May 2018 Montana Bureau of Mines and Geology Open-File Report 703

THREE-DIMENSIONAL HYDROSTRATIGRAPHIC MODEL OF THE SUBSURFACE GEOLOGY, FLATHEAD VALLEY, KALISPELL, MONTANA

James Rose

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Ground Water Investigations Program

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Cover image: Aerial view of the Flathead Valley looking northeast. Photo by Chris Saulit.

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PREFACE

The Montana Bureau of Mines and Geology (MBMG) Ground Water Investigations Program (GWIP) has prepared this report. The purpose of GWIP is to investigate specific areas, as prioritized by the Ground-Water Assessment Steering Committee (2-15-1523 MCA), where factors such as current and anticipated growth of industry, housing, commercial activity, or agriculture have created elevated concern about groundwater issues. Additional program information can be accessed at http://www.mbmg.mtech.edu/gwip/. GWIP uses various scientific tools to interpret hydrostratigraphic data, investigate how the groundwater resource has responded to past stresses, and project future responses.

The final products of the Flathead Valley deep aquifer study include:

A **Hydrostratigraphic Report** that presents a 3-dimensional model of the subsurface geology in the Kalispell Valley. This model is based on interpretations of drillers' well logs, previous geology maps and reports for the area, gravity data, and seismic data. Electronic files for the geologic contacts and stratigraphic units can be downloaded from our website.

An **Interpretive Report** that presents interpretations of the hydrogeologic data and summarizes the project results within the context of the study area and the issues to be addressed. The Interpretive Report includes all investigation results, and is intended for use by the public, special interest groups, decision-makers, and hydrogeologists. A comprehensive dataset is permanently stored in the MBMG's Groundwater Information Center (GWIC) online database:

http://mbmggwic.mtech.edu/sqlserver/v11/menus/menuProject.asp?mygroup=GWIP&myroot=BWIPKL&ord=1&

ABSTRACT

Groundwater-level declines in the deep alluvial aquifer in the Flathead Valley near Kalispell, Montana have raised concerns about impacts to groundwater resources from groundwater withdrawal. With local population growth has come the addition of new wells completed in the deep alluvial aquifer, the valley's primary, regional water supply.

The deep alluvial aquifer and the overlying lacustrine-till aquitard are the two most important hydrogeologic units of the groundwater supply in the Flathead Valley. The deep alluvium is composed of coarse gravels and sand that allow high production rates to water wells. The lacustrine-till aquitard is composed of silt and clay that isolates the deep aquifer from shallow systems. The lacustrine-till aquitard protects the deep alluvial aquifer from surface contamination, influences areas of drawdown from pumping in the deep aquifer, and maintains pressure head in the deep aquifer by limiting vertical communication.

A 3-dimensional, hydrostratigraphic model was constructed using Aquaveo GMS. The purpose of this model was to build a visual representation of the subsurface hydrostratigraphy with emphasis on the lacustrine-till aquitard, due to its importance in managing the deep alluvial aquifer.

The hydrostratigraphic model was constructed using 959 lithologic logs from water wells in the Flathead Valley, combined with the results of previous work. The valley geology was categorized into six hydrostratigraphic units for model construction: the basement Belt bedrock aquifer; Tertiary aquifer; deep alluvial aquifer; silt, clay, gravel zone of the deep alluvial aquifer; lacustrine-till aquitard; and the shallow aquifer.

Model results show the lacustrine-till aquitard is continuous over the top of the deep alluvial aquifer throughout the Flathead Valley. The modeled thickness of the aquitard ranges from 4 ft to 790 ft. More importantly, in the center of the basin, the lacustrine and till deposits are thicker than 50 ft almost everywhere. The thickness of the deep alluvium, the host rock of the deep aquifer system, is interpreted to be in the range of 1,000 ft to more than 1,300 ft. The top surface of the deep alluvium slopes downward to the south, toward Flathead Lake, at about 19 ft per mile. There are no data describing deep alluvium beneath Flathead Lake. Shallow core samples have shown lacustrine silt, of the lacustrine-till aquitard, on the lake bottom. At the southernmost data points in the study area, at the north shore of Flathead Lake, the top of the deep alluvium is at an elevation of about 2,200 ft above mean sea level in well logs, and slopes down to the south. This elevation is roughly 700 ft below the lake surface at the north shore and 340 ft below the deepest point on the lake bottom, 16 mi south of the north shore. The elevations of the top of the deep alluvium and the lake bottom indicate that there may be separation between the two, probably by the lacustrine-till aquitard.

The hydrostratigraphic model combines all available geologic information into a single comprehensive, 3-dimensional, visual display of the subsurface valley geology for groundwater management purposes. The model provides a graphical representation of the valley hydrostratigraphy, estimates of thicknesses and volumes of the modeled units, and probable drilling depths for future wells. One benefit is the ability to input the hydrostratigraphic data directly from this model into MODFLOW to represent subsurface hydrostratigraphic conditions. The model files are publicly available for water managers to use in future assessments. Incorporation of new data into the model as additional wells are drilled in the basin will provide continual refinement.

INTRODUCTION

Project Background

Groundwater-level declines in the deep alluvial aquifer, possibly related to population growth, have raised concerns about potential impacts from increased use of groundwater resources in the Flathead Valley near Kalispell, Montana. The deep alluvial aquifer is the primary, regional water supply in the valley. The top of this aquifer lies 100 ft or more beneath the valley floor and is buried beneath an aquitard composed of lacustrine silt and glacial till that averages nearly 200 ft in thickness (Smith, 2004d).

This investigation was prompted by several years of declining water levels observed through monitoring of the deep aquifer. Local residents were concerned about the ability of the aquifer to sustain groundwater production as additional wells are completed in the deep alluvial aquifer to support population growth, and increasing water demand. There was also local interest in knowing if a hydrologic connection exists between the deep alluvial aquifer and surface water, shallow groundwater, or Flathead Lake, for water-use planning.

Purpose and Scope

The purpose of this investigation was twofold: (1) determine whether withdrawals from the deep aquifer affect surface-water resources; and (2) determine if current stresses are creating declining water-level trends in the deep aquifer.

Three objectives were established:

- investigate and describe the geologic and hydrogeologic characteristics of the lacustrine-till aquitard;
- identify probable sources and mechanisms of recharge to, and discharge from, the deep aquifer; and
- explain long-term and seasonal water-level trends in the deep alluvial aquifer.

The objectives of the Flathead Valley deep aquifer study are addressed in two separate reports:

1. a hydrostratigraphic model of the Flathead Valley (this report); and
2. a hydrogeologic interpretive report (Wheaton and others, in review).

This report only addresses the first objective: configuration of the subsurface hydrostratigraphy with particular emphasis on the lacustrine-till aquitard. This report includes a 3-dimensional hydrostratigraphic model and associated electronic files.

The valley hydrostratigraphy was modeled in three dimensions using Aquaveo GMS software (Aquaveo-GMS, 2015). The model was constructed from water-well lithology logs recorded in the valley combined with interpretations from previous geologic and hydrogeologic studies. The GMS software has the capability to develop graphical representations of 2-dimensional surfaces (hydrogeologic contacts) and 3-dimensional solids (hydrogeologic units). The results can be exported in different formats, and are compatible with GIS software. Aquaveo GMS is designed to be a MODFLOW data pre- and post-processor and graphical user interface.

The hydrogeologic interpretive report (Wheaton and others, in review) applies the modeled hydrostratigraphic configurations with hydrologic interpretations, to address concerns about stresses on the deep aquifer in the Flathead Valley. The hydrogeologic report, along with the modeled hydrostratigraphy, attempts to identify potential areas of recharge to groundwater and locates areas of deep groundwater discharge to the shallow groundwater, to surface water, or to Flathead Lake.

Project Location

The Flathead Valley project area is in the Rocky Mountains of northwestern Montana. The hydrostratigraphic model boundary is slightly larger than the project boundary to incorporate all of the valley-fill sediments to the bedrock valley margins to the west, north, and east. The valley is a north–northwest-trending intermontane basin that lies north of Flathead Lake (fig. 1). The Flathead Valley encompasses an area of nearly 200,000 acres (312 mi^2), and includes the communities of Kalispell, Bigfork, Columbia Falls, and Whitefish (U.S. Geological Survey, 2018). The east and west model boundaries include the bedrock mountain slopes that define the valley margins. The north boundary is at or near the bedrock margin and includes the area where the Flathead River enters the northeast corner of the valley. The southern model boundary is about 3 mi south of the north shore of Flathead Lake and joins well lithology interpretations with bathymetry and seismic data from the north end of the lake.

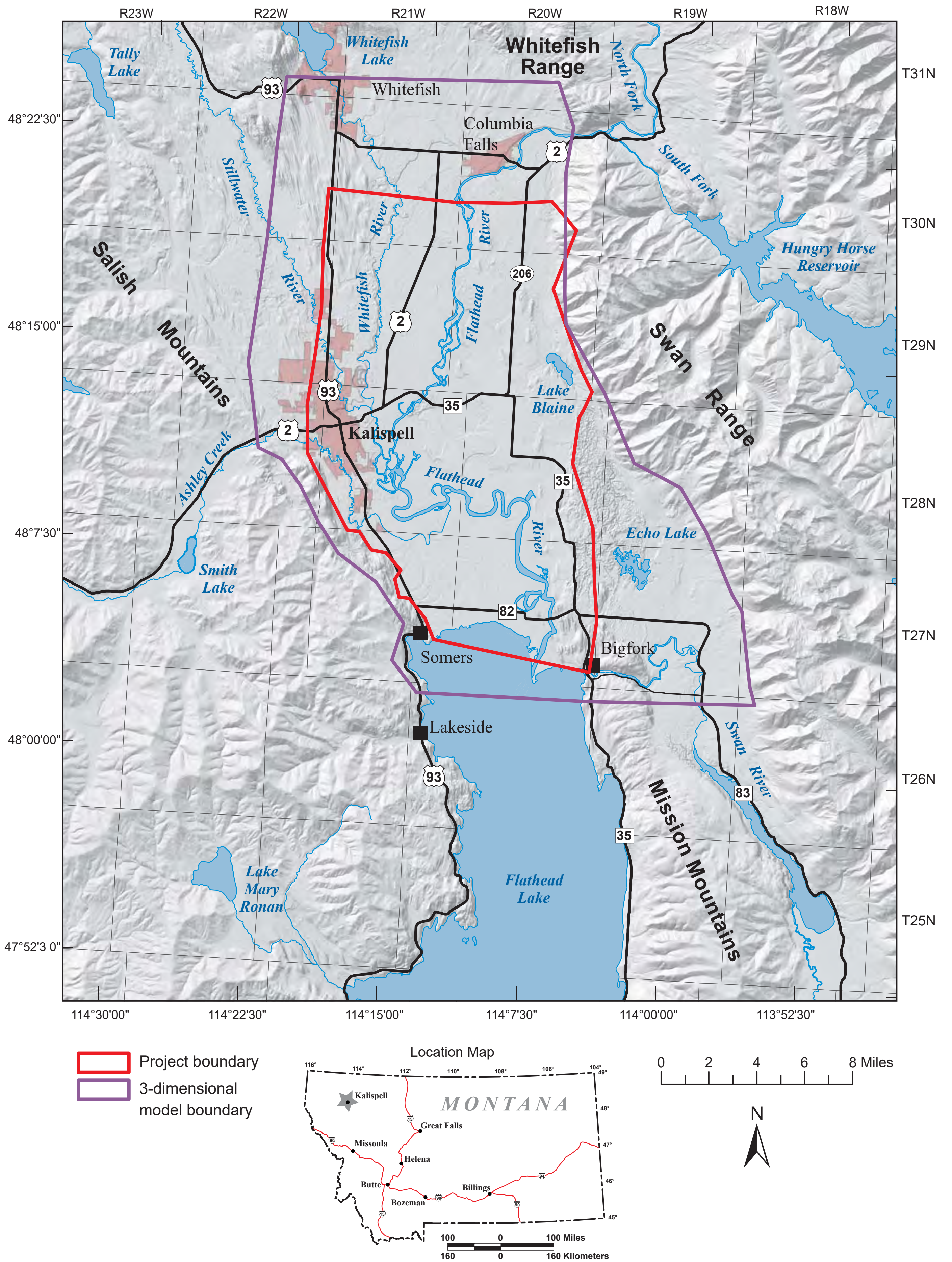


Figure 1. The project study area is located in the Flathead Valley of northwestern Montana.

The Swan Range bounds the valley to the east, the Whitefish Range to the north, and the Salish Mountains to the west (fig. 1). The valley floor has low topographic relief, with elevations ranging from about 3,100 ft above mean sea level (ft-amsl) at the valley edges (higher on some terraces), 3,060 ft-amsl where the Flathead River enters near Columbia Falls, and 2,900 ft-amsl, 24 mi to the south where the river enters Flathead Lake. The valley is the southernmost segment of the Rocky Mountain Trench, a large structurally formed valley in the Northern Rocky Mountains (Garland and others, 1961).

Previous Studies

Previous workers have described the geology and formational processes of the Flathead Valley and the Northern Rocky Mountain region, and the hydrogeology of the area. Alden (1953) wrote the first comprehensive summary of the geologic history of the region, including some detail about glacial landforms and descriptions of the formational processes and events that occurred in the valley.

Konizeski and others (1968) presented the first summary of the subsurface geology of the Flathead Valley, which included an interpretation of the depth to bedrock from portable gravimeter measurements. Stickney (1980) investigated subsurface structures of the Belt bedrock north of Flathead Lake. Wold (1982) interpreted seismic reflection data to define the depth to the Belt bedrock and the bedrock surface topography beneath Flathead Lake. A bathymetry map of Flathead Lake details the bottom sediment depth contours (Flathead Lakers, 2011). Harrison and others (1992) mapped the regional geology and structure of the Kalispell 1 x 2-degree quadrangle. Uthman and others (2000) drilled a series of deep groundwater-monitoring wells across the northern part of the valley and created the first detailed cross-section interpretation of the subsurface geology.

Previous investigations have identified the area subsurface geology as composed of Belt Supergroup bedrock overlain by Tertiary sediment, Quaternary alluvial sediment, and modern shallow, surface alluvium. However, no outcrops of Tertiary sediments have been found in the project area of the Flathead Valley (Alden, 1953; Konizeski and others, 1968; LaFave and others, 2004). Based on mapping in nearby valleys, previous authors have inferred the Tertiary history of the Flathead Valley. Willis (1902) mapped Tertiary sediments in the northern Rocky Mountains of Montana just south of the Canadian border. Daly (1912) mapped Tertiary sediment along the North Fork of the Flathead River in Canada, and Erdmann (1944) mapped remnant Tertiary deposits on the slopes of the North Fork, Middle Fork, and South Fork Valleys of the Flathead River just a few miles northeast of the project area. Russel (1954) identified Tertiary sediments in the Flathead Valley about 30 mi north of the project area. Garland and others (1961) and Smith (1965) indicated that Tertiary sediments probably occur at depth within the Rocky Mountain Trench. Constenius (1981) did extensive work on the Tertiary units along the North Fork and Middle Fork of the Flathead River.

In 1996, the MBMG Ground Water Characterization Program (GWCP) undertook a hydrogeologic characterization study of the Flathead Valley north of Flathead Lake and the Mission Valley south of the lake. This study resulted in the release of 15 publications: LaFave (2000); LaFave (2004a,b,c,d); Smith and others (2004); Smith (2004a,b,c,d,e,f); Patton and others (2003); and McDonald and LaFave (2004). These publications cover the area's geology and hydrogeology in detail. Information from the GWCP publications that were especially useful in constructing the model include subsurface maps of the contoured thickness of, or depth to, individual geologic units (Smith 2004a,b,c,d,f). The maps were created from the interpretation of lithology logs from water wells drilled into the valley sediments, and from the construction of geologic cross sections between these wells. Additional descriptions of the units and their depositional environments are reported in LaFave and others (2004) and Patton and others (2003). These publications, especially the geology presented by Smith, were used as a template to outline the hydrostratigraphic model presented in this report.

More recent research includes Smith (2004g) on the glacial geologic history of valley formation and the mechanisms of valley sedimentary deposition. Hoffman and others (2006) interpreted seismic reflection data from beneath Flathead Lake to define sediment fill and depth to bedrock.

