Geologic Map of the Adna 7.5-minute Quadrangle, Lewis County, Washington

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ABSTRACT

New 1:24,000-scale geologic mapping of the Adna quadrangle in southwest Washington focuses on improving geologic understanding of natural hazards that may pose a risk to people and infrastructure, including a proposed flood-retention structure near Pe Ell. Potential hazards include: (1) landslides due to ground instability and (2) seismicity associated with the Doty–Salzer Creek fault system.

New mapping and geophysical data refine previous work by characterizing geologic structures in greater detail, refining fault locations, and updating structural interpretations. West- and northwest-striking oblique reverse faults in the quadrangle may be capable of producing damaging earthquakes. Newly acquired gravity and ground-magnetic geophysical data constrain the locations of fault strands and strongly support 4,000 to 6,000 ft of structural relief on the Lincoln Creek uplift in the north-central map area.

Radiometric dating (U-Pb) of detrital zircons refines the stratigraphic framework for southwest Washington. Analyses reveal new maximum depositional ages for the Lincoln Creek Formation (<30.4 ±5.2 Ma), the Astoria(?) Formation (<14.8 ±3.5 Ma and <15.3 ±1.7 Ma), the Wilkes Formation (<6.2 ±1.0 Ma, <13.4 ±1.0 Ma, and <13.6 ±1.9 Ma), and the Logan Hill Formation (<1.6 ±0.5 Ma). U-Pb age spectra of detrital zircons identify marine rocks as the Eocene McIntosh Formation (<40.5 ±3.6 Ma and <38.5 ±4.2 Ma).

GEOLOGIC SYMBOLS

Mass-wasting landforms (overlay pattern)—Landforms that suggest mass movement on unstable slopes, but evidence for landslide deposits is inconclusive.

Contact—Solid where location accurate; long-dashed where approximate; short-dashed where inferred; dotted where concealed; queried where identity or existence questionable

Gradational contact—Location accurate; queried where identity or existence questionable

Fault, unknown offset—Short-dashed where approximate; dotted where concealed; queried where identity or existence questionable

Reverse fault—Long-dashed where approximate; dotted where concealed; queried where identity or existence questionable

Oblique-slip fault, reverse left-lateral offset—Solid where location accurate; short-dashed where inferred; dotted where concealed; queried where identity or existence questionable; relative motion shown by arrows; rectangles on upthrown block

High-angle dip-slip fault—Short-dashed where inferred; dotted where concealed; relative vertical motion shown by U and D; queried where identity or existence questionable

Oblique-slip fault, high-angle right-lateral offset—Long-dashed where approximate; short-dashed where inferred; dotted where concealed; relative horizontal motion shown by arrows, relative vertical motion shown by U and D; queried where identity or existence questionable

Oblique-slip fault, high-angle left-lateral offset—Long-dashed where approximate; dotted where concealed; relative horizontal motion shown by arrows, relative vertical motion shown by U and D; queried where identity or existence questionable

Anticline—Long-dashed where approximate; short-dashed where inferred; dotted where concealed; queried where identity or existence questionable; arrow on line indicates plunge direction

Syncline—Long-dashed where approximate; short-dashed where inferred; dotted where concealed; queried where identity or existence questionable; arrow on line indicates plunge direction

Monocline, synclinal bend—Short-dashed where inferred; dotted where concealed; arrow on line indicates direction of dip; shorter arrow on steeper limb; queried where identity or existence questionable

Monocline, anticlinal bend—Short-dashed where inferred; dotted where concealed; arrows show direction of dip; shorter arrow on steeper limb; queried where identity or existence questionable

A — A′ Cross section line

Perennial stream

Intermittent stream

Fluvial terrace—Solid where location accurate; short-dashed where inferred; hachures point down slope

Scarp of unknown origin—Identity or existence certain, location accurate; hachures point down slope

Inclined bedding—Showing strike and dip; **black symbols** indicate data collected by Washington Geological Survey (WGS); **red symbols** indicate data compiled from Snavely and others (1958)

