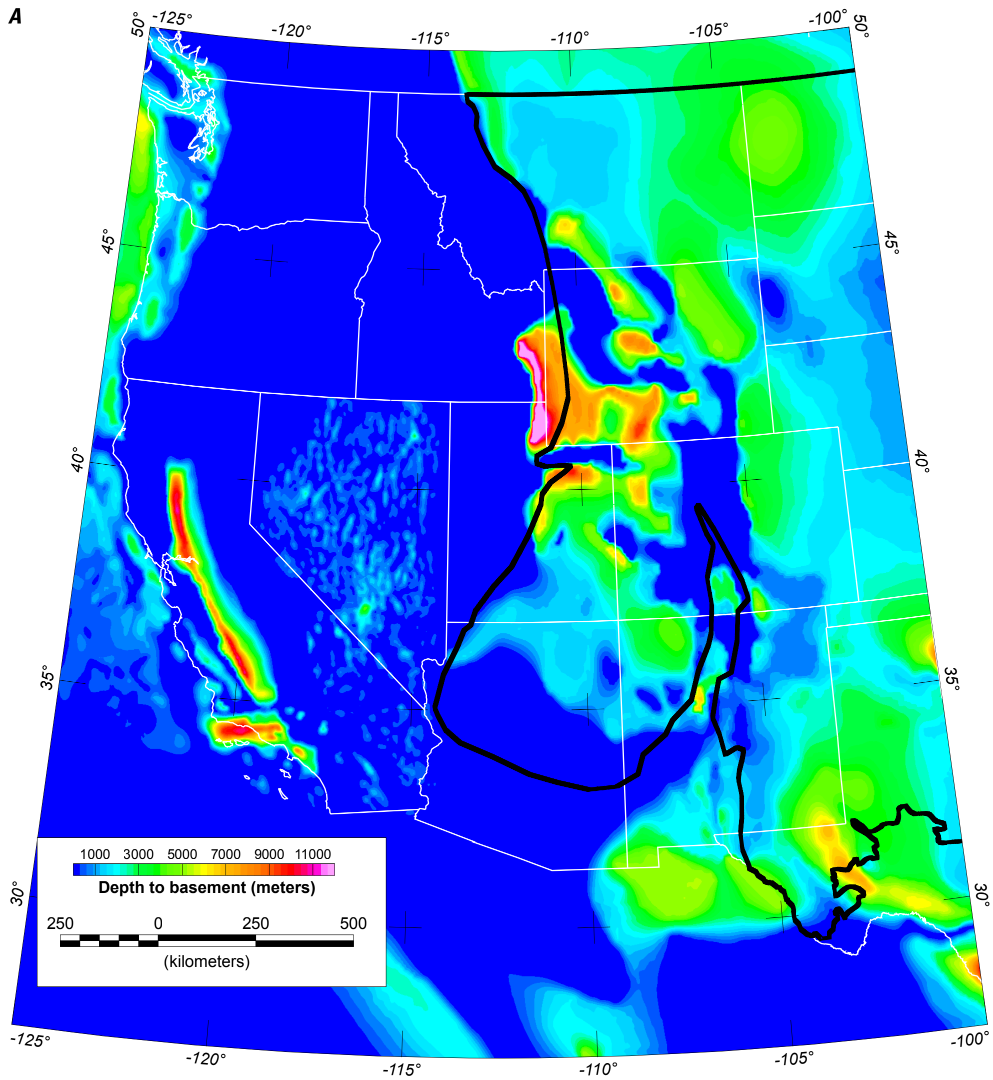