Geologic Setting

The Flathead Valley lies at the south end of the

Rocky Mountain Trench, a large intermontane valley in the Northern Rocky Mountains that extends 990 mi into Canada (van der Velden and Cook, 1996). The valley was formed, like most valleys in the region, within structural depressions in the basement bedrock, the Belt Supergroup (Belt). The top of the Belt surface defines the valley-fill bottom. The Belt crops out in the Whitefish Range to the north, the Swan Range to the east, and the Salish Mountains to the west (fig. 2). The north end of the Mission Mountains, also composed of Belt bedrock, defines the southeast boundary of the valley. Tertiary extensional faulting displaced segments of the Belt bedrock along a series of north–south normal faults, creating the half-graben that forms the Flathead Valley. Gravity data show that the bedrock valley bottom tilts east, and is 1,500 ft lower in elevation at the Swan Mountains at the valley's east boundary (Konizeski and others, 1968; Smith, 2004a; Gibson, 2012, written commun.).

The bedrock valley has been infilled with a series of fluvial, glacial, and lacustrine sediments deposited during the Tertiary and Quaternary periods (fig. 3). The Flathead River continues to transport and deposit sediment from the surrounding mountains onto the valley floor, and into Flathead Lake.

Belt Supergroup Bedrock

The highly competent Belt bedrock defines the margins of the valley, and the deeply buried bedrock surface forms the base of the valley-fill (figs. 2, 3). The Precambrian (1.4–1.5 Ga) Belt Supergroup is the most widespread geologic unit in the Flathead Valley region. The Belt Supergroup consists of metamorphically altered quartzite, argillite, and carbonates, and includes mafic sills (Hobbs, 1984). Belt bedrock is described in valley well logs simply as rock, distinct from gravel and other unconsolidated sediments. Well lithologic descriptions and cuttings samples demonstrate that Belt rock is the primary parent source for nearly all 3,000 ft of unconsolidated sediment valley-fill.

The Belt bedrock is strongly fractured in outcrop from structural uplift of the region and from surficial weathering. Near-surface fractures in the bedrock that transmit water are the bedrock aquifer. Wells are completed in the fractured bedrock around the perimeter of the valley where the bedrock aquifer is the only source available.

Tertiary Sediments

Regional mapping by other authors (Erdmann, 1944; Russel, 1954; Garland and others, 1961; Smith, 1965) suggest that Tertiary deposits (66 to 2.6 Ma) constitute the lowermost valley-fill in most valleys of the region, and are assumed to exist within the Flathead Valley.

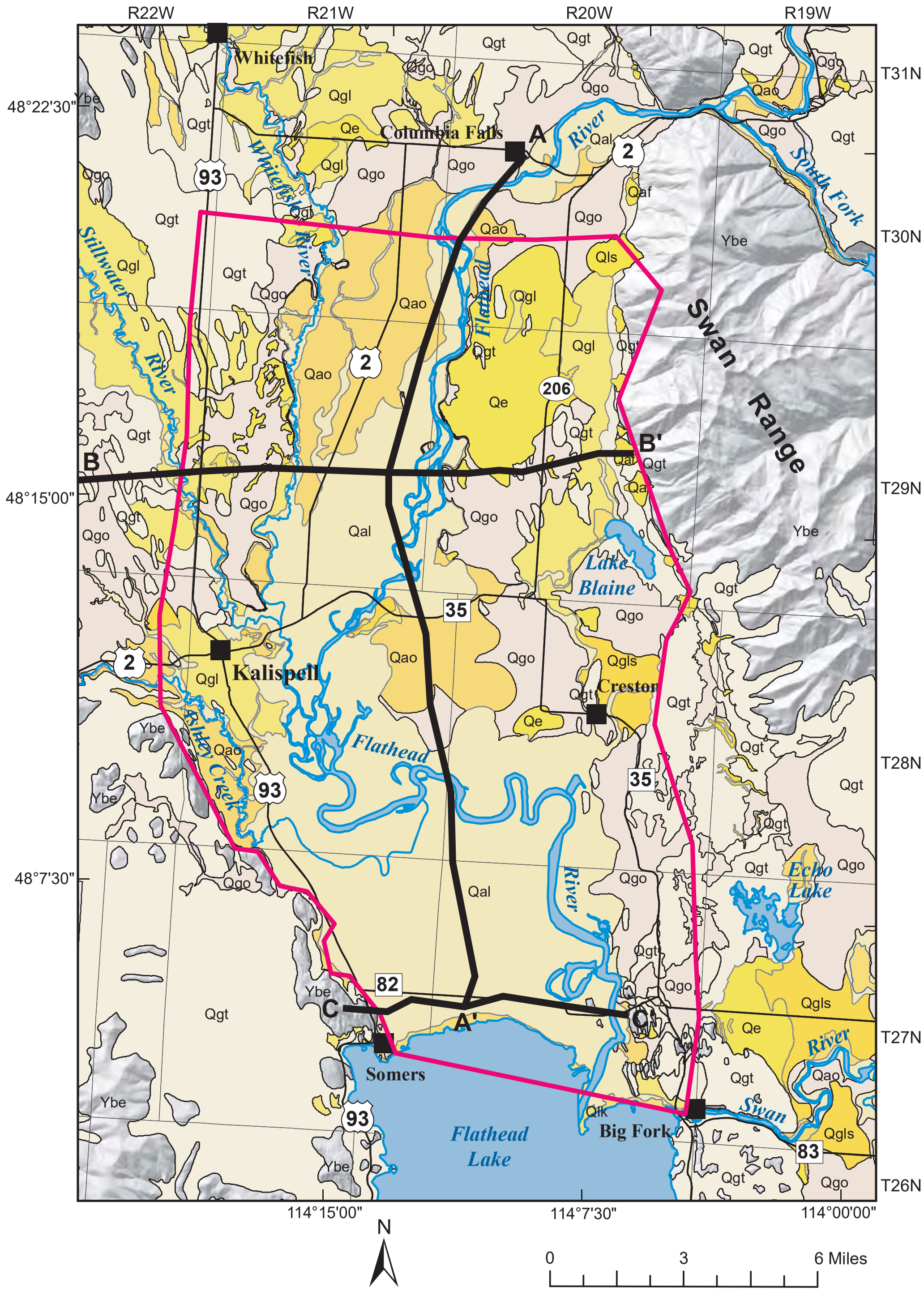
Early Tertiary mountain building raised the elevation of the Precambrian and Paleozoic bedrock, uplifting and exposing the material to intense weathering and erosion. Material eroded from the high mountains was deposited onto the Belt bedrock in the valley bottoms as thick sequences of fluvial material. Tertiary sediments mapped in adjacent valleys are described as semi-consolidated to consolidated, pre-glacial, fluvial deposits consisting of fine-grained, silty sand and gravel, shale, cemented sand and gravel, and sandy conglomerate (Erdmann, 1947; Alden, 1953; Constenius, 1981).

Konizeski and others (1968) estimate that the Tertiary sediments could have filled the Flathead Valley as much as 4,800 ft deep. Mapping in adjacent valleys by Constenius (1981) suggests that the Tertiary units are most likely distorted from faulting and sloughing of material, although the top contact surface was probably lowered and smoothed by glacial erosion (Konizeski and others, 1968).

The top contact of the Tertiary deposits defines the Quaternary/Tertiary depositional boundary and forms an inferred bottom limit to the Quaternary deep alluvium. During the Quaternary period, thick sequences of sediments were again deposited into the valley, this time by glaciers and fluvial processes, burying the Tertiary sediments. Lithology logs from the deepest wells in the valley are completed in the Quaternary outwash alluvium, 800 ft below the land surface. None of the lithologies described in Flathead Valley well logs have been identified as Tertiary sediments (GWIC, 2016). The Tertiary deposits are deeper than the wells. The deep well logs indicate a minimum possible depth to the Quaternary/Tertiary contact, but do not provide information on the Tertiary sediments that might be present.

Quaternary Sediments

All valley-fill sediments above the Quaternary/Ter-



Explanation

Project Boundary

Geologic map units

Shallow sediments

Qal	Alluvium of Modern Channels and Floodplains
Qaf	Alluvial Fan Deposits
Qe	Eolian Deposits
Qlk	Lake Deposit
Qls	Landslide Deposit
Qao	Alluvium Older
Qgo	Glacial Outwash Deposit
Qgt	Glacial Till
Qge	Glacial Esker Deposit

Confining units

Qgl	Glacial Lake Deposit
Qgls	Glacial Lake Deposit, Sandy

Bedrock

Ybe	Belt Supergroup Rocks, undivided

Geologic Cross Section Locations

Figure 2. Surficial geologic units in the Flathead Valley include Quaternary river alluvium in the north, river delta sediments in the south, and glacial deposits, surrounded by Belt bedrock of the mountains (modified from Smith, 2004a). Location of cross-section lines are shown for figures 12, 13, and 17.

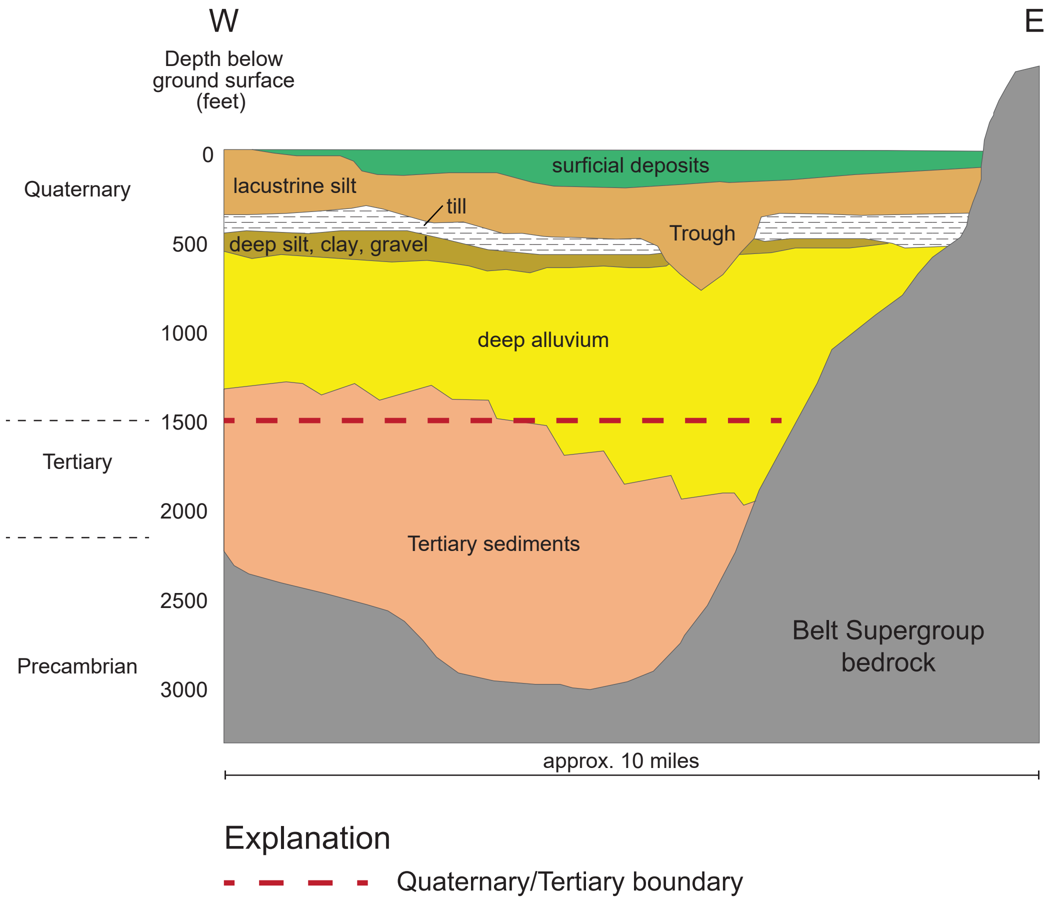


Figure 3. This generalized schematic of the Flathead Valley includes the structural depression in the Belt bedrock that forms the valley. Tertiary sediments fill the Belt depression to an unknown level and are overlain by Quaternary sedimentary units. The sand and gravel unit shown in yellow represents the deep alluvial aquifer from which most Flathead Valley wells draw water.

tiary contact were deposited in the Quaternary Period. During the Pleistocene Epoch (2.6 Ma to 12,000 yr ago), continental glaciers entered the Flathead Valley from the northwest following the Stillwater and Whitefish river valleys (fig. 1; Alden, 1953). During the same period, alpine glaciers advanced into the valley from the east, out of the canyon of the Flathead River, and from the southeast down the Swan River Valley. These glaciers merged in the Flathead Valley and continued to move south through what is now Flathead Lake and beyond Polson.

Glacial advances and retreats, formation of a late-Pleistocene/Holocene lake, and fluvial and other Holocene surface deposits produced a thick sequence of Quaternary valley-fill sediments. From oldest to youngest, these sediments are the deep alluvium, the deep silt, clay, gravel zone of the deep alluvium, till, lacustrine silt; and the surficial deposits of predominantly river alluvium and delta sediments, all consisting mostly of Belt bedrock material (fig. 4).

Deep alluvium system

From interpretations of well logs for this project, and from observations reported by Smith (2004g), the deep alluvium system has been separated into two distinct zones: the deep alluvium, which is the thickest, most transmissive, and produces the most water to wells; and the silt, clay, gravel zone that overlies the deep alluvium in some areas.

Deep alluvium. The deep alluvium is the thickest portion of the deep aquifer system. As the glaciers advanced, they scoured the valleys and surrounding mountains, removing massive amounts of material from the land surface. Glacial meltwater transported the eroded material into the valley and deposited it as thick layers of outwash and alluvium (Clague and others, 1980). The fluvial and outwash valley-fill is composed primarily of coarse sands and gravel over tens of feet thick (fig. 5), occasionally interrupted by thinner silt or clay-rich sand and gravel. The thick accumulation of glacial alluvium buried existing valley-fill sediments, including Tertiary sediment (fig. 3). On a valley-wide scale, the deep alluvium forms a relatively homogeneous unit.

	Geologic Units	Description	Age	Unit Thickness (ft)		Hydrostratigraphic units
	surficial deposits	River alluvium and delta sediments of gravel, sand, silt, and clay	Quaternary Holocene	0–200		shallow aquifer
	lacustrine deposits	Glacial lake deposits of silt and clay	Quaternary Pleistocene-Holocene	<10–790		lacustrine-till aquitard
	till	Sand and gravel embedded in clay				
deep alluvium system	deep silt, clay, gravel alluvium	Periglacial fluvial and lacustrine sediment of thinly layered coarse gravel with abundant sand, silt, and clay	Quaternary Pleistocene	0–100	deep aquifer system	silt, clay, gravel zone of the deep alluvial aquifer
deep alluvium system	deep alluvium	Glacial outwash, clean, coarse gravel and sand with occasional silt or clay-rich intervals	Quaternary Pleistocene	~1,000–1,500	deep aquifer system	deep alluvial aquifer
	Tertiary sediments	Preglacial fluvial deposits of semi-consolidated, fine-grained, silty-sand, sand and gravel, shale, and conglomerate	Tertiary	~1,500		Tertiary aquifer
	Belt Supergroup bedrock	Metasedimentary deposits of argillite, siltite, mudstone, marble, dolomite, and some igneous rocks	Precambrian			bedrock aquifer

Figure 4. The Flathead Valley hydrostratigraphic section includes the Belt valley-bounding bedrock and the infilling Tertiary and Quaternary alluvium, glacial, and lake sediments (modified from LaFave and others, 2004).

Figure 5. The deep alluvial aquifer is composed of clean, coarse gravel and gravel with sand, visible in this photograph of drill discharge cuttings from well 260889.

The deep alluvium lies above the Tertiary/Quaternary contact and below either the silt, clay, gravel zone of the deep alluvial aquifer (where present) or below the lacustrine and till deposits. The top of the deep alluvium is defined in drillers' logs as the first occurrence of mostly silt and clay-free, water-bearing gravel beneath the lacustrine and till deposits. The alluvial deposit is thick, extending below the deepest water wells in the valley (fig. 3). Alden (1953) estimated that Pleistocene outwash and alluvium might be as much as 1,000 ft thick. However, the full thickness of the deep alluvium is not known.

