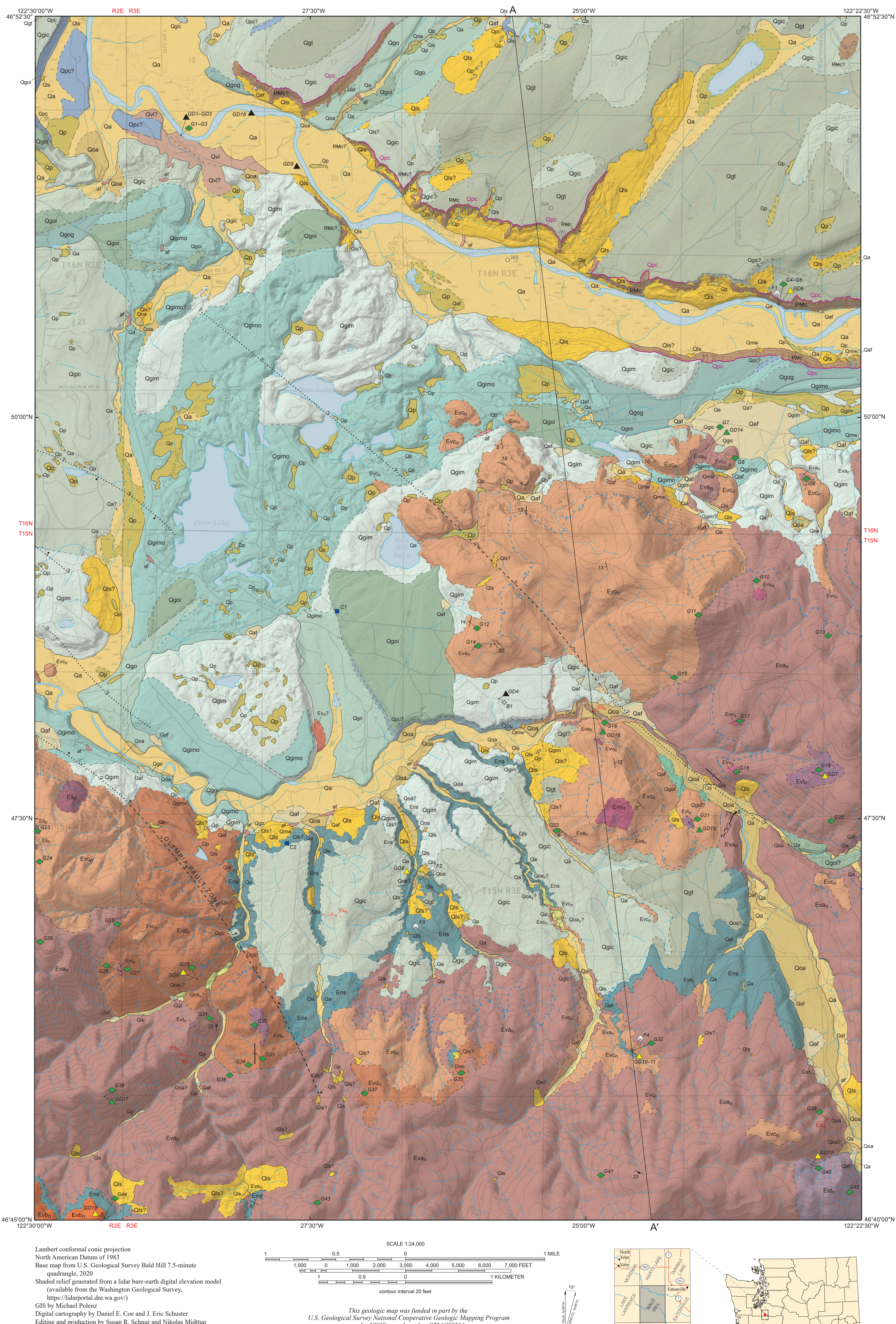


Geologic Map of the Bald Hill 7.5-minute Quadrangle, Thurston, Pierce, and Lewis Counties, Washington

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ABSTRACT

We present a geologic map of the Bald Hill quadrangle located along the Nisqually River in Washington's Puget lowland. The map describes the age, stratigraphy, and distribution of glacial, fluvial, and volcanic deposits along the southern margin of the Tacoma basin. We use 38 geochronological analyses to characterize volcanic, volcanoclastic, and intermediate igneous intrusive rocks of the Eocene Northcraft Formation. The volcanic rocks are mostly andesitic but range from basalt to rhyolite. These rocks commonly include porphyritic alteration, especially near intrusions. The volcanoclastic rocks range from welded to unwelded tuff, tuff breccia, and coarse, bouldery lahar deposits. Eleven new ages from the Northcraft Formation range from 42.5–44.1 Ma to <35.2 ± 1.2 Ma.

