The Belt Basin (fig. 3) probably formed about 1,600 m.y. as the North American craton rifted and began to subside and fill with sediment (Cressman, 1989). Along the eastern margin of the Basin, shale and limestone accumulated on a shallow, continental shelf, whereas near the tectonically active southern boundary, coarse-grained arkosic conglomerate accumulated. As rifting decreased, shallow, continental shelf and subaerial deposition became predominant and continued through Late Proterozoic time (Cressman, 1989). Deposition of at least 60,000 to 65,000 ft (Harrison and others, 1974; 1986) of coarse-grained clastic, fine-grained clastic, and carbonate sediment filled the Belt Basin between about 1,500 to 900 m.y. (Reynolds, 1984). During deposition, faulting caused a trough in the basin. This trough is called the Lewis and Clark Line (fig. 3)—a complex zone of normal, reverse, and strike-slip faults (Harrison and others, 1986; Wallace and others, 1990).

Paleozoic through Late Jurassic paleogeography in the study area was influenced by the two persistent depositional environments that were created in Late Precambrian time: a broad, cratonic, shallow-carbonate shelf extending across western Montana and a deep-ocean basin extending across Idaho. During this time, western Montana and Idaho were the location of the North American continental margin and sediment was deposited in what is called the Cordilleran Sea. In an area that now lies east of a north-trending line at about 114° longitude, deposition was on the shallow-carbonate shelf; west of this line, deposition was in the deep-ocean basin. As the Cordilleran Sea transgressed eastward, a westward-thickening sequence of limey mud, sand, and silt was deposited. The resultant Paleozoic carbonate and clastic rocks (Pzls) range in thickness from about 2,500 ft in what is now southwestern Montana to over 26,000 ft in central Idaho near the Lemhi Range (Scholten, 1957).

Regional tectonic activity throughout Paleozoic and early Mesozoic time produced uplifts and frequent regressions of the Cordilleran Sea and interrupted the depositional environments. In Late Silurian through Early Devonian time, widespread warping of the North American continent caused several uplifts in the eastern part of the study area. In Late Devonian through Early Mississippian time, the Antler Orogeny altered the depositional environments into a restricted shallow-carbonate shelf and several highland areas in Montana, and a narrow trough in west-central Idaho (Smith and Gilmour, 1979; Skipp and others, 1979). Deposition in the narrow trough, or foreland basin, in Idaho resulted in a sequence of interbedded conglomerate, sandstone, siltstone, mudstone and limestone (Pzls) (Poole, 1974). In Early to Middle Pennsylvanian time, and again in Late Permian and Early Triassic time differential uplift and faulting eroded some pre-existing rocks (Skipp and others, 1979). A long period of erosion occurred during Middle Triassic through Early Jurassic time in Montana and parts of Idaho. In Middle to Late Jurassic time, the last significant widespread sea transgressed over the study area and deposited sand and limey mud. The resultant Mesozoic clastic and carbonate rocks (Mzsh) mostly occur as isolated outcrops and erosional remnants in western Montana.