The deep alluvial aquifer is in the saturated, deep alluvium, which is the highly transmissive portion of the aquifer. Most water wells that tap into the deep alluvial aquifer are completed within the upper 10 to 50 ft of the sand and gravel, just deep enough to draw water from the aquifer. The deepest water wells penetrate 500 ft of the outwash alluvium (800 ft below the land surface). The deep alluvium is highly transmissive; drillers' logs report pumping rates from hundreds of gallons per minute (gpm), with a few in the thousands of gpm range.

Troughs in the deep alluvium. Using the few deep water well logs available at the time, Konizeski and others (1968) first identified a north–south-trending linear trough incised into the deep alluvium along the east side of the Flathead Valley near the base of the Swan Mountains. The trough is filled with silt and clay lacustrine sediments of the ancestral Flathead Lake to a greater depth than in the rest of the valley (fig. 3). No till is present in the troughs. Konizeski and others (1968) interpreted the trough to be the result of faulting along the Swan Range front.

Smith (2004g) located four additional linear, north–south-trending troughs in the valley through well log interpretations, and concluded they were not structural in origin, but were eroded as tunnel channels formed by pressurized water eroding the sediment beneath glacial ice. Because they formed only beneath the glacial ice, the troughs often do not extend the entire length of the valley and may begin and end abruptly. At the toe of the glacier, the pressurized water discharged to the surface, or in this case, into Flathead Lake. The depths of some troughs are well below the present lake level, a level that is thought to have existed since Pleistocene glaciers filled the valley. The evidence of historic lake levels consistently at higher elevations than the trough bottoms suggests that the troughs were formed by mechanisms other than surface-water action (Smith, 2004g). Interpretation of well logs for this project show that the silt, clay, gravel zone of the deep alluvium was also removed during tunnel channel formation.

Silt, clay, gravel alluvium of the deep alluvium system. The silt, clay, gravel alluvium is a distinct zone within the deep alluvium system. It is located at the top of the deep alluvium and beneath the lacustrine and till deposits. The zone is differentiated from the deep alluvium by the higher percentage of silt and clay that infills the gravel. The deep silt, clay, gravel alluvium is composed of thin beds of silt- and clay-filled gravel (fig. 3).

Smith (2004g) noted the finer-grained nature of the silt, clay, gravel zone at the top of the deep alluvium, but did not separate it from the well-sorted coarse gravel and sand that is more typical of the deep alluvial aquifer. The gravels of this zone are identical to those found in the deep alluvium, but the zone frequently includes medium- to coarse-grained sand and intervals of cemented, medium-size gravel, mixed and alternating with the more common coarse gravel and sand. Each layer is typically less than 1 ft to a few feet thick.

Interfingering of sedimentary layers of the silt, clay, gravel zone may indicate a change in the depositional environment from fluvial outwash conditions to depositional environments of the overlying glacial till and lacustrine deposits (Smith, 2004g). Smith (2004g) describes this unit as possibly ice-marginal deposits, deposition that occurred close to the glacier. The silt, clay, gravel zone at the top of the deep alluvium is present in many, but not all well logs, suggesting the unit may not be continuous. Where present in well logs, the silt, clay, gravel zone is 50–100 ft thick and is distinct enough, and prevalent enough, to segregate from the clean sand and gravel of the deep alluvium, and map as a distinct unit using well lithology logs.

The silt, clay, gravel alluvium is the silt, clay, gravel zone of the deep aquifer system. The top contact is defined as the first occurrence of an extensive interval of coarse gravel beneath the lacustrine and till deposits. The silt, clay, gravel zone is best defined by the driller-reported pumping rate. Pumped wells completed in this interval usually produce less than

100 gpm, and often closer to 20 gpm, a 1 to 2 order of magnitude decrease from the deep alluvial aquifer. A second indicator of the silt, clay, gravel zone is that the pumped water will often not clear of silt and clay particles, even after extended development. As the well casing is driven closer to the contact with the clean gravel of the deep alluvium, pumping rates may increase as the water is drawn through the cleaner gravel and less through the silt- and clay-filled gravel.

Lacustrine and till deposits

Overlying the deep alluvium system are fine-grained sediments composed of glacial till and glacial lake (glaciolacustrine) deposits. Both adjoining units exhibit the same very low-permeability properties, and in this model are referred to together as a single lacustrine-till aquitard (fig. 4).

Till deposits. As glaciers advanced and retreated across the landscape, they deposited a layer of till a few feet to tens of feet thick on top of valley-fill sediments, and on bedrock along the valley margins. Till directly overlies the deep alluvium and the silt, clay, gravel zone of the deep alluvium. The weight of the ice and basal shear stresses under the active glacier compacted the till, often forming lodgment till, a dense, low-permeability layer. Several episodes of till deposition probably occurred in the valley. One till, the till logged in water wells that directly overlies the deep alluvium, is pervasive throughout the Flathead Valley and is included in the valley subsurface stratigraphy as a discrete unit.

Till is composed of a random mixture of boulder, gravel, sand, and silt, in a clay matrix, and is identified in well logs as clay-bound gravel, or as medium gravel embedded in clay (fig. 4). Till colors range from tan to gray to buff, brown, and red. The clay-rich till intervals are often described by drillers as hard and tight. Where it has not been identified in well logs, it may have been removed by erosion (Smith, 2004), or simply may not have been described by the drillers. The till, overlying the deep aquifer system, ranges from a few feet thick to almost 100 ft thick in well logs.

Lacustrine sediments. Lacustrine (lake-derived) sediments lie directly on top of the till. As the glaciers retreated in late Pleistocene/Holocene, the water of ancient Flathead Lake advanced to fill the valley. Lake levels fluctuated in the post-glacial period as the lake outlet elevation varied due to ice blockage and erosion of the bedrock channel near Polson, but the lake never fully receded from the Flathead Valley (Smith, 2004g). The lake inundated the valley from Polson to Whitefish and Columbia Falls for extended periods (Smith, 2004g), reaching a maximum elevation of 3,400 ft (Konizeski and others, 1968). Over time, lake sediments accumulated as a continuous layer on the valley floor that ranges from a few tens of feet to nearly 500 ft thick, averaging about 200 ft thick (Smith, 2004g; lacustrine silt, fig. 4), the most widely varied thickness of all valley-fill sediments. The thickest sections occur where the sediment fills topographic lows in the surface of the deep alluvium (troughs). The lacustrine sediments are exposed on the land surface in the north half of the valley (fig. 2).

In drillers' logs, the top of the lacustrine sediment was identified by the change from gravel, sand, and silt of the surficial deposits to dominantly fine-grained silt or silt-with-clay material in a thick sequence of sand, silt, and clay (figs. 3, 4). In the northern half of the valley, the shallow sand- and gravel-bearing river alluvium at the surface is clearly distinguishable from the underlying fine-grained lacustrine deposits in well logs. However, in the delta area in the south half of the valley, the contact between the surficial deposits and the lacustrine sediment is less certain. The transition from fine-grained river delta sand and silt surficial deposits to the clay or silt-with-sand lacustrine sediments is subtle. Due to the lack of distinguishing descriptions in some wells, the contact was not always assigned. The bottom contact is the till, or in the absence of identified till, the first occurrence of coarse gravel.

Water wells drilled throughout the valley all record some interval of dominantly fine-grained, lake-deposited material. Given the depositional environment and the high lake levels, the lacustrine deposits would be expected to be deposited throughout the valley. Drillers describe the interval as tan, yellow, light brown or gray silt, silt with clay, or fine-grained material. The unit offers almost no resistance to the drill bit and well casing. In cuttings, the silt is typically saturated and behaves as a semi-fluid, viscous material (fig. 6). Water does not decant from the discharged drilled cuttings and the saturated sediment will not yield adequate water to wells to be of practical use.

Drillers occasionally reported intervals of medium to small gravels in silt within the lacustrine deposits, especially in the upper third of the unit. Gravel lay-

Figure 6. Clay and silty-clay drill discharge cuttings of lacustrine sediments of the lacustrine-till aquitard from well 260889 shows the fine-grained, saturated, and semi-fluid nature of the sediment.

ers were observed infrequently, and cannot be traced between water wells for any distance. The gravel and interlayered silt and clay intervals are typically thin, less than 10 ft thick, and may have been derived from short-lived stream channels when the lake retreated or from other changing depositional conditions.

Surficial deposits

Surficial deposits include all sediments emplaced above the lacustrine deposits and includes post-glacial, Holocene deposits of fluvial river and delta sediments, unconsolidated colluvium, mountain-front landslide debris, till on bedrock along the valley margins (Qgt, fig. 2), glacial drift, debris flows, and eolian sands. The different geologic materials are identified at the land surface from geologic mapping (fig. 2; Harrison and others, 1992; Smith, 2004), and from well lithology logs.

Surficial deposits are predominantly river alluvium north of Kalispell, and river delta deposits south of Kalispell and in Flathead Lake, identified as Qal in figure 2 and surficial deposits in figures 3 and 4.

The shallow river alluvium in the north valley, deposited by the Stillwater, Whitefish, and Flathead Rivers, forms a thin sedimentary unit consisting of poorly sorted fine-grained sand and sand with small gravel that may locally include silt, clay, and some organic material. The river alluvium ranges from a few feet up to 100 ft thick and is not a continuous layer, but rather a series of overlapping and adjacent fluvial deposits created as the rivers meandered across the valley.

Where the rivers entered the ancestral Flathead Lake, the fine-grained fraction of river sediments were transported by the quiet water of the lake, forming an extensive deposit of fine-grained sand, silt, and clay, south of Kalispell. The earliest delta deposits occurred at the Kalispell Moraine, near the city of Kalispell. With continued deposition, the delta was deposited farther south into the lake, expanding the north lakeshore from Kalispell out to the present north shore of the lake. Delta sediments in well logs were 50 ft to as much as 200 ft thick.

The shallow aquifer lies within the surficial deposits. The bottom of the shallow aquifer is where the geologic material is dominantly sand on top of the lacustrine silt and clay, and where the sediment can consistently transmit water to a well in a volume that can be put to use.

METHODS

Overview

The Flathead Valley 3-dimensional model was based on a conceptual hydrostratigraphic model compiled from previous work by LaFave and others (2004), surficial geology from Harrison and others (1992) and Smith (2004), subsurface stratigraphy from Smith (2004a) (fig. 2), cross sections from Uthman and others (2000), and gravimetric data from Konizeski and others (1968).

Nomenclature and materials descriptions for the modeled hydrostratigraphic units are presented in the Introduction section of this report (fig. 4). The 3-dimensional model contains hydrostratigraphic units consisting of valley geologic strata assigned by their known or interpreted hydrologic properties.

The hydrostratigraphic 3-dimensional model was constructed using Aquaveo GMS software (Aquaveo-GMS, 2015). Aquaveo developed GMS as a MODFLOW graphical user interface to create visual, spatial-grid formats for hydrogeologic investigations. MODFLOW is the U.S. Geological Survey's 3-dimensional, finite-difference groundwater flow model (U.S. Geological Survey, 2016). The GMS software was used for this project to interpolate and grid well lithologies and geophysical elevation data into a 3-dimensional space and to develop a numerical representation of 2-dimensional contacts and 3-dimensional units.

GMS Terminology

GMS software utilizes standard geologic and hydrogeologic concepts but assigns software-specific terminology to the attributes. GMS terms include:

- Borehole: a water well or other drilled hole from which geologic information is recovered.
- Horizon: A geologic contact between two separate geologic or hydrostratigraphic layers.
- Hydrogeologic Unit (HGU): In this report, referred to as a hydrostratigraphic unit, but maintaining the GMS acronym HGU. Single or multiple combined geologic layers grouped by their common hydrogeologic properties; includes aquifers and aquitards.
- Material Code: A numeric value assigned in a table to each defined geologic unit, layer, formation, or material. The table includes descriptive terms such as silt, sand, gravel, sandstone, and shale, each associated with a numeric value and a color code used by the model to represent that unit.
- Soil ID: A numeric value assigned in the Materials Code table to distinct, individual geologic intervals, such as silt, clay, sand, sandstone, shale.
- Solid: the 3-dimensional geometric shape that represents a particular geologic layer or hydrostratigraphic unit.

In this report, traditional geologic terms are used and the GMS terms are included in parentheses where appropriate.

Modeled Hydrostratigraphy

To populate the model for GMS, an individual Soil ID was assigned to each lithologic interval described in drillers' well logs. The Soil IDs were assimilated and assigned to user-defined hydrostratigraphic units (HGU). For example, contiguous intervals of glacial till and lacustrine silt are two separate Soil IDs that were combined into a single HGU, referred to as the lacustrine-till aquitard. Based on the interpretation of previous and new data, the valley hydrostratigraphy is divided into six hydrostratigraphic units for the model (fig. 4). A conceptual cross section in figure 3 shows the hydrostratigraphic relationships between the units. Within the GMS architecture, references and identifications for all Soil IDs and HGUs are maintained in the Material Codes table.

To create the modeled units (solids) (fig. 4), the top contact (horizon) of each hydrogeologic unit was defined by manually correlating matching hydrostratigraphic contacts between water wells in GMS-constructed cross sections. The numerically defined contacts in the water-well profiles were then connected throughout the model by constructing a triangulated irregular network (TIN) in GMS, using Delaunay criterion. Hydrostratigraphic contacts (horizons) are represented by the TIN surfaces.

Hydrostratigraphic units (solids of HGUs) were created by digitally infilling the volume between contacts. The top contact of the underlying unit defines the bottom of the overlying unit. The completed model includes six contacts (horizons, the top contact of each unit) and five units (solids) (fig. 4).

Data Management

Smith and others (2004) compiled a list of well logs to construct maps as part of a Ground Water Characterization Program study. This list of wells provided the base to begin 3-dimensional model data input. The well list was supplemented with wells drilled between 2000 and 2015 (GWIC, 2016).

Well coordinates, elevation, lithologic intervals, and interval elevations are recorded in the GMS boreholes table. Gravity data collected by Konizeski and others (1968) were included in the model dataset. DEM topographic data were merged with the gravimetric data to create a TIN representing the digital bedrock surface. Imaginary wells were added to the GMS project database, in a separate boreholes dataset folder, to define the top contact of the Tertiary sediments at the Quaternary/Tertiary boundary.

Well location coordinates, elevation, completion details, and the lithologic record reported by the well driller were selected for the model from the MBMG's GWIC database (http://mbmggwic.mtech.edu/).

The wells used for the model are linked by the GWIC Project ID code: BWIPKL_LITHMODEL and can be downloaded at:

http://mbmggwic.mtech.edu/sqlserver/v11/menus/menuProject.asp?mygroup=GWIP&myroot=BWIPKL&ord=1&

The list of wells used to derive the hydrostratigraphic model is included in appendix A. Wells referred to in this report are denoted by the GWIC identification number (e.g., well 139534). All well locations were defined in NAD83, Montana State Plane coordinates and NAVD88 elevation coordinates in feet, the same coordinate system as the GMS model.

Well Selection Criteria

The GWIC database contains records from several thousand wells located within the model boundary. Of those, 959 were selected (including wells used in previous studies), for use in the model (fig. 7; appendix A). The working database included 596 that were drilled since 2000. The wells were selected based on two criteria: (1) a reasonably detailed lithologic log; and (2) confirmed locations. Confirmed locations were determined by:

- Professional surveys: (elevation accurate to ± 0.1 ft). Licensed surveyors using survey-grade GPS systems surveyed monitoring wells used during this project.
- Land ownership: For sites not visited by surveyors, parcels were confirmed by matching well owner names and addresses with state cadastral data (land ownership; Montana Cadastral Framework, 2015). Elevations for non-surveyed well locations were derived from a 3-ft resolution Light Detection and Ranging (LiDAR), aerial survey map of the Flathead Valley (Montana State Library, 2009) (elevation accurate to ± 1.0 ft). Well locations outside of LiDAR mapped boundaries (elevation accurate to ± 10 ft) were derived from a 1/3 arc-second (~30 ft) DEM (U.S. Geological Survey, 2015a).

Soil Identification Codes

In GMS modeling, soil identification codes (Soil ID) are assigned to geologic units to organize and correlate well log data first into geologic stratigraphic units, then into hydrostratigraphic units. The recorded drillers' lithologic descriptions were assigned a soil identification (Soil ID) code. An example is shown in figure 8. Columns 1, 2, and 3 are taken directly from a driller's well log. The lithologic descriptions were evaluated and assigned to a Soil ID classification (column 4), which includes a Soil ID color (column 5) for graphic representation.