Our analysis of existing aeromagnetic and new gravity data suggests that the map area marks the southeastern terminus of the Olympia fault. Joint two-dimensional forward modeling of aeromagnetic and gravity data permits either a faulted or folded southern edge of the Tacoma basin. New detrital zircon ages reveal that sediment (unit PMc), which closely resembles the Mabel Formation in outcrop, is Pliocene—significantly younger than the fossil-based Miocene age of the Mabel Formation. Definitive determination of whether unit PMc is equivalent to the Mabel Formation awaits improved geochronologic age control on the Mabel Formation type section. Based on three radiocarbon dates, heavy mineral content in pumice pebbles, and geochemical analyses of three clasts, we associate lahar deposits near the northern map boundary with Mount Rainier's late Holocene Summerland eruptive period. These deposits document infrequent but life-threatening volcanic hazards. Vashon glacial deposits, Holocene alluvium, and underlying Cascade Range-derived sediment provide productive aquifers. High arsenic content in groundwater in the northeastern part of the map area may be associated with unit PMc.

LIST OF MAP UNITS

Holocene to Pleistocene Nonglacial Deposits

af Artificial fill (Holocene)—Cobbles, pebbles, sand, silt, clay, and boulders, all in varied amounts, engineered and non-engineered; placed to raise surfaces. Excludes small or shallow fills (usually less than 1.5 m thick) such as most road-related deposits.

Qp Peat (Holocene to late Pleistocene)—Organic and organic-matter-rich sediment (peat, gyttja, muck, silt, clay, and sand) in flat-bottomed depressions or other poorly drained flat areas; mostly mapped where lahar reveals such landforms and we interpret true-color or infrared aerial photos as suggesting hydrophilic vegetation and/or wet conditions.

Qa Alluvium (Holocene to late Pleistocene)—Fluvial and channel sediment, including mostly andesitic clasts (pebbles, cobbles, and boulders), as well as sand, silt, clay, and peat, all in varied amounts; loose, mostly well rounded and moderately to well sorted; sourced from the Cascade Range and its ancestral western foothills, and commonly reworked from units Qp, PMc, Qg, Ev, and Ens. Forms a highly remobilized, product, usually unconfined surface. Unit Qa is mapped where alluvial transport appears active; unit Qoa identifies alluvial deposits that no longer receive sediment. Compared to unit Qg, where relief terrace landforms suggest Vashon Glaciation-aged alluvium deposited in response to down-valley ice-damming.

Qaf Alluvial fan (Holocene to late Pleistocene)—Pebbles, cobbles, sand, diatomite, silt, and boulders, all in varied amounts, deposited in broad fans where confined channels spill out onto broader surfaces; gray to brown, loose; subangular to rounded; moderately to poorly sorted; bedded to unbedded. Unit Qaf was mostly mapped where the presence of fan-shaped landforms.

Qls Landslide deposits (Holocene to Pleistocene)—Sand, silt, clay, pebbles, cobbles, and boulders, all in varied amounts, derived from deposits (spikes; variably weathered; particles angular to rounded, mostly loose, unsorted, and jumbled; stratified and/or compact in some blocks; mostly mapped from landforms (for example, hummocky slopes, degraded and disrupted drainages, disrupted or irregular slopes, tilted benches in hillsides, and concave upper and convex lower slope forms).

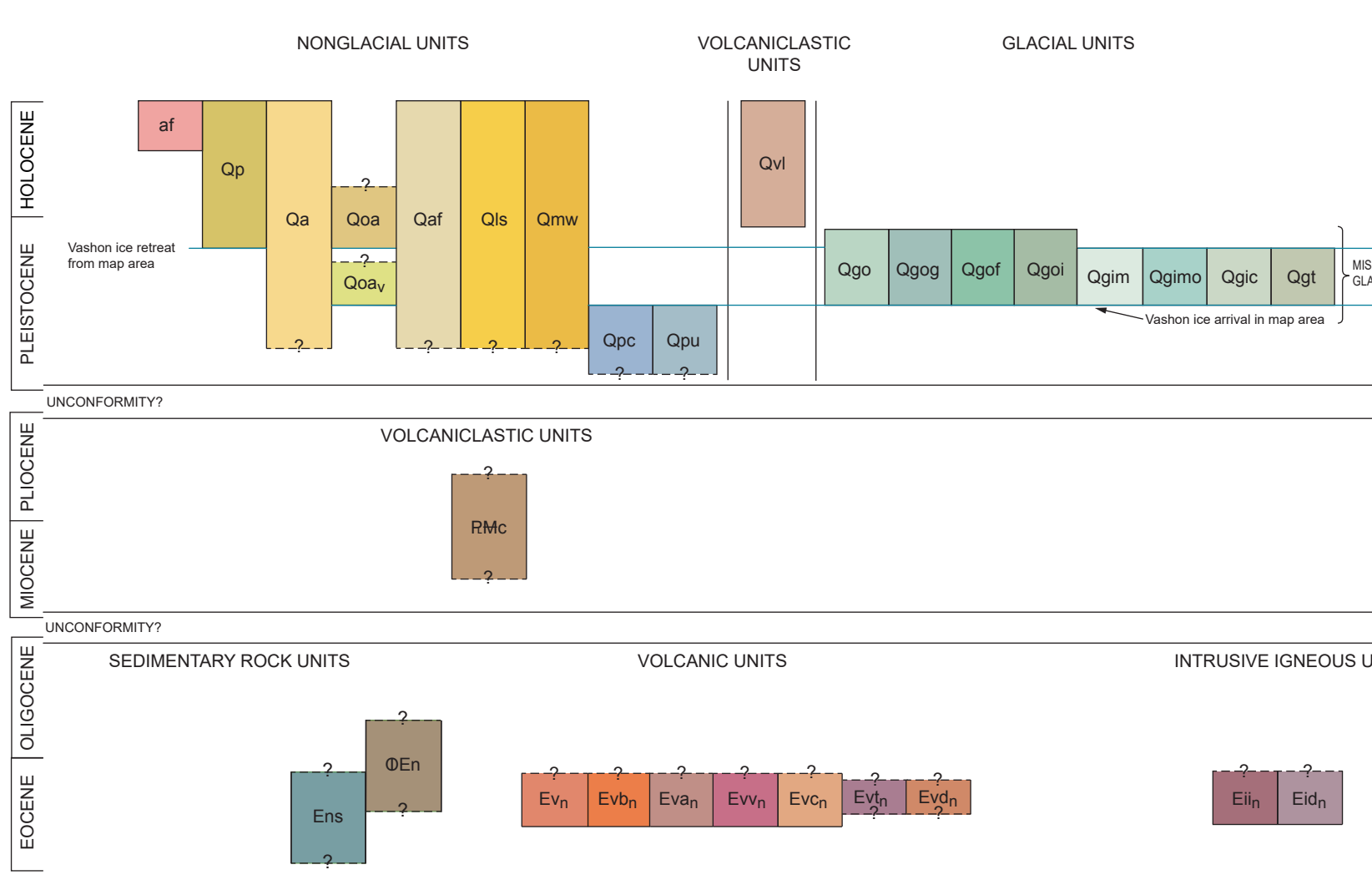
Qmw Colluvium (Holocene to Pleistocene)—Loose soil, rocks, sand, silt, and clay, all in varied amounts; deposited by shallow navel and soil creep; locally includes small landslides and alluvial fans, but fan-shaped deposits in unit Qmw are typically steeper than those in unit Qaf; mapped where colluvium conceals the underlying geology but may locally include outcrops of underlying deposits, especially where those are volcanic; not mapped where creeping, clayey soils appear to mantle otherwise undisturbed, smooth slope surfaces.