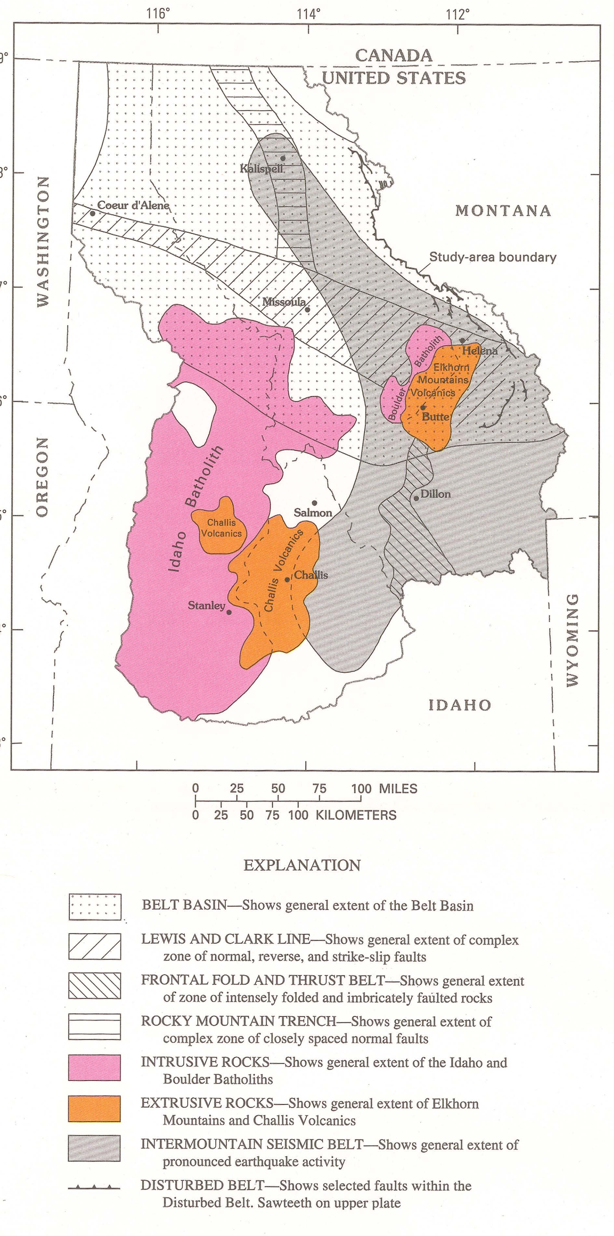

Figure 3. Selected structural and geologic elements in the study area (modified from Harrison and others, 1974, 1986; Rupple and others, 1993).

From Late Jurassic through middle to late Eocene time, western Montana and all of Idaho was an area of complex tectonic, plutonic, and volcanic activity associated with a north-south trending magmatic arc along the western edge of the North American continent (Suttner and others, 1981). During this time, uplift in Idaho and extreme western Montana was associated with initial intrusion of the Idaho Batholith. Rocks in Idaho were eroded and deposited in a rapidly subsiding foreland basin in western Montana (Suttner and others, 1981). In general, Mesozoic clastic and carbonate rocks in the study area (Mzsh) represent westward-thickening, intertonguing wedges of nonmarine sandstone, continental coastal-plain sediments, and marine shale and limestone that formed as rocks were eroded from the rising highland in Idaho and extreme western Montana.

About 125-65 m.y., the magmatic arc migrated eastward into central Idaho and southwestern Montana resulting in a frontal fold and thrust belt (Suttner and others, 1981). Deformation along the frontal fold and thrust belt progressed from western Idaho about 100 m.y. to southwestern Montana about 80 to 75 m.y. (Ruppel, 1993; Schmidt and Garihan, 1983). Deformation continued from southwestern Montana north to the Disturbed Belt (fig. 3) ending in middle to late Eocene time (Mudge, 1970; Suttner and others, 1981). This migrating thrust belt resulted in a zone of intensely folded and faulted rocks that in most areas have been displaced eastward.

Major episodes of intrusive and extrusive igneous activity accompanied and followed thrusting in western Montana and central Idaho (Chadwick, 1981). Intrusive and extrusive episodes peaked about 80–65 m.y. in Late Cretaceous and early Paleocene time with the Idaho and Boulder Batholiths and Elkhorn Mountains Volcanics, and again about 54 to 45 m.y. in Eocene time with the Challis Volcanics (Ruppel, 1993; Chadwick, 1981; Chadwick 1985). Magmatism generally followed the same west-east trend as thrusting and progressed from western Idaho to western Montana (Ruppel, 1993; Chadwick, 1981; Chadwick 1985). Tertiary through Cretaceous intrusive rocks (TKi) include the Idaho Batholith in central Idaho and the Boulder Batholith in west-central Montana, and large areas of Quaternary, Tertiary and Cretaceous extrusive rocks (QTKe) include the Elkhorn Mountains Volcanics in west-central Montana and the Challis Volcanics in central Idaho (fig. 3).

By middle to late Eocene time, about 50 to 40 m.y., compressional tectonic deformation ceased. However, faulting continued and began to form fault-controlled structural basins (Fields and others, 1985). Some structural features such as the Rocky Mountain Trench (fig. 3)—a complex zone of closely spaced normal faults that forms a continuous depression from northwestern Montana to northwestern Canada—are thought to have formed during this period. The fault-controlled structural basins subsided rapidly, becoming depositional centers for locally derived Tertiary clastic sediment (Ts) that was deposited on irregular topography of older bedrock (fig. 4, diagrammatic hydrogeologic sections A and C). These sediments (Ts) were deposited in low-energy, meandering stream channels, flood plains, ponds, and shallow and ephemeral lakes during a time when the climate was moderately arid (Rasmussen, 1989).