Drillers' descriptions often include general estimates of grain size (silt, sand, gravel, and pebbles), a dominant material color, and the locations of water-bearing zones. However, the material that drillers reference by the terms sand, silt, and clay are not always consistent. Descriptions of sediments with mixtures of the sand, silt, and clay can vary greatly between drillers. Lithologic descriptions from the selected drillers' logs were interpreted and assigned Soil ID codes by a hydrogeologist to more consistently define lithologic units. Thirty-five Soil ID codes were defined for this project, to address as many individual well log descriptions as practical.

Each separate Soil ID was assigned to one of the

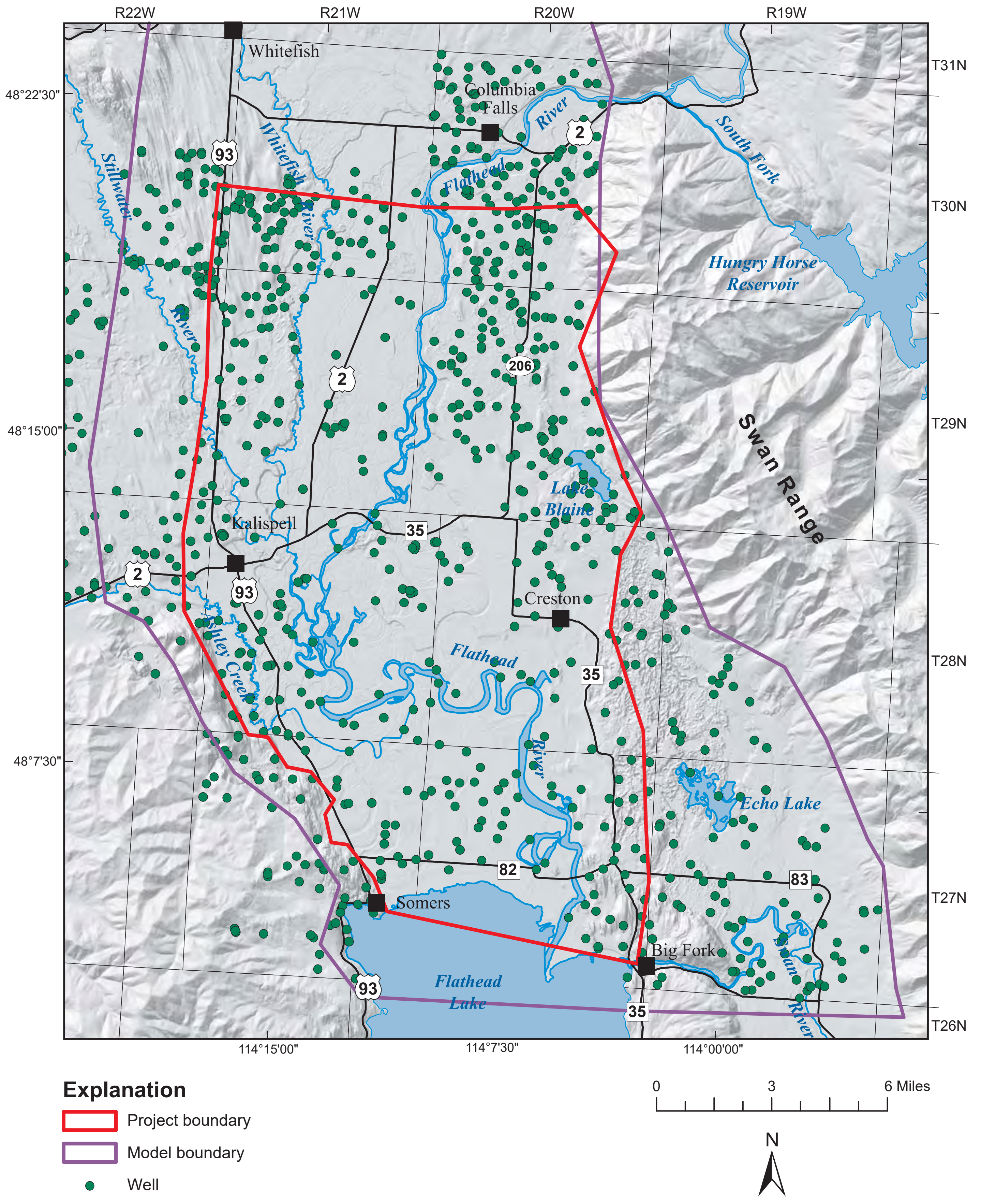


Figure 7. The locations of wells completed in the deep alluvial aquifer were confirmed for construction of the 3-D hydrostratigraphic model.

1	2	3	4	5	6	7	8	9	10
From	To	Well log lithology	Soil ID	SOIL ID color	HGU ID	HGU From	HGU To	HGU Color	Horizon
0	14	clayey silt, Brown, dry	silt with clay		shallow aquifer	0			5
14	25	sand with silt, Brown	sand with silt		shallow aquifer				
25	56	sand with silt, wet, saturated	sand with silt		shallow aquifer		56		
56	156	Sand with silt, wood chips, saturated, soupy	sand with silt, wood chips		lacustrine-till aquitard	56			4
156	176	sand with sticky clay, saturated	sand with clay		lacustrine-till aquitard				
176	196	sandy silt with sticky clay, saturated	silt with clay		lacustrine-till aquitard				
196	200	sandy silt with sticky clay, saturated	silt with clay		lacustrine-till aquitard				
200	212	sandy silt with sticky clay, saturated	silt with clay		lacustrine-till aquitard				
212	236	sandy silt with sticky clay, saturated	silt with clay		lacustrine-till aquitard				
236	260	sticky clay	clay		lacustrine-till aquitard				
260	276	silty clay	clay		lacustrine-till aquitard				
276	286	clay, tan, plastic	clay		lacustrine-till aquitard				
286	396	silty clay, tan	clay		lacustrine-till aquitard				
396	402	clay, tan, plastic	clay		lacustrine-till aquitard		402		
402	416	sand and gravel, pebbles, silty water	sand and gravel		silt, clay, gravel zone of the deep aquifer	402			3
416	445	gravel with sand and pebbles	gravel with sand		silt, clay, gravel zone of the deep aquifer				
445	476	sand and gravel, pebbles, silty water	sand and gravel		silt, clay, gravel zone of the deep aquifer				
476	480	sand and gravel, pebbles, silty water	sand and gravel		silt, clay, gravel zone of the deep aquifer				
480	496	sand with gravel, silty water	sand with gravel and silt		silt, clay, gravel zone of the deep aquifer				
496	506	gravel with sand and silt	gravel with sand and silt		silt, clay, gravel zone of the deep aquifer				
506	526	gravel with sand, pebbles and silt	gravel with sand and silt		silt, clay, gravel zone of the deep aquifer				
526	536	gravel with sand and more silt	gravel with sand and more silt		silt, clay, gravel zone of the deep aquifer				
536	545	gravel with silty water	gravel with silt		silt, clay, gravel zone of the deep aquifer				
545	556	sand with some gravel, brown, thick silt	sand with gravel and silt		silt, clay, gravel zone of the deep aquifer				
556	570	sand with gravel and pebbles, brown tan silt	sand with gravel and silt		silt, clay, gravel zone of the deep aquifer				
570	580	sand with some gravel, tan silty water	sand with gravel and silt		silt, clay, gravel zone of the deep aquifer				
580	585	gravel with some sand	gravel with sand		silt, clay, gravel zone of the deep aquifer				
585	608	sand with gravel, brown silty, sandy water	sand with gravel and silt		silt, clay, gravel zone of the deep aquifer		608		
608	616	sand with gravel and pebbles	sand with gravel		deep alluvial aquifer	608			2
616	630	sand and gravel, pebbles, some tan, brown silt	sand and gravel		deep alluvial aquifer				
630	642	sand and gravel with some light brown silt	sand and gravel		deep alluvial aquifer				
642	648	coarse gravel with sand	gravel with sand		deep alluvial aquifer				
648	656	sand and gravel, light brown silt	sand with gravel and silt		deep alluvial aquifer				
656	670	sand and gravel , pebbles	sand and gravel		deep alluvial aquifer				
670	676	sand with some gravel	sand with gravel		deep alluvial aquifer		676		

Figure 8. To configure data for the 3-D model, drillers' well log lithologic descriptions were simplified to GMS Soil IDs and assigned to hydrostratigraphic layers (hydrogeologic unit, HGU IDs).

six HGUs based on the descriptions and selection criteria for each unit (columns 6 through 9 in fig. 8).

Hydrostratigraphic Units

The six HGUs were assigned contact (horizon) numbers. As required by GMS, the HGUs are numbered beginning at the bottom of the model, with the deepest stratigraphy, and working upwards to the top of the model with successive numbers. Unit assignment is based on well location, depth of the strata, type of material, and the surrounding lithologies (column 6 in fig. 8).

6. shallow aquifer
5. lacustrine-till aquitard
4. deep aquifer system, silt, clay, gravel zone
3. deep aquifer system, deep alluvial aquifer
2. Tertiary aquifer
1. bedrock aquifer

Contacts (horizons) that define the top of each unit were manually selected and assigned in a GMS table for each well lithology log. GMS plotted each well location with its HGU profiles onto the model grid in 3-dimensional space. Using the well contacts, hydrostratigraphic cross sections were constructed by correlating HGU contacts between the wells. The final 2-dimensional surfaces representing the top of each unit were reviewed and corrected using manually constructed cross sections in GMS.

Hydrostratigraphic units in the upper 800 ft of valley-fill, the depth of the deepest wells in the valley, were delineated from lithologic records from water wells. For interpretation of deeper sediments, information from previous authors was used to estimate the geologic units between the deepest well logs (800 ft below land surface) and the geophysical data (1,500 ft to 3,000 ft below land surface) (Alden, 1953; Konizeski and others, 1968; LaFave and others, 2004).

Bedrock Aquifer

Gravimetric and seismic data were used to define the elevation of the top of the Belt Supergroup bedrock beneath the valley. A land surface topographic digital elevation model (DEM; U.S. Geological Survey, 2015a) was joined to the gravimetric data (Konizeski and others, 1968) to define the model boundary of the Belt bedrock, which contains the bedrock aquifer, in the subsurface and where it is exposed at the land surface.

The modeled bedrock surface was constructed from three datasets:

- Gravity measurements recorded on 1-mi^2 intervals across the valley (Konizeski and others, 1968).
- Surface terrain of Belt bedrock mapped above the valley-fill, including the surrounding mountains, defined by a 1/3 arc-second DEM (U.S. Geological Survey, 2015a).
- Bedrock surface elevations from wells drilled into bedrock.

The three datasets were merged in a table and used to construct a 2-dimensional TIN (horizon) representing the surface elevation of the bedrock. The bedrock surface delineates the buried valley margins and the DEM surface defines the outer boundaries of the 3-dimensional model.

Tertiary Aquifer

The Belt Supergroup bedrock surface defines the bottom of the Tertiary sediments. No well log or geophysical data are available to define the top Tertiary contact. A representative planar TIN surface was created at an elevation of 1,600 ft-amsl, based on levels estimated by previous authors. However, the actual top of the Tertiary sediment package is probably irregular in shape and at varied elevations (fig. 4). The top-contact elevation was defined as a planar horizon representing the Tertiary contact in the model in 19 image wells (appendix A). The image boreholes were assigned location values within the model boundaries, and the Tertiary aquifer HGU was assigned at 1,600 ft elevation. The image wells data are stored in a separate borehole dataset folder.

The remaining Quaternary hydrogeologic unit boundaries were constructed from the GMS-generated TIN surfaces for each contact. There are four Quaternary Hydrogeologic Units.

Deep Aquifer System

Deep alluvial aquifer

The top and bottom deep aquifer HGU boundaries were constructed from the GMS-generated TIN surfaces for each contact. The top of the deep aquifer system was defined at the occurrence of thick, water-bearing gravel beneath the lacustrine and till deposits identified in drillers' logs. The bottom contact was defined at the top Tertiary contact. The deep aquifer system was identified based on the following criteria:

1. The gravel unit was the deepest sedimentary unit recorded on the driller's log. Where bedrock was shallow, some logs penetrated Belt bedrock beneath a relatively thin deep aquifer system. Otherwise, the bottom of the deep aquifer was not encountered.
2. The water-producing sands and gravels of the deep alluvial aquifer were encountered beneath significant silt and clay layers (lacustrine-till aquitard) that did not produce water during drilling.

Silt, clay, gravel zone of the deep alluvial aquifer

Once identified as the deep aquifer system, the upper portion was evaluated to determine if the silt, clay, gravel zone was present. If the first productive gravels encountered in drilling were silt and clay bearing and produced less than 100 gpm, they were assigned to the silt, clay, gravel zone HGU. Otherwise the gravels were assigned to the deep alluvial aquifer HGU.

Lacustrine-Till Aquitard

The top of the lacustrine-till aquitard was identified in drillers' logs by the change from gravel, sand, and silt of the surficial deposits to dominantly fine-grained silt or silt-with-clay of the lacustrine deposits. Beneath the lacustrine deposits was till, identified as clay-bound gravel or medium gravel in clay. Both units were assigned to the lacustrine-clay aquitard HGU.

Shallow Aquifer

The top of the shallow aquifer was built from the LiDAR-based land surface DEM. The bottom was the assigned transition at the top of the lacustrine-till aquitard.

Developing the Hydrostratigraphic Model

The preceding unit descriptions were used to define the modeled hydrostratigraphic units. Model construction followed a series of data management and interpretation steps. The steps to construct the hydrostratigraphic model included:

1. Developed conceptual hydrostratigraphic model.
2. Defined and constructed model boundaries:
    a. Compiled gravimeter location and bedrock elevation data into tabular, digital x and y location and elevation (z) format.
    b. Imported U. S. Geological Survey DEM land surface for bedrock exposures around valley.
    c. Depth to bedrock interpreted from gravimetry data (Konizeski and others, 1963) were merged with DEM surface data.
    d. Imported merged digital bedrock dataset.
    e. Constructed TIN contact (horizon) of bedrock surface above and below ground surface using GMS.
3. Built top contact of Tertiary sediments:
    a. Assigned inferred top of Tertiary at 1,600 ft-amsl.
    b. Created imaginary wells to simulate the Tertiary top contact elevation.
    c. Defined the elevation for the top of the Tertiary sediments (TIN horizon) in the GMS imaginary wells data table.
4. Constructed units above Tertiary:
    a. Selected wells:
        i. Confirmed location;
        ii. Validated or corrected elevation; and
        iii. Compiled lithologic data.
    b. Imported wells dataset.
    c. GMS converted depth intervals of lithologic logs to elevations based on well collar elevation.
    d. Assigned Soil ID from the materials code table to each lithologic interval in every well (fig. 8).
    e. Defined six units (HGU) for the model.

f. Grouped the Soil IDs into the six HGUs.

g. Defined contact (horizons) numbers and colors in the materials code table for each hydrogeologic unit in sequence from bottom to top.

h. Marked the top of each unit (HGU) in the horizon column for each well log with appropriate contact (horizon) value from the Materials Code Table (bedrock aquifer; Tertiary aquifer; deep alluvial aquifer; silt, clay, gravel zone of the deep alluvial aquifer; lacustrine-till aquitard; and shallow aquifer).

i. Manually created cross sections based on HGUs by correlating the horizon values between wells.

j. Created TINs for each contact (horizon) by connecting matching horizon values between all model wells.

5. Created hydrogeologic units (solids) between the TINs. The solids represent the actual unit material.

Lacustrine-Till Aquitard Thickness Contour Map

The lacustrine-till aquitard thickness map was constructed from the combined thicknesses of the lacustrine and till deposit descriptions reported in drillers' well logs. The top and bottom contacts of the lacustrine and till deposits were flagged in the well logs in the GMS project database (column 10, fig. 8). In GMS, TIN surfaces representing unit contacts were constructed for the top and bottom of the lacustrine-till aquitard. The TIN files for each contact are recorded in data files of x and y triangulated point (node) coordinates, and z contact elevation.

The (x, y, z) point-location data files from each TIN surface were exported to Surfer and recreated as new TIN surfaces. Using Surfer functions, the bottom contact elevation was subtracted from the top contact elevation at each data file x and y location. The output file contains the x and y node locations and the lacustrine-till aquitard thickness in feet at each point. Thickness contours were hand drawn using the contact elevation data for each data point-location, and using knowledge of the subsurface hydrostratigraphy. A comparison between the resulting contours and contours created by Smith (2004d) identified any discrepancies that would require resolution.