Qd Lahar deposits and lahar run-out deposits (Holocene to late Pleistocene)—Diamonction, sand, silt, and clay, and a locally bouldery gravel facies that we infer from down-valley exposures noted by Polenz and others (2022); commonly contains pumice; clasts mostly undeformed, other Cascade Range-sourced lithologies (see *Vashon Drift*) less common; matrix mostly sand, rich in pumice and volcanic glass fragments; mostly pale gray to dark gray or lavender, mildly to moderately weathered; generally loose but diamonction commonly silt; clasts mostly rounded, ranging to angular, unsorted to moderately sorted; unstratified, less commonly poorly bedded, in some exposure unbedded to well bedded, locally with overstepped, swirl-shaped bedding.

Late Pleistocene Glacial and Nonglacial Sediments
Vashon Drift in the map area consists mostly of rock types found in the Cascade Range east of the map area but is distinguished from entirely Cascade Range-sourced sediment by inclusion of diagenetic lithologic constituents distally sourced from the north Cascades and British Columbia. Therefore, like many Puget Lowland publications, we label Vashon Drift as "northern-sourced." Purely Cascade Range-sourced sediment contains >60 percent intermediate to felsic volcanic rocks (mostly porphyritic andesite), less abundant dacite, felsic to intermediate rocks, and basalt. Cascade Range-sourced sand in the map area, while gray in color, commonly has a faint lavender hue that subtly distinguishes it from northern-sourced gray sand.

CORRELATION OF MAP UNITS

PERIODS AND EPISODES BASED ON USGS FACT SHEET 3010-068



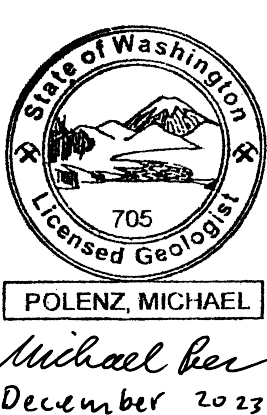
CROSS SECTION EXPLANATION

Qp, Qg: Geologic units too thin to show as polygons on the scale of the cross section; vertical tick marks separate units.

Water well or boring

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Aside from these Cascade Range-sourced constituents, northern-sourced sediment contains the following diagenetic units: mostly sorted matrix of sand, silt, and clay, all in varied amounts; usually includes a loose, surficial cover of 0.5–3 m of ablation till and (or) outwash silt, silt, sand, and gravel, and scattered erratic boulders on the surface; usually matrix supported; gray to pale reddish brown; mildly to moderately weathered except south of the Deschutes River, where weathering is varied; mostly compact and acting as an aquifer; clasts well rounded to faceted or angular, occasionally striated; matrix mostly angular, unsorted, unbedded but in some exposures flow banded. Unit Qgt tends to be more compact than unit Qgic. North of the Deschutes River, unit Qgt tends to form southwest-oriented drumlins and flutes. Compared to unit Qgic, unit Qgt tends to form better-developed flutes and drumlins and fewer irregular surfaces (mostly meltwater channels, kettles, and eskers).

VASHON DRIFT

Late Pleistocene continental glacial sediment in the map area consists of Vashon Drift—sediment deposited in the map area by, or owing to the presence or approach of, the Cordilleran (continental) ice sheet that advanced from British Columbia into the map area during the Vashon Stage of the late Wisconsinan Fraser Glaciation about 15.3–16 ka (Polenz and others, 2015; Hangerud, 2021).

