FINAL TECHNICAL REPORT

PALEOSEISMOLOGY OF THE MOUNT ANGEL FAULT IN THE WILLAMETTE VALLEY, OREGON: COLLABORATIVE RESEARCH WITH WILLIAM LETTIS & ASSOCIATES, INC. AND THE OREGON DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES

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ABSTRACT

The 1993 M_L 5.7 Scotts Mills earthquake, the most damaging earthquake in Oregon's history, revealed one of several shallow crustal faults in the northern Willamette Valley of Oregon that threaten the Portland Metropolitan region. The Mount Angel fault (MAF), the likely source of the Scotts Mills earthquake, is a 17-km-long northwest-striking northeast-dipping fault zone that accommodates dextral oblique reverse slip (Madin et al., 1993; Thomas et al., 1996). Probabilistic seismic hazard models (Petersen et al., 2008) consider the Mount Angel fault to be part of the larger Gales Creek-Mount Angel fault zone, capable of producing a M_w 6.8 earthquake. Previous studies (Wang et al., 2003) imaged offset late Pleistocene Linn Gravels in shear-wave velocity profiles in the near subsurface and identified earthquake-related deformation in Missoula flood deposits coincident with the fault. This study was designed to validate observations by Wang et al. (2003) and establish a paleoseismic history of the Mount Angel fault.

During this study we conducted a multidisciplinary geologic and geophysical investigation of the Mount Angel fault that included site specific investigations at the Dominic and Miller Road sites (Wang et al., 2003) and Quaternary geologic/geomorphic mapping using 'bare earth' LiDAR data. Despite reasonable evidence for near surface deformation from previous investigations, no compelling paleoseismic targets were identified at either site. Structure contour maps and geologic cross sections developed along the fault indicate a structural high where bedrock and Pleistocene gravels are preserved northeast of the fault in the hanging wall confirming previous observations (Hampton, 1972). Geologic cross sections spanning the fault suggest that the Mount Angel fault vertically displaces these gravels by as much as 20 to 61 m (65 to 200 ft)

Detailed Quaternary geologic/geomorphic mapping using LiDAR data revealed several pre-and post-Missoula flood (12-22 Ka) surfaces preserved on either side the of Mount Angel fault, however there is little sign of recent surface rupture where flood-related fill terraces (Qt2) cross the surface projection of the fault. The overall lack of post-flood tectonic geomorphology indicates the fault has likely not produced surface fault rupture since the Missoula floods (12-22 Ka) despite 1) seismicity associated with

the Mount Angel fault; and 2) inferred displacements of Pleistocene sedimentary and Tertiary bedrock units. The lack of geomorphic evidence for surface fault rupture indicates that the fault has not accumulated enough strain to produce a large surface-rupturing earthquake since deposition of Missoula flood deposits. Alternatively, the lack of surface expression along the fault may indicate that the fault is blind and does not reach the surface or has a complex geometry near the surface that may leave little surficial evidence of large surface rupturing events.

The vertical-slip rate on the Mount Angel fault remains poorly constrained. Slip-rate estimates from offset Eocene to Miocene bedrock units and Pliocene to early Pleistocene units are low (<0.01 to 0.03 mm/yr). Maximum rates calculated from middle to late Pleistocene gravel units have considerable uncertainty, but are significantly higher (e.g. 0.1 to >1.0 mm/yr). The highest estimates are unreasonable based on the surficial geomorphology. These vertical slip-rates hinge on the correlation of gravels across the fault and the poorly constrained gravel ages. Future studies should focus on improving the age constraints and correlation of these gravels to improve late Quaternary vertical slip-rate estimates on the Mount Angel fault.

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1.0 INTRODUCTION

The 1993 Scotts Mills Earthquake (M_L 5.7) demonstrated that shallow crustal faults in the northern Willamette Valley pose a considerable seismic hazard to the greater Portland metropolitan region (Figure 1). The earthquake, the most costly earthquake in Oregon's history, caused over 30 million dollars of damage (Madin et al., 1993; Wong et al., 2000). Analyses of aftershock hypocentral locations and focal mechanisms suggest that the Scotts Mills earthquake was produced by right-lateral, oblique reverse slip on the northwest-striking Mount Angel fault (Madin et al., 1993; Thomas et al., 1996). Previous workers (Werner et al., 1992; Liberty et al., 1999; Pratt et al. 2001; Liberty et al., 2003; Wang et al., 2003) have shown that the Mount Angel fault and other northwest-striking faults in the region are Quaternary active and represent a significant seismic hazard to growing population centers and urban expansion in the northern Willamette Valley (Petersen et al., 2008; Wong et al., 2000). Information on the earthquake recurrence intervals on these faults is crucial for improving ground shaking and seismic hazard maps for the Northern Willamette Valley (Figure 1).

Previous subsurface and geophysical studies have established that the Mount Angel fault zone offsets Tertiary bedrock and late Pleistocene Linn Gravels (Werner et al., 1992; Liberty et al., 1999; Tolan et al., 1999; Wang et al., 2003; Yeats et al., 1996) (Figure 2). However, the late Quaternary expression of the fault has been obscured by repeated catastrophic floods from glacial lake Missoula that often bury and obscure preexisting geomorphology (Waitt Jr, 1985; O'Connor et al., 2000; Benito and O'Connor, 2003). To date, no studies have documented definitive surface fault-related deformation along the Mount Angel fault zone.

This study was designed to reconstruct the paleoseismic history of the Mount Angel fault zone and develop a geologic/geomorphic map using LiDAR topography (Figure 1). We originally proposed to excavate a paleoseismic trench at the Dominic Road trench site identified by Wang et al. (2003) as the best site for future paleoseismic study of the MAF (Figure 2 and 3). They identified near surface displacement of buried Linn Gravels (O'Connor et al., 2000) and nearby potential earthquake-related deformation of Missoula Flood deposits along the Pudding River. We also investigated an alternate site along Miller Road (Figure 2 and 4) where near surface faulting has also been identified (Liberty et al. 1999; Wang et al. 2003).

As discussed in Section 4.0, our geophysical investigation across the MAF at the Dominic and Miller Road sites did not present compelling enough evidence for near surface deformation to warrant paleoseismic trenching. To increase our chances for success, we inspected newly acquired 2-meter bare earth LiDAR data collected along the fault for this study in search of possible tectonic geomorphology that could yield a previously unidentified trench site. Inspection of these data revealed no compelling paleoseismic targets. As a result, we changed the scope of the project to a Quaternary geomorphic mapping project along the MAF.

Our detailed Quaternary geologic/geomorphic mapping was developed using bare earth LiDAR data, acquired in 2007, and revealed several pre-and post-Missoula flood (22-12 Ka) surfaces preserved on either side the of MAF. Despite high-quality topographic data, our mapping revealed little evidence of surface rupture or tectonic geomorphology along the MAF of Missoula Flood geomorphic surfaces. However, a compilation of geologic borings and magnetic modeling (Madin et al., 2007) across the MAF suggest the fault displaces Pleistocene gravels and has a poorly constrained vertical slip-rate (Wong et al., 2000).

2.0 TECTONIC SETTING AND REGIONAL GEOLOGY

The prevailing kinematic model of the Pacific Northwest attributes upper-plate earthquakes (<25 km depth) to northward translation of the Oregon Coast Range causing dextral transpression in the northern Willamette Valley (Wells et al., 1998; Lewis et al., 2003). This model is evidenced by multiple faults, folds, and diffuse crustal seismicity in the region (Figure 1). Faults mapped in the valley include northwest and northeast striking faults. The Gales Creek, Mount Angel, Oatfield, Portland Hills, East Bank, and Sandy River faults are a series of right-stepping, northwest-striking potentially seismogenic faults in the northern Willamette Valley (Figure 1) and Portland Metropolitan area. These faults were imaged in a recent high-resolution aeromagnetic survey (Blakely et al., 2000), which implied that the Gales Creek, Mount Angel, and other faults had experienced significant dextral slip.

Diffuse crustal seismicity in the region is consistent with a dextral transpressional strain regime (Lewis et al., 2003) that characterizes the northern Willamette Valley. Northwest-striking dextral reverse faults and east-west-trending folds (e.g. the Tualatin Basin and Bull Mountain Anticline) reflect a similar strain regime driven by north-directed compression (Yeats et al., 1996).

Previous geophysical and geologic investigations have established that the MAF (1) is the probable source of the Scotts Mills earthquake (Madin et al., 1993; Thomas et al., 1996), (2) offsets buried Pleistocene deposits (Wang et al., 2003), (3) is spatially coincident with post-Missoula Flood earthquake-related deformation (Wang and Madin, 2001), and (4) is capable of producing a 6.8 Mw or greater earthquake (Petersen et al., 2008). These data suggest the Mount Angel fault may have produced surface rupture in the late Quaternary and is a potentially damaging seismic source that may have produced a large earthquake since the deposition of the Missoula flood deposits (22-12.5 Ka) (Wait, 1980; 1985; Atwater, 1986; O’Connor and Waitt, 1995; Madin et al.,2008).

Mount Angel Fault

Geologic mapping and geophysical studies indicate that the MAF is a northwest-striking dextral reverse fault that is part of the larger (~100 km long) Gales Creek-Mount Angel structural zone (Yeats et al., 1996), which also includes the Gales Creek and Newberg faults to the northwest (Figure 1). The MAF was first identified by Hampton (1972) and subsequently characterized by Werner (1992), Yeats et al. (1996), and Tolan and Beeson (1999). The fault dips 60-70° to the northeast with 100-500 m of northeast-side-up vertical offset that increases toward the southeast (Liberty et al., 1999; Werner et al., 1992; Yeats et al., 1996). Mapping by Tolan and Beeson (1999), indicates that a northeast-dipping homocline in 12-16 Ma Miocene Columbia River Basalt (CRB) originally interpreted as a flower structure (Werner, 1992), occurs in the hanging-wall of the fault. Unconformably overlying the CRB are a series of late Miocene to early Pleistocene glacial outwash gravels and claystones (Yeats et al., 1996). In the Waldo Hills, a 1-km dextral offset of individual CRB flows indicates that the fault has a significant component of dextral slip on the fault (i.e. H:V ratio ranging from 10:1 to 2:1) (M.H. Beeson, Portland State Univ., oral Communication, 1990 cited in Yeats et al. 1996). This description of the fault is consistent with the northwest-striking dextral reverse focal mechanism solution of the Scotts Mills earthquake (Thomas et al., 1996). Onlapping relationships and buttress unconformities between individual CRB flows indicate that the MAF was active before ~15 Ma (Tolan et al., 1999).

Northwest of Mount Angel, Liberty et al. (1999) collected a series of high-resolution seismic reflection profiles along two transects across the MAF near Woodburn, Oregon (Figure 2). This 24-fold seismic reflection data imaged Columbia River Basalt (CRB) and overlying sediment offset as much as 100-200 meters at depths of 300 to 700 meters. Above CRB reflectors, sediments are imaged folded and/or offset with decreasing amplitudes at depths as shallow as 40 meters suggesting a growth structure. Further magnetic modeling along of the MAF suggests that the underlying magnetic Siletzia terrane is offset “at least 500 m” (Liberty et al., 1999).

Wang et al. (2003), using SH-wave seismic reflection and refraction techniques, imaged the MAF in the near subsurface offsetting buried late Pleistocene Linn Gravels (420 to 22 Ka; O’Connor et al. 2000) (Figure 2). SH-wave common-depth-point (CDP) reflection profiles were collected along Miller Road, and Arbor Grove Road, and a SH-wave refraction profile was collected along Dominic Road. Each profile imaged faults and/or deformation of Missoula Flood Deposits or Linn Gravels. At Miller Road, SH-wave profiles imaged two faults offsetting the top of the Linn Gravels by 3 and 5 m buried by less than 10 meters of Missoula flood silt.

At the Dominic Road site a SH-wave profile imaged two faults offsetting the top of the Linn Gravels by 18.3 m across the entire profile (Figure 2) (Wang et al., 2003). One fault is interpreted to offset the top of the Linn Gravels reflector by 50 milliseconds or ~6 m (See Figure 5 Wang et al., 2003). Wang et al. (2003) continue that displacement of the Linn Gravels reflection increases from no resolvable offset in the Arbor Grove profile to ~18 m in the Dominic Road profile. This observation is supported by southeast-directed increases in topographic relief and increased offsets toward the southeast in previous seismic reflection lines (Liberty et al., 1999; Yeats et al., 1996), and well data, which indicate that the CRB is offset ~200 m. Wang et al. (2003) conclude that the MAF is a potentially active Quaternary fault and the Dominic Road site is the ideal location to conduct future paleoseismic trenching.

Geologic evidence of deformation of Quaternary deposits and discontinuities in structure contour maps of Pleistocene deposits suggest that deformation related to seismogenic slip on the MAF exists at the ground surface (Wang and Madin, 2001). Previous research (NEHRP grant #00HQGR0009 to Wang and Madin) identified deformation of Pleistocene and possible Holocene (?) deposits that are coincident with the mapped trace of the MAF in bank exposures along the Pudding River near Dominic Road. This work consisted of reconnaissance mapping along several kilometers of the Pudding River. This survey identified several geologic relationships in bank exposures consistent with late Quaternary deformation, including liquefaction dikes intruding Missoula Flood deposits, tilted Missoula flood deposits, and faulted Quaternary fluvial deposits (Figure 2). Charcoal sampled from deformed or intruded deposits produced anomalously young radiocarbon ages. Thus, definitive radiometric age determinations for this deformation are not available, and non-tectonic origins cannot be completely ruled out. This earlier work suggests that earthquake-related deformation may have occurred in the vicinity of the MAF since the deposition of the Missoula Flood Deposits (latest Pleistocene) and possibly has occurred during Holocene time. A re-evaluation of these exposures is discussed in Section 4.4.