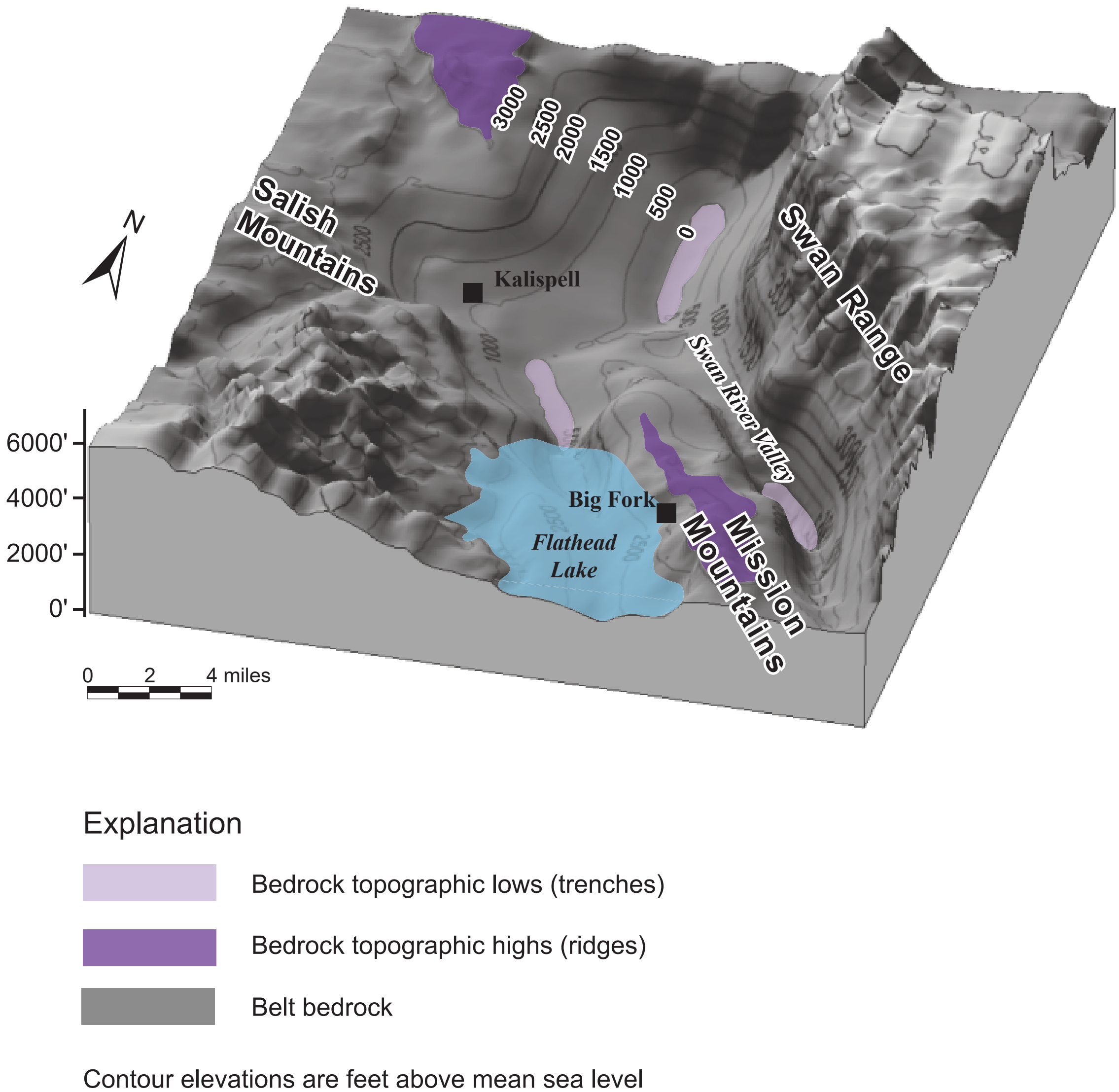


Figure 9. GMS software produced a 3-dimensional block model of the Belt bedrock surface using gravity survey and land-surface topography DEM data points. On the block model view, low-elevation areas are highlighted in light purple and topographic high ridges are shown in dark purple.

RESULTS

Hydrogeologic Units

The valley hydrostratigraphic sequence is shown in figures 3 and 4. The 3-dimensional model displays the hydrogeologic units and their stratigraphic relationships based on user-assigned Soil ID and HGU inputs. Model results and associated geologic cross sections are described below. The locations of cross sections are shown in figure 2.

Belt Bedrock Aquifer

A TIN surface of the bedrock aquifer defines the model boundaries and the extent of the unconsolidated valley-fill on the north, east, and west. The Belt TIN also defines the bottom of the unconsolidated valley-fill. The modeled, 3-dimensional bedrock surface topography shows a wide range of elevations, from near 0 ft-amsl in trenches on the east valley bottom to over 3,500 ft-amsl on the slope of the Swan Range at the east side of the valley. The modeled bedrock surface shows three very deep (low elevation), elongate, north- to northwest-trending trenches and two subsurface bedrock ridges (fig. 9).

One bedrock trench trends northwest beneath the east side of the Swan River Valley. A second trench trends north at the east side of the Flathead Valley. These two trenches form deep canyons in the bedrock along the foot of the Swan Range at the east side of the valley. These deep canyons are the result of Tertiary extensional faulting that formed the Flathead Valley. The bedrock surface at the bottom of the trenches is about 3,000 ft below the land surface (0 ft-amsl).

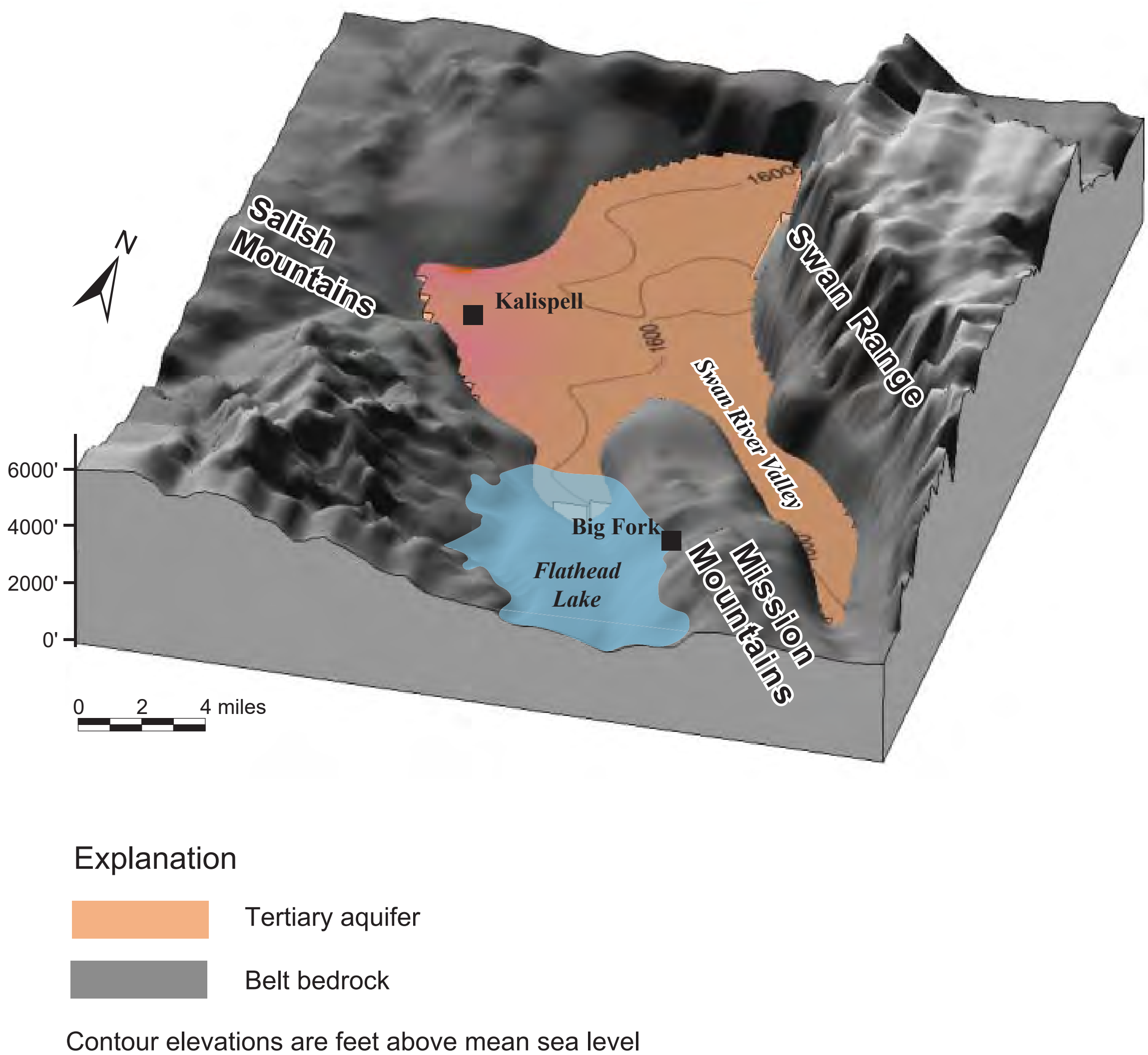


Figure 10. The elevation of the Quaternary/Tertiary boundary contact in the valley fill is unknown because it has not been penetrated by wells or detected by geophysical measurements. Based on previous investigations, a planar surface representing the contact at 1,600 ft-amsl was defined using a set of image wells in GMS.

A third trench extends mid-valley from Flathead Lake, northwest, beneath the Flathead River. The bottom of this trench descends to 2,400 ft below land surface (500 ft-amsl). At the south end of the trench, near the north shore of Flathead Lake, the bedrock surface rises steeply to about 1,500 ft below land surface (1,500 ft-amsl).

The most prominent bedrock high is the northwest plunging extension of the Mission Mountains, which forms a high-elevation, narrow, subsurface bedrock ridge that extends northwest from Big Fork (fig. 9). The bedrock ridge is less than 2 mi wide and plunges steeply northwest. Several domestic wells completed in this ridge intercept bedrock at less than 300 ft below the valley floor. Based on well logs the ridge extends about 7 mi to the northwest. From there, the bedrock surface descends at a very steep angle. A second bedrock ridge is located across the valley to the northwest (fig. 9).

A third bedrock high (not shown on the map) is located along the far eastern flank of the Mission Mountain ridge north of Bigfork at Echo Lake. Three wells near Echo Lake in the Swan River Valley intercepted shallow depth bedrock at 160 to 200 ft depth (wells 81611, 139534, and 240202). These intercepts appear to contradict gravimeter measurements indicating bedrock is 2,500 ft below the land surface in this area. However, gravity measurements in the Swan River Valley and especially around Echo Lake are sparse (Konizeski and others, 1968), and a topographic bedrock high could have been missed. These three wells are located immediately west of the 3,000-ft-deep bedrock trench along the Swan Mountain front (fig. 9). Over a distance of less than 2 mi east to west, the bedrock surface rises from 3,000 ft below the land surface to less than 200 ft deep, and eventually emerges above

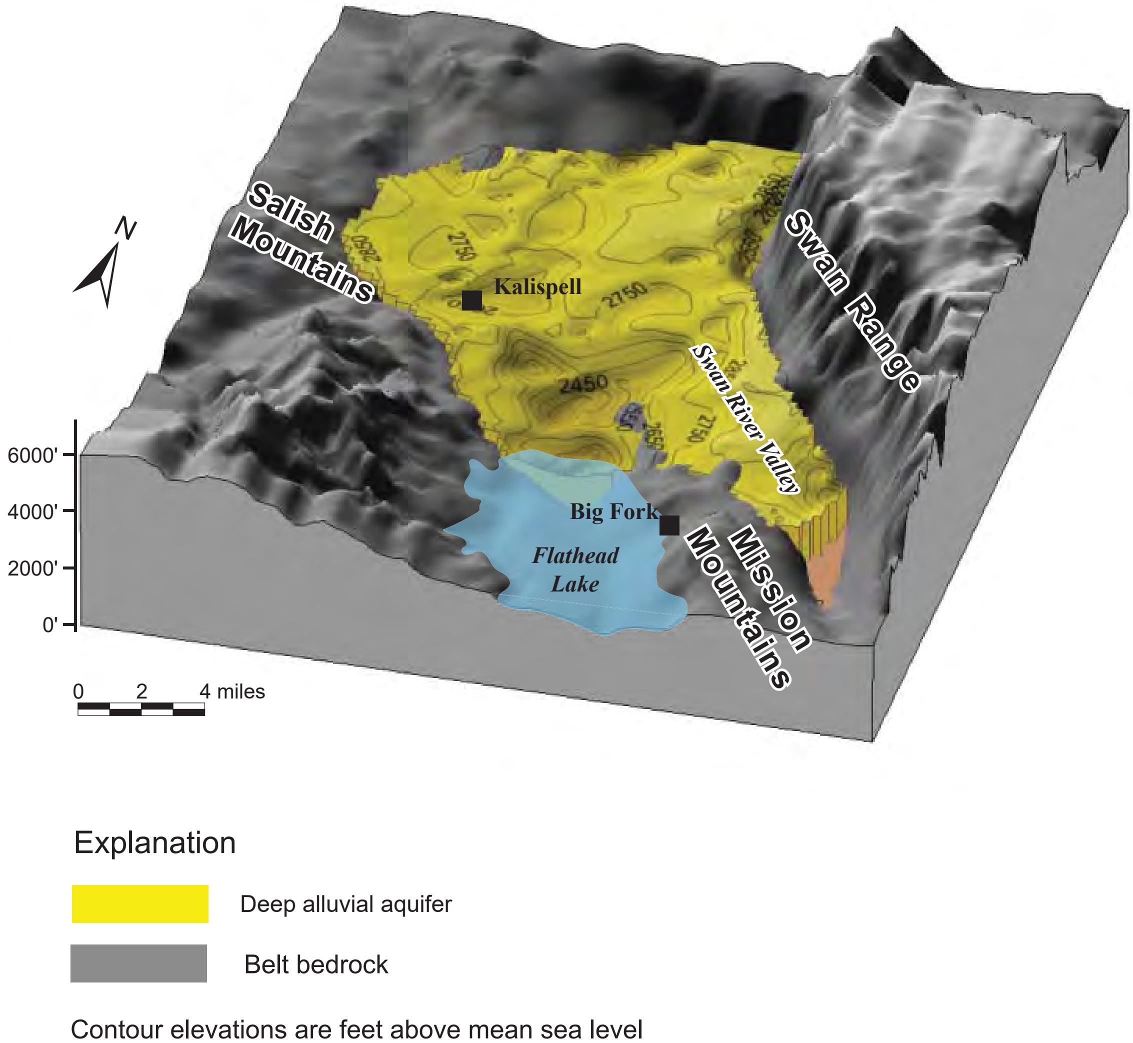


Figure 11. Surface erosion formed the irregularities in the top of the deep outwash alluvium. Some of the irregularities define linear subglacial troughs incised into the unit surface.

the land surface at Bigfork. This illustrates the extreme and sudden elevation changes of the bedrock.

Tertiary Aquifer

The top of the Tertiary aquifer, which defines the Tertiary/Quaternary contact in the model, is estimated at 1,600 ft-amsl (fig. 10). With no data available to define the contact, the surface is defined as a planar feature approximating what may exist at the boundary, but is by no means definitive.

Deep Aquifer System

Deep alluvial aquifer

Directly overlying the Tertiary aquifer in the model is the deep alluvial aquifer. The 3-dimensional model shows the irregular and undulating nature of the top contact of the deep alluvial aquifer (fig. 11). The modeled top of the deep alluvial aquifer ranges in depth from about 100 ft to 790 ft below the land surface. The elevation of the top contact surface, where not disturbed by troughs, ranges from 2,950 ft-amsl where the Flathead River enters the valley, to 2,660 ft-amsl at the north shore of Flathead Lake. The southward slope of the contact surface averages about 19 ft/mi (cross section A–A', fig. 12).