Uncompacted outwash, undivided late Pleistocene—Pebble gravel, less commonly cobble and boulder gravel, pebbly sand, or sand, all in varied amounts; gray to pale gray, or milky weathered to pale brown, brown, or variegated with iron stains; loose and commonly cohesionless; well rounded to subrounded; moderately sorted to well sorted, and in gravel facies, clast supported; locally with matrix and interbeds of silt and sand; otherwise unbedded. Unit Qgt tends to form flat to gently sloping terraces with relief, mostly broadly channel forms. Unit Qgo is generally proglacial of Vashon recessional age. Locally subdivided into:

Qggo Recessional proglacial outwash gravel (late Pleistocene)—Loose, pebbly, cobble, and boulder gravel, sand, silt, and clay, all in varied amounts; gray to pale gray, or milky weathered to pale brown, brown, or variegated with iron stains; loose and commonly cohesionless; well rounded to subrounded; moderately sorted to well sorted, and in gravel facies, clast supported; locally with matrix and interbeds of silt and sand; otherwise unbedded. Unit Qgt tends to form flat to gently sloping terraces with relief, mostly broadly channel forms. Unit Qgo is generally proglacial of Vashon recessional age. Locally subdivided into:

Qggs Proglacial outwash silt (late Pleistocene)—Silt, clayey silt, and fine sand; gray to brown, loose, well sorted and well bedded; unbedded to planar bedded, observed between Green Hill and the Deschutes River and inferred to surrounding and nearby benches.

Qggt Recessional ice-contact outwash (late Pleistocene)—Cobble gravel, pebble gravel, and less commonly sand, deposited in ice-contact braided plains or channels; also sand or mixed sand and gravel in kettle walls, and sand or silt in kettle bottoms, some of which are draped with post-glacial peat where kettle bottoms are flat; tan to gray; loose; moderately to well rounded and sorted; unbedded to planar or gently cross-bedded in lake settings, gently cross-bedded in channels or braided plains, and due to kettle collapse locally with overstepped and/or chaotic and disrupted bedding. Compared to unit Qgic, unit Qggt forms a more continuous, orderly drape of outwash and a more intact, relatively level surface with less exposure of underlying marine.

End moraine (late Pleistocene)—Till, pebbles, sand, cobbles, silt, clay, and boulders, all in varied amounts, some lacustrine sand and silt in kettles and peat in flat kettles; gray, tan, and reddish brown, loose to compact; unbedded to well sorted; unbedded to bedded in other facies. Boulders (glacial erratics) commonly rest on the surface of unit Qgim. Landforms in unit Qgim tend to be more hummocky than in other units except Qa, and more kettled than unit Qgim. Unit Qgim includes eskers and small, patchy terraces smoothed by meltwater and (or) draped with outwash. Slumps in unit Qgim are mostly periglacial relicts, and unit Qgim tends to be more permeable than unit Qgic, with more efficient and more organized drainage. Compared to units Qgic and Qgt, unit Qgim tends to form less streamlined surfaces with little or no evidence of drumlins and flutes. Lower compaction usually separates it from unit Qgt.

End moraine draped with outwash (late Pleistocene)—Clay-rich outwash, pebbles, sand, cobbles, and boulders, all in varied amounts, resting on an end moraine consisting of till, pebbles, sand, cobbles, silt, clay, and boulders, all in varied amounts; gray, tan, and reddish brown; loose to compact; moderately to well sorted in outwash, unsorted in till; unbedded to bedded in outwash, unbedded in till. Unit Qgim is distinguished from unit Qgim by systematic presence in unit Qgim of surficial outwash deposited in ice-contact channel surfaces that are now heavily fragmented by kettles.

Kettles and exposures of moraine in unit Qgim are more pervasive than those in unit Qgic, and the outwash drape is less continuous.

Ice contact deposits (late Pleistocene)—Undivided till and, less commonly, outwash; loose to compact diamonction, pebble gravel (locally cobbly) and sand, all in varied amounts; pale gray to brown and reddish brown; mildly weathered except south of the Deschutes River, where weathering is varied; mostly loose and crumbly in ablation till and outwash, ranging to compact in lodgment till, but typically lacking thick, continuous, or widespread sheets of lodgment till near the surface. Particles range from cobbles to mudfine sand, with finer particles common in till matrix and boulders locally in till and outwash, and loosely scattered as erratics on the surface. Rounding, sorting, and unit thickness are varied.

North of the Deschutes River, irregular landforms (mostly kettles and sinuous channels) mark unit Qgic. Drumlins and flute surfaces in unit Qgic tend to be more distinct than in unit Qgt and coarser by till, sand, and gravel that is less compact, more permeable, more fragmented, more friable, and geotechnically weaker than in unit Qgt. Landform irregularities are absent or more subdued south of the Deschutes River, where unit Qgic is also thinner.