Approximate orientation of inclined bedding in unconsolidated deposits or bedrock—Showing approximate strike and dip; **black symbols** indicate surface data collected by WGS; **blue symbols** indicate subsurface data compiled or derived from mining records

Inclined bedding, where top of beds is known from local features—Showing strike and dip

Small, minor inclined joint—Showing strike and dip

Inclined flow banding, lamination, layering, or foliation in igneous rock—Showing strike and dip

Shear—Showing strike and dip

Spring—Line angle indicates downslope direction

Age site, fossil

Age site, U-Pb, uranium-lead

Geochemistry sample location

Water well

Significant site

Geologic unit too small to show as a polygon at map scale

Drill hole for hydrocarbon exploration

Drill hole or test pit

Clast count sample

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Lambert conformal conic projection
North American Datum of 1927, to place on North American Datum of 1983, move the projection lines approximately 23 meters north and 96 meters east as shown by crosshair on neatline
Base map from scanned and rectified U.S. Geological Survey Adna 7.5-minute quadrangle, 1986, revised 1993
Shaded relief generated from a lidar bare-earth digital elevation model (DEM) produced by the Washington Geological Survey. http://lidarportal.dnr.wa.gov/
GIS by Andrew Sadowski and Rebeca Becerra
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SCALE 1:24,000

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INTRODUCTION

The Adna 7.5-minute quadrangle is located in Lewis County, Washington, west of Centralia and Chehalis and within the southwest Washington coast range between the Willapa Hills, Black Hills, and Doty Hills. Uplands in the map area—the Lincoln Creek uplift of Snavely and others (1958)—contain widespread and actively managed timber resources. The lowlands of the Chehalis Basin are developed for residential and agricultural uses. The Chehalis River flows east through the map area and north into the Puget Lowland. Undeveloped energy resources include small coal deposits ranked from lignite to subbituminous C. Snavely and others, 1958) and small natural gas shows from several oil and gas exploration wells drilled from 1926 to 1972. Columbia River Basalt was mined in a few small, inactive quarries in the southern half of the Adna quadrangle.

The primary purpose of this study is to assess the Doty fault and associated geologic structures that may pose a seismic hazard to a proposed flood-retention structure near Pe Ell, about 5 mi to the southwest of the quadrangle. This work supplements recent investigations by Anderson and others (2018) and Lau and others (2018). This mapping will also assist with landslide hazard assessment, forestry, and mining.

We report results for more than 200 samples processed for clast counts (24 sites, Table DS5), biostratigraphic age constraints from macrofossils and microfossils (53 sites, Table DS2), major and trace-element geochemistry (57 sites, Table DS3A-B), U-Pb analyses of detrital zircons (10 sites, Table M1, Table DS4), and petrographic thin sections (75 sites). We define and interpret structural interpretations in or near the map area (Pease and Hoover, 1957; Snavely and others, 1958; Sadowski and others, 2018), and present significant modifications to the locations, extents, fault displacements, and dip directions of major structures.

GEOLOGIC OVERVIEW

The map area is located where the Puget Lowland meets the Willapa Hills in the forearc of the Cascadia subduction zone, which has repeatedly produced large-magnitude earthquakes in southwest Washington (Clague, 1997). The Cascadia forearc has been experiencing ongoing oblique shortening, which includes counterclockwise rotation (Wells and McCaffrey, 2013) and north–south shortening (Wells and others, 1998). Deformation is accommodated by west- and northwest-striking faults and folds with kilometer-to-decade-scale lengths (Bowman and Czajkowski, 2019).