Structure contour maps of the base of the Willamette Silt and top of the Linn Gravels reflect apparent vertical deformation in late Pleistocene deposits coincident with the surface trace of the MAF (Wang and Madin, 2001). These structure contour maps were constructed using over 300 water-well logs. Maps of the base of Missoula Flood deposits (Willamette Silt) and the top of Linn Gravels illustrate relatively smooth surfaces southwest of the fault that become more irregular to the northeast near the mapped trace of the MAF. At least 2 m vertical deformation of the top of the Linn Gravels, based on borehole information, was measured near the proposed paleoseismic trench site along Dominic Road. Because of poorly constrained vertical errors (3.5 to 5 m), fault perpendicular profiles elsewhere cannot accurately constrain vertical deformation of these surfaces. Below we discuss our improvement of these structure contour maps by relocating additional water-well logs further southeast along the mapped location of the MAF.

One previous study has discussed the surficial geomorphic evidence for Quaternary activity of the MAF. Unruh et al. (1994) characterized the MAF for a seismic source model for Scoggins Dam in the northern Willamette Valley. They noted that the valley floor on both sides of the fault has well-defined horizontal surfaces that are incised by streams draining the western flank of the Cascade Range toward the Pudding River (Figure 2). They depict topographic profiles that show the average elevation of surfaces northeast of the MAF as 6-13 m higher than similar surfaces southwest of the fault. Their profiles across Abiqua Creek (SW-side of the fault) and Butte Creek (NE-side of the fault) show that the streams have cut down to virtually the same elevation, despite the higher surface on the northwest side of the fault. Based on these observations they hypothesize two models to explain the elevation difference of these surfaces across the fault. 1) The surfaces may have been cut by Abiqua Creek and tributaries of the Pudding River and the lower elevation of the surfaces southwest of the MAF reflect greater incision and lateral cutting by Abiqua Creek than cutting by Butte Creek. This interpretation implies that the lower surface is a younger geomorphic surface. Unruh et al. (1994) continue to suggest that the "difference in the magnitude of erosion may be attributed to different or 'complex' responses of the watersheds of Abiqua and Butte Creeks to Pleistocene climatic variations." 2) The alternate hypothesis considers that these surfaces may be rough time equivalent surfaces (e.g. cut at the same time). If the surfaces are actually the same age then Quaternary faulting is the best explanation for the northeast-side up elevation difference across the fault. Unruh et al. (1994) prefer the more conservative fault model base on a lack of available data on the age of the surfaces. However, a possible test of the geomorphic or tectonic models posed by Unruh et al. (1994) would be to compare the degree of soil profile development on the surfaces across the fault. If surfaces are similar in age then a tectonic model is reasonable. In contrast if the lower surface is younger the geomorphic model is more reasonable (Unruh et al., 1994). We propose and discuss below that a hybrid model incorporating both a tectonic and geomorphic model better matches the geomorphic and geologic data.

3.0 LOCAL GEOLOGIC SETTING

3.1 Quaternary Geology of the Northern Willamette Valley

The study area lies within the northern Willamette Valley, a broad alluvial plain that lies between the Cascade Range on the east and the Coast Range on the west (Figure 1). The Quaternary geology of the northern Willamette Valley was originally mapped by Glenn (1965) and then by Hampton (1972) who first mapped the MAF and built much of the Quaternary geomorphic framework discussed below. Recently, the Willamette Valley was remapped by O'Connor et al. (2001) at 1:250,000 scale. They provide a thorough review of literature and past mapping efforts. Although there are major differences between the mapping presented here (Plate 1) and mapping by O'Connor et al. (2001), the discussion below summarizes many of the conclusions and discusses the major geologic units is in the map area using the unit designations developed by O'Connor et al. (2001).

The Quaternary deposits in the Mount Angel study area are underlain by bedrock composed of Early Eocene Siletz River Volcanics, Oligocene Scott Mills Formation, Miocene Columbia River Basalt, and Mio-Pliocene glaciofluvial and fine grained fluvial deposits (pre-Linn Gravels sedimentary deposits) (Hampton, 1972; Yeats et al., 1996; Liberty et al., 1999; Tolan and Beeson, 1999). Bedrock is identified in outcrop at Mount Angel Abbey, in multiple wells throughout the field area, and in geophysical profiles (Figure 2).

The major Quaternary geologic units in the study area as mapped by O'Connor et al. (2001) are discussed below and include: 1) Plio-Pleistocene Weathered Terrace gravels, 2) Pleistocene Linn Gravels, 3) Missoula Flood Deposits, and Post-flood Quaternary deposits.

Plio-Pleistocene Weathered Terrace Gravels

The oldest mapped Quaternary geologic unit in the area is the Plio-Pleistocene weathered terrace gravels (QTg) that flank the northeastern margin of the Waldo Hills (Unit QTg from O'Connor et al., 2001; Hampton, 1972). These gravels represent remnant fan deposits from west-flowing Cascade tributaries (e.g. Abiqua Creek and Silver Creek). This unit varies in thickness in the study area from typically 10 to 20 feet thick, but can be as thick as 60 to 100 feet thick (Hampton, 1972). O'Connor et al (2001) reports that these deposits have 'planar to undulating' surfaces with diagnostic 'thick strongly-developed' red clay-rich soils (Xeric Haplohumults or Ultic Haploxeralfs) with 'severely weathered clasts' easily cut by a knife. The age of Unit QTg is most likely between 2.5 and 0.5 Ma based on dating intercalated volcanic deposits (summarized by O'Connor et al., 2001). This geologic unit is mapped at the surface just outside of the study area at Rocky Four Corner in Marion County, Oregon.

Linn Gravels

The late Pleistocene Linn Gravels (Qg2) are Cascade-derived unconsolidated clay, silt, sand, and gravel that underlie the majority of the field area (Hampton, 1972; O'Connor et al. 2001). The unit is separated into an upper unit consisting of widespread sheets of gravel and sand and a lower fine-grained facies not mapped in the field area. Soil profiles typically are 2-3 m thick with reddening, incipient zones of clay accumulation (argillic Bt horizons), reddish clay-coating on cobbles, and volcanic cobbles that have greater than 5 mm thick weathering rinds. The base of the Linn Gravels is often marked by a cemented gravel layer (See C-C' O'Connor et al. 2001). A poorly constrained maximum age of 0.42 Ma was calculated from Ar-Ar incremental heating analysis of two obsidian clasts and the minimum age of 22-23 Ka is constrained by radiocarbon dating and tephra chronology (O'Connor et al., 2001). A post-Missoula flood gravel (Qg1) is mapped north of the field area along Butte Creek and throughout the Willamette Valley, but is not mapped in the field area.

Missoula flood deposits

The late Pleistocene Missoula flood deposits (Qff2) were deposited throughout the lowlands of the Willamette Valley resulting from multiple outbursts of glacial Lake Missoula in western Montana (Benito and O'Connor, 2003; O'Connor et al., 2000; Waitt Jr, 1985). These deposits blanket the field area with a thin (2 meters) to very thick (up to 35 meters) cover of rythmically bedded laminated silt, clay, and minor sand. Dozens of floods are inferred by mapping flood rythmites at other locations. Within the study area Unit Qff2 is mapped up to 300 feet elevation and obscures much of the pre-flood geomorphology (discussed below) (Minervini et al., 2003). The Missoula Floods occurred between 22,000 and 12,700 year ago based on radiocarbon (Wait, 1980; 1985; Atwater, 1986; O’Connor and Waitt, 1995) and optically stimulated luminescence (OSL) dates (Madin et al., 2008).

Geomorphically the Missoula flood deposits form a planar to undulating surface that masks the buried topography in the center of the valley, but along the margins of the valley, where the deposits are thinner (2-3 meters or less), the flood silts drape and subdue paleotopography (Figure 2; Plate 1). This surface has been incised by multiple streams and rivers such as the Pudding River and Abiqua Creek forming complex meandering drainage systems in the lowlands and broad mildly dissected surfaces in the uplands.

Holocene and upper Pleistocene Alluvium

The post-Missoula flood (< 12 ka) geomorphic environment includes an incised meandering river system with construction of a fine grained flood plain with gravelly channel deposits. Within the study area O’Connor et al. (2001) map a single geologic unit (Qalf) to represent the unconsolidated clay, silt, sand, and gravel deposited in the flood plains and channels of small creeks and river in the study area.

4.0 APPROACH AND METHODOLOGY

Our approach to investigate the paleoseismology of the MAF involved three components. The first component used magnetometer, ground penetrating radar and Global Positioning System (GPS) topographic surveys to assess the suitability of two paleoseismic trenching sites. The second component entailed interpretation of aerial photography and LiDAR topography and reconnaissance field mapping along the fault zone to develop a detailed Quaternary geologic and geomorphic map of the MAF. Finally, the third component of the investigation involved the compilation and relocation of additional water-well logs south and southwest of the fault to construct structure contour maps and geologic cross sections.

4.1 Geophysical Data Acquisition

We completed multiple geophysical surveys across the inferred trace of the MAF at the Dominic Road and Miller Road site (Figure 2 through 5) to identify a location where a shallow paleoseismic trench would expose deposits deformed by faulting. Multiple magnetic surveys were conducted to evaluate the presence or absence of fault-related deformation in Miocene Columbia River Basalt (CRB) and Pleistocene Linn Gravels that underlie Missoula Flood deposits. Topographic contour map and profiles at the Miller Road site were derived using data acquired with a Trimble 5700/5800 Real-Time Kinematic Differential Global Positioning System (GPS). These surveys were followed by ground penetrating radar surveys across the inferred magnetic anomalies (Figures 4 and 5).

4.2 LiDAR-Based Quaternary Geologic and Geomorphic Mapping

Our Quaternary geologic and geomorphic map was developed primarily using detailed bare-earth LiDAR data (1-meter grid), black and white, 1:20,000 scale stereo-paired aerial photography flown in 1955, and a compilation of water well drillers logs (Plate 1). We also referenced topographic maps from the U.S. Geological survey and existing geologic maps of the area (Hampton, 1972; Tolan and Beeson, 1999; O'Connor et al., 2001). We consulted the Marion County soil survey (Williams, 1972) to correlate the mapped soils in the area with our geomorphic units, although only general correlations exist between the soil surveys and our updated mapping.

Field reconnaissance included traverses across and along the MAF to verify to the geomorphic mapping interpretations shown on Plate 1. Much of the reconnaissance was limited to traverses along public roads with limited exposures, except along stream cuts along Abiqua Creek and one pipe line excavation (waypoint #188). We investigated the thickness of Missoula Flood deposits (up to 2 meters) using a hand auger, often in drainage ditches along the right of way. During our field reconnaissance, we carefully searched for yet found no field evidence of late Quaternary tectonic-geomorphic features coincident with the MAF. We also re-evaluated natural bank exposures of reported Quaternary deformation along the Pudding River by Wang et al. (2003) (Figure 2 and 7).

Topographic and Longitudinal terrace profiles greatly aided our understanding of the geomorphic environment. Using detailed LiDAR data, we developed topographic profiles (Figures 7 and 8) across the MAF and constructed terrace profiles along the Pudding River (Figure 9) and channel A of Abiqua Creek (Figure 10), which involved a multi-step process using ArcGIS. Topographic profiles were first constructed across each geomorphic surface at the highest possible elevation along each surface parallel to the either the Pudding River or Abiqua Creek channel A. Profiling the top of each terrace should avoid profiling an 'eroded' surface and assumes that the surfaces were essentially planar after each was formed.

Then each profile was deaggregated into a series of points spaced 1-m apart and projected onto a line that is coincident with the center of the Pudding River or the Abiqua Creek channel 'A' flood plains.

The sinuosity of the Pudding River across the MAF was determined to validate claims made by previous investigators (Unruh et al., 1994). Sinuosity measurements were made by splitting the river valley along the Pudding River into separate 1000-foot-long segments and then measuring the length of the river channel within each segment.

4.3 Drillers Log Database, Structure Contour Maps, and Geologic Cross Sections

To evaluate the subsurface expression of the MAF, we constructed a series of structure contours maps of key stratigraphic horizons in the study area (Figures 11, 12, and 13). This work built off of previous work by Wang and Madin (2001) who compiled over 300 drillers logs wells from the Oregon Water Resources Department in the area surrounding the fault. Every effort was made to locate each well in the field. Otherwise the location was estimated using a combination of digital tax lot data and orthophoto quadrangles. Raw lithologic data from each well log has been entered into a GIS-based borehole visualization software package (Borehole Mapper) to allow us to readily construct cross sections and look for stratigraphy and possible deformation. Elevation data for each well was derived from LiDAR data. Three separate structure contour maps were developed for key stratigraphic horizons including: 1) the top of Columbia River Basalt (Figure 11), 2) the base of gravels (Figure 12), and 3) the top of the gravels (Figure 13). The maps were derived using Mapinfo ™ GIS software and then contoured with 5 to 20 meter contour intervals. This database then allowed the quick generation of multiple geologic cross sections to better place the structure contour maps in geologic context (Figures 14 and 15).

5.0 RESULTS

We conducted a multi-disiplinary investigation of the MAF that included site-specific investigations to identify a suitable paleoseismic trench site and developing a Quaternary geologic/geomorphic map of the MAF using newly acquired LiDAR data. Our mapping effort was augmented by building off of an existing database of water well logs (Wang and Madin, 2001) and constructing both geologic cross section and structure contour maps. Our site specific investigations targeted two potential trench sites where previous studies had identified near surface faulting, the Dominic Road and Miller Road sites (Figure 2).

5.1 Dominic Road Site

In July 2006, we completed multiple geophysical surveys across the inferred trace of the MAF at the Dominic Road site (Figure 2) to identify a location where a shallow paleoseismic trench would expose deposits deformed by faulting.