Lodgment till (late Pleistocene)

Diamonction containing cobbles, pebbles, sand, silt, and clay, all in varied amounts; usually includes a loose, surficial cover of 0.5–3 m of ablation till and (or) outwash silt, silt, sand, and gravel, and scattered erratic boulders on the surface; usually matrix supported; gray to pale reddish brown; mildly to moderately weathered except south of the Deschutes River, where weathering is varied; mostly compact and acting as an aquifer; clasts well rounded to faceted or angular, occasionally striated; matrix mostly angular, unsorted, unbedded but in some exposures flow banded. Unit Qgt tends to be more compact than unit Qgic. North of the Deschutes River, unit Qgt tends to form southwest-oriented drumlins and flutes. Compared to unit Qgic, unit Qgt tends to form better-developed flutes and drumlins and fewer irregular surfaces (mostly meltwater channels, kettles, and eskers).

PRE-VASHON SEDIMENT

Pre-Vashon alluvium from the Cascade Range, undivided (late Pleistocene)—Pebbles, cobbles, sand, silt, clay, peat, and lahar-deposited bouldery gravel and diamonction, all in varied amounts; Cascade Range-sourced (see *Late Pleistocene Glacial and Nonglacial Sediments*); pale gray to light brown, reddish brown, and pinkish brown; moderately to mildly weathered—generally more than Vashon Drift; compact; sand usually rich in plagioclase and andesite, commonly glassy volcanic lith fragments, with somewhat lesser amounts of quartz and (or) K-feldspar and usually distinctly less abundant opaque minerals, pyroxene, and ilmenite. Dates from unit Qp north and northwest of the map area suggest a peakwork of ancestral Nisqually River alluvium from a potentially wide range of late(?) Pleistocene ages (Polenz and others, 2022).

Pre-Vashon sediment, undivided (Pleistocene)—Pebbles, cobbles, boulders, diamonction, sand, silt, clay, and peat, all in varied amounts; color and weathering variable; compact; varied grain sizes, rounding, sorting, and bedding; mapped in the subsurface north of the Deschutes River mainly based on sediment cuttings from drill hole H (0.34 km north of the Deschutes River), which include Vashon Drift above nonglacial sediments that yielded a radiocarbon-infinite age 35 m below the surface (GDS, see Tables 1 and A1 in accompanying pamphlet). We separate unit Qpu from unit Qp because Qpu may include pre-Vashon, northern-sourced glacial sediment. Its nonglacial component likely combines deposits reworked from nearby and sediment that an ancestral Deschutes River sourced from the Northcraft Formation and unit Ens.

Pliocene to Miocene(?) Sediments

Continental sediments (Pliocene-Miocene?)—Volcanic-lithic sand and silt with clayey matrix; commonly ranging from block and ash to lapilli-ash to ash tuff; (2) massive boulder diamict with varied amounts of matrix and bedding, unbedded to subangular; locally in fluvial-sungay, mud matrix-supported, and graded beds; interpreted as lahars; (3) volcanic-lithic sandstone, clay-rich to clay-fine, planar and graded, very thin to thick-bedded, moderately sorted, immature, locally tuffaceous with minor angular lapilli and detrital ash; (4) sandy, subrounded, rounded-pebble conglomerate; (5) rare fine-meter-wide channel fills of coarse, granular, and poorly sorted sandstone; (6) other isolated features including tuff breccias, gradually bedded clastic sediments, scour surfaces, and paleosols.

Felsic tuff (late to middle Eocene)—Ash flow tuffs (vitrified, crystal vitric, and little lapilli-ash to ash tuff); pale yellow to tan to medium light gray; dacitic; west of Green Hill unbedded and often crystal deficient; at least 75 percent altered glass, locally with pumice lapilli and rare small blocks; east and north of Green Hill contains up to 5 percent hornblende up to 3 mm in size, up to 15 percent plagioclase up to 4 mm in size, and pumice as flammage; at geochronology site G21, little with blocks up to 10 cm in size of light gray felsic lava, red scoria, and yellowish-tan pumice; near the western map edge, less crystalline, usually more altered, and often commingled with blocky dacite lava along gradational to indistinct boundaries; at geochronology site G28, with flame bent around phreatic vents indicating welding; altered feldspar and irregular epidote inclusions indicating hydrothermal alteration, and andesite plagioclase phenocrysts with rounded boundaries indicating abrasive transport.

Dacite and minor rhyolite (late to middle Eocene)—Felsic lava flows, mainly dacite but ranging to rhyolite, with some intercalated felsic tuff; yellowish tan to brown to medium dark gray; blocky to massive; sparsely porphyritic, with 3–5 percent slightly phenocrystized and chloritized plagioclase phenocrysts up to 3 mm in diameter; locally (to trachyte), the groundmass of variably dominant olive green glass and plagioclase microlites with <15 percent calcite, opacites, and quartz. Rhyolite is 95 percent devitrified glass and mostly found near the western map edge.

Sedimentary rocks (Oligocene-Eocene) (cross-section only)—Fine grained sedimentary rocks inferred aspect of unit Ev, in the northern third of Cross Section A–A', because fine-grained sedimentary rocks near Northcraft Formation(?) volcanoclastic rocks and lava flows at the E. E. Wilhoite et al. No. 1 well (Fig. M1A) and potential folds two-dimensional forward modeling suggests boundaries in the northern part of the map area (Figs. M1B, C). Unit thickness is poorly constrained.