Basin-bounding faults—the Doty and Scammon Creek faults—flank the Lincoln Creek uplift in the map area. The faults also interact with other faults within and outside the map area—the Salzer Creek and Kopiah faults, respectively. The Chehalis River and Centralia synclines flank the faults and have been folded and locally overturned by the uplift. Mapped Eocene and Oligocene units are as much as 3,000 ft thick in the Chehalis River syncline. Uplift may have continued until at least the late Miocene. Alternately, the two blind reverse faults could dip south and sole into a low-angle thrust (décollement) and not the Doty fault. Either scenario may satisfy geophysical modeling constraints.

GEOPHYSICS

Potential fields geophysics—gravity and magnetics—reveal zones of variation in density or magnetic properties, respectively. New potential fields geophysical data were collected using a LaCoste Romberg model G-908 gravimeter and a G-859 Cesium vapor portable magnetometer. Data resolution are ~1.2 km (2,000 ft)-spaced traverses with profile lines at 250 m (820 ft) spacing. A horizontal-gradient filter applied to the isostatic gravity grid helps identify gravitational gradients, commonly associated with structures. Short wavelength gradients may imply lateral changes in density. For example, high-amplitude gradients may indicate the presence of a fault juxtaposing two rocks of different densities. Conversely, broad, low-amplitude gradients may imply lateral changes in density that are more gradational, such as a fault zone rather than a single continuous fault.

In southwest Washington, gravity highs generally represent high-density Crescent Formation basalt exposed at or near the surface. The Lincoln Creek uplift (LCU in Fig. M1A) is a gravity high in the northern half of the quadrangle. Gravity lows result from deeper Crescent basalts overlain by thick, low-density sediment. A northwest-trending gravity low known as the Rochester basin (RB in Fig. M1A), which is northeast of the Lincoln Creek uplift and is bounded by gravity gradients associated with the Kopiah and Scammon Creek faults. Another significant gravity low known as the Chehalis basin (CBn in Fig. M1A) is south of the Doty fault. This low extends laterally to the southeast and west of the Adna quadrangle, and is co-located with the Chehalis River syncline.

Geophysical gradients calculated from newly collected potential fields data aid location and characterization of the Doty, Scammon Creek, and Lincoln Creek faults and associated smaller, transverse faults (Anderson and others, 2018; Lau and others, 2018)(Fig. M1B). The strongest and widest gravity gradient trends westward through and beyond the map area and is spatially correlated with the mapped location of the Doty fault (DF in Fig. M1A). Gravity change across this gradient indicates a relative north-side-up motion. The strength of the gradient indicates large vertical separation along the fault, and its width may suggest a fault zone rather than a single continuous fault.

A subtle gravity gradient is associated with the Salzer Creek fault, which suggests the fault is a subsidiary strand in the Doty fault zone, with much less vertical offset in the map area. A northeast-trending gravity gradient associated with the Scammon Creek fault (SCF in Fig. M1A) extends from the Doty fault to the Rochester fault (RF in Fig. M1A). We infer a steep, east-dipping, reverse-fault-dominated zone from north to south, this continuous, steep gradient splits into two gradients near the northern map boundary, indicating separate fault strands, each with significant offset. We separate the previously unmapped northern strand and formally name it the Lincoln Creek fault. Isostatic gravity indicates the presence of multiple, subtle northeast-trending gradients within the Lincoln Creek uplift (LCU in Fig. M1A), that align with mapped transverse faults.

Offset of the Crescent Formation as inferred from geologic and modeled geophysical cross sections suggests slips of about 4,000 and 1,000 ft for the Doty and Salzer Creek faults, respectively (Anderson and others, 2018; Lau and others, 2018). Similarly, estimates for slip on the Scammon and Lincoln Creek faults are about 2,000 and 1,500 ft, respectively. Preliminary modeling also strongly suggests variations in the thickness of concealed Miocene strata, as well as deformation of these strata, particularly the Wilkes Formation and underlying GRB. Modeling shows an increase in thickness of strata from south to north within the Chehalis River syncline. Paleogeography does not explain such a large change in thickness—recursion is a more likely explanation. Accordingly, three concealed folds are inferred solely from geophysical data to the south of the Doty fault, and we speculate that these three concealed folds were produced by concealed, south-verging splay faults associated with the Doty fault. The development of accommodation space in the Miocene may have permitted the development of growth strata in the footwall of the Doty fault.