Renewed extensional faulting, about 20 m.y. during early Miocene time, caused significant folding and tilting of lower Tertiary rocks (fig. 4, diagrammatic hydrogeologic sections A and B). This tectonic activity, coupled with a change in climate from moderately arid to humid, caused deep erosion of lower Tertiary rocks resulting in a major unconformity that probably exists in all basins (Fields and others, 1985). Middle to upper Eocene through lower Miocene deposits and rocks are now as much as 4,300 ft thick (Robinson, 1967). The erosional episode ended about 15 m.y. as the climate changed to semiarid, faulting continued, and basins began to fill with coarse-grained deposits (Ts or QTd).

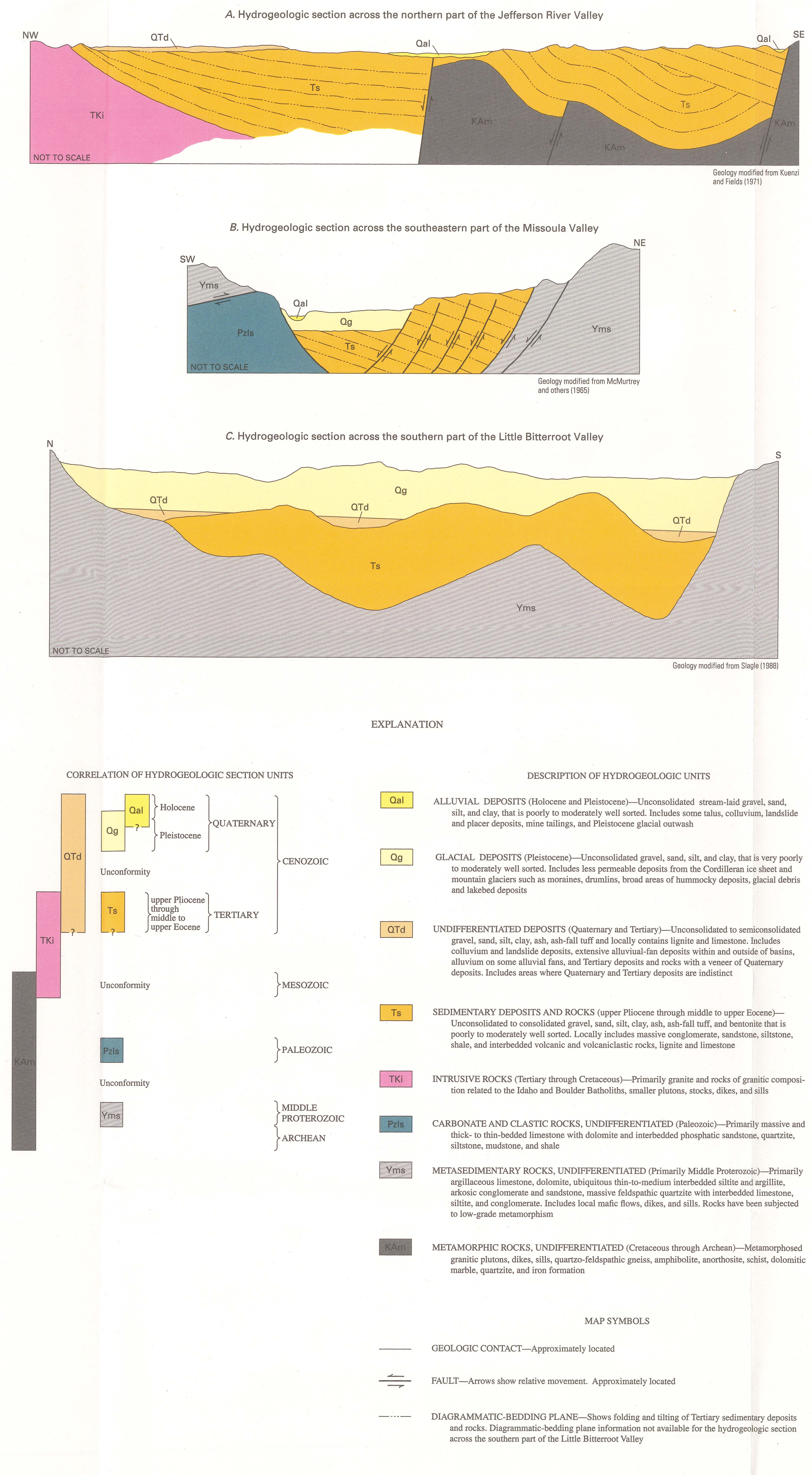

Figure 4. Diagrammatic hydrogeologic sections across the: (A) northern part of the Jefferson River Valley, (B) southeastern part of the Missoula Valley, and (C) southern part of the Little Bitterroot Valley.