Multiple magnetic surveys were conducted to evaluate the presence or absence of fault-related deformation in Miocene Columbia River Basalt (CRB) and Pleistocene gravels that underlie Missoula Flood deposits at the Dominic Road site (Figure 2; Plate 1). We expected to image near surface discontinuities because previous studies indicated the top of the gravel reflector should be offset by more than 18 m (Wang et al, 2003).

Despite these previous results, our magnetic survey resolved only low-amplitude magnetic anomalies providing little evidence of faulting in strata beneath the site (Figure 3). Several GPR surveys across the site, collected by David Percy (Portland State University) with help from Witter and Madin, imaged flat-lying reflectors, also consistent with undeformed stratigraphy. Lacking results that provided conclusive or even compelling evidence for near surface fault-related deformation at the Dominic Road site reduced our confidence in our ability to locate a trench where we were most likely to expose deformed Missoula flood strata. After careful consideration of these data, we decided to explore an alternative trench site along Miller Road (Figure 2).

5.2 Miller Road Site

In August 2006, using the same geophysical tools, we investigated an alternative trenching location along Miller Road in Marion County, Oregon (Figure 2) (Madin et al., 2007). This site is a reasonable alternative to the Dominic road site because seismic reflection and refraction profiles across the fault (Liberty et al., 1999; Wang et al., 2003) show nearly 200-m of vertical offset of the CRB, 20- to 30-m amplitude folding in overlying Plio-Pleistocene deposits and as much as 8m of vertical offset of the top of the Linn Gravel.

At this site a detailed topographic map of the site developed using GPS surveys revealed a subtle topographic scarp coincident with the projected trace of the MAF (Figure 4a). Magnetic data collected at the site showed a linear anomaly beneath the scarp, also coincident with the fault trace (Figure 4b). However, additional anomalies in the magnetic data that connect with the primary linear anomaly suggest a pattern that may reflect a dendritic buried channel system. The results of multiple GPR surveys across the topographic scarp and magnetic anomaly showed near-surface layering subparallel to topography and no conclusive evidence for near-surface fault-related folding or other deformation (Figure 5).

A variety of forward modeling experiments were developed to better understand the cause of ground-magnetic anomalies in this area, as reported in Madin et al. (2007; see Appendix A). We developed a hypothesis that if the Missoula flood deposits are sufficiently magnetic, even slight topography will create magnetic anomalies at ground levels. To test the possibility that ground magnetic anomalies are merely caused by topography, we tested a model in which all subsurface contacts are flat and horizontal. To account for the amplitude of ground-magnetic anomalies in this way requires that Pleistocene flood deposits have unreasonably high magnetic susceptibility. Topography alone cannot account for the ground-magnetic anomalies.

Thus, observed ground-magnetic anomalies at the Miller Road site require vertical folding or vertical offsets of underlying deposits. A cross-sectional model based on our new ground-magnetic survey and high-resolution topography, constrained by earlier seismic-reflection results, is consistent with 17 m of vertical offset of late Pleistocene (22-34 ka) Linn Gravels (?) known to lie at about 30 m depth. This suggests an average vertical slip rate of 0.5 to 0.8 mm/y.

Considering the results of all the surveys, we lost confidence that we could locate a shallow trench across the fault that might reveal evidence for recent deformation. Therefore, after careful consideration and discussion between all principal investigators, we decided to delay trenching, save our remaining resources and continue to evaluate other alternative sites.

5.3 Pudding River Bank Survey

In September 2006, we resurveyed natural bank exposures along the Pudding River by canoe to evaluate possible earthquake-related deformation features reported by Wang and others (2003). We relocated three features interpreted as possible evidence for Quaternary deformation coincident with traces of the MAF inferred from geophysical data and well logs (Figure 2). During the survey, we examined sedimentary structures and grain size trends enhanced by sediment peels using a hydrophilic resin to reevaluate the likely origin of the unusual features observed in the river banks. The features examined included steeply dipping to slightly overturned bedding in river deposits (Figures 6a-6c) and near-vertical sand dikes intruding horizontally deposited Missoula Flood deposits (Figure 6d). Although fault-related deformation is a possible explanation for bedding orientations, we did not directly observe any causative faults in the bank exposures we examined. Alternative explanations for the unusual bedding dips include foreset beds of point and channel bars that dip downstream or collapse of bank exposures undercut by the river. We interpret that the vertical sand dikes in Missoula Flood deposits probably reflect seismic shaking produced by local earthquakes, although we cannot specify the source. If the sand dikes were in fact caused by strong shaking during a local earthquake, the timing of the event can only be constrained to be younger than late Pleistocene (the age of the Missoula Flood deposits) because the dikes did not penetrate upward into younger, overlying deposits.

5.4 Structure Contour Maps/Geologic Cross Sections

Structure contour maps (SCMs) and geologic cross sections across the MAF trace illustrate a consistent thinning of post-CRB geologic deposits in the hanging wall or northwest-side of the fault (Figures 11-15). Deep wells are sparse southwest of Abiqua Creek channel A, so many of the contours on the southwest-side of the MAF are controlled only by a few deep wells (e.g. well 50456). Top of CRB structure contour maps illustrate a northwest-trending asymmetric bedrock high that parallels the fault with a gently sloping northeast-side and a steep southwest-side (Figure 11). The top of the CRB SCM southwest of the fault appears to have considerable relief, which may be truly erosional, fault-related, or could be a product of sparse geologic borings. Geologic cross sections A-A' and B-B' suggest the elevation change of CRB across the fault ranges between 90 to 120 m (300 to 400 ft), which is consistent with other estimates (Hampton, 1972; Yeats, 1996; Tolan and Beeson, 1999) (Figures 14 and 15).

Water well logs and geologic cross sections show post-CRB and pre-Pleistocene gravel sedimentary deposits preserved on both sides of the fault (Figures 14 and 15). Yeats et al. 1996 describes these deposits as coarse grained glaciofluvial deposits and fine grained fluvial overbank deposits inferred to be Miocene to early Pleistocene in age. In water well logs, these deposits consist of clay, sand, and silt along with siltstone, claystone, blue clay with sand, and clay with minor gravel. Hampton (1972) presents a structure contour map of the base of this deposit that shows a similar morphology to the top of CRB SCM (see Plate 2 from Hampton, 1972). This deposit thins across the fault from 90-137 m (300-450 ft) thick southeast of the fault to 0-46 m (0-150 ft) thick northeast of the fault. Both sections A-A' and B-B' infer a bedrock high coincident with the mapped trace of the fault and consistent with structure contour maps (Figures 14 and 15).

The construction of the base of gravel and top of gravel structure contour maps hinge on the correlation of gravels across the fault. Our ability to correlate these units is based on the descriptions given by water well drillers, which vary in quality and are generally poor. In addition, there are no detailed geologic borings available to correlate clast lithology/mineralogy, matrix composition, and soil characteristics between borings on either side of the fault to provide a more definitive correlation. As discussed in the following section there are no surface outcrops near the MAF to help this correlation.

Based on the limited data available, we prefer the interpretation that the entire gravel package represents the broad and extensive late Pleistocene Linn Gravels and not the early to middle Pleistocene remnant terrace gravels for several reasons, including:

- The gravels are mapped as a broad aerially extensive surface that continues several kilometers northeast of the fault, thickens across the fault, and extends many kilometers to the southwest;
- The description of the gravel in the hanging wall of the fault is consistent with other the Linn Gravels (e.g. cemented basal gravel; O'Connor et al., 2000);
- Detailed LiDAR data show that there is only a minor elevation difference at the apex of Abiqua Creek indicating there is little reason to believe the hanging wall was isolated from Pleistocene deposition; and
- Previous investigators with extensive mapping experience in the Willamette Valley name these gravels as Linn Gravels (Wang et al., 2003).

Despite this reasoning, it is possible the gravels in the footwall of the MAF (southwest side of the fault) represent a younger gravel (e.g. Linn Gravels) inset into the older early to middle Pleistocene terrace gravels in the foot wall (Wang and Madin, 2001). Along the North Fork of the Santiam River, O'Connor et al. (2000) illustrates a 30 meter elevation difference between the top of the older terrace gravels and the Linn Gravels attributed entirely to erosion (see Figure 3 section C-C' from O'Connor et al. 2000). Conversely, it is also possible that the base of gravels discussed below represents both deposits with the older terrace gravels at the base buried by the younger Linn Gravels further up section. Because of the uncertainty regarding the correlation of the gravels across the MAF, we generically refer to 'gravels' in the discussion below rather than assigning them a particular age or name. We discuss the implications of the gravels ages on vertical slip-rate calculations for the MAF in section 5.0.

Structure contour maps of the base of the gravels shows that they are higher in elevation and thin across the MAF (Figures 11-15). The base of gravel SCM is well-constrained with well density decreasing to the south near Silverton, Oregon and extending northeast as a continuous surface several kilometers northeast of the MAF. Driller's logs indicate the base of the gravel southeast of the MAF is often well-cemented and are characteristic of the base of the Linn Gravels (O'Connor et al. 2001). Data density is high within the town of Mount Angel and along the northeast side of the MAF. Similar to the top of CRB SCM, the base of gravel map illustrates a persistent northeast-striking asymmetric high along the northeast margin of the fault. The northeast-side of the high appears to dip gently to the north-northwest while the southwest-side is roughly coincident with the MAF and dips more steeply to the southwest. A northeast-striking topographic low coincident with the channels A and B of Abiqua Creek is present in the SCM suggesting the gravels may have filled pre-gravel erosional topography. The gradient on the northwest-tilted surface southwest of the MAF becomes lower with closed depressions near the confluence with the Pudding River and west of the river, which is likely the result of decreasing drainage gradients away from the Abiqua and Silverton Creek fans. Cross Sections A-A' and B-B' indicate the gravels thin from 110 to 190 feet thick southwest of the fault to 20 to 60 feet thick northeast of the fault (Figures 14 and 15). Interpreted in section A-A' are nested gravel deposits and shallow CRB (e.g. well 3036) in the hanging wall of the MAF. This 18 m (60 ft) thick gravel is interpreted to pinch out against a CRB bedrock high to the northeast and is 6-9 m (20-30 ft) thick on the northeast side of the bedrock high (Figure 14). The gravel is generally thinner in section B-B' and is preserved as a very thin deposit further to the northeast (<1.5 m or 5 ft thick) between Missoula flood deposits and Pre-gravel sedimentary deposits. The geologic cross sections infer the base of the gravel is potentially vertically offset across the fault by 46-61 m (150-200 ft) in A-A' and 20-30 m (65-100) ft B-B' (Figures 14 and 15).

Structure contour maps of the top of gravels indicate the top of this unit becomes higher on the northeast side of the fault, similar to Pleistocene and older deposits (Figure 13). This SCM covers a larger area than the other SCMs because higher well density extending as far south as Silverton, Oregon. Similar to other SCMs, this map illustrates that the top of the gravels are thinner over areas of shallow bedrock, indicating a pre-gravel bedrock high extending along the trace of the fault to near the Pudding River. The top of gravel SCM displays a similar broad northwest sloping surface on the northeastern side of the bedrock high and a steep southwest dip on the southwest side of the bedrock high adjacent to the MAF. A broad slightly west-dipping surface underlies the Abiqua and Silverton Creek fans. On both sides of the MAF this surface appears reasonably flat with only minor undulations (post-gravels channels?), which suggests the top of this deposit was a relatively broad flat surface southeast of the fault with minor pre-Missoula flood erosional topography. Underneath the Pudding River, the SCM reflects large closed-contours suggesting the relief on the top of the gravel surface is associated with the MAF and is generally absent west of the Pudding River. The geologic cross sections infer the top of the gravels becomes potentially 15 to 24 m (50 to 80 feet) higher on the northeast side of the MAF in the hanging wall (Figures 14 and 15).

5.5 Quaternary Geologic and Geomorphic Mapping

Through our detailed geologic and geomorphic mapping, we identified at least ten different geomorphic surfaces in the Mount Angel study area (Plate 1). We differentiated geomorphic units based on slope, topographic position, and overall morphology (e.g. degree of incision) and present a schematic for understanding the gross stratigraphic and geomorphic relationships in Figure 16. We did not find a robust correlation between various soils in the field area and our geomorphic surfaces, although some soil exposures encountered in the field are discussed. This is likely a result of the Missoula flood silt that blankets the area and obscures deeper soils. Surfaces with a moderate slope along the margins of Abiqua and Silverton Creek were designated as 'fan' surfaces (e.g. Qf2 – Quaternary fan 2). Surfaces with similar topographic positions, but a lower slope and further from foothills were designed as 'terrace' surfaces and represent fill terraces from the catastrophic Missoula floods (e.g. Qt2 – Quaternary terrace). After field inspection and construction of longitudinal profiles, we determined most of these paired surfaces represent essentially the same flood surface. Where the 'fan' surface is mapped the flood silt is generally thin and the underlying fan morphology is often visible in LiDAR data.

5.5.1 Description of Quaternary Geologic and Geomorphic Units

Qf0/Qt0

The Qf0/Qt0 geomorphic surface represents a remnant terrace and alluvial fan deposit mantled by Missoula flood silt and preserved on either side of Zollner Creek northeast and east of the City of Mount Angel (Figure 2, 7, and 8; Plate 1). Boring data, field observations and geologic cross sections indicate these terraces are covered by a thin (1.8 m or 6 ft) to relatively thick (7.6 m or 25 feet) blanket of Missoula Flood overlying Pleistocene gravels, Pre-Pleistocene gravel sediments, and CRB (Figure 14 and 15). Near the Dominic Road site bedrock is covered by a thin mantel of Missoula flood deposits and shallow bedrock underneath the Qt0 surface.