STRUCTURES

The Lincoln Creek uplift is the largest structural feature in the map area. The uplift has older rocks in its core and is bounded by faults with large displacements near laterally extensive folds. Faults in the Adna quadrangle fit into a regional-scale pattern (Bowman and Czajkowski, 2019; Wells and others, 2017) of west- and northwest-striking faults, where west-striking faults accommodate north–south compression with possible oblique slip, and northwest-striking faults accommodate dextral reverse slip in the modern stress regime.

The Doty and Scammon Creek faults are two large displacement, west- or northwest-striking, high-angle, reverse faults with components of inferred sinistral or dextral oblique slip, respectively. These faults juxtapose the Lincoln Creek uplift and produce the structural high. The Salzer Creek and Lincoln Creek faults are subparallel and synthetic to uplift-flanking faults. New, higher-resolution geophysical data in this report correct the dip direction of the Salzer Creek fault of Sadowski and others (2018) to be north-dipping. The Salzer Creek fault has only about a quarter of the displacement of the Doty fault, whereas the Lincoln Creek fault has displacement equivalent to the Scammon Creek fault. Geophysical evidence from gravity data suggests a ~1.5 mi-wide step between dextral reverse faults, where deformation may have transferred from the Lincoln Creek fault to the Scammon Creek fault. This deformation may have produced a zone of progressively shallower uplifted basement to the southwest, in the configuration of a flower structure.

Within the uplift, smaller north–northeast-striking, steeply(?) dipping reverse faults with oblique slip—inferred from field relationships and geophysical modeling—may terminate against larger faults. Displacement on transverse faults is inferred to be minimal (<1,000 ft) based on patterns of map units. The Spoonebergh Creek fault was modified from Snavely and others (1958), who mapped the fault without naming it, and is identified by offset along the upper contact of Skookumchuck Formation across Spoonebergh Creek. This transverse fault has northwest-up offset (Polenz and others, 2019) with sinistral(?) oblique slip. Transverse faults tend to align with similarly oriented dolomite gypsum veins within the uplift.

Two laterally extensive pairs of folds are sub-parallel to uplift-bounding faults. The Doty fault parallels a west-trending monocline identified from seismic reflection profiles (W. Stephenson, USGS, written commun., 2017) and the west-plunging Chehalis River syncline. The Scammon Creek fault parallels the southern-plunging Chehalis anticline and the west-plunging Centralia syncline, which decreases in plunge to the northwest. The Chehalis River and Centralia synclines are broad footwall synclines, suggesting that these folds—and their anticlinal neighbors in their respective hanging walls—are fault-related folds. Thickened Miocene strata in the Chehalis River syncline suggest that folding may have contributed to the development of accommodation space generated by larger faults.

MODERN ACTIVITY

The lack of recorded seismicity along structures in the map area from the Pacific Northwest Seismic Network documents modern inactivity. Evidence favoring recent activity is inconclusive and relies on numerous assumptions of uncertain origin within landslides. These escarpments may be related to mass-wasting events or faulting. Trenching at one site suggests that fault activity is neither inferred nor ruled out. Paleoseismic trenching at a significant site (S2) across an escarpment in Miocene(?) rocks is recommended to evaluate activity and amount of slip on the Doty fault.

The timing of the Lincoln Creek uplift—and with it the activity on the Doty fault—is based on a U-Pb age (site G29) and geophysically inferred thickness variations of the Wilkes Formation on the north limb of the Chehalis River syncline. Uplift may have continued until at least the late Miocene. Alternately, the two blind reverse faults could dip south and sole into a low-angle thrust (décollement) and not the Doty fault. Either scenario may satisfy geophysical modeling constraints.