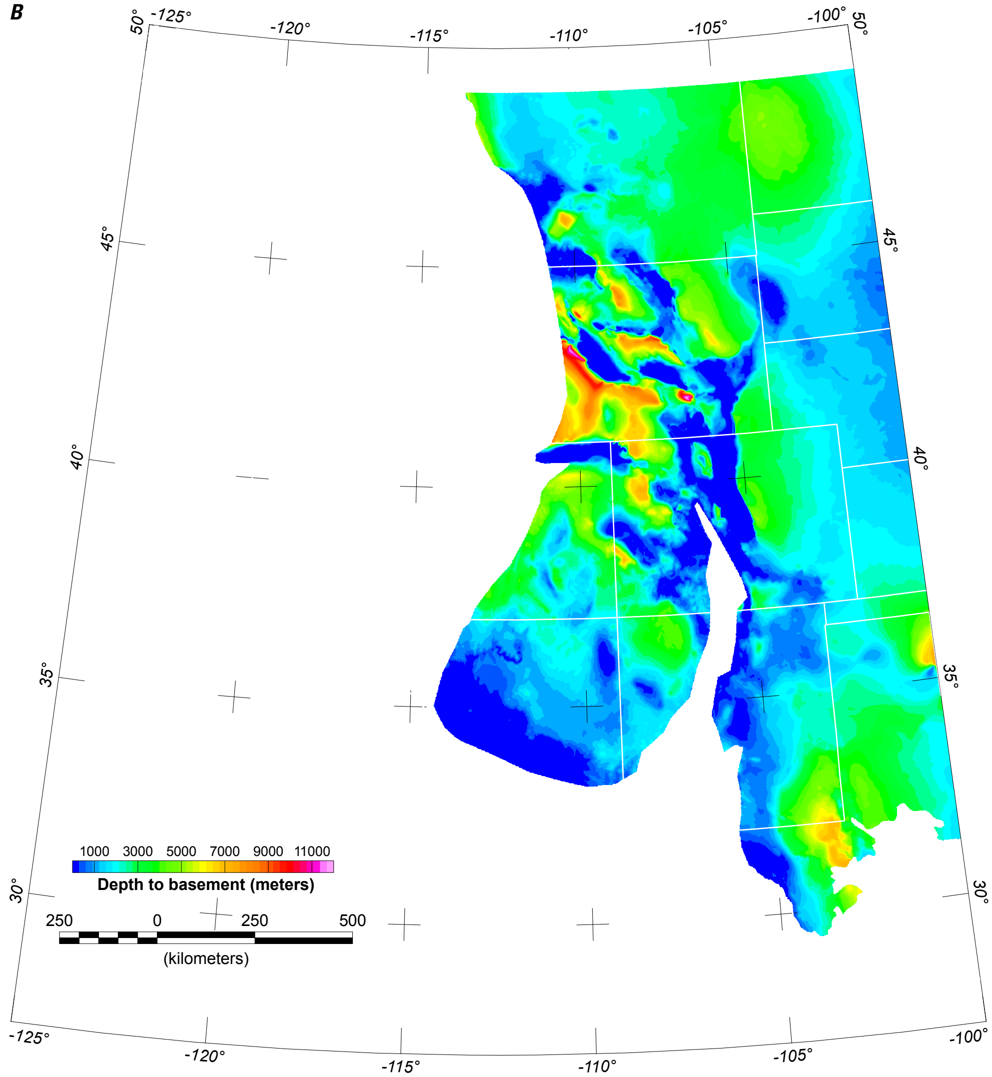