Terraces profiles (Figure 10) and topographic profiles (Figure 7) indicate the Qf0/Qt0 surface is eroded and incised by broad gently sloping tributaries of Zollner Creek. The Qt0 terrace is 10 to 15 meters above the Qt2/Qf2 surface. The southwest margin of Qt0 is steep along the projected location of the MAF and the northeast margin appears less steep with the Qt2 inset into the Qt0 surface (Figure 9, 10, and 11). The Qf0 surface is mapped primarily on the northeast side of Abiqua Creek channel A at the eastern boundary of study area with a small remnant mapped south of Abiqua Creek (Figure 8; Plate 1), which appears slightly lower (~3 m) than correlative surfaces on the northeast-side of the fault. West of the Pudding River, the Qf0/Qt0 surface is not mapped, which is consistent with structure contours that illustrate that the bedrock high associated with the MAF disappears to the west.

Qf1/Qt1

Our limited field reconnaissance and interpretation of water well logs suggest that the Qf1/Qt1 geomorphic surface represents a former alluvial fan deposit composed of Pleistocene gravel and draped by up to 5 m (15 ft) of flood silt (Figure 8). The Qf1 surface is primarily east of Abiqua Creek channel A with a thin remnant mapped along the south bank of Abiqua Creek along Meridian Road (Plate 1; Figure 8). The Qt1 surfaces are primarily preserved along the banks of Zollner Creek, although a small remnant is mapped along the trace of the MAF 300 meters south of the City of Mount Angel. The Qt1 surface is not mapped southwest of channel A of Abiqua Creek and the projection of the MAF.

Terrace profiles and topographic profiles indicate the Qf1 and Qt1 surfaces are inset into and vertically below the Qf0/Qt0 surfaces by 3-5 meters (Figure 10). Northeast of Mount Angel, the Qf1 surface is gently northwest dipping and is incised by the tributaries of Zollner Creek. However, the Qf1 surface mapped on the south margin of Abiqua Creek along Meridian Road is slightly lower in elevation (~3 m) than similar surfaces on the northeast side of channel and the MAF (Figures 8 and 10). It is unclear if these surfaces are the same surface because the correlation is based on topography and surrounding geomorphology. This northeast-side-up relationship is consistent with structure contours maps and the sense of slip on the MAF.

Qf2/Qt2

The Qf2/Qt2 geomorphic surface is a fill terrace composed of Missoula flood silt rythmites and is the most widely mapped geomorphic surface (Figures 7, 8, 9 and 10; Plate 1). The Qf2/Qt2 surface is preserved on both the southwest and northeast of the fault, and mapped across the MAF parallel to the Pudding River (Figures 11, 12, and 13). The Qt2 surface is preserved at lower elevations near the Pudding River where Missoula silt is up to or greater than 30 m (100 ft) thick, masking the underlying topography. Where the Qf2 surfaces are mapped the Missoula flood deposits are thin enough that the preexisting fan surface remains preserved (i.e. the gently west dipping fans of Abiqua and Silverton Creeks). The height of the Qf2/Qt2 surface above the Qf4 surface along Abiqua Creek channel A varies between 10 to 15 m (33 to 50 ft) near the confluence with the Pudding River and less than 1 m (3 ft) near the apex of the Abiqua Creek fan (Figures 7 and 8). This height difference further down the fan likely reflects incision of the Abiqua Creek into Missoula flood deposits during Holocene time.

Longitudinal profiles indicate the Qf2 and Qt2 surfaces are essential the same geomorphic surface (Figure 10). Several Qf2 surfaces separated by one to two meters are preserved along Abiqua Creek that may represent minor Qf2 strath terraces that developed during the incision Abiqua Creek in late Pleistocene to Holocene time or may have formed immediately post flood (Figure 7, 8, and 10). Longitudinal profiles of the Qf2/Qt2 surface along Abiqua Creek illustrate a consistent approximately 5 m (16 ft) rise in the eastern portion of the profile near the Pudding River confluence (Figure 10). We interpret this high as a possible former levee related to the Pudding River before river incision or related to Missoula flooding. Geomorphic mapping and longitudinal profiles along the Pudding River suggest the Qt2 surface is eroded and gently sloping subparallel to the present day river (Figure 10). Deep, broad channels are carved into the deposit despite a relatively small drainable area (460 m [1500 ft] south of waypoint #107; Plate 1). We speculate that these channels maybe post-flood drainage channels that formed during drainage of the valley immediately post-flood.

The Qt2 terraces are well-preserved along the eastern bank approximately 15 to 20 m (50 to 65 ft) above the Pudding River (Figures 7, 8, and 9). A poorly expressed surface is mapped slightly lower than the Qt2 terrace. We designated these terraces as Qt2’, but believe these surfaces are likely eroded remnants of the higher Qt2 surface. Interestingly, neither of the Qt2 or Qt2’ surfaces are preserved along the western bank of the Pudding River across the MAF. Within Profile 1, the Qt2 surface maybe offset across the Pudding River by 2.0 to 2.5 m (6-8 ft) northeast-side-up (Figures 7 and 9), which is consistent with bedrock offsets (Figure 14).

Qf3/Qt3

The Qf3/Qt3 geomorphic surface/geologic deposit is likely a later fill terrace (post-Qf2) composed of Missoula flood silt rythmites draping paleo-alluvial fan of Abiqua and Silverton Creeks (Figures 7 and 10). No natural exposures of this deposit were encountered during field reconnaissance, but shallow cores indicate the deposit/surface is composed of Missoula flood deposits. The Qf3 surface and Qt3 surface are likely correlative and represent a later catastrophic flooding event within the northern Willamette Valley (O’Connor et al. 2001).

Terrace profiles and topographic profiles indicate the Qf3/Qt3 surface is 5-7 m (16-23 ft) above and below the Qf4/Hfp and Qf2/Qt2 surfaces, respectively. The Qf3 surface in Abiqua Creek channel A appears to have a steeper slope more consistent with the alluvial fan of Abiqua Creek than the overlying fill terrace of Qf2 (Figure 10). This suggests the Qf3 surface may be a strath terrace cut into Missoula flood deposits related to down cutting of the Abiqua Creek rather than a fill terrace associated with a catastrophic flood. No geologic data is available to determine the origin of the Qf3 surfaces. The Qt3 surface is generally flat along the west bank of the Pudding River and slightly higher (2-3 m, 6-10 ft) and less eroded than the Qt3 surface mapped along the east bank.

Qf4

The Qf4 Quaternary fan surface is composed of alluvial fine sand and gravel with silt overlying Linn Gravels (?) and Missoula Flood silt (Figures 14 and 16). This unit commonly has a mottled silty sandy to clayey silt cap (1-4 meter) with a poorly developed Bt horizon above loose matrix supported cobble gravels. In some exposures, further west up slope (waypoint #112 Plate 1), a young soil caps the Qf4 surface with weak blocky soil structure above rounded gravel deposits. The Qf4 gravels can have thick red manganese oxide cement binding gravel clast, which is likely the result of precipitation from groundwater and not a soil horizon (waypoint #110, Plate 1). Gravels, composed of Columbia River Basalt and Scotts Mills Formation lithologies, within the Qf4 deposit commonly have weathering rinds up to one centimeter thick. Borehole data suggest this deposit is up to 30 feet thick (e.g. water well 50456, Figure 15).

At waypoint 122, Abiqua Creek is incised 3-4 m (10-13 ft) into the Qf4 deposit exposing approximately three meters of silt and fine sand with fine laminations and crossbedding (Plate 1). The unit is capped by a thin weakly developed soil (likely Holocene in age). At the base of a stream cut a reddish brown cobble gravel with a coarse sandy matrix is exposed and is interpreted as Linn Gravels (?).

Terrace profiles indicate a decreasing slope along the Qf4 surface from east to west (Figure 10). Similarly the Qf4 surfaces in Abiqua creeks channels A, B, and C essentially merge into the modern flood plain of the Pudding River. Terrace profiles indicate the Qf4 surface is more deeply incised into the flood deposits where the flood deposits are thicker. This suggests the difference in elevation between the Qf4 and Qf2/Qt2 surfaces is a result of incision into the Missoula flood deposits.

Holocene Flood Plain (Hfp)

This unit is mapped within channels of Abiqua Creek labeled A, B, and C (Plate 1). Local residents reported that in 1969, the channel was straightened and modified at several hundred feet west of Meridian Road to prevent winter flooding of the adjacent channels B and C. This report suggests, as does the geomorphology, that historically Abiqua Creek migrated between channels B and C. Topographic and terrace profiles indicate the Qf4 and Hfp surfaces are rough time-stratigraphic equivalents. These units were differentiated because the Qf4 surfaces have a steeper slope related to Abiqua and Silverton Creek fans and the Hfp surface has a gentle slope similar to the Pudding River.

Holocene channel deposits are preserved within the Abiqua Creek, Zollner Creek and the Pudding River contain widely varied bed load. Within Abiqua Creek bed load is composed of cobble to boulder sized clasts of CRB and Silverton Formation. Conversely, further from the foothills Zollner Creek and the Pudding River bed load is composed of primarily fine-grained Missoula Flood sediment with a relative absence of coarse bed load.

6.0 DISCUSSION

Our data compilation, structure contour maps, and geologic cross sections of the MAF provide direct evidence for Tertiary through latest Pleistocene deformation. The direct observations that indicate the MAF zone is Quaternary active include multiple seismic lines, magnetic data, structure contour maps, and geologic cross sections. Geophysical lines and magnetic data that cross the fault image or model deformation of Columbia River basalt, pre-Pleistocene sedimentary deposits, Pleistocene gravels and, possibly Missoula Flood deposits (Yeats et al., 1996; Liberty et al., 1999; Wang et al., 2003) indicate a long history of movement along the MAF. Structure contour maps and geologic cross section augment these observations illustrating the MAF fault likely displaces late Pleistocene Linn Gravels (420 to 22 Ka; O'Connor et al, 2001) by 20-61 m (65-200 ft) southwest-side-down (Figures 11 and 12) (Yeats et al., 1996; Liberty et al., 1999; Tolan and Beeson, 1999). We believe that collectively, these data support the conclusion that the MAF is a Quaternary active fault.

Indirect evidence for Holocene activity of the MAF includes: 1) the spatial association of the fault zone with deep laterally extensive aeromagnetic anomalies; 2) the spatial association of the fault zone with similar oriented Quaternary active faults in the northern Willamette Valley (e.g. Portland Hills and Canby-Molla faults) (Pratt et al., 2001); 3) the spatial association of several earthquake swarms near the fault (e.g. Scotts Mills earthquake); 4) subtle geomorphic evidence for vertical deformation of the Qt2 surface; and 5) sinuosity changes of the Pudding River across projected location of the fault (Figure 1). The coincidence of the Woodburn earthquake swarm and the nearby 5.7 M_L Scott Mills earthquakes with the MAF is the most compelling evidence for Holocene activity (Madin et al., 1993; Thomas et al., 1996). In addition, the dextral oblique focal mechanisms from the Scotts Mills quake agree kinematically with the sense of slip and deformation style of the MAF. The spatial association of the fault with other Quaternary activity faults (Pratt et al., 2001), extensive aeromagnetic anomalies in the northern Willamette Valley (Blakely et al., 2000), and recent earthquakes is compelling, but these faults and associated geophysical features generally lack evidence of post-Missoula flood surface-fault rupture. Lastly, sinuosity measurements of the Pudding River illustrate a gradual increase in sinuosity in the downstream direct toward the MAF with a marked increase in between the two fault strands of the fault (Figure 9b). These changes may be the result of a increase in stream gradient on hanging wall-side of the MAF (i.e. up thrown side) causing an increase in sinuosity (Unruh et al, 1994).

The overall geomorphic signature of the MAF remains consistent with other suspected Quaternary active faults in the northern Willamette Valley where signs of post-Missoula flood activity are generally lacking despite other evidence suggesting late Quaternary activity (Wang et al., 2003). At both the Dominic road and Miller road sites, we were unable to identify a suitable paleoseismic trench site (e.g. near surface discontinuities) using GPR, despite compelling geophysical data that infer up to 17 to 18 meters of faulted Linn Gravels (Wang et al., 2003; Madin et al., 2007). There is a possibility that the thick clay-rich Bt-horizons developed in the Missoula flood deposits prevented adequate penetration of the radar signal suggesting that other subsurface techniques, such as a detailed boring investigation, may be more successful.

The detailed Quaternary geomorphic and geologic mapping presented here (Plate 1) identified no prominent or distinct tectonic geomorphology along the MAF, with the exception of the 105-m to 140-m-high Mount Angel range front and the uplifted Pre-Missoula flood Qt0/Qf0 surface. Topographic profiles across the Qt2/Qf2 surface were used to assess vertical deformation across the fault zone. Profiles oriented across the bedrock high (Figures 7 and 8) illustrate that the Qf2/Qt2 surface is slightly higher (1-3 m) along Zollner Creek than along Abiqua Creek channel A. We hesitate to interpret this as tectonic deformation because these surfaces are far apart, in separate drainages, and the Qf2/Qt2 surface has multiple terraces separated by several meters making the precise correlation of these terraces between the drainages difficult. Topographic profile 1, however, is parallel to the Pudding River and illustrates a possible 2-3 meter elevation difference along the Qt2 surface (Figure 7). This poorly constrained elevation change may be the result of faulting or simply a result of the broad gently undulating topography of the post-Missoula flood surface. This minor elevation difference suggests a lack of post-Missoula flood deformation because it does not coincide with the mapped location of the fault.