DESCRIPTION OF MAP UNITS

Quaternary

HOLOCENE TO PLEISTOCENE NONGLACIAL DEPOSITS

af — **Artificial fill**—Rubble of cobbles, pebbles, sand, and boulders in varied amounts and rock types (mostly basalt); poorly sorted and unconsolidated; used for raising roadbeds, trails, railroads, and other infrastructure.

ms — **Modified land**—Rubble of cobbles, pebbles, sand, and boulders in varied amounts and rock types; locally sourced but redistributed to modify topography; includes some industrial, agricultural, and residential zones; excludes local roads, individual homes, golf courses, farms, and harvested timber lands. Also excludes some pits where underlying units can be readily identified; fill areas appear minor, excavation exposes the same unit as the surrounding surface, or exposure of underlying units was deemed likely to be permanent. Mapping of alluvial and glacial Quaternary units takes priority over delineating modified land.

Qls — **Landslide deposits**—Diamicton; colors vary from light to medium brown with shades of gray; weathering is variable, generally moderate; unsorted; poorly compacted; angular to rounded sand, silt, clay, cobbles, pebbles, and diamicton formed as a result of slope failure of bedrock; unsorted and chaotically mixed; no internal structure; unit thicknesses vary and can range in the tens of feet. These deposits can be identified by their hummocky topography, cracks, wet seeps, and curvilinear bare spots. Landslides and landslide complexes are widespread along hillslopes north of the Doty fault, within the Lincoln Creek uplift. A mass-wasting overlay is used to delineate more ambiguous landforms with landslide-like characteristics. More than 350 landslides cover 23% of the map area, and approximately 30% of the map area exhibits some degree of ground instability, including mass wasting. This instability is probably due to unit E_{Tmq} being weathered or poorly cemented, or because adit in that unit has altered to clay. Absence of mapped landslides or mass wasting features does not imply stability, the absence of a hazard, nor the absence of a landslide deposit. The age, timing, and re-activation of these features are unknown, and the level of activity should be evaluated on a site-by-site basis with field visits by a professional geologist.

Qp — **Peat**—Organic and organic-rich sediment; includes peat, gyttja, muck, silt, and clay; typically in closed depressions, shapes in wetland areas and distinctly flat-bottomed depressions; also mapped on the basis of spectral analysis of Landsat data and (or) evaluation of infrared and color aerial photos. The thickness of most peat deposits is largely unassessed and unknown. Peat deposits are more common near and along the northern tributaries to the Chehalis River, typically occupying former channels of the ancestral Chehalis River.

Qa — **Alluvium**—Stream channel deposits, flood plains, and older terrace deposits; pebbles, cobbles, sand, silt, clay, peat, and boulders in various amounts along stream channels and on flood plains; color ranges from light to medium brown to shades of gray, depending on the amount and source of fine-grained material; fresh to lightly weathered except where streams have incorporated older deposits, resulting in a blended weathering distribution; not compacted and not cemented; typically well rounded and moderately to well sorted; lithology of the clasts varies based on the deposits the stream flows through; clasts are primarily extrusive volcanic rocks, metamorphic rocks, chert, and granite; alluvium is 50 to 80 ft thick based on well logs (wells W6, W7, W18, W22, W24, and W26) and an interpreted seismic reflection profile along Doty Creek Road (W. Stephenson, USGS, written commun., 2018). Mapped as small Qa where the youngest, lowest-lying alluvium is not distinguishable from older alluvial terraces (G–I). Alluvial terraces are not mapped where more than 5 ft above the younger alluvial surface. Ages are roughly constrained to Quaternary.

Qaf — **Alluvial fan**—Sand, silt, clay, pebbles, and cobbles in varied amounts; gray to brown; loose; subangular to rounded; moderately to poorly sorted; stratified to unstratified; commonly derived largely from sedimentary bedrock. Most instances of the unit are inferred from distinctive lobate landforms with steeper topographic gradients than the surrounding terrain; typically composed of alluvium.