Continental to nearshore sedimentary rocks (late to middle Eocene)—Clay-rich sandstone, brown to dark gray; fine- to very-fine-grained, moderately to well-sorted, thin bedded and fissile; volcanic lithic, locally calcareous at marine mollusk fossil site F4 (along Cross Section A–A'); shaly and slightly micaceous at geochronology site G44 along the southern map edge; elsewhere includes exposures that resemble andesite of unit Ev, All classify as graywackes. Hackly siltstone and shale is included in the unit 200–300 m north-northeast of G35 in the southern central part of the map. We suggest the mostly sandy unit Ens corresponds to Skookumchuck Formation, although more silty parts likely correspond to the mostly marine McIntosh Formation.

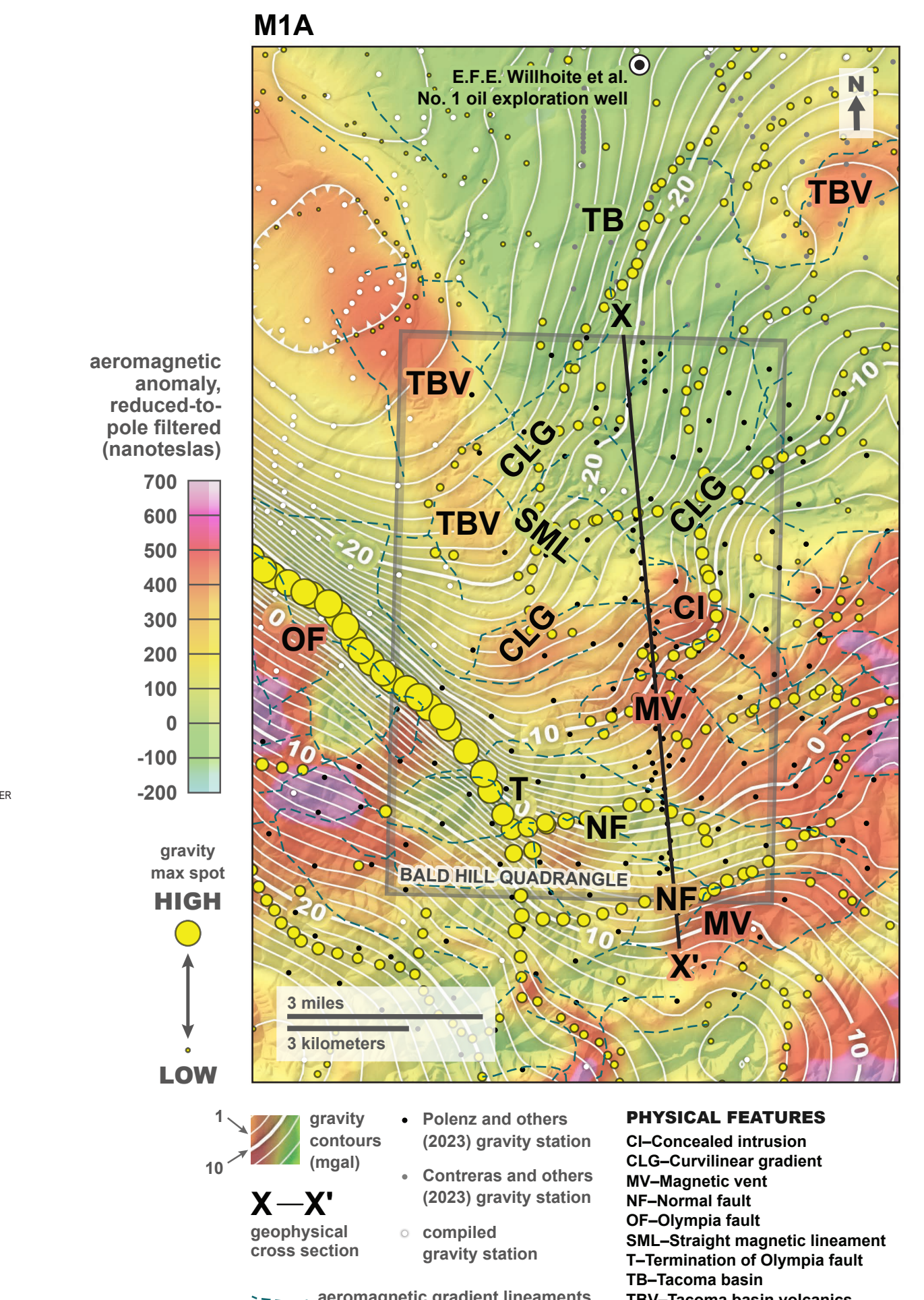


Figure M1A. Combined map of isotactic gravity (contours), reduced-to-pole filtered aeromagnetic anomaly (nanotesla), and gravity spot (yellow dots). The map shows the Bald Hill Quadrangle with various geological units and features. A scale bar indicates 3 miles and 3 kilometers. A north arrow is present. The map is labeled with various geological units and features.