The overall apparent lack of Post-Missoula flood tectonic geomorphology along the MAF can be explained in several ways: 1) the MAF is not active in the Holocene; 2) the MAF has not produced surface fault rupture in the last 12,000 to 22,000 years (post-Missoula flood); or 3) the MAF is a blind or complex fault zone. 1) As discussed above there is both direct and indirect evidence that the MAF has been active through the Tertiary into the Quaternary. Thus, the hypothesis that the MAF is no longer active or that the elevation difference across the fault is the result of differential erosion (Unruh et al, 1994) is less likely because it disagrees with geologic data that illustrates a long history of slip along the fault. 2) The absence of tectonic geomorphology along the fault may indicate the fault has not produced surface rupture since Missoula flood (post 12 ka). This hypothesis is permissible if the MAF has a low or variable slip rate (<0.1 mm/yr), which generally agrees with the minimum vertical slip-rates (discussed below) (Wong et al., 2000; Petersen et al., 2008) (Table 2). 3) Another possible explanation for the subdued tectonic geomorphology is the MAF may be a blind fault or is more complex than imaged in seismic lines (Yeats et al, 1996; Liberty et al., 1999) and geologic mapping (Tolan and Beeson, 1999). Thus, fault rupture may not be constrained to a single fault strand. A more complex fault zone geometry as suggested by Werner (1991) could distribute rupture on multiple strand and reduce the signs of deformation to a threshold below detection using LiDAR data and other techniques. In summary, all of the available geologic data suggest that the MAF is a Quaternary active fault that has either not produced surface ruptured since the Missoula Floods (~12 Ka) or signs of rupture are poorly expressed and remain unidentified.

Despite this and other research, the vertical-slip rate on the Mount Angel fault remains poorly constrained with estimates that vary widely (Yeats et al., 1996; Liberty et al., 1999; Wang et al., 2003; Madin et al., 2007). A compilation of offset measurements and calculated vertical-slip rate estimates are presented in Table 2. Using vertically offset bedrock units and assuming constant deformation since deposition, the vertical slip-rate of the MAF is very low and ranges from 0.01-0.02 mm/yr (CRB and Siletz terrane) (Yeats et al., 1996; Liberty et al., 1999). Younger offsets of 1 to 2 million year old units identified in seismic lines by Liberty et al. (1999) yield similar low vertical rates (0.02 to 0.03 mm/yr). Conversely, rates determined by Wang and Madin (2003) and Madin et al. (2007) from offset Linn Gravels yields vertical-slip rates between 0.04 and 0.82 mm/yr. Likewise, we calculate a wide range of offsets from the base of the gravel (20-61 m), top of the gravel (15 to 24 m), and tentatively infer offset in the post-Missoula flood surface (2-3 m) producing slip-rates that range from 0.02 to >1.0 mm/yr (Table 2).

The variability of vertical slip-rates calculated from offset Pleistocene gravel deposits are driven by the poorly-constrained characteristics and age of the gravels in the study area. As discussed earlier, the correlation of gravels on either side of the MAF is somewhat uncertain (See section 5.4). The gravels may represent 1) two separate gravel packages (e.g. older terrace gravels [QTg] and Linn Gravels), 2) the older terrace gravels (QTg), or 3) the younger Linn Gravels. 1) If the gravels on either side of the MAF represent two separate deposits, the inferred elevation difference of the base and top of the gravels across the fault could be generated by purely differential erosion, not faulting (Unruh et al., 1994). We believe this is less likely based on the amalgamation of geologic and geophysical data illustrating direct and indirect evidence for Quaternary activity (e.g. bedrock offsets showing increasingly large offsets with progressively older units, structure contour maps, faults in geophysics showing offset latest Tertiary deposits [Yeats et al., 1996], seismicity associated with the fault, etc). 2) Alternatively, it is possible that the gravels represent the older terrace gravels (Unit QTg from O'Connor et al. 2001) producing a vertical slip-rate that ranges from 0.1 to 0.12 mm/yr. 3) It is also plausible these gravels represent the younger Linn Gravels and if so, the vertical slip-rate ranges from 0.02 to 2.77 mm/yr. These maximum rates (e.g. >1 mm/yr) appear too high and do not match the overall lack of post-flood tectonic geomorphology along the fault. In summary, all the available data indicate the vertical slip-rate estimates on the MAF remain poorly constrained with uncertainties too large to assign a vertical slip-rate without additional data. Future subsurface investigations should focus on correlating and dating the gravels on either side of the MAF to reduce the uncertainty in slip-rate estimates (Table 2).

The USGS national seismic hazard map models the MAF as a low-slip rate (0.065 mm/yr) thrust fault within the northern Willamette Valley (Petersen et al., 2008). This model estimates a long return period (~15 ka) for a characteristic event (e.g. Mmax 6.8 Mw), which agrees with the overall lack of geomorphic evidence for a post-Missoula flood surface rupturing earthquake. However, future updates of the seismic source model for the national seismic hazard maps may want to consider incorporating the considerable uncertainties in vertical-slip rate, general lack of geomorphic evidence for Holocene fault activity, and consider the poorly characterized oblique component of slip on the MAF.

7.0 SUMMARY OF FINDINGS

Our investigation of the MAF provides additional direct and indirect evidence for Quaternary activity of the fault. This study included site specific paleoseismic investigations, construction of structure contour maps, developing geologic cross sections, and geologic/geomorphic mapping along the MAF. Site specific investigations at the Dominic and Miller Road sites included topographic, gravity surveys and GPR surveys, but these data did not generate evidence for near surface deformation despite compelling evidence reported in previous investigations (Wang et al., 2003; Liberty et al., 1999). Structure contour maps revealed a consistent and persistent structural high coincident with the hanging wall of the MAF in Miocene bedrock through late Pleistocene flood deposits. Geologic cross sections across the MAF indicate Columbia River Basalt and Pleistocene gravels are potentially offset across the fault 76 to 91 m (250 to 300 ft) and 20-61 m (65 to 200 ft), respectively. This bedrock separation is consistent kinematically with bedrock offsets (Yeats et al., 1996; Tolan and Beeson, 1999). Our mapping infers the offset of the Pleistocene gravels across the MAF, which suggests the fault accommodated deformation into the Pleistocene consistent with offset in seismic lines and magnetic modeling (Yeats et al., 1996; Liberty et al., 1999; Madin et al., 2007).

This geologic and paleoseismic investigation of the MAF improves our understanding of the likelihood of active seismogenic sources in the northern Willamette Valley, Oregon. The overall lack of post-flood tectonic geomorphology despite seismicity associated with the fault and inferred displacements of Pleistocene sedimentary and bedrock units indicate the fault may not have produced surface fault rupture since the Missoula floods (12-22 Ka). Geomorphic mapping, topographic profiles, and terrace profiles using detailed LiDAR data indicate only minor poorly constrained elevation changes of the post-flood surface (Qt2 surface; 12-22 Ka) despite inferred Pleistocene offsets. Thus, all of the available data suggest the MAF is an active fault; but likely has either a low-slip rate and has not accumulated enough strain to produce a large earthquake, is blind, or produces complex ruptures leaving little evidence of large surface rupturing events.

8.0 ACKNOWLEDGEMENTS

This research was supported by the U.S. Geological Survey's National Earthquake Hazard Reduction Program, under Award No's. 06-HQ-GR-0147 and 06-HQ-GR-0148. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government. We are thankful to those people who helped make this project possible, including Ray Wells and Craig Weaver (U.S. Geological Survey). David Percy performed ground penetrating radar surveys and processed the data at Portland State University. Marco Ticci drafted the geologic map and Carolyn Mosher drafted the figures contained in this report.

9.0 REPORTS/ABSTRACTS PUBLISHED

As part of this U.S. Geological Survey NEHRP-funded research an abstract was presented to discuss the initial findings of the study:

Madin, I.P., Blakely, R.J., Witter, R.C., Givler, R.W., and Percy, D.C., 2007, High-resolution Geophysical Surveys of the Mount Angel Fault, Northern Willamette Valley, Oregon, Geological Society of America Abstracts with Programs, 103rd Cordilleran Section meeting.

10.0 REFERENCES

Atwater, B.F., 1986, Pleistocene glacial-lake deposits of the Sanpoil River valley, northeastern Washington: U.S. Geological Survey Bulletin 1661, 39 p.

Benito, G., and O'Connor, J.E., 2003, Number and size of last-glacial Missoula floods in the Columbia River valley between the Pasco Basin, Washington, and Portland, Oregon: Geological Society of America Bulletin, v. 115, p. 624-638.

Blakely, R.J., Wells, R.E., Tolan, T.L., Beeson, M.H., Trehu, A.M., and Liberty, L.M., 2000, New aeromagnetic data reveal large strike-slip (?) faults in northern Willamette Valley, Oregon: Geological Society of America Bulletin, v. 112, p. 1125-1233.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E., Dickman, N., Hanson, S., and Hooper, M., 1996, National seismic-hazard maps: documentation, June 1996, U.S. Geological Survey, p. 110.

Glenn, J.L., 1965, Late Quaternary sedimentation and geologic history of the north Willamette Valley, Oregon: Corvallis, Oregon State University PhD dissertation, 231 p.

Hampton, E.R., 1972, Geology and ground water of the Molalla-Salem Slope Area, northern Willamette Valley, Oregon: U.S. Geological Survey Water-supply Paper 1997, 79 p., 3 pls., scale 1:48,000.

Lewis, J.C., Unruh, J.R., and Twiss, R.J., 2003, Seismogenic strain and motion of the Oregon Coast block: Geology, v. 31, p. 183-186.

Liberty, L.M., Hemphill-Halley, M.A., and Madin, I.P., 2003, The Portland Hills Fault: uncovering a hidden fault in Portland, Oregon using high-resolution geophysical methods: Tectonophysics, v. 268, p. 89-103.

Liberty, L.M., Trehu, A.M., Blakely, R.J., and Dougherty, M.E., 1999, Integration of High-Resolution and Aeromagnetic data for Earthquake Evaluations: An Example from the Willamette Valley, Oregon: Bulletin of the Seismological Society of America, v. 89, p. 1473-1483.

Madin, I.P., Priest, G.R., Mabey, M., Malone, S.D., Yelin, T.S., and Meier, D., 1993, March 25, 1993, Scotts Mills earthquake - Western Oregon's wake-up call: Oregon Geology, v. 55, p. 51-57.

Madin, I.P., Ma, l., and Niewendorp, C. A., 2008, Preliminary Geologic Map of the Linton 7.5 ‘ quadrangle, Multnomah and Washington Counties, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-08-06.

Minervini, J.M., O’Connor, J.E., and R.E. Wells, 2003, Maps showing inundation depths, Ice-rafted erractics, and sedimentary facies of Late Pleistocene Missoula floods in the Willamette Valley, Oregon. U.S. Geological Survey Open-file Report OF03-408.

O’Connor, J.E. and Waitt, R.B., 1995, Beyond the Channeled Scabaland – A field trip guide to Missoula Flood features in the Columbia, Yakima, and Walla Walla Valleys of Washington and Oregon: Oregon Geology, Part I, v. 57, no. 3. p. 51-60; Part II, v. 57, no 4. p. 75-86; Part III, v. 57, no 5. p. 99-115.

O'Connor, J.E., Sarna-Wojcicki, A., Wozniak, K.C., Polette, D.J., and Fleck, R.J., 2000, Origin, extent and thickness of Quaternary geologic units in the Willamette Valley, Oregon, U.S. Geological Survey Professional Paper 1620, p. 52, 1 plate.

Personius, S.F., compiler, 2002, Fault number 873, Mount Angel fault, in Quaternary fault and fold database of the United States: U.S. Geological Survey website, http://earthquakes.usgs.gov/regional/qfaults, accessed 12/17/2008

Petersen, Mark D., Frankel, Arthur D., Harmsen, Stephen C., Mueller, Charles S., Haller, Kathleen M., Wheeler, Russell L., Wesson, Robert L., Zeng, Yuehua, Boyd, Oliver S.,Perkins, David M., Luco, Nicolas, Field, Edward H., Wills, Chris J., and Rukstales, Kenneth S., 2008, Documentation for the 2008 Update of the United States National Seismic Hazard Maps: U.S. Geological Survey Open-File Report 2008–1128, 61 p.

Pratt, T.L., Jackson, O., Stephenson, W., Williams, R., Dadisman, S., Holmes, M., and Haug, B., 2001, Late Pleistocene and Holocene Tectonics of the Portland Basin, Oregon and Washington, from High-Resolution Seismic Profiling: Bulletin of the Seismological Society of America, V. 91, No. 4, p. 637-650.

Thomas, G.C., Crosson, R.S., Carver, D.L., and Yelin, T.S., 1996, The 25 March 1993 Scotts Mills, Oregon, Earthquake and Aftershock Sequence: Spatial Distribution, Focal Mechanisms and the Mount Angel Fault: Bulletin of the Seismological Society of America, v. 86, p. 925-935.

Tolan, T.L. and Beeson, M.H., 1999, Geologic Map of the Scotts Mills, Silverton, and Stayton Northeast 7.5 Minute Quadrangles, northwest Oregon: a digital Database: U.S. Geological Survey Open-File Report 99-141, p. 11 http://wrgis.wr.usgs.gov/open-file/of99-141.

Unruh, J.R., Wong, I.G., Boot, J.D.J., Silva, W.J., and Lettis, W.R., 1994, Seismotectonic evaluation, Scoggins Dam, Tualatin Project, northwest Oregon: Final Report prepared for U.S. Department of Interior, Bureau of Reclamation, 206 p., 4 pls., scale 1:500,000.

Waitt Jr., R.B., 1980, About 40 last-glacial Lake Missoula jökulhlaups through southern Washington, Journal of Geology, v. 88, p. 653-679.

Waitt Jr, R.B., 1985, Case for periodic colossal jökulhlaups from Pleistocene glacial Lake Missoula: Geological Society of America Bulletin, v. 96, p. 1271-1286.

Wang, Z., and Madin, I.P., 2001, Mt. Angel Fault characteristics using SH-wave refraction and reflection methods: U.S. Geological Survey National Earthquake Hazard Reduction Program Final Technical Report.

Wang, Z., Madin, I.P., and Woolery, E.W., 2003, Shallow SH-wave seismic investigation of the Mt. Angel Fault, Northwest Oregon, USA: Tectonophysics, v. 368, p. 105-117.