The deepest water wells in the valley are drilled to 800 ft below the land surface, and are completed within the deep alluvial aquifer. No wells have been drilled through the bottom of the aquifer, and therefore very little is known about the unit below the top few feet. It is also uncertain if other geologic units might lie between the Tertiary aquifer and the deep alluvial aquifer. For lack of additional information, it was assumed for the 3-dimensional model that the deep alluvial aquifer extended to the estimated elevation of the Tertiary contact. Calculating the difference between the model-defined top elevation of the deep alluvial

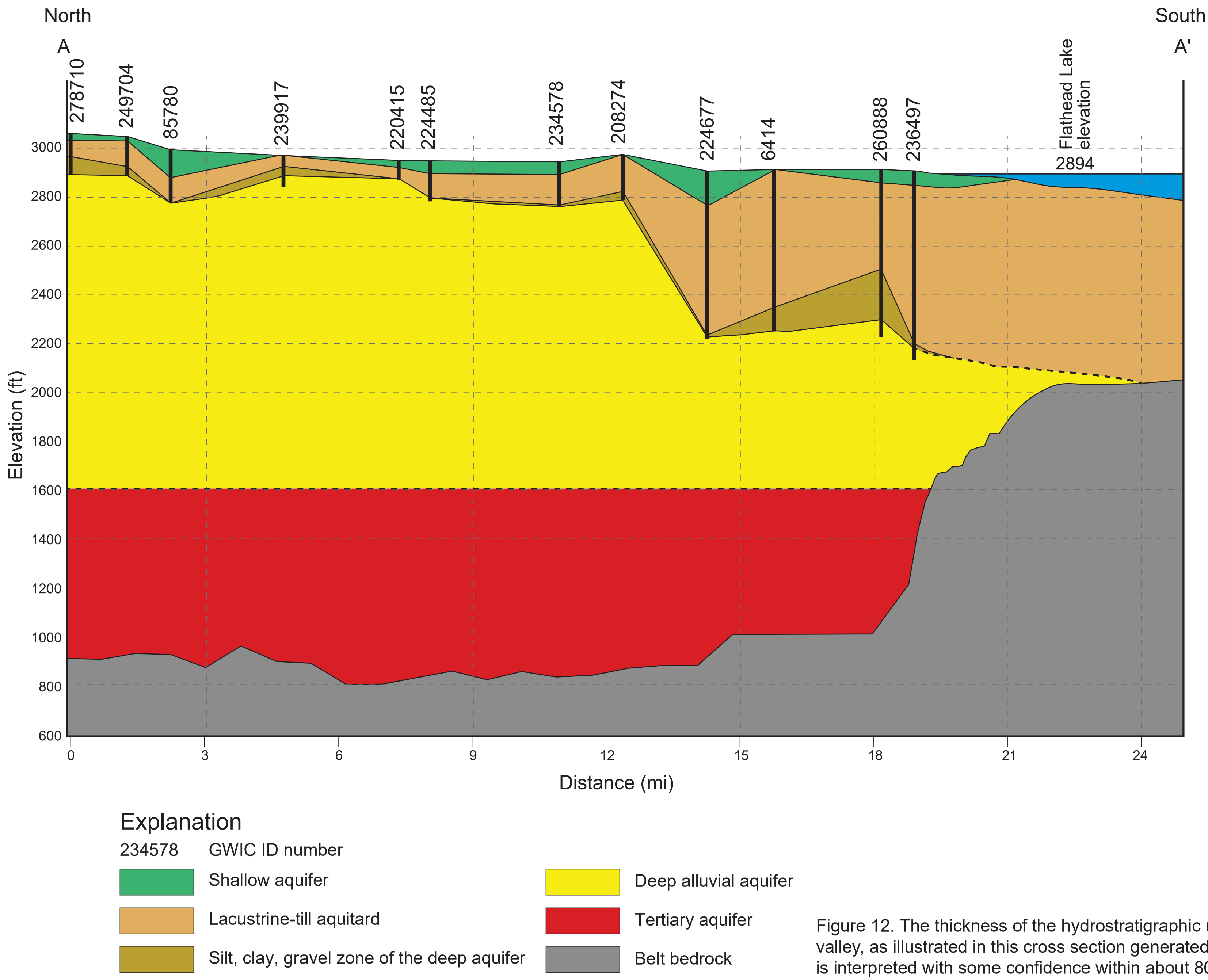


Figure 12. The thickness of the hydrostratigraphic units vary through the valley, as illustrated in this cross section generated in GMS. The lithology is interpreted with some confidence within about 800 ft of land surface, the depths penetrated by well drilling. The cross-section location is shown in figure 2.

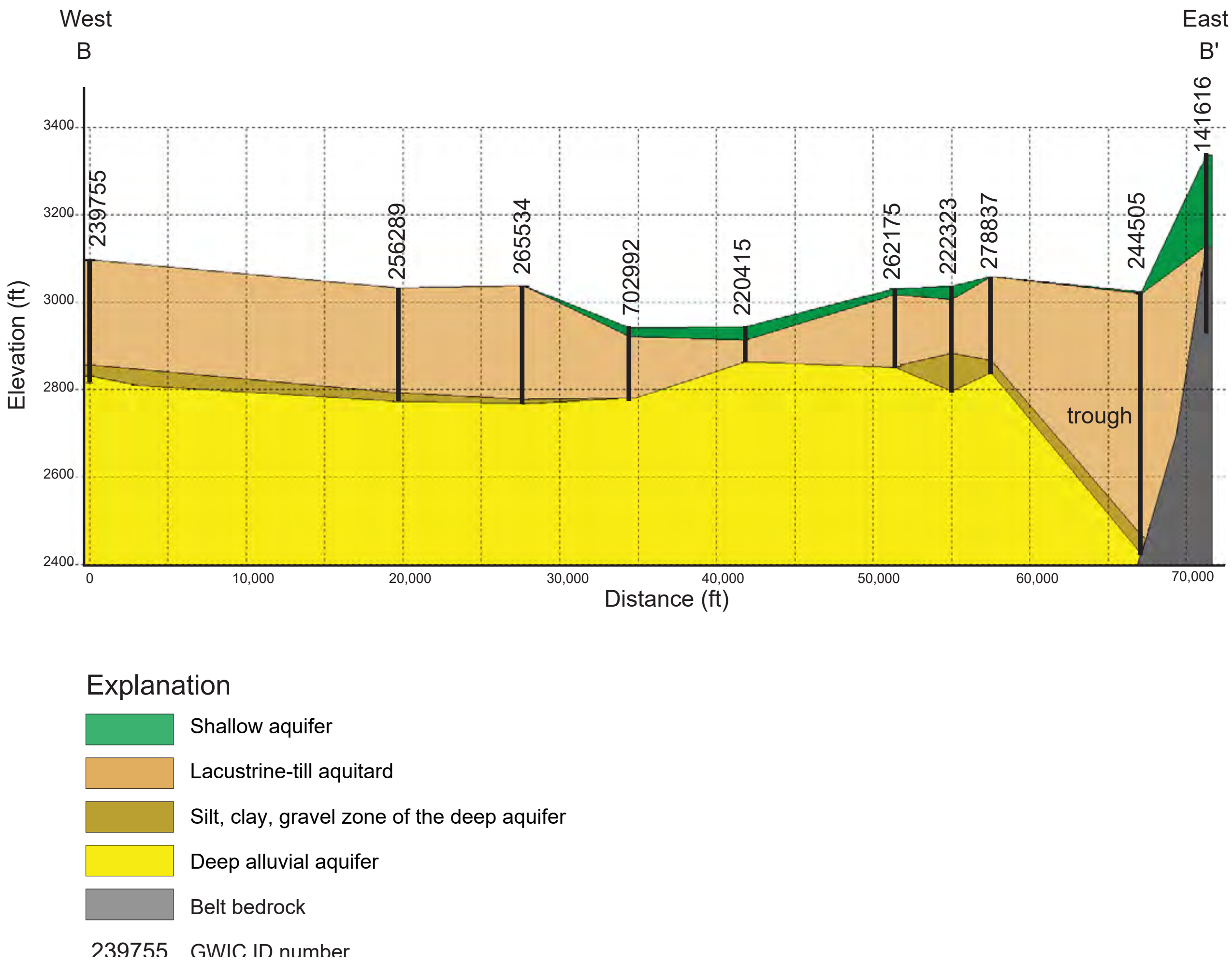


Figure 13. An east–west cross section through the 3-dimensional model shows lacustrine-till aquitard sediments filling a trough in the surface of the deep alluvial aquifer. The cross-section location is shown in figure 2.

aquifer and the estimated top contact of the Tertiary aquifer yields a potential thickness range of 1,060 ft to 1,350 ft for the deep alluvial aquifer.

Troughs in the deep alluvial aquifer

Several troughs are incised hundreds of feet into the top surface of the deep alluvium. These troughs were defined in the 3-dimensional model where a series of lithology logs in adjacent wells record lacustrine silt intervals thicker than in neighboring wells. Wells in troughs report a deep lacustrine-till bottom contact (cross section B–B’, fig. 13). The troughs generally trend north to south and appear to begin and end abruptly (fig. 14). Based on well spacing in the modeled grid, and the interpretation of 35 cross sections generated using GMS, trough widths range from approximately 0.5 to 1.5 mi. Trough depths are irregular, rising and falling along their trend, which is an indicator of erosion by subglacial tunnel channels (Smith, 2004g). The trough depths ranged from 100 ft to about 500 ft deep, and average 242 ft below the top contact of the deep aquifer system.

Three-dimensional digital mapping revealed troughs mapped by Smith (2004g) and Konizeski and others (1968), plus two additional troughs not previously mapped. Both newly identified troughs are located in the Swan River Valley, each about 10–15 mi in length (fig. 14). The deepest of these two Swan troughs (the black hachured trough east of Echo Lake in fig. 14) extends northwest about 11 mi from where the Swan River turns west near Bigfork. At the south end of the model, the trough bottom is at 2,873 ft-amsl and descends to 2,753 ft-amsl on bedrock east of Echo Lake. The red hachured trough (fig. 14) is much

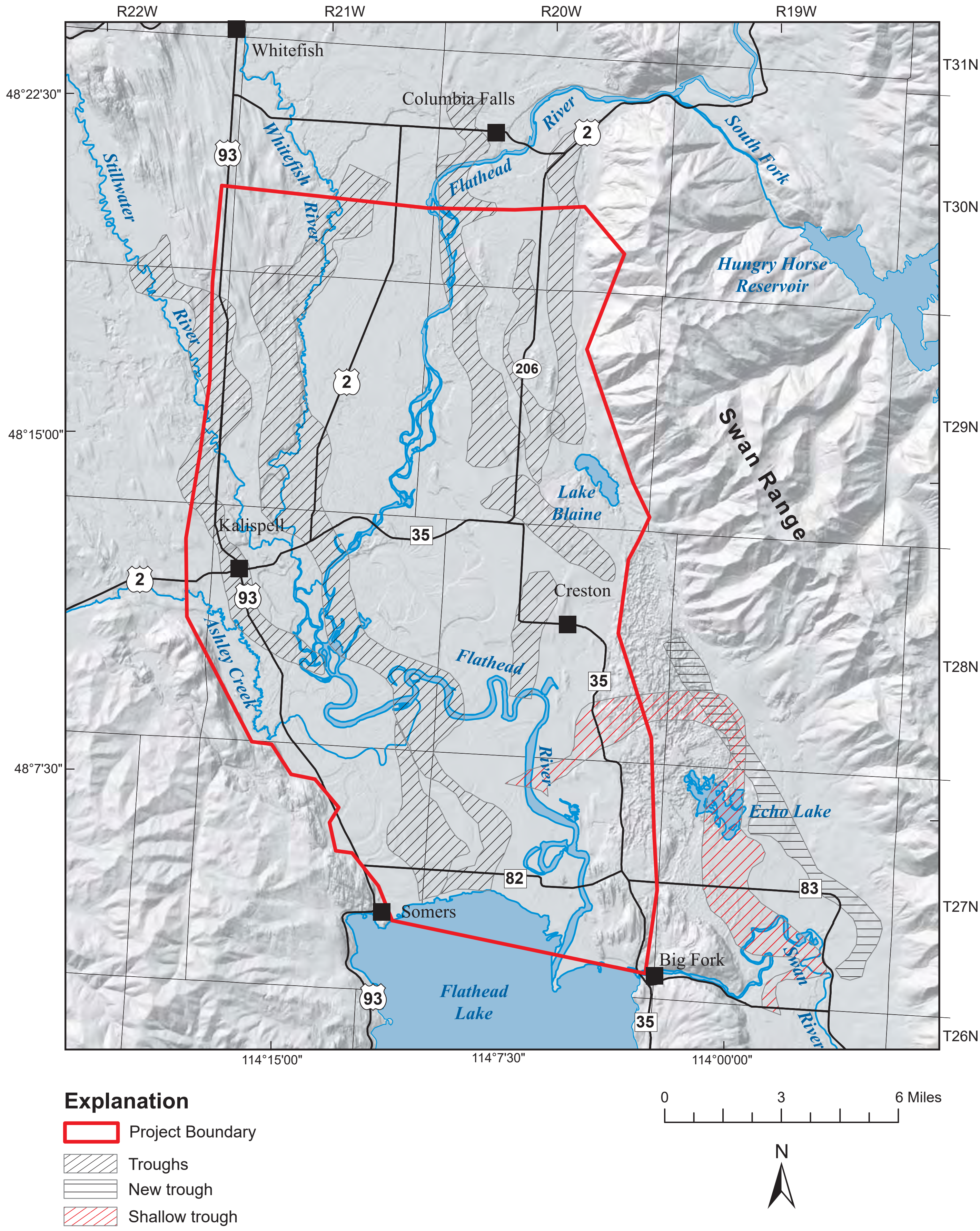


Figure 14. The location of troughs in the surface of the deep alluvial aquifer could be represented by the modeled surface with well log data. The troughs align north to south and begin and end abruptly. A shallow channel in the surface of the modeled deep alluvial aquifer (hachured in red), may not be a trough, but is probably a shallower depth river channel on the surface of the unit.