Figure 3. Previous models of depth to basement. *A*, Sediment thickness compiled by Mooney and Kaban (2010). Solid black line shows the outline of the grid derived by Marshak and others (2017). *B*, Depth to Precambrian basement calculated using the basement elevation model of Marshak and others (2017) and the SRTM30 digital elevation model of Becker and Sandwell (2011).

B



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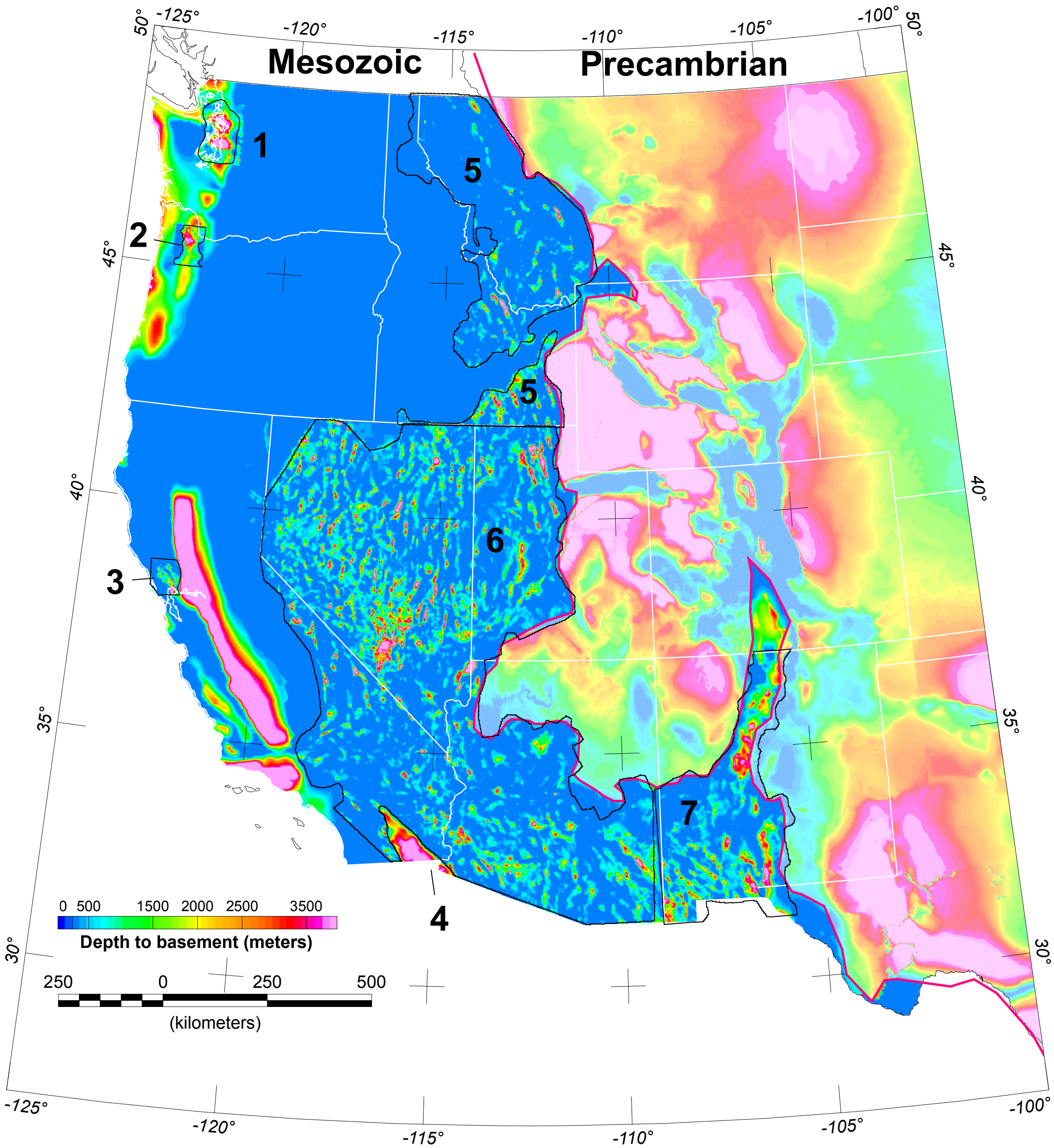

Figure 4. Compiled depth to basement. Polygons show bounds of regional models—1, Puget Sound; 2, Tualatin basin; 3, northern San Francisco Bay; 4, Salton Trough; 5, Basin and Range of Idaho and Montana; 6, Basin and Range of Arizona, California, Nevada, and Utah; 7, Basin and Range of New Mexico. Pink line marks eastern boundary of the depth to Mesozoic basement grid (this study); values north or east of this line represent the depth to Precambrian rock (Marshak and others, 2017). White lines represent State boundaries.

Table 2. Regional models used in the depth to basement layer.

[Area indexes used in figure 4]

Area index	Location	Reference	Method
1	Puget Sound, Washington	Brocher and others (2001)	Gravity
2	Tualatin basin, Oregon	McPhee and others (2014)	Gravity
3	Northern San Francisco Bay, California	Langenheim and others (2010)	Gravity
4	Salton Trough, California	Lovely and others (2006)	Gravity
5	Basin and Range of Idaho and Montana	This study; Shah and others (2018)	Gravity
6	Basin and Range of Arizona, California, Nevada, and Utah	Saltus and Jachens (1995)	Gravity
7	Basin and Range, New Mexico	This study; Shah and others (2018)	Gravity

Available Data Files

Grid data for this portion of the National Crustal Model are provided in comma-separated text files, which may be downloaded freely (Shah and Boyd, 2018; Shah and others, 2018). All layers are defined relative to the land surface. The grids cover the western United States from the west coast to longitude 100°E for the thickness of unconsolidated sediments and to the boundary shown in figure 4 for the depth to Mesozoic basement. Future work may include updates of the grids, as new local models describing these layers become available, and extension of these grids to include the full conterminous United States.

Notes for Specific Areas

The Basin and Range in Arizona, California, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming

Previous models using the Jachens and Moring (1990) gravity separation approach were developed to estimate the depth to basement for a subset of the Basin and Range Province in Nevada, Arizona, Utah, and California (Saltus and Jachens, 1995). This approach was used to extend these models to areas showing similar extensional features in New Mexico, Idaho, and Montana using the same layered density structure as Saltus and Jachens (1995). State geologic maps (Luddington and others, 2007; Stoeser and others, 2007) were used to define areas where Cenozoic sediments are present at the surface. Gravity data by McCafferty and others (1998) and National Oceanic and Atmospheric Administration (1998) were used to constrain the models.