Wells, R.E., Weaver, C.S., and Blakely, R.J., 1998, Fore-arc migration in Cascadia and its neotectonic significance: Geology, v. 26, p. 759-762.

Werner, K.S., Nabelek, J.L., Yeats, R.S., and Malone, S.D., 1992, The Mount Angel Fault - Implications of seismic-reflection data and the Woodburn, Oregon, earthquake sequence of August 1990: Oregon Geology, v. 54, p. 112-117.

Williams L.H, 1972, Soil Survey of Marion County Area, Oregon: National Soil Conservation Service, United States Department of Agriculture, 134 p. 67 plates.

Wong, I., Silva, W., Bott, J., Wright, D., Thomas, P., Gregor, N., Li, S., Mabey, M., Sojourner, A., and Wang, Y., 2000, Earthquake scenario and probabilistic ground shaking maps for the Portland, Oregon, metropolitan area, Oregon Department of Geology and Mineral Industries Interpretive Map Series 16, p. 11 maps, 1 CD.

Yeats, R.S., Graven, E.P., Werner, K.S., Goldfinger, C., and Popowski, T.A., 1996, Tectonics of the Willamette Valley, Oregon, *in* Rogers, A.M., ed. al., Assessing earthquake hazards and reducing risk in the Pacific Northwest, U.S. Geological Survey Professional Paper 1560, p. 183-222.

TABLES

Table 1. Correlation of map units between O'Connor et al. (2000) and this study (Plate 1)

O'Connor et al. (2000)			This study	
Unit	Description	Age	Geomorphic Unit	Description
Qalc	Holocene floodplains of the Willamette River and major tributaries	generally < 4 ka	Hch, Rch, Hfp, Qf4	Holocene channels and floodplain along the Pudding River and Abiqua Creek
Qg1	Latest Pleistocene sand and gravel of Willamette River and major Cascade Range tributaries	13 to 7 ka	Not mapped in study area	NA
Qff1	Missoula flood deposits - Younger and lower Columbia River provenance clay and silt that is inset into the surround Missoula flood deposits	13.5 to 12.7 ka	Qt3/Qf3	Fill or strath surface composed entirely of Missoula flood deposits representing later flood (?) inset into main body of Missoula flood deposits preserved along Pudding River and Abiqua Creek
Qff2	Missoula flood deposits - Main body of Columbia provenance clay and silt	13.5 to 12.7 ka	Qt2	Fill terrace composed of thick (up to 33 m) Missoula Flood deposits that mask underlying topography.
			Qf2	Fan Surface (?) composed of a thin cover (1-8 m) of Missoula flood silt mantling underlying alluvial fan deposits (e.g. gravel). Underlying fan morphology still visible
Qg2	Pleistocene sand and gravel of Willamette River and Major Cascade Range tributaries (Linn Gravels). Most extensive gravel deposit in the valley. Base marked by cemented gravels in study area.	0.42 Ma to 22 ka	Qt0/Qf0, Qt1/Qf1	Pliocene to late Pleistocene gravel deposits covered by a thin mantle of Missoula flood deposits (1 to 8 meters). Gravels are mapped primarily in the subsurface. Generally covered by blanket of Missoula Flood Silt.
QTg	Fluvial deposition pedimentation, and pedogenesis	2.5 to 0.5 Ma		

Table 2. Compilation of Vertical Slip-rate data on the Mount Angel fault

Geologic Rate*	Source	Location	Techniques	Geologic Unit	Offset (meters) min	Offset (meters) max	Age (Ka)** min	Age (Ka)** max	Vertical*** Slip Rate (mm/yr) min	Vertical*** Slip Rate (mm/yr) max
Eocene	Liberty et al. (1992)	Miller Road	magnetic modeling	Siltez terrane	500		50,000		0.01	
Miocene	Yeats et al. 1996)	Sections A-A', B-B', C-C'	seismic lines	CRB	100	250	12,000	15,000	0.01	0.02
Miocene	Liberty et al. (1992)	Miller Road	seismic lines	CRB	100	200	12,000	15,000	0.01	0.02
Miocene	This study	Sections A-A' B-B'	geologic borings	CRB	90	120	12,000	15,000	0.01	0.01
Plio-Pleistocene	Liberty et al. (1992)	Miller Road	seismic lines	Plio-Pleistocene	20	30	1,000	1,000	0.02	0.03
late Pleistocene	Wang et al. (2003)	Dominic Road	shear wave velocity line	Linn Gravels	0	18	22	420	0.04	0.82
late Pleistocene	Wang et al. (2003)	Miller Road	shear wave velocity line	Linn Gravels	0	8	22	420	0.02	0.36
late Pleistocene	Madin et al. (2007)	Miller Road	magnetic modeling	Linn Gravels	0	17	22	420	0.04	0.77
late Pleistocene	This study	Sections A-A' B-B'	geologic borings	Linn Gravels	19.8	61	22	420	0.05	2.77
early to middle Pleistocene	This study	Sections A-A' B-B'	geologic borings	Terrace gravels (QTg)	19.8	61	500	2,500	0.01	0.12
latest Pleistocene	This study	Sections A-A' B-B'	geologic borings	Top of gravels	15	24	22	22	0.68	1.09
latest Pleistocene	This study	geomorphology	Profile 1-1' Figure 7	Flood surface (Qt2)	1	3	12	22	0.05	0.25

Abbreviations: CRB, Columbia River Basalt;
*Geologic rate assumes fault activity since the geologic deposit was formed.
** Ages discussed in text. Age of Siletz terrane is based on the emplacement of the Siletz terrane (Snavely et al., 1968)
*** Vertical slip-rates calculated based on maximum and minimum observed offsets. QTg rate is a hypothetical rate, see text for further discussion.

FIGURES

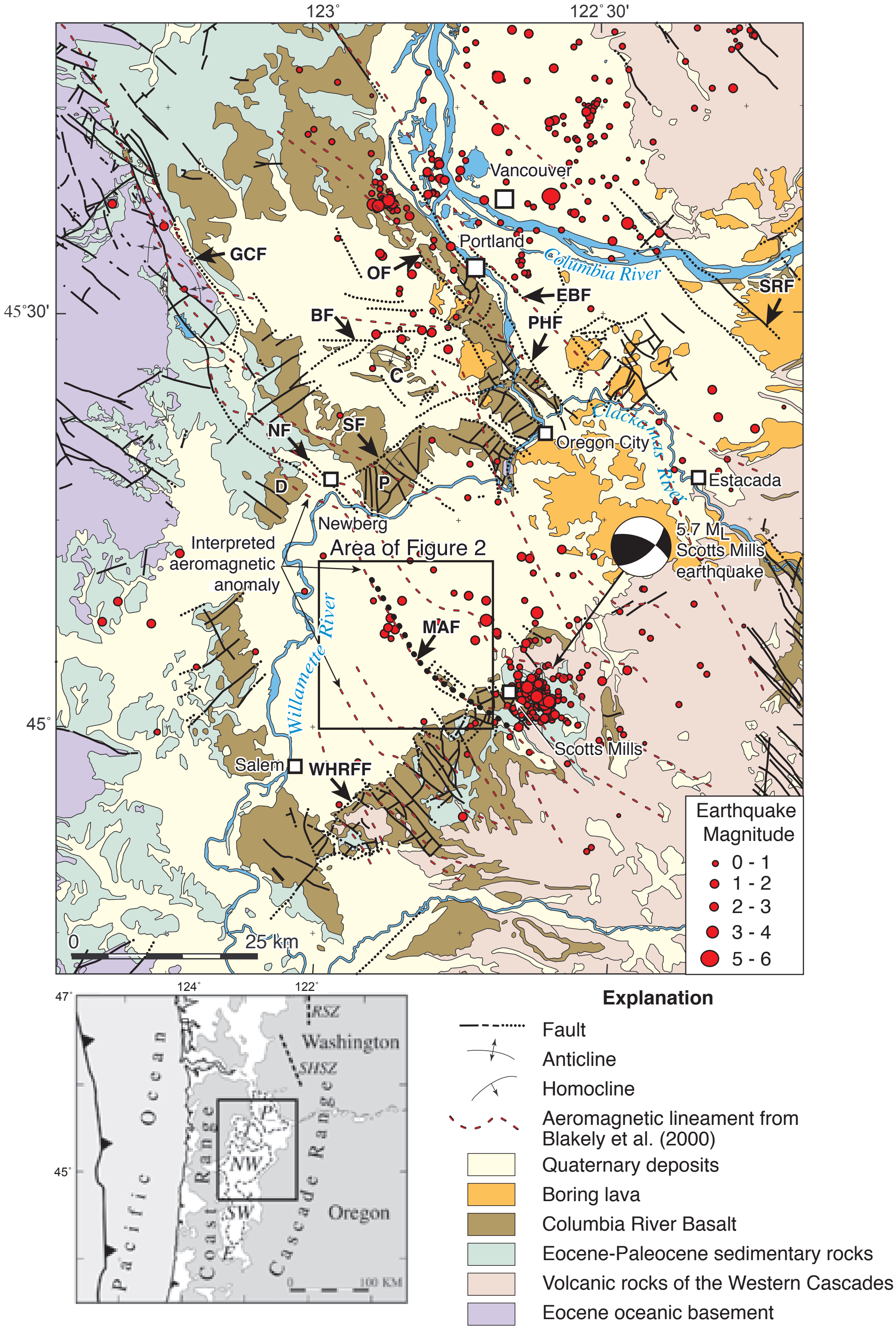


Figure 1. Location and generalized geologic map of the Northern Willamette Valley and the Portland Metropolitan region, modified from Blakely et al. (2000). Interpreted aeromagnetic lineaments from Blakely et al. (2003). Abbreviations are as follows: MAF - Mount Angel Fault; EBF - East Bank Fault; PHF - Portland Hills Fault: OF - Oatfield fault: SRF - Sandy River Fault: BF - Beaverton Fault: GCF - Gales Creek Fault; SF - Sherwood fault: WHRFF - Waldo Hills Range Front fault; NF - Newberg Fault; C - Cooper Mount; P - Parrette Mountain; D - Dundee Hills.

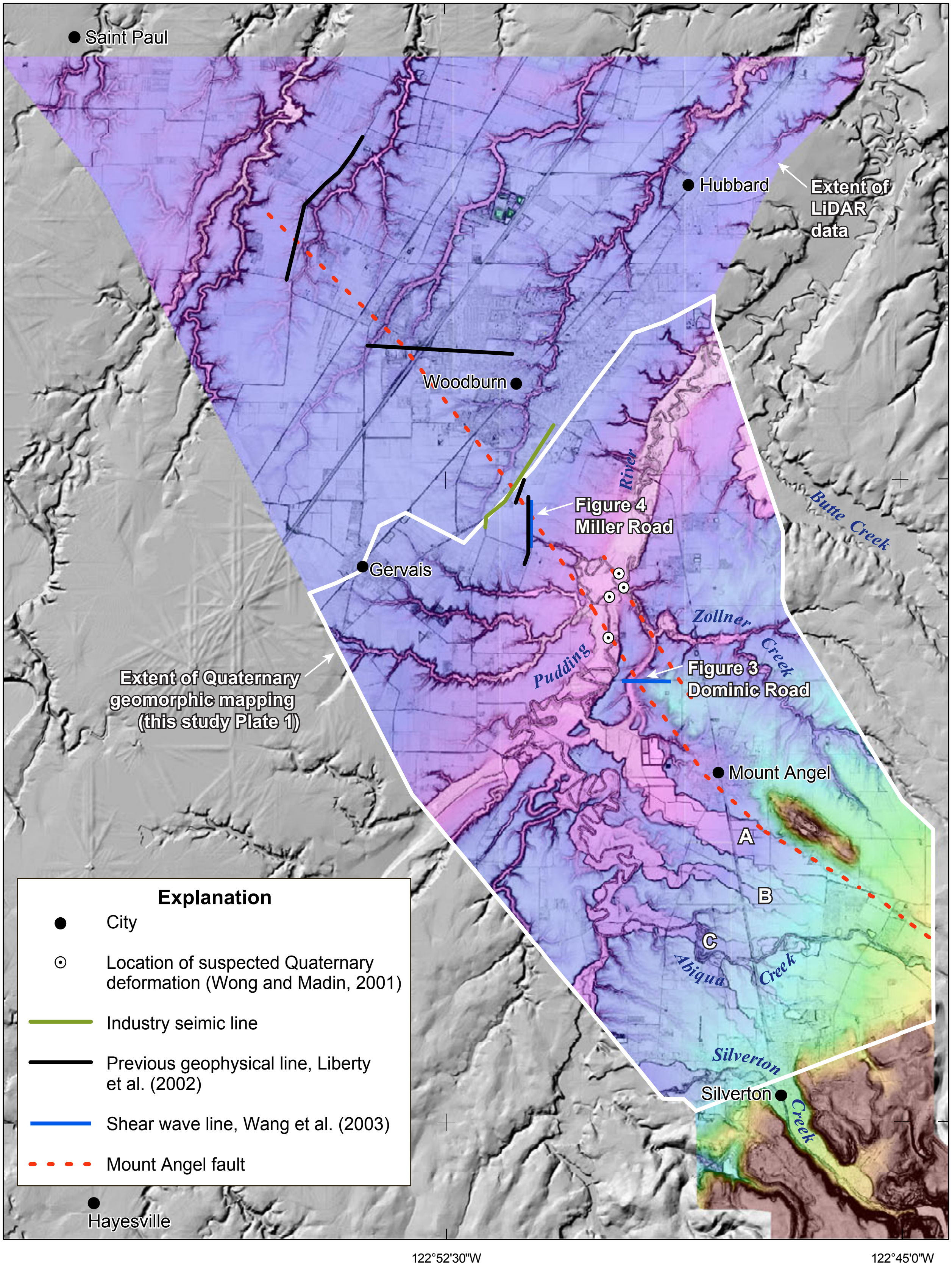


Figure 2. Slope map of LiDAR data acquired in 2007 over a DEM shaded relief map. The map illustrates the extent of Quaternary geologic and geomorphic mapping, previous geophysical lines (Liberty et al., 2002 and Wang et al., 2003), and location of the Mount Angel fault modified from Tolan and Beeson (1999) and Wang and Madin (2001). Labels A, B, and C are channels cut by Abiqua Creek referred to in the text. Topography outside colored areas is from 10-meter USGS digital elevation models.