Undivided igneous rocks (late to middle Eocene)—Dark gray to medium gray lava flows, mostly andesite and basaltic andesite, but ranging from basalt to rhyolite; interbedded with basaltic breccia, pyroclastic tuff, flow breccia, and other volcanoclastics; locally intruded and hydrothermally altered by chemically similar dikes, sills, and stocks. Locally subdivided into:

Basalt flows (late to middle Eocene)—Basalt lava; gray, weathers brown; porphyritic, with 20–25 percent subdral plagioclase phenocrysts up to 2 mm in size in 75–80 percent altered greenish gray glass with up to 15 percent opaque minerals and up to 10 percent chalcocyanite-filled oval vesicles. Petrography revealed groundmass chloritization, alteration of feldspars, and chalcocyanite alteration. The alteration far exceeds that of most other lava flows sampled and is consistent with (syndepositional?) water interaction. Where observed along the southwestern corner of the map, unit Evbn overlies unit Ens which produced the youngest date in the map area (<35.2 ± 1.2 Ma at age site GD13).

Andesite and basaltic andesite flows (late to middle Eocene)—Lava flows of mainly andesite, basaltic andesite, and less commonly trachyandesite and basaltic trachyandesite, and minor, interbedded volcanoclastic rocks; medium-dark to dark gray to dark olive gray; dense, porphyritic with plagioclase phenocrysts up to 4 mm in size except where locally aphanitic; blocky. Groundmass textures range from hyaloclastic to trachytic. Hydrothermal phyllic alteration (silicification, chloritization, and slight pyritization) is common near intrusions such as unit Eids. Unit Evbn includes the oldest date in the map area (42.51 ± 0.11 Ma at age site GD17 near the western map edge).

Volcanoclastic deposits (late to middle Eocene)—Basaltic andesite to andesite volcanoclastic deposits, variably weathered; including: (1) lithic vitric pyroclastic flow deposits with mostly angular to subangular blocks up to 10 cm in size, moderately to poorly sorted, massive to thick-bedded, mostly matrix-supported, mostly welded, devitrified, ranging from block and ash to lapilli-ash to ash tuff; (2) massive boulder diamict with varied amounts of matrix and bedding, unbedded to subangular; locally in fluvial-sungay, mud matrix-supported, and graded beds; interpreted as lahars; (3) volcanic-lithic sandstone, clay-rich to clay-fine, planar and graded, very thin to thick-bedded, moderately sorted, immature, locally tuffaceous with minor angular lapilli and detrital ash; (4) sandy, subrounded, rounded-pebble conglomerate; (5) rare fine-meter-wide channel fills of coarse, granular, and poorly sorted sandstone; (6) other isolated features including tuff breccias, gradually bedded clastic sediments, scour surfaces, and paleosols.