PLEISTOCENE TO PLIOCENE GLACIAL SEDIMENTS

The Puget lobe of the cordilleran ice sheet extended southward to within a few miles of the northern edge of the map area during the Vashon Stade of the late Wisconsinan Fraser Glaciation. Outwash deposits (unit Qgopg) from this and earlier glaciations contain appreciable percentages of intrusive igneous and metamorphic rocks (termed "northern-sourced" drift). Farther south, at elevations above Vashon deposits, glacial sediments exhibit severe weathering and clast compositions containing abundant percentages of andesite from the Cascade Range ("Cascade-sourced" drift)(Table DS1). These deposits therefore likely represent pre-Vashon drift interpreted as outwash from earlier alpine glaciation(s) in the Cascade Range (unit Qapog).

Continental Drift

Qgopg — **Vashon recessional outwash, gravel**—Cascade- and northern-sourced, sandy to silty, pebble to cobble gravel; medium to dark gray, medium to light brown, and maroon where iron stained; highly weathered; moderately compact; weakly to moderately cemented; poorly sorted; clasts of cobble- to pebble-sized clasts in a medium- to coarse-grained sand matrix; well rounded to subrounded; moderately sorted; lithic clasts are a diverse mix of outwash primarily from the Cascade Range, with lesser amounts of northern-sourced clasts, including about 40% intermediate to felsic extrusive rocks, 26% intermediate to felsic intrusive rocks, 12% mafic igneous rocks, 12% metamorphic rocks, 10% quartz, and rare chert. Well data in Fords Prairie suggests unit thicknesses of 20 to 44 ft (well W28). The unit flatly covers Fords Prairie. A subtle, fan-shaped topographic pattern north of the Chehalis River was used to delineate the outwash deposit. The southern maximum ice extent of the Puget lobe is mapped in the adjacent quadrangles to the north and northeast (Polenz and others, 2017; 2018; 2019). Sand and gravel deposits from this glaciation record recessional outwash from the southernmost extent of the Vashon ice advance.

Alpine Drift

Qapog — **Logan Hill Formation (Pleistocene)**—Pre-Vashon, Cascade-sourced, alpine glacial outwash of volcanic cobbles and pebbles in a matrix of sandy, silty clay; multicolored, reddish brown, medium light brown, and purplish light gray to medium gray; moderately to severely weathered and rotten; crumbles easily; easy to scrape or cut with a knife; poorly to moderately compacted, poorly indurated, poorly cemented; pebble- to cobble-sized clasts in a cohesive, clayified, sandy to silty matrix; clasts are rounded to subrounded with oblate to equant shapes; generally matrix-supported; local clast supported; moderately to poorly sorted; structureless, unstratified; clasts generally include <50% intermediate to felsic volcanic rocks, 25% mafic igneous rocks, ~20% metamorphic rocks, and 5% or more quartz and chert; unit includes sand-sized grains that are generally quartz rich and mica poor; unit thickness varies from about 15 ft thick south of the Doty fault, to about 55 ft thick in the central map area on the east flank of the uplift, to 90 ft thick on Cook Hill, and to less than 100 ft thick on the south side of Michigan Hill in the northern map area (wells W25, W26); deposits are restricted to a few elevated terraces—between 330 ft and 520 ft elevation—south of the Doty fault and on Cook and Michigan Hills, where they unconformably mantle bedrock topography. The sorting and grain size of the unit suggest it was deposited in a braided channel paleoenvironment. The basal contact of the Logan Hill Formation is commonly concealed by landslide deposits, suggesting that the base of this highly weathered, clayified rock unit forms a favorable slide plane for mass transport (Sadowski and others, 2018). On the northwestern edge of Cook Hill, a petrified tree was excavated circa 2010(?) at significant site S1 (P. Pringle, Centralia College, written commun., 2019) from either Miocene or Pleistocene rocks. A 30°N dip of bedding at this site represents either rapid Pleistocene deformation or tilted Miocene stratigraphy with a thin veneer of Logan Hill Formation. The latter explanation is preferred because site photos show gravel above sandstone in excavation. Age is roughly Pleistocene based on the youngest population of zircons (U-Pb site GD10), and unit has age spectra similar to age spectra for Miocene deposits, which suggests reworking. Unit is best exposed at clast count sites C7, C8, C12, C13, C16/G2010, C17, and C22.