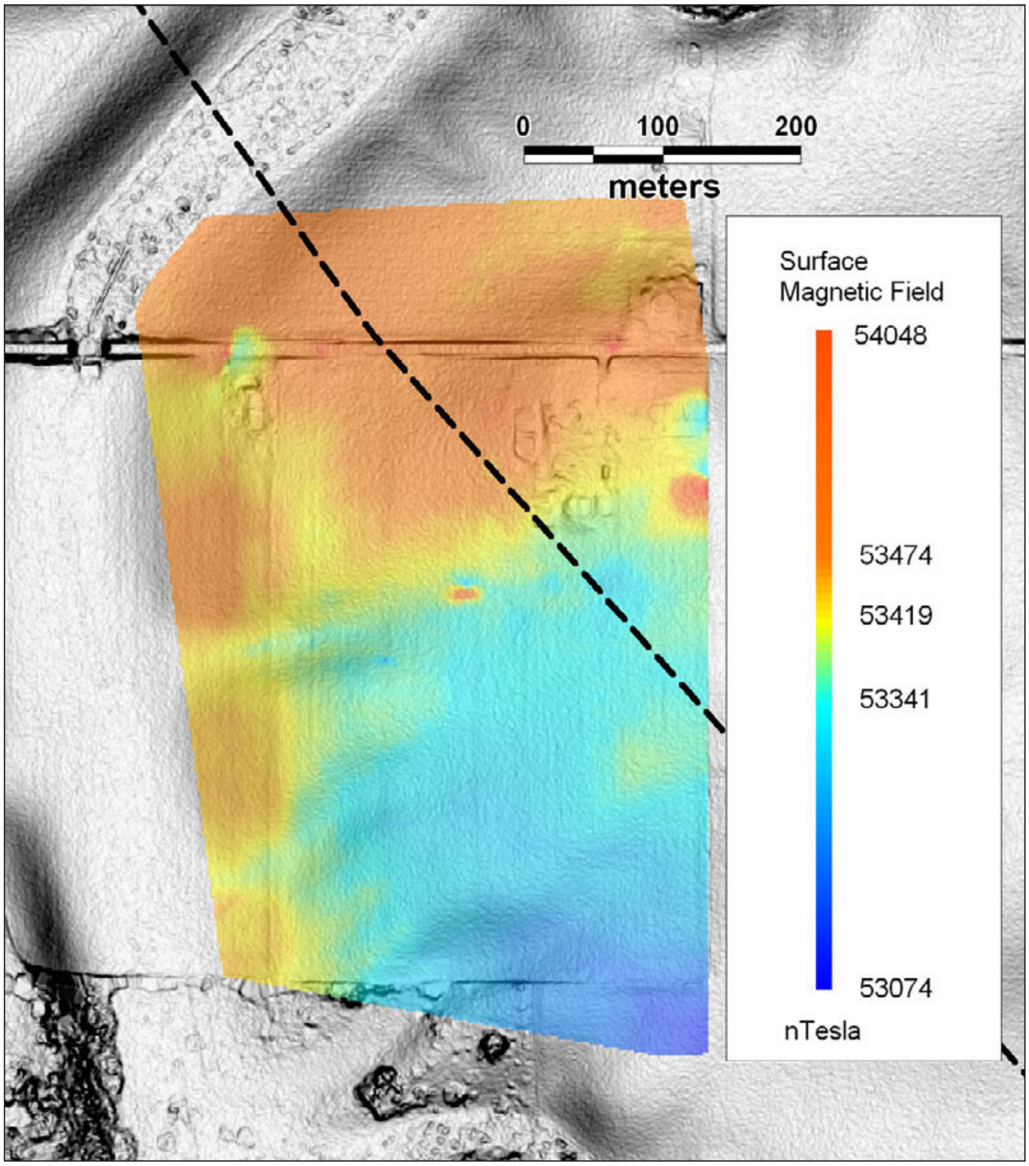


Figure 3. Magnetic survey along Dominic Road. Black dashed kube marks trace of Mount Angel fault.

A)

B)

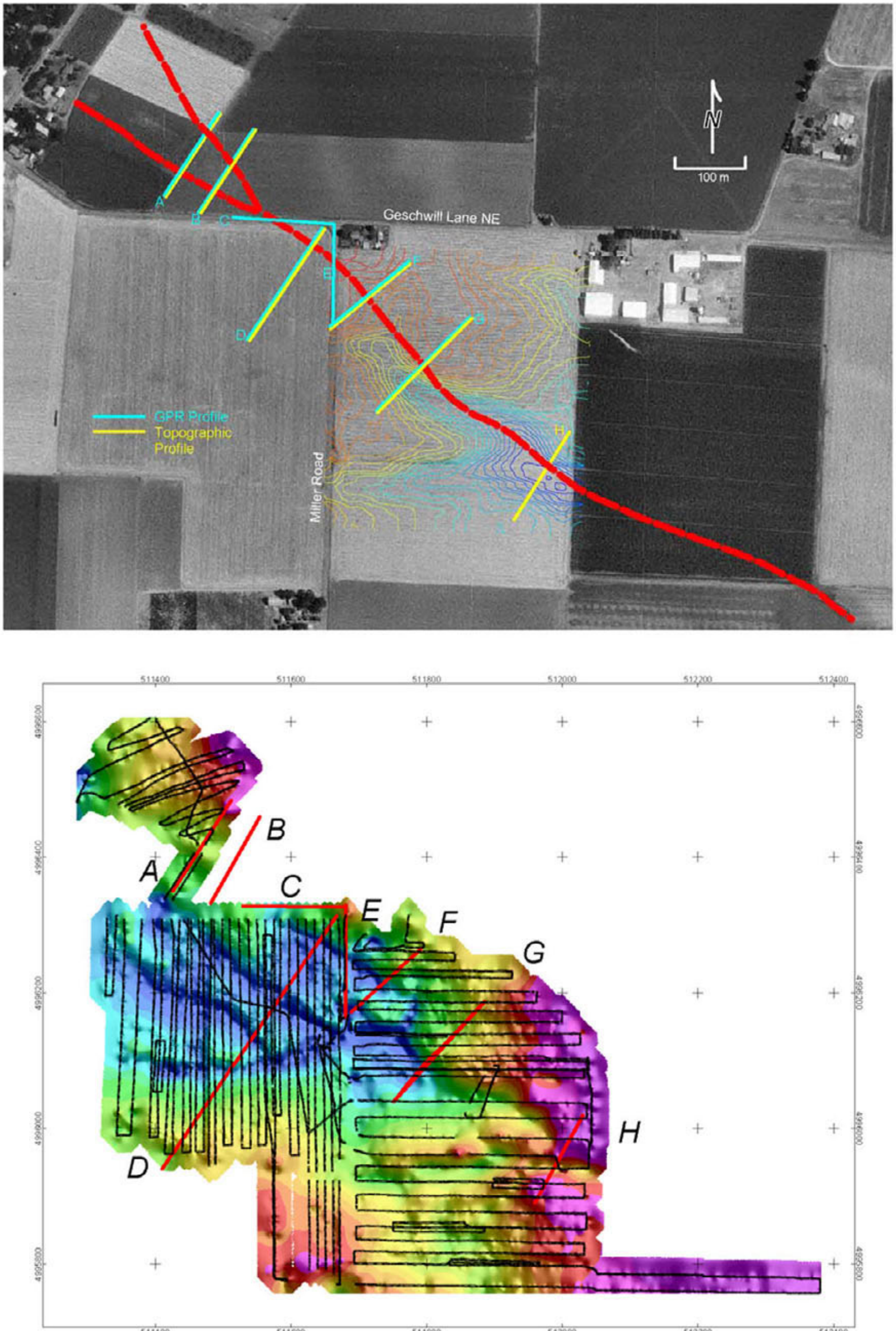


Figure 4. (A) Map of Miller Road site showing location of the inferred trace of the Mount Angel fault, ground penetrating radar (GPR) and topographic profiles, and topography (0.1-meter contour interval, warm colors indicate higher elevations). (B) Results of ground magnetic survey that revealed anomalies forming a dendritic pattern that may reflect a system of buried channels. The inferred fault trace coincides with the northeastern margins of prominent linear magnetic anomalies that intersect profiles D through G.

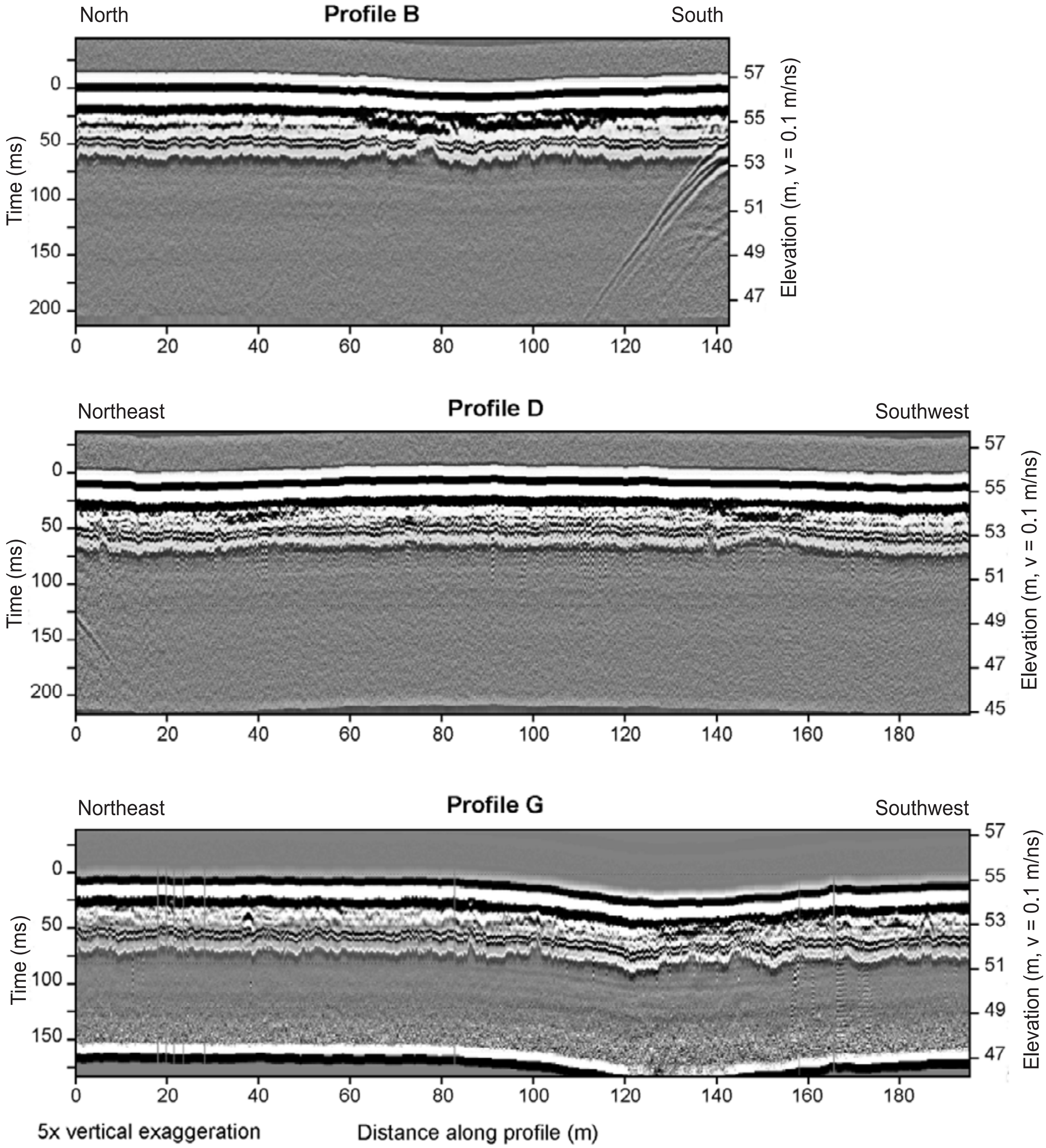


Figure 5. Selected ground penetrating radar (GPR) profiles across prominent magnetic anomalies and a subtle topographic scarp at the Miller Road site. Locations of profiles shown in Figure 4A.

Figure 6. (A) Ian Madin applies hydrophilic resin to an outcrop exposed along the Pudding River. (B) After the resin sets, a sediment peel is removed from the outcrop for further analysis in the lab. (C) The outcrop exposed after application of the resin and removal of the peel. Sandy beds, possibly foresets of a migrating river bar, dip downstream. Length of tape is approximately 0.5 meter. (D) Vertical sand dike in Missoula Flood deposits observed in the bank of the Pudding River. Length of tape is approximately 1 meter.