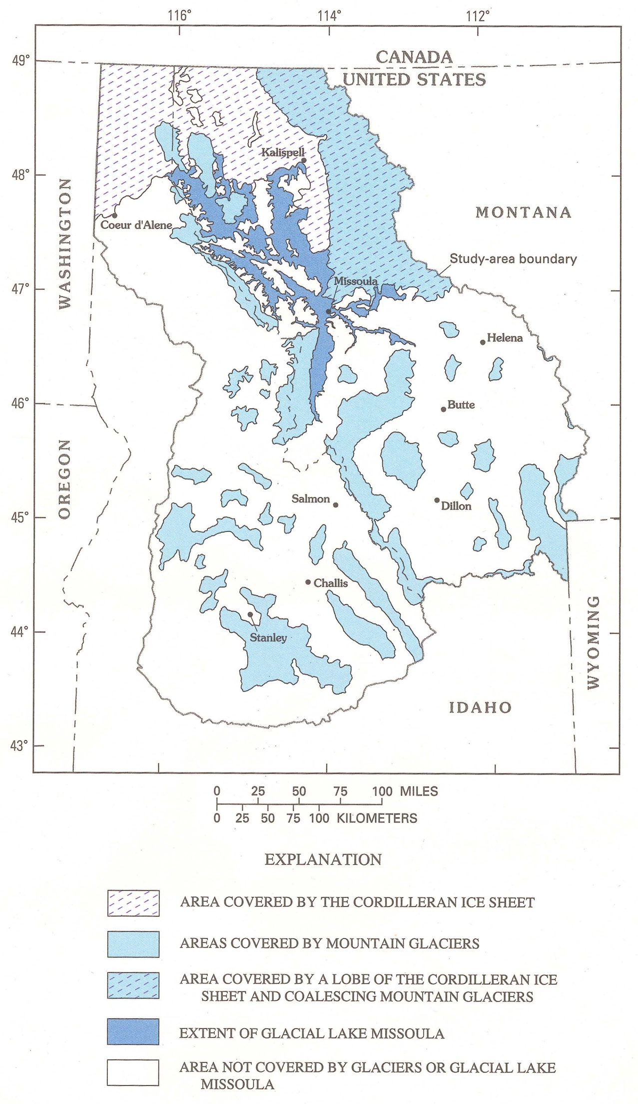

Figure 5. General extent of late Pleistocene glaciers and glacial Lake Missoula in the study area (modified from Alden, 1953; Dingler and Brekenridge, 1982; Porter and others, 1983).

Streams continued to deposit unconsolidated gravel, sand, silt, and clay (Qal) along stream channels, flood plains, and low-level terraces as faulting and basin subsidence also continued during late Pleistocene and Holocene time. Significant displacement occurred along many faults in the southern basins (Haller, 1990; Rodgers and Anders, 1990). Much of the study area continues to be seismically active and is part of the intermountain seismic belt (fig. 3), a north-trending zone of earthquake activity (Smith and Sbar, 1974). In the study area, this belt extends from northwestern Montana to the Upper Madison River Valley area, and continues south of the study area. Another area of earthquake activity within the intermountain seismic belt extends from the Upper Madison River Valley area west to the Lost River Range in Idaho. The intermountain seismic belt is thought to reflect zones of crustal weakness associated with a mantle plume, or hot spot, now centered below Yellowstone National Park (Smith and Sbar, 1974).