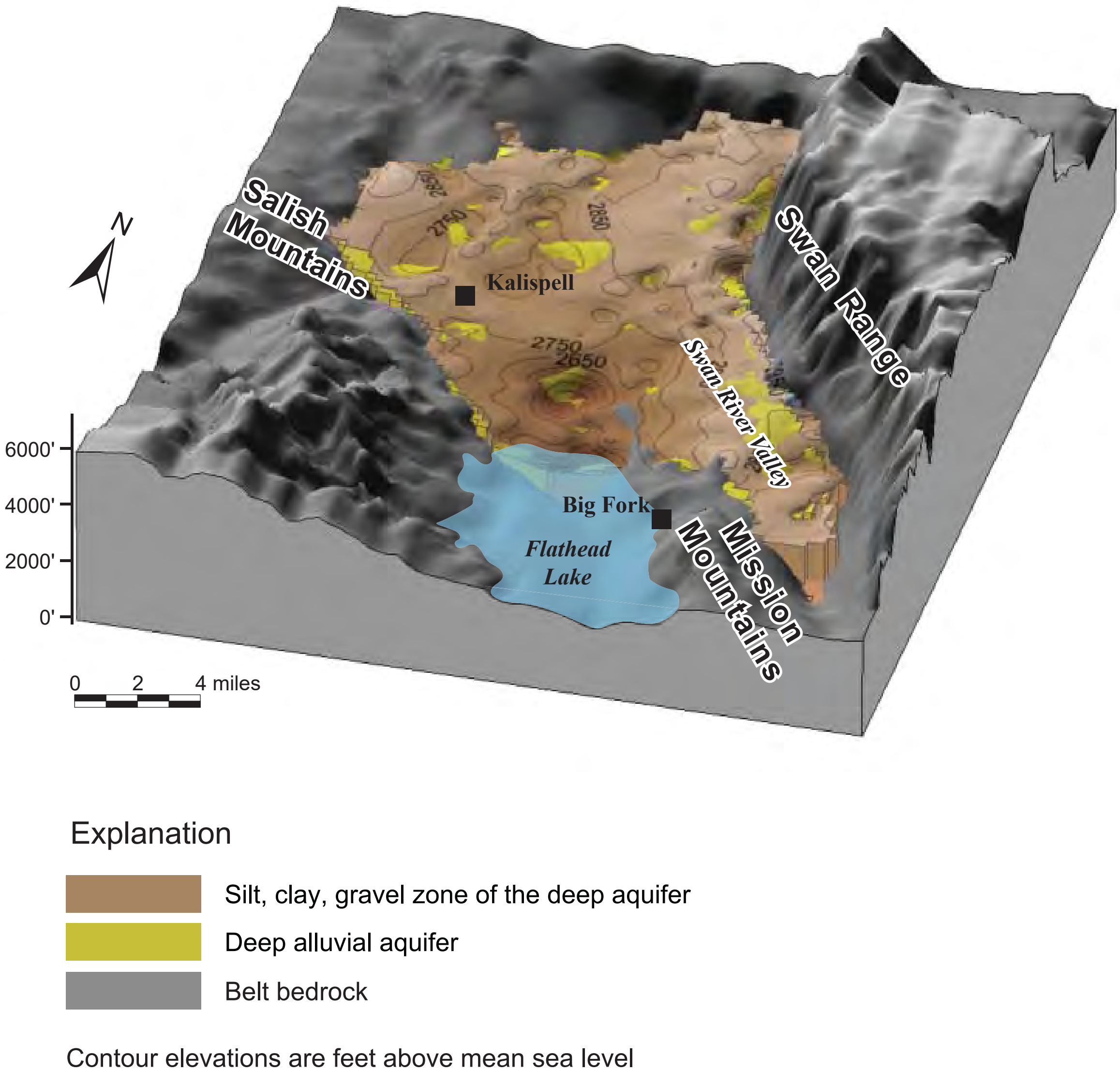


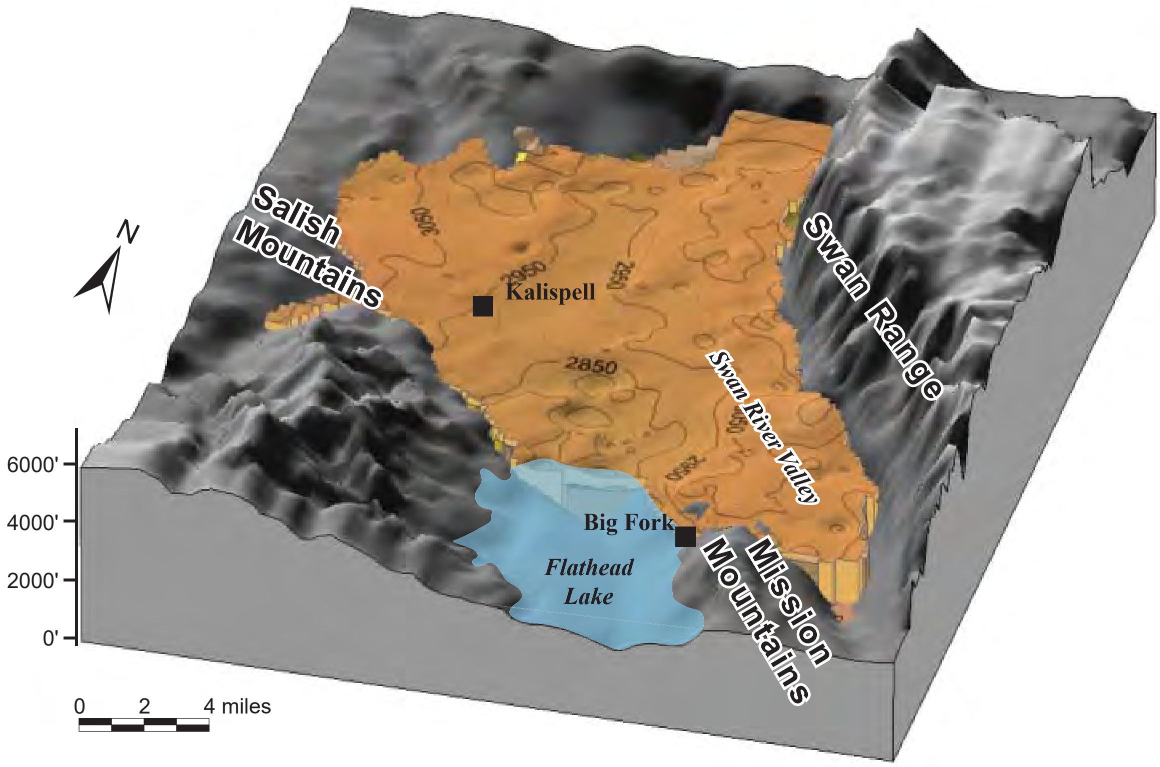
Figure 15. The silt, clay, gravel zone of the deep alluvial aquifer (brown unit) lies directly on top of the deep alluvial aquifer (yellow unit). The discontinuous nature of the silt, clay, gravel zone creates gaps in the layer that are visible where the deep alluvial aquifer shows through the unit.

shallower in depth (about 40 ft deep) and probably represents an ancient alluvial river channel that flowed along the land surface near the shallow depth bedrock ridge north of Bigfork. This trough turns abruptly west into the Flathead Valley, where the bedrock ridge begins to drop steeply in elevation.

Four isolated wells were drilled deep through a thick section of lacustrine silts to reach the deep alluvium, while adjacent wells reached the deep alluvium at much shallower depths. These four wells, clustered in an area west of Lake Blaine, may be in yet undefined troughs, or remnants of pre-existing troughs. The four wells were drilled 100 to 340 ft below the predominant deep alluvium surface and contain 265 ft to 378 ft of lacustrine sediment. The surrounding wells have less than 200 ft of lacustrine sediment. On the lacustrine-till aquitard contour map (plate 1), the thicknesses of the lacustrine silt in these isolated wells appear as deep, circular contoured features because they are created using data from only one well log; the shapes and extents of these features are not known. The four deep drilled wells and the adjacent wells that reach the deep alluvium at much shallower depths are shown in plate 1.

Silt, clay, gravel zone of the deep alluvial aquifer

The silt, clay, gravel zone of the deep alluvial aquifer is a hydrogeologic segregation of the top of the deep aquifer system. Where present, the silt, clay, gravel zone lies directly beneath the sediments of the lacustrine-till aquitard. The silt, clay, gravel zone is not present in every well log and was interpreted to



Explanation

Lacustrine-till aquitard

Belt bedrock

Contour elevations are feet above mean sea level

Figure 16. The 3-dimensional block model shows the confining unit to be fully competent and continuous above the deep alluvial aquifer throughout the Flathead Valley. The modeled thickness ranges from 4 ft thick to over 790 ft thick.

contain gaps and be discontinuous (fig. 15). The silt, clay, gravel zone, where present, ranges from less than 50 ft thick to over 200 ft thick. Where the zone is not present, the deep alluvial aquifer is in direct contact with the lacustrine-till aquitard.

The silt, clay, gravel zone of the deep aquifer system may represent a transitional sequence between outwash deposition and the introduction of lake sediments. The interlayering of sand and gravel with layers dominated by silt and clay are comparable to the intermediate aquifers described by LaFave and others (2004).

Lacustrine-Till Aquitard

Silty and clayey sediment was logged everywhere in wells between the surficial deposits and the deep alluvium, confirming the interpretation that the lacustrine-till aquitard is continuous across the study area. Within the modeled valley-fill, the lacustrine-till aquitard forms a unit that covers the entire valley, does not have any gaps or holes through the unit, and is near to, or in contact with, bedrock on all sides. The model results suggest that the aquitard is continuous throughout the modeled area (fig. 16).

In a few drillers' well logs, materials descriptions that fit the lacustrine or till characteristics were not reported. A driller's log that lacks a description of lacustrine sediments or till intervals could indicate the driller misidentified the material, inaccurately described the drill cuttings, or that the lacustrine-till aquitard truly does not exist at that location. Because there are multiple possible explanations, well logs with thin or no aquitard material were further evaluated by looking for confirmation from logs in surrounding wells. In all cases it was found that logs from surrounding wells had well-defined intervals of the lacustrine-till aquitard.

Lacustrine deposits of the lacustrine-till aquitard unit are exposed at the land surface in river terraces in the north valley (map units Qgl and Qgls, fig. 2), and are buried beneath 150–200 ft of modern river delta sediments in the delta region of the southern valley. A cross section through the model (cross section B–B', fig. 13) shows the lacustrine sediment exposed at the land surface. The top contact of the modeled lacustrine-till aquitard ranges between 3,100 ft-amsl in the north end of the valley and 2,800 ft-amsl at Flathead Lake (fig. 12). Konizeski and others (1968) estimated the water level of the ancestral Flathead Lake rose to at least 3,400 ft elevation.

Logged thicknesses of the lacustrine-till aquitard range from 4 ft to 790 ft, with a mean of 195 ft between the top and bottom contacts (plate 1). The thickness of the lacustrine-till aquitard throughout the modeled area was estimated by generating a GMS solid representing the unit in three dimensions. In the modeled unit (solid), none of the nodes reported zero thickness, suggesting the lacustrine-till aquitard is present throughout the valley.

The aquitard is thinnest along the Flathead River north of Kalispell, where modern fluvial erosion has removed some of the material. The aquitard is thickest where the lacustrine sediment has infilled troughs in the surface of the underlying deep aquifer system (plate 1 and fig. 13). Coincidentally, the thickest intervals of the lacustrine-till aquitard are in the troughs, which contain lacustrine sediments but not till. The till may have been removed by tunnel channel erosion along with the deep alluvial material (Smith, 2004f). Wells drilled into troughs show lacustrine sediment thicknesses of 200 ft to 790 ft.

The lacustrine-till aquitard model and the thickness map (plate 1 and fig. 16) compare favorably with the contours produced by Smith (2004d). Of the 959 wells used in the current thickness calculations, 595 were drilled since 2000 and therefore provide data that were not available to the previous work.

Modifications of contour lines are primarily due to the addition of these new wells. The most notable difference is east of Echo Lake toward the Swan Mountains. This area was mapped as being underlain by a thin section of lacustrine-till aquitard material (Smith, 2000d). With data from new wells, this area is now interpreted to have a lacustrine-till aquitard thickness of up to 300 ft (plate 1).

The lacustrine-till aquitard thickness map includes highlighted areas to show where the unit is less than 100 ft thick (yellow polygons in plate 1). The resolution in plate 1 is 100 ft. As such, the minimum thickness contoured is 100 ft, and the highlights indicate thinner areas. It is within these areas that future well drilling and careful lithologic descriptions might discover gaps in the lacustrine-till aquitard, if any exist. In addition, much of the highlighted area north of Bigfork is located on shallow bedrock, and does not directly overlie the deep alluvial aquifer (fig.11).

Shallow Aquifer

For simplicity, the shallow aquifer unit was modeled as a composite of all surficial deposits above the lacustrine-till aquitard. The majority of the surficial deposits are sand and gravel river alluvium and river delta deposits (Qal, fig. 2). Overall thickness of the surficial deposits is less than 200 ft.

The river alluvium was deposited across the land surface and in fluvial-eroded channels on the lacustrine sediment surface. Cross sections through the model show the shallow aquifer deposits do not form a continuous cover on the land surface, but locally infill low-lying areas where the ancient rivers have deposited the alluvium (figs. 13, 17). In some areas the silt deposits of the lacustrine-till aquitard are not covered by surficial deposits, and are exposed at the land surface (fig. 18).

South of Kalispell, the contact between sediments of the lacustrine-till aquitard and the shallow delta sediments of the shallow aquifer was difficult to identify in some wells. Many lithology logs report sandy-silts and silty-sands over long intervals in the first 200 ft of the well bore, without distinguishing changes in composition that would define the delta/lacustrine contact. In wells with poor differentiation of the sediments, the top of the lacustrine-till aquitard was not identified for model construction.

Alignment of Erosional Features

It is interesting to note comparisons between the modeled hydrogeologic surfaces. One similarity between the modeled surfaces is the locations of erosional features in the geologic units. Overlaying the modeled units shows that the trenches in the bedrock

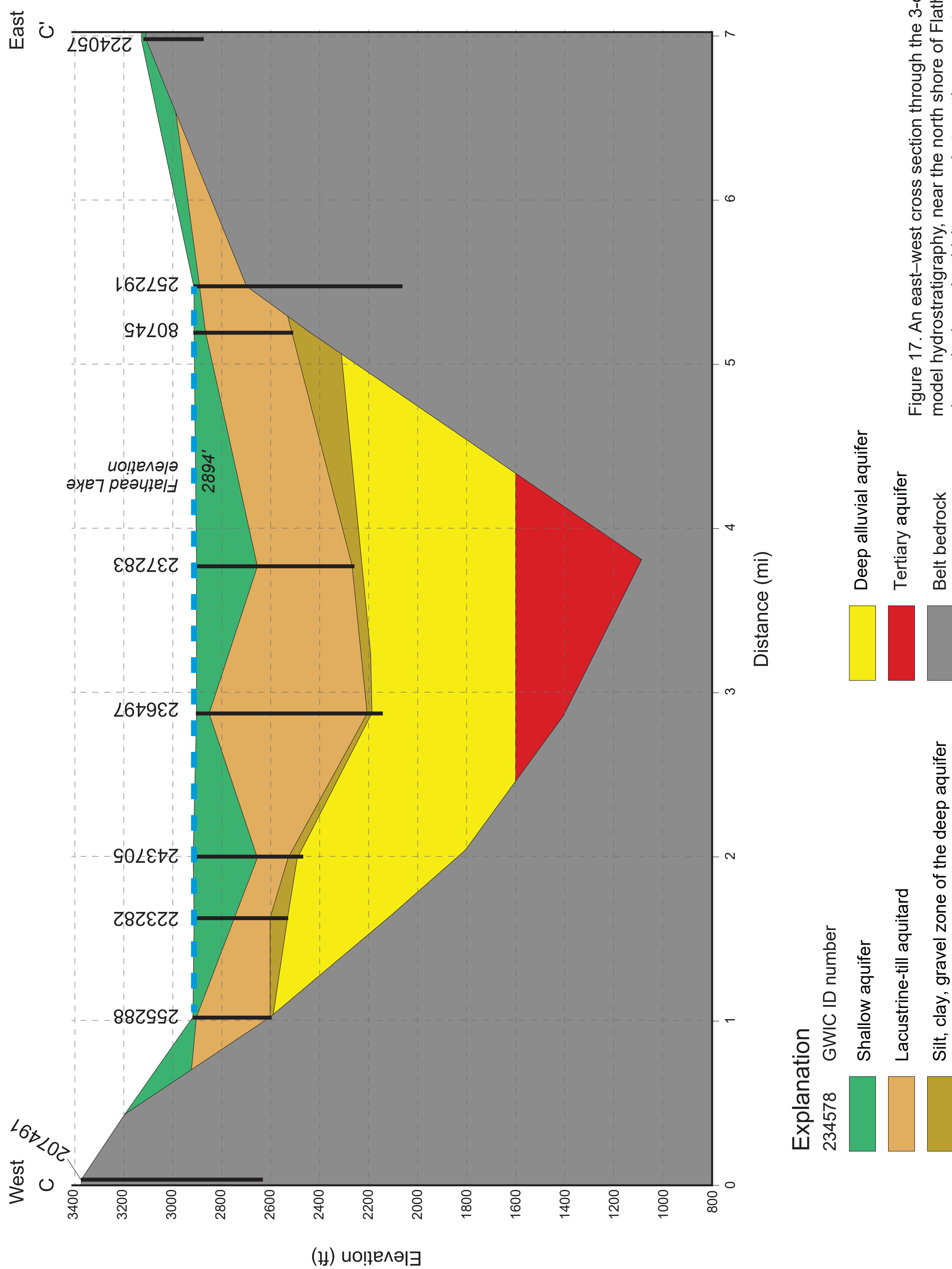


Figure 17. An east–west cross section through the 3-dimensional model hydrostratigraphy, near the north shore of Flathead Lake, shows the irregular thicknesses, but continuous nature, of the deposited sediments. The cross-section location is shown in figure 2.