Qapog — **Logan Hill Formation (Pliocene)**—Pre-Vashon, Cascade-sourced, alpine glacial outwash of volcanic cobbles and pebbles in a matrix of sandy, silty clay; multicolored, reddish brown, medium light brown, and purplish light gray to medium gray; moderately to severely weathered and rotten; crumbles easily; easy to scrape or cut with a knife; poorly to moderately compacted, poorly indurated, poorly cemented; pebble- to cobble-sized clasts in a cohesive, clayified, sandy to silty matrix; clasts are rounded to subrounded with oblate to equant shapes; generally matrix-supported; local clast supported; moderately to poorly sorted; structureless, unstratified; clasts generally include <50% intermediate to felsic volcanic rocks, 25% mafic igneous rocks, ~20% metamorphic rocks, and 5% or more quartz and chert; unit includes sand-sized grains that are generally quartz rich and mica poor; unit thickness varies from about 15 ft thick south of the Doty fault, to about 55 ft thick in the central map area on the east flank of the uplift, to 90 ft thick on Cook Hill, and to less than 100 ft thick on the south side of Michigan Hill in the northern map area (wells W25, W26); deposits are restricted to a few elevated terraces—between 330 ft and 520 ft elevation—south of the Doty fault and on Cook and Michigan Hills, where they unconformably mantle bedrock topography. The sorting and grain size of the unit suggest it was deposited in a braided channel paleoenvironment. The basal contact of the Logan Hill Formation is commonly concealed by landslide deposits, suggesting that the base of this highly weathered, clayified rock unit forms a favorable slide plane for mass transport (Sadowski and others, 2018). On the northwestern edge of Cook Hill, a petrified tree was excavated circa 2010(?) at significant site S1 (P. Pringle, Centralia College, written commun., 2019) from either Miocene or Pleistocene rocks. A 30°N dip of bedding at this site represents either rapid Pleistocene deformation or tilted Miocene stratigraphy with a thin veneer of Logan Hill Formation. The latter explanation is preferred because site photos show gravel above sandstone in excavation. Age is roughly Pleistocene based on the youngest population of zircons (U-Pb site GD10), and unit has age spectra similar to age spectra for Miocene deposits, which suggests reworking. Unit is best exposed at clast count sites C7, C8, C12, C13, C16/G2010, C17, and C22.

Tertiary Volcanic and Sedimentary Bedrock

Evidence of submarine eruption and subsequent accretion of the Siletzia terrane is not recorded at the surface in the map area. Rocks of the Crescent Formation that represent the Siletzia terrane are geochemically identified below ~2,000 ft depth in the Seifert No.1 Well (HC5) within the Lincoln Creek uplift. Eocene deposition of marine sediments related to the McIntosh Formation mudstones may interfudge (Pease and Hoover, 1957) or be otherwise unconformable with Crescent Formation basalts at about 50 Ma to 42 Ma (Wells and others, 2014). U-Pb analyses of detrital zircons in the footwall of the Doty fault were able to identify the McIntosh Formation by the dearth of Proterozoic zircons, whereas younger units have a clear Proterozoic signal.

Post-McIntosh deposition of the Skookumchuck sandstone suggests that the depositional environment gradually changed from offshore marine to nearshore deltaic in the middle to late Eocene. The depositional environment changed again around the earliest Oligocene, from deltaic to marine as reflected by the Cascade-derived sediments related to the Lincoln Creek Formation.