Areas of present-day faulting and basin subsidence can be divided into a relatively stable zone and an unstable zone. These zones are geographically defined by the Lewis and Clark Line (fig. 3) which is the northern boundary of basin-and-range-type active faulting (Stickney and Bartholomew, 1987). In the relatively stable zone north of the Lewis and Clark Line, diffuse earthquakes and earthquake swarms generally are smaller in number, have magnitudes less than 5.5, and most faults are considered inactive (Stickney and Bartholomew, 1987). However, some fault scarps in the Mission Valley indicate that earthquakes with magnitudes greater that 7.0 have occurred during the middle Holocene (Ostenaa and others, 1993). In the relatively unstable zone south of the Lewis and Clark Line, earthquake activity increases as does earthquake magnitude (as much as 7.5), and active faults have ruptured the surface (Stickney and Bartholomew, 1987). Most seismic activity is centered in four areas along the southeastern study area boundary: Red Rock Valley, Centennial Valley-southern Gravelly Range, Upper Madison River Valley, and the Lost River Range (Stickney and Bartholomew, 1987).

HYDROGEOLOGIC UNITS

Water-yielding properties of the 10 hydrogeologic units presented in this report are, in part, based on data collected during the study by the U.S. Geological Survey, 1991–92. These data were retrieved from the U.S. Geological Survey's National Water-Data Storage and Retrieval System (WATSTORE). Water-yielding properties are also based on data compiled from previous studies and drillers' logs.

Basin-fill deposits

Basin-fill deposits principally are composed of unconsolidated to consolidated gravel, sand, silt, and clay that typically form a thick sequence of complexly stratified deposits. In most basins these hydrogeologic units probably respond as a complex aquifer system. Fine-grained confining units or leaky-confining units within basin-fill deposits generally are laterally discontinuous, allowing interconnection between the coarse-grained sediments of the different hydrogeologic units.

Figure 6 shows the depth of wells completed in hydrogeologic units of the basin-fill deposits in the study area. The median depth of wells completed in basin-fill deposits ranges from 75 to 153 ft, indicating little variation between the hydrogeologic units (table 1). Fifty percent of wells in the study area are between about 40 ft (25th percentile) and 270 ft (75th percentile) deep. Additionally, little variation in well depth between these units is indicated by the 10th and 90th percentiles (table 1). The depth of wells completed in basin-fill deposits does not vary substantially because depth to water and depth to a water-bearing zone that yields a sufficient quantity of water do not vary substantially.

Holocene and Pleistocene alluvial deposits (Qal) consist of unconsolidated stream-laid gravel, sand, silt, and clay in flood plains and low terraces along present-day streams and rivers. This unit also includes Pleistocene glacial outwash. Holocene and Pleistocene alluvial deposits (Qal) are the second most productive aquifer in the study area (fig. 6, table 1). The median well yield for this unit in the study area is 30 gal/min with 50 percent of the wells yielding between 15 gal/min (25th percentile) and 100 gal/min (75th percentile). The median specific capacity is 2 (gal/min)/ft which indicates that transmitting properties of Holocene and Pleistocene alluvial deposits (Qal) are twice that of Pleistocene glacial deposits (Qg) and Tertiary sedimentary deposits and rocks (Ts), but half as much as Quaternary and Tertiary undifferentiated deposits (QTd). The ranges of yield and specific capacity for wells completed in Holocene and Pleistocene alluvial deposits (Qal) are large (1 to 4,550 gal/min and 0.1 to 661 (gal/min)/ft, respectively), primarily because of the various depositional environments represented by this unit. Small well yields and specific capacities are typical for wells completed in alluvium deposited by rivers and streams with a small carrying and sorting capacity because deposits can contain substantial quantities of fine-grained material. In contrast, large well yields and specific capacities are typical for wells completed in alluvium deposited by rivers and streams with large carrying and sorting capacity. For example, wells completed in deposits near large rivers such as the Spokane River near Coeur d' Alene, Idaho, can have very large yields and specific capacities.

Pleistocene glacial deposits (Qg) consist of unconsolidated gravel, sand, silt, and clay that generally is fine grained and very poorly sorted. Wells completed in this hydrogeologic unit typically are the least productive in terms of yield and specific capacity (fig. 6, table 1). The median yield for wells completed in this unit in the study area is 15 gal/min with 50 percent of the wells yielding between 10 gal/min (25th percentile) and 31 gal/min (75th percentile). The median specific capacity is 1 (gal/min)/ft which indicates that the transmitting properties are similar to Tertiary sedimentary deposits and rocks (Ts) and 2 to 4 times less than Holocene and Pleistocene alluvial deposits (Qal) or Quaternary and Tertiary undifferentiated deposits (QTd), respectively. The ranges of yield and specific capacity for wells completed in Pleistocene glacial deposits (Qg) are large (0.2 to 1,500 gal/min and 0.1 to 475 (gal/min)/ft, respectively), primarily because this unit is less permeable and includes predominantly fine-grained material and very poorly sorted gravel, sand, silt, and clay in moraines, drumlins, glacial debris and lakebed deposits. This unit also contains discontinuous or poorly connected lenses of gravel and sand that probably function as minor aquifers. Laterally continuous and extensive gravel, such as buried alluvial channels or outwash, that is hydraulically connected with other more permeable units or a recharge source probably accounts for the few larger well yields and specific capacities.