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GEOLOGIC SYMBOLS

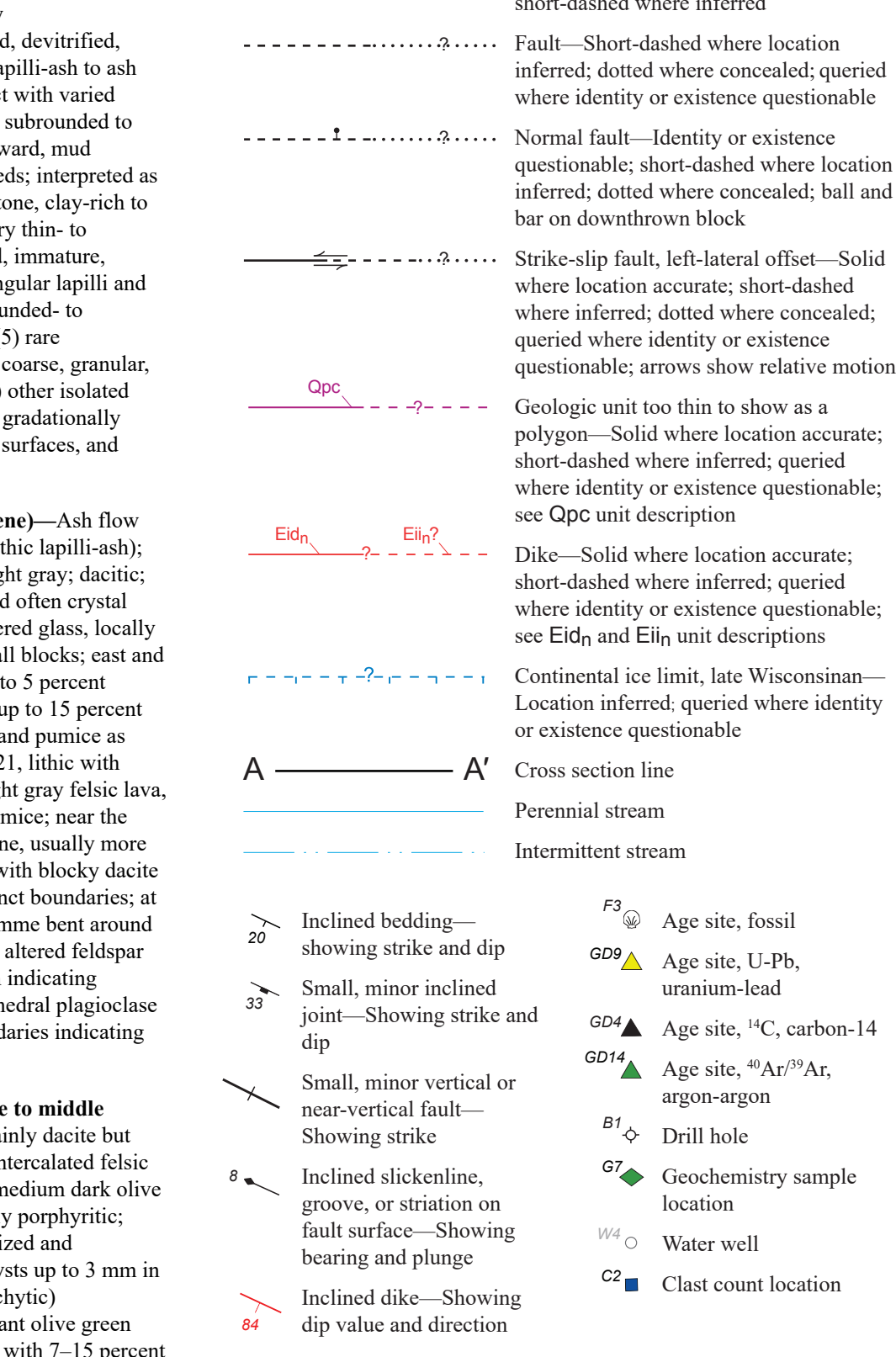


Figure M1B: Two-dimensional potential-fields forward models along profile X–X'. Both models fit anomalies equally well. Units and properties shown in the table predict gravitational and magnetic

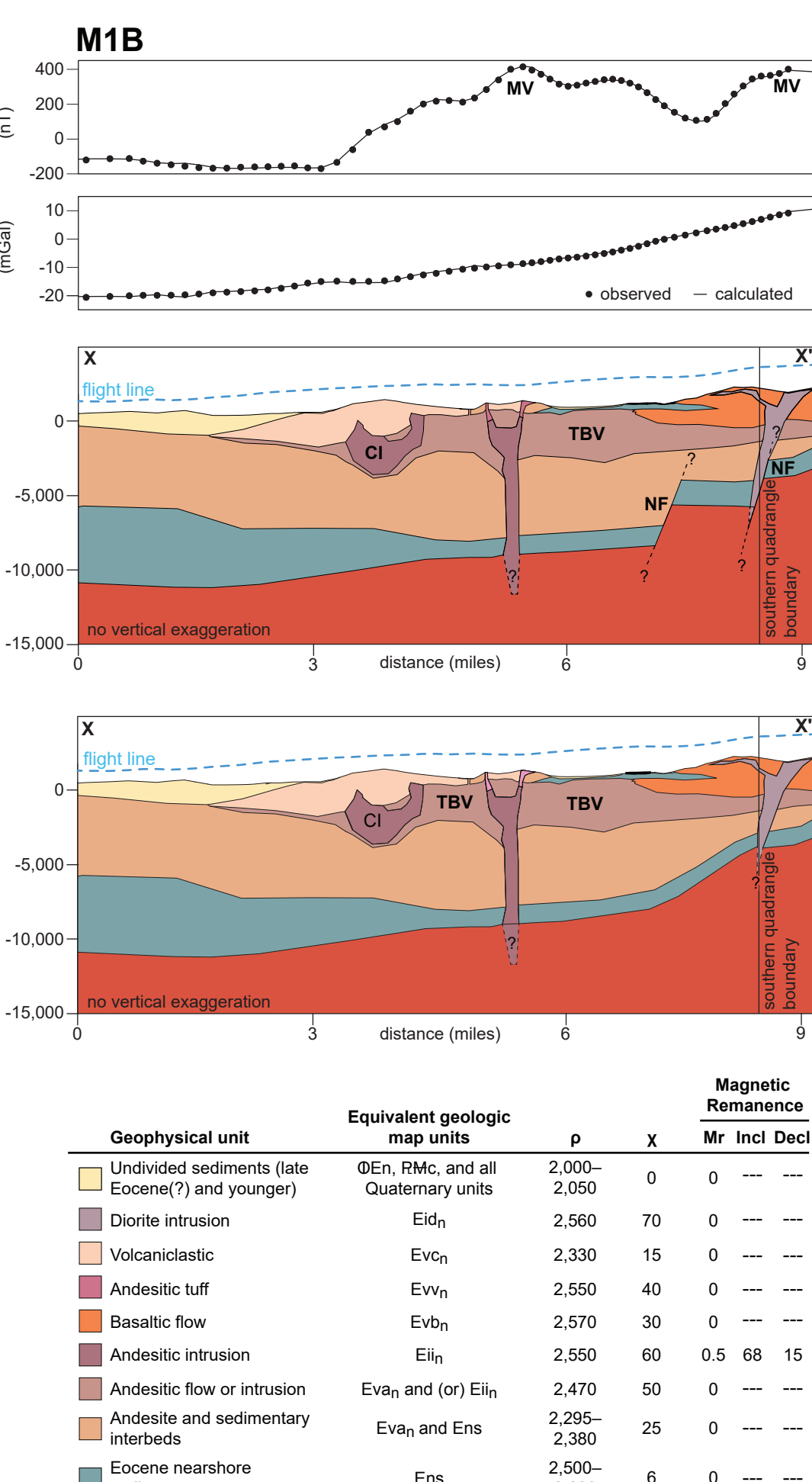


Figure M1B. Two-dimensional potential-fields forward models along profile X–X'. Both models fit anomalies equally well. Units and properties shown in the table predict gravitational and magnetic