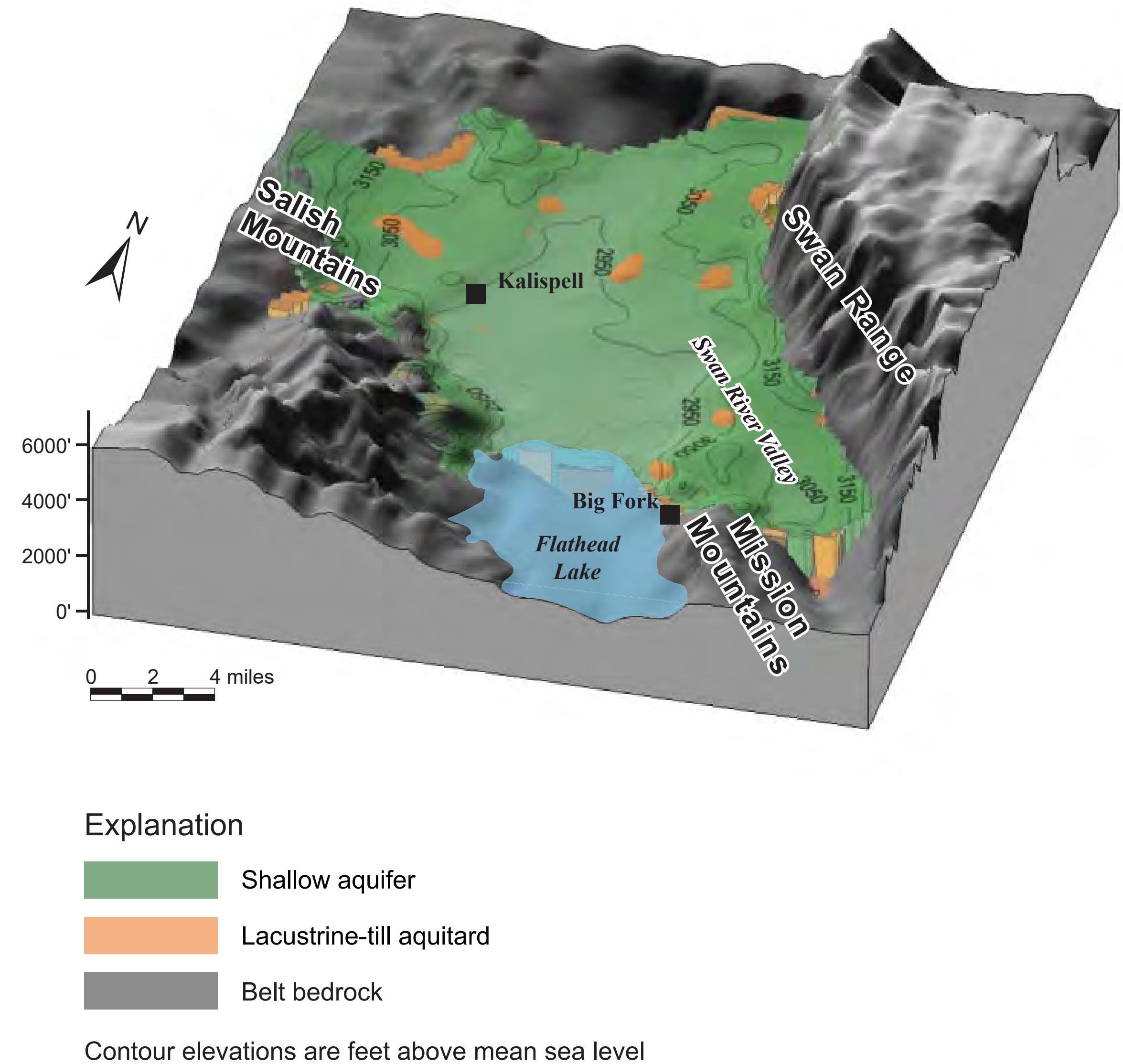


Figure 18. The modeled shallow sediment layer at the land surface is more extensive in the delta area south of Kalispell, where the block model surface is mostly green. The 3-dimensional modeled interval is relatively thin, ranging from less than 50 ft to over 200 ft thick, and is absent in areas where the modeled lacustrine-till aquitard is visible at the land surface.

(fig. 9), troughs in the deep aquifer system, and some modern river channels at the land surface line up on top of one another (fig. 14). This is probably indicative of the depositional setting, valley configuration, and similar source areas for the origin of ice and water entering the valley.

Southern Model Boundary

The 3-dimensional hydrostratigraphic model is bounded on the east, north, west, and bottom by the Belt bedrock surface. The southern boundary of the model is near the north shore of Flathead Lake (cross section C–C’, figs. 2, 17). Well logs near the north shore (fig. 7) are the southernmost, subsurface lithologic descriptions in the Flathead Valley.

In the southern part of the valley the bedrock elevation rises steeply toward Flathead Lake, where it is interpreted as being in direct contact with the base of the deep alluvial aquifer (cross section A–A’, fig. 12). The top of the Tertiary aquifer is deeper than the bedrock elevation at the lakeshore. The exception is in the bedrock trench near mid-valley (fig. 17). Because of the lack of data, it is not known if the material that fills this trench is Tertiary sediments, deep alluvium (deep alluvial aquifer), or lake sediments of the lacustrine-till aquitard.

Along the southern boundary, the lacustrine-till aquitard reaches a maximum thickness of over 600 ft, in a trough drilled in well 236497 (figs. 12, 17). The elevation of the base of the aquitard deposit, near the center of this section, is 2,200 ft-amsl, about 1,000 ft above the top of the Belt bedrock. On both the west and east margins of the valley along this line, the lacustrine-till aquitard deposits are in direct contact with the Belt bedrock (fig. 17).

Projecting the modeled hydrostratigraphic contacts south, from the north–south cross section and through wells along the lake shoreline (fig. 12), the lacustrine-till aquitard and deep aquifer system appear to extend south of the model boundary, and beneath the north shore of Flathead Lake.

DISCUSSION

Characteristics of the Lacustrine-Till Aquitard

The lacustrine-till aquitard is composed of silty-clay or clayey-silt lacustrine sediment that is relatively homogeneous in composition on a valley-wide scale, underlain by discontinuous glacial till. No gaps could be identified that would allow communication between the deep aquifer system and the shallow aquifer or streams. Based on the study of almost 1,000 well lithology logs for this project, and referencing conclusions by Smith (2000d), neither project located any gaps in the lacustrine-till aquitard within the boundaries of this study area. If a hydrologic connection does exists between shallow and deep groundwater, it would probably be in the areas where the map (plate 1) shows the lacustrine and till aquitard deposits are the thinnest (<100 ft thick).

The thinnest areas of the lacustrine-till aquitard are similar to the locations of the thinnest areas contoured by Smith (2004d). Model results, however, did indicate smaller areal expanse of the thinnest portions of the aquitard deposits than those contoured by Smith (2004d), due primarily to the additional data from new wells. East of Echo Lake, well log data from 2004–2016 revealed two trenches not previously identified. Smith (2004d) mapped this area as having 100 ft or less of lacustrine-till aquitard deposits. With the addition of new wells, the area is now mapped with 100 ft to 300 ft of aquitard thickness (plate 1).

A driller's log that did not specifically record lacustrine or till aquitard material is not proof that the aquitard unit is missing in that area. Well logs with thin or no lacustrine or till material listed were further evaluated by looking for confirmation from logs in surrounding wells. It was found, in all cases, that logs from surrounding wells had well-defined intervals of lacustrine or lacustrine-till sediment.

The potential for direct contact between the deep aquifer system and Flathead Lake is a critical question for water management decisions. The 3-dimensional model shows that the bedrock surface rises and the deep aquifer system thins at the south end of the model, near the lake. The elevation of the top of the deep alluvium at this location is well below the elevation of the lake bottom (Flathead Lakers, 2011) at the southernmost data point in the model, indicating an apparent separation between the two, probably filled

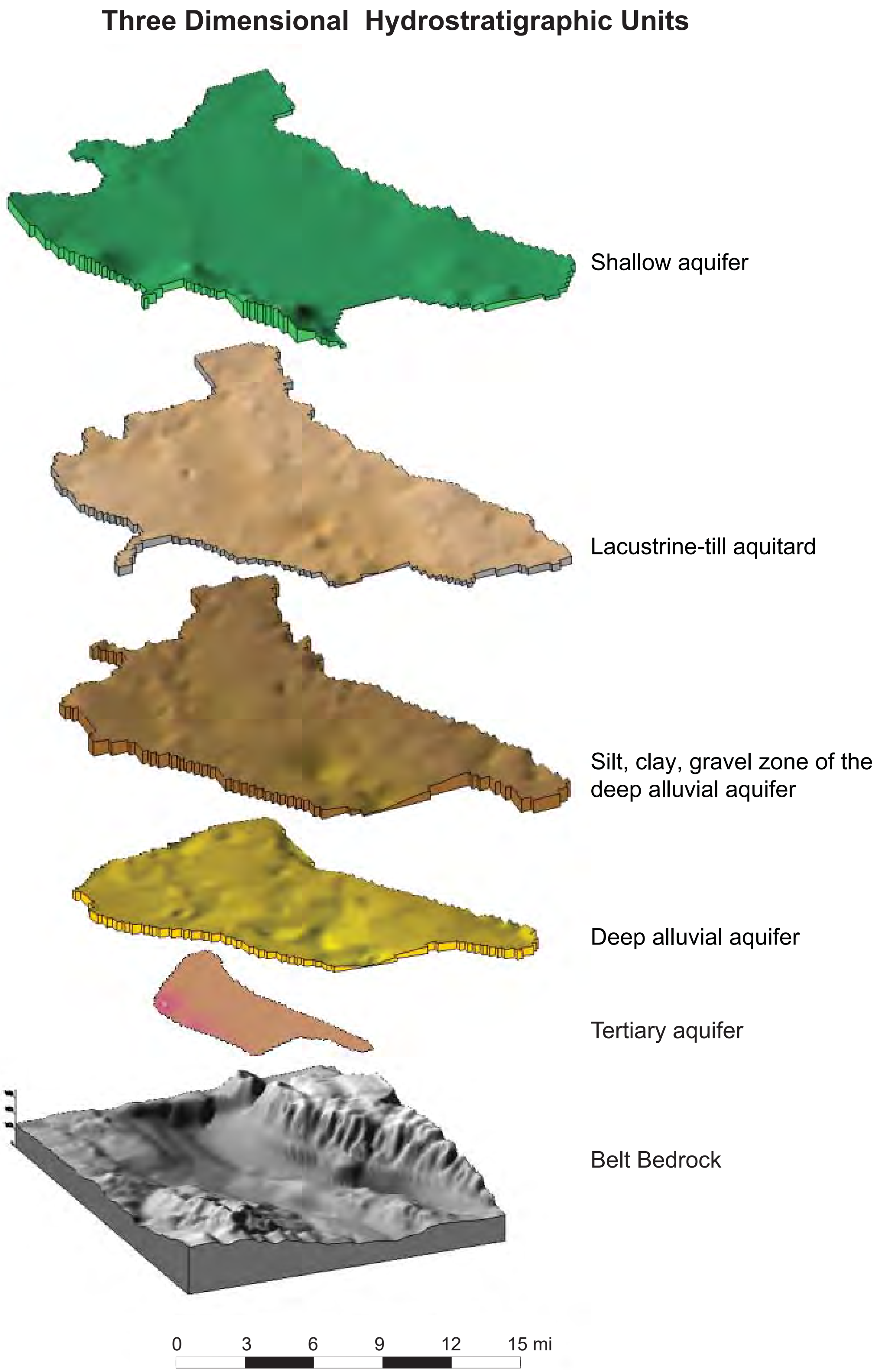


Figure 19. Exploded view of the modeled layers (solids) stacked in their hydrostratigraphic position shows the relationship between units and the shapes of the individual modeled layers.

by lacustrine-till deposits. However, no geologic data indicate the actual relation between the deep alluvium and the lake. At the south model boundary, both the lacustrine-till aquitard and possibly the deep aquifer system are likely present between the bedrock surface and the bottom of Flathead Lake. Ultimately, it is not known which hydrogeologic units are present.

Implications for Drilling Water Wells

For consideration during well drilling, the silt, clay, gravel zone of the deep alluvial aquifer is a comparatively poor water-producing unit. The interval is also discontinuous and relatively thin. If the silt, clay, gravel zone of the deep alluvial aquifer is encountered, continued drilling until clean gravel is reached will improve well productivity as much as 10 times.

Troughs incised through the basal till of the lacustrine-till aquitard and into the top of the deep alluvial aquifer are significant features that can affect well productivity and drilling depths. Troughs create an irregular and undulating top surface of the deep alluvial aquifer. Modeling shows that the depth to the top of the deep aquifer system varies greatly, averaging 250 ft and reaching up to 800 ft deep. Most significantly, tunnel-channel erosion that created the unusually deep troughs removed long stretches of the deep alluvial aquifer and infilled it with lacustrine silt, altering the character of the alluvium of the deep aquifer, and possibly influencing groundwater movement in the upper portions of the deep aquifer system.

The hydrostratigraphic model results can be used to help landowners and drillers anticipate drilling depths for wells by constructing cross sections and evaluating proposed well sites prior to drilling. For water-well drilling and groundwater management purposes, the hydrostratigraphic model has the advantage of combining all available geologic information into a single comprehensive, 3-dimensional, visual display of the subsurface hydrostratigraphy. Evaluating points or cross sections in the model will allow for improved water-well drilling plans.

Hydrostratigraphic Model

The hydrostratigraphic model provides a numerical representation and a 3-dimensional visual image of the configuration and relationships between subsurface hydrostratigraphic units in the Flathead Valley (fig. 19). The model provides a useful and practical method to correlate the lithologic data from well logs. Logs for wells drilled in the future can be added to further refine the model. Fortunately, the hydrostratigraphy of the Flathead Valley, in general terms, is distinct enough to differentiate in most well logs.

The full functionality of the model is achieved by running it in GMS (at this writing, GMS does have a free, basic trial software available). Realizing that GMS software may not be readily available, delimited text files of the model surfaces are included in the MBMG publications page for this report (http://mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=32017&). The text files contain location and elevation coordinates (x, y, z) for the hydrogeologic unit contacts that can be used to recreate DEM or TIN surfaces. These text files can be imported to other 3-dimensional software programs (such as ESRI ArcMap®, Surfer®, Earthware, etc.).

An added benefit is the ability to import the model files and data directly to a MODFLOW groundwater numerical model. For groundwater modeling, the hydrostratigraphic units created in the model can be used to represent the actual dimensions and variability of the deep alluvial aquifer, the lacustrine-till aquitard unit, and surrounding geologic intervals to produce a more accurate groundwater flow model. The following hydrostratigraphic model files are available for download (http://mbmg.mtech.edu/mbmgcat/public/ListCitation.asp?pub_id=32017&):

GMS Project Files

- Text delimited files
- Shallow aquifer top contact.txt
- Lacustrine-till aquitard top contact.txt
- Silt, clay, gravel zone of the deep alluvial aquifer top contact.txt
- Deep alluvial aquifer top contact.txt
- Tertiary (estimated) top contact.txt
- Bedrock surface.txt
- Lacustrine-till aquitard thickness contours.txt

RECOMMENDATIONS

The hydrostratigraphic model provides a tool for evaluating subsurface hydrostratigraphy prior to undertaking new water development and water-management decisions. The model provides output showing the thicknesses of, and the depths to, specific subsurface units at any location within the model boundary. Prior to drilling water wells, the model should be consulted to determine anticipated drilling depths and completion options. It may be advantageous to identify a principal person or agency in the area with operating knowledge of the software to generate responses to requests.

Interconnection or separation of the deep aquifer system, the shallow aquifer, and the land surface can be shown by generating a cross section at any location of interest. The graphical representation of the lithology can provide visual aids for public meetings as well as providing a common reference point for discussions between development entities, consultants, and/or agency staff.

As new lithologic information is developed in the Flathead Valley, the model can be improved. The best way to improve the accuracy of the model is to incorporate new well-log lithology data. As drillers become more familiar with the subsurface geology and stratigraphic contacts, where to look for those changes, and develop consistent drill-cutting descriptions, better accuracy can be achieved in reporting the hydrostratigraphy. Making available examples of drill cuttings with the correct description might be one approach. A uniform logging system could be developed among all area drillers through mailings, a workshop focused on Flathead Valley drillers, or in a public display. Areas where the model indicates a thin lacustrine-till aquitard are locations where well cuttings should be carefully monitored and recorded in future well drilling.

Geologic research has occurred in the area for decades. No doubt additional research will occur in the future. This model provides an electronic format to aid future interpretations.

Specific future research that would be most beneficial include:

- Investigate critical areas where there is incomplete or lacking well information, such as in the north-central valley where very few water wells have been drilled.
- Review new well logs in areas where the lacustrine-till aquitard unit is thin, <100 ft thick, for potential gaps in the unit that have not yet been identified.
- Investigate subsurface geology to the south of the modeled area and beneath the north shore of Flathead Lake by drill coring or geophysical methods.

ACKNOWLEDGMENTS

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