Quaternary and Tertiary undifferentiated deposits (QTd), consist of unconsolidated to semi-consolidated gravel, sand, silt, clay, ash, and ash-fall tuff that locally contain lignite (low-rank coal) and limestone. This unit is the most productive aquifer in the study area in terms of well yield and specific capacity (fig. 6, table 1). The median yield for wells completed in this unit in the study area is 60 gal/min with 50 percent of the wells yielding between 15 gal/min (25th percentile) and 1,820 gal/min (75th percentile). The median specific capacity is 4 (gal/min)/ft, which indicates that the transmitting properties of Quaternary and Tertiary undifferentiated deposits (QTd) are 2 to 4 times greater than those of the other basin-fill deposits. The ranges of yield and specific capacity for wells completed in Quaternary and Tertiary undifferentiated deposits (QTd)

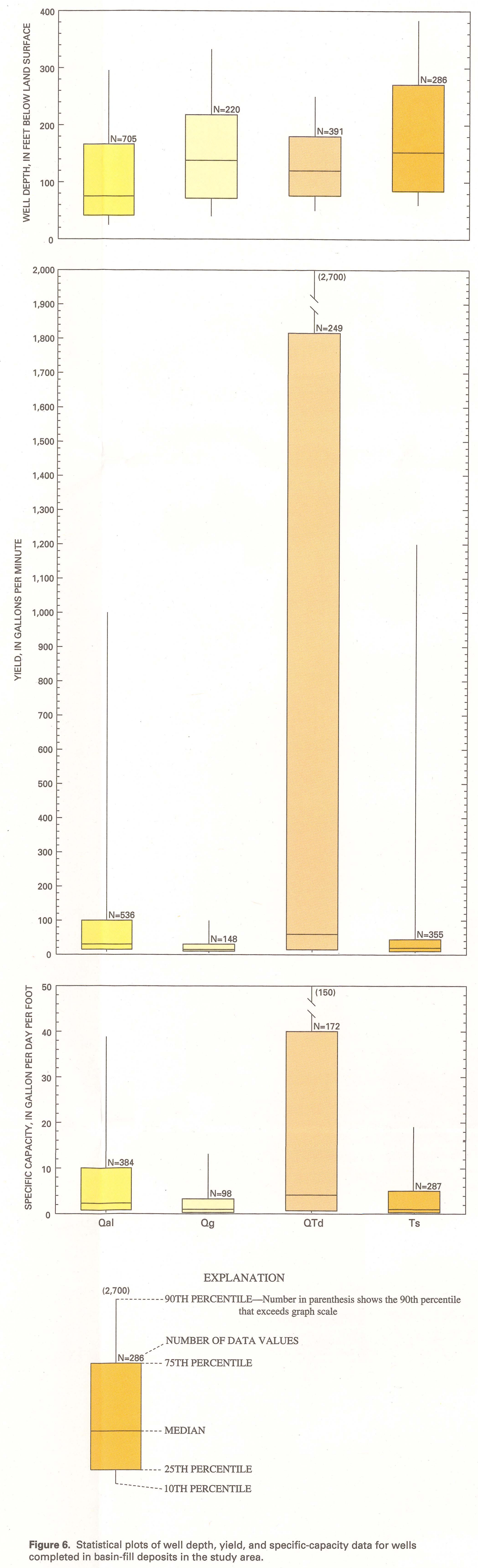

Figure 6. Statistical plots of well depth, yield, and specific-capacity data for wells completed in basin-fill deposits in the study area.

Table 1. Statistical summary of well depth, yield, and specific-capacity data for wells completed in basin-fill deposits in the study area

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GEOLOGIC HISTORY AND HYDROGEOLOGIC UNITS OF INTERMONTANE BASINS OF THE NORTHERN ROCKY MOUNTAINS, MONTANA AND IDAHO

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