To estimate depth to bedrock, we applied the separation approach to find the thickness of Miocene and younger sediments rather than Cenozoic sediments and to cover a wider area that also includes New Mexico, Idaho, Montana, and a small part of Wyoming. We used the same density structure as Saltus and Jachens (1995) (table 3), which is based on well data. However, because only the upper two layers have density contrasts large enough to represent unconsolidated sediments, we capped the sediment thickness at 600 m. Deeper model layers are assumed to represent sedimentary bedrock. Additionally, the algorithm assigns a sediment thickness of zero to areas outside of the basin fill (in this study, rocks that are older than Miocene age). This approach is different from that of Pelletier and others (2016), who included both soil and sedimentary deposits. We thus combined the gravity model with the Pelletier and others (2016) model by comparing the two thickness estimates at each grid node and using the larger of the two. This method provides nonzero sediment thickness values over much of the region and effectively smooths the models near the edges of the basin fill.

Data used as inputs to the depth to bedrock gravity model include an isostatic residual gravity anomaly, which was calculated from public gravity-station data (University of Texas at El Paso Regional Geospatial Service Center, 2016) assuming a density contrast of 0.5 grams per cubic centimeter (g/cm^3) at the Moho and using the method of Simpson and others (1986). The boundaries of Miocene fill areas were derived from USGS

Table 3. Density structure used for gravity modeling in the Basin and Range Province (after Saltus and Jachens, 1995).

[m, meter; g/cm^3, gram per cubic centimeter]

Depth (m)	Density contrast (g/cm^3)
0–200	–0.65
200–600	–0.55
600–1,200	–0.35
>1,200	–0.25

State geologic map compilations (Luddington and others, 2007; Stoeser and others, 2007). The SRTM30_Plus digital elevation map (Becker and Sandwell, 2011) was used to estimate surface topography.

The depth to bedrock gravity model includes estimates in subareas from previous, more detailed studies, including the Salt Lake Valley, Mimbres Basin, Hueco Bolson, and San Luis and Albuquerque Basins (see table 1). Estimates from those studies supersede the gravity model estimates.

Central Valley of California

An estimate for post-Eocene sediment thickness developed by Williamson and others (1989) was used for the thickness of unconsolidated sediments in California's Central Valley. This package of sediment consists of Miocene and younger sediments over most of the valley because Oligocene deposition was limited mostly to the southern San Joaquin Valley (Bertoldi and others, 1991). The map provided by Williamson and others (1989) was digitized by Faunt (2009). The area covered by this map is larger than the area described as Miocene or younger in State geologic maps (Luddington and others, 2007), so it was trimmed to match the maps of surface geology.

Glacial Deposits East of the Rocky Mountains—Montana, North Dakota, and South Dakota

The grid of glacial deposits by Soller and Garrity (2018) primarily describes Quaternary deposits, which is different from the definition of unconsolidated sediments used here. Additionally, zero values are assigned to various areas without glacial deposits. To include sediments of Miocene age or younger, as well as soil deposits, the maximum value between the Soller and Garrity (2018) and Pelletier and others (2016) grids was used.

Puget Lowland and Willamette Valley

Both the Puget Lowland and Willamette Valley are underlain by volcanic rocks ranging in age from Miocene to Holocene. The thickness of unconsolidated sediments refers to sediments above volcanic layers. Additionally, in the Puget Lowland, Eungard (2014) defined unconsolidated sediments as younger than Miocene. The definition for this region therefore differs slightly from that used elsewhere.

Northern San Francisco Bay

Langenheim and others (2010) generated a model of depth to Cenozoic basement for a region north of the San Francisco Bay; this model is incorporated in our grid of depth to basement. We modified this model to also provide estimates of sediment thickness. The model was trimmed so that only areas where Miocene or younger sediments are present at the surface were used; other parts of this region were assigned the sediment thickness derived by Pelletier and others (2016). Additionally, the model uses a layered density function such that material in the upper 300 m has a density contrast with the basement closest to that of sediments (0.48 g/cm^3), whereas deeper layers have densities more similar to that of sedimentary rock (<0.32 g/cm^3). The thickness of the sediment layers was therefore capped at 300 m.

High Plains, South Dakota to Texas

In the northern High Plains, well data providing the depth of Miocene layers were available for South Dakota and northern Kansas (Houston and others, 2013), so these data were used. For the rest of the region, the maps presented by Gutentag and others (1984) and digitized by Cedarstrand and Becker (1998) were used.

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