Miocene rocks in the map area reflect a regional transition from marine to terrestrial depositional environment around 14–16 Ma. Prior to this age, marine rocks of the Astoria(?) Formation were deposited in the Chehalis basin until the terrestrial eruptions of the Columbia River Basalt Group (CRBG). The Grande Ronde Basalt (GRB) is the most voluminous CRBG unit, with an eruptive volume of 150,100 km^3 (72.3% of the total volume of the CRBG)(Reidel, 2015). The GRB contains members that can be differentiated based on whole-rock and trace-element geochemistry. The depositional environment is inferred to be continental, with subaerial fluvial deposition of the Wilkes Formation in the map area following emplacement of the CRBG.

Em_{sc} — **McIntosh Formation (middle Eocene)**—Lithic-rich mudstone to sandstone; dark greenish gray where fresh to dark olive brown where weathered; moderately weathered; moderately to strongly compacted; moderately indurated; moderately to well cemented; clay granules to silt and clay; rounded to subangular; moderately to poorly sorted; structureless with spheroidal weathering to very thickly bedded with interbedded mudstone and sandstone; fossiliferous with macrofossils and microfossils (Table DS2); diagenetically rich in lithic fragments composed primarily of basalt, otherwise tuffaceous(?) with minimal mica; thickness ~3,500 ft but may be greater outside map area; crops out irregularly at the lowest stratigraphic and structural intervals in core of uplift and within a major anticline; probable depositional environment; gradational contact with overlying Skookumchuck Formation commonly obscured by landslides; middle Eocene or younger based on maximum depositional age (youngest single zircon grain for detrital sample)(U-Pb sites GD1 and GD2); matches description of lower McIntosh Formation mudstones mapped by Payne (1998); best exposed at sites GD1, GD2, GD26, GD6, and G56.

E_{Tu} — **Volcanic rocks of the Crescent Formation (Eocene)(cross section only)**—Aphanitic basalt to andesite; dark gray to dark forest green; fresh and observed from core numbers 18 and 21 recovered from Siletzia Well 1 (well HC5); at a 3,142–3,148 ft depth (G41); and 3,000–3,007 ft depth (G47), respectively; dense, hard, crystalline rock with soft pockets of soft green chlorite or serpentine-consult(?) material; aphyric to medium grained; euhedral. The two recovered well samples (sites G45 and G47) classify as tholeiitic basalts (47.6–48.1 wt.% SiO_2, 7.3–7.5 wt.% MgO). Both samples show close compositional similarities to Crescent Formation basalts analyzed during recent mapping (Contreras and others, 2012; Polenz and others, 2012a, 2012b; 2014, 2017) and differ mainly in being slightly more primitive and having notably higher Ba (235–294 ppm vs. 12–176 ppm). Basal contact is not exposed and unit thickness is unconstrained. Contact relationship with McIntosh Formation could be invasive, interfingering, or unconformable. The unit is identified in Seifert No. 1 cores deeper than 3,140 ft.

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Table M1. Summary of U-Pb ages from the Adna quadrangle. The reported age for each U-Pb sample is from the single, youngest grain. See Data Repository for detailed analytical results and stratigraphic ages.

Sample	Unit symbol	Longitude / Latitude	Result
GD1	E_{Tmu}	−123.063075, 46.714199	<40.5 ±3.6 Ma
GD2	E_{Tmu}	−123.110988, 46.709556	<38.5 ±4.2 Ma
G23	E_{Tmu}	−123.116469, 46.571725	<30.4 ±5.2 Ma
G26	E_{Tmu}	−123.098804, 46.576417	<20.6 ±1.2 Ma
G45	E_{Tmu}	−123.098160, 46.622645	<14.8 ±3.5 Ma
G47	E_{Tmu}	−123.063137, 46.744856	<15.3 ±1.7 Ma
G7	Mm_{sp}	−123.113564, 46.638206	<13.6 ±1.9 Ma
G28	Mm_{sp}	−123.097538, 46.653895	<13.4 ±1.0 Ma
G29