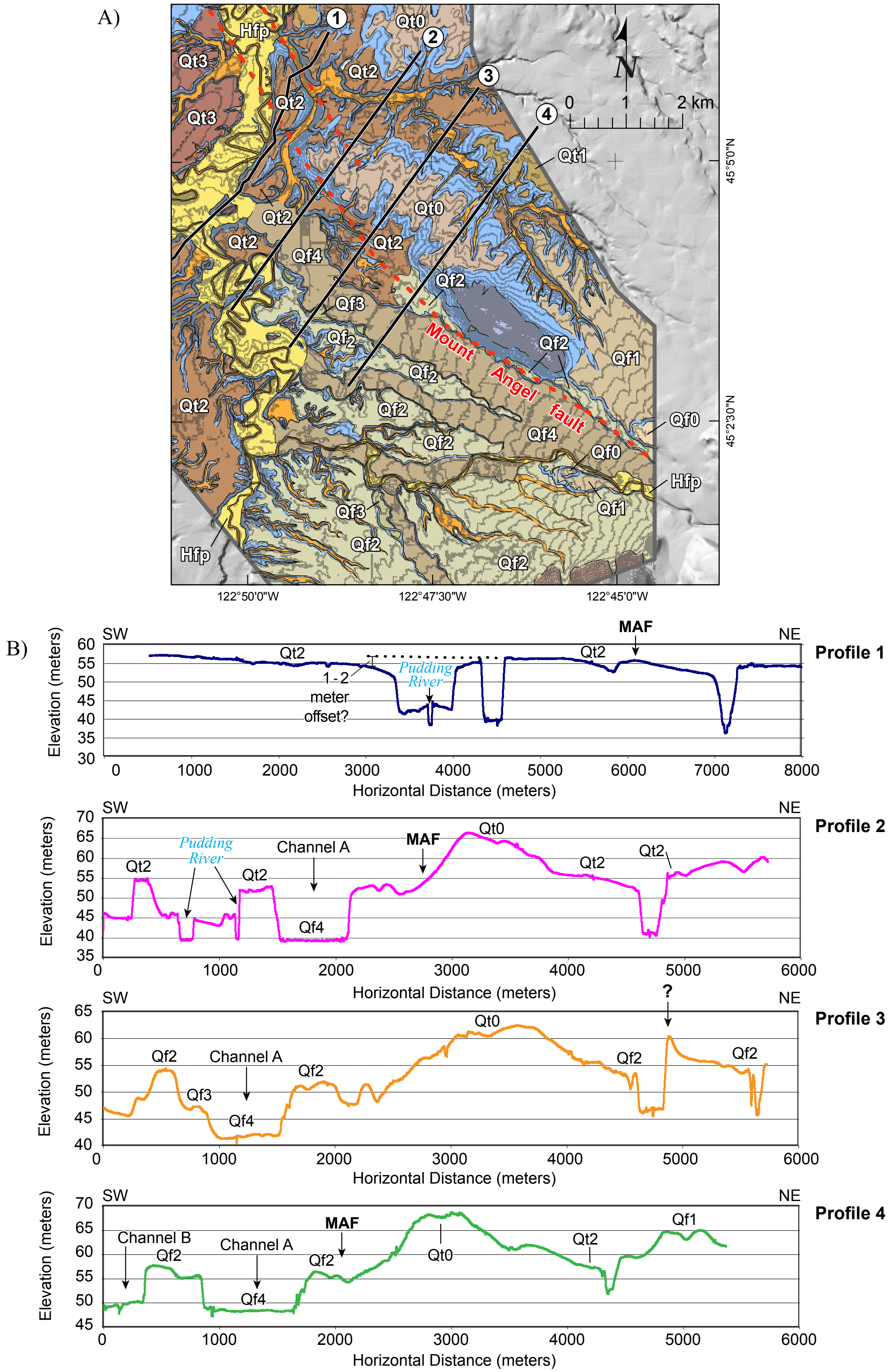


Figure 7. A) Location map of topographic profiles 1 through 4 across the Mount Angel fault and B) topographic profiles. Detailed mapping shown on Plate 1. Black lines mark locations of topographic profiles.

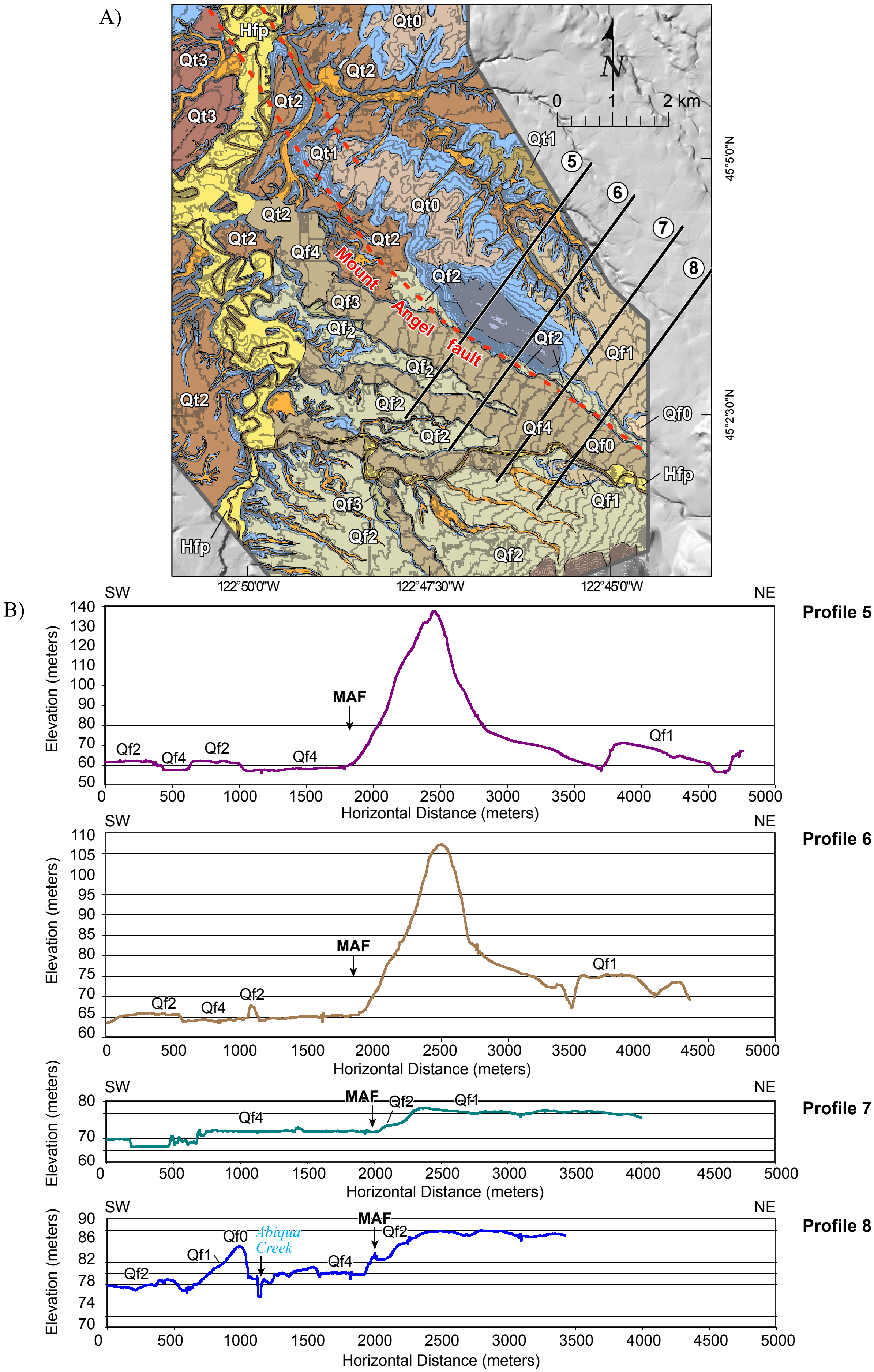


Figure 8. A) Location map of topographic profiles 5 through 8 across the Mount Angel fault and B) topographic profiles. Detailed mapping shown on Plate 1. Black lines mark locations of topographic profiles.

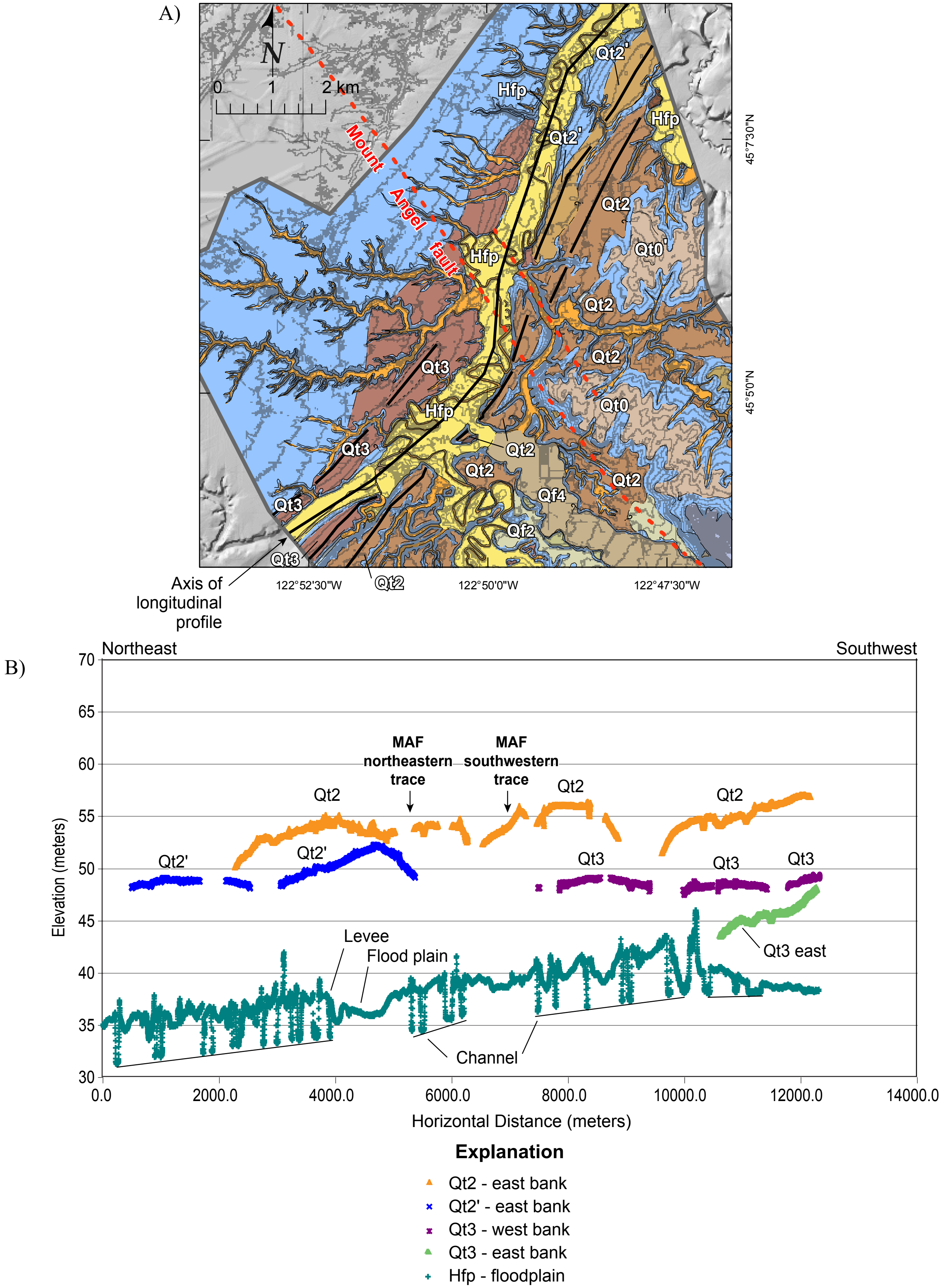
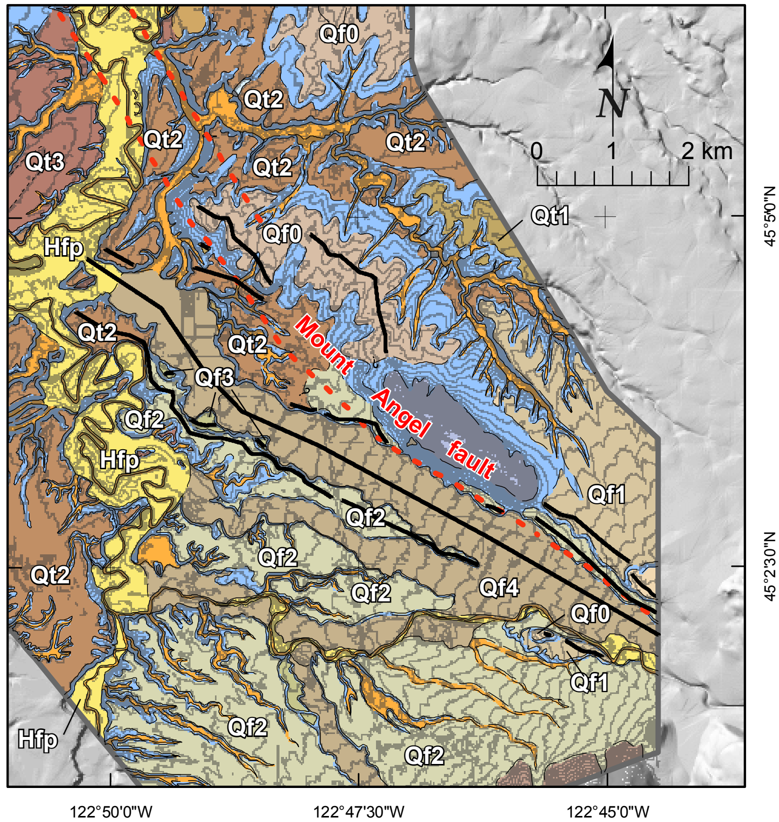


Figure 9. A) Location map and B) longitudinal profiles along the Pudding River. Detailed mapping shown on Plate 1. Black lines in A) mark locations of terrace profiles. Note the apparent change in gradient of the Pudding River between the two mapped traces of the MAF.

A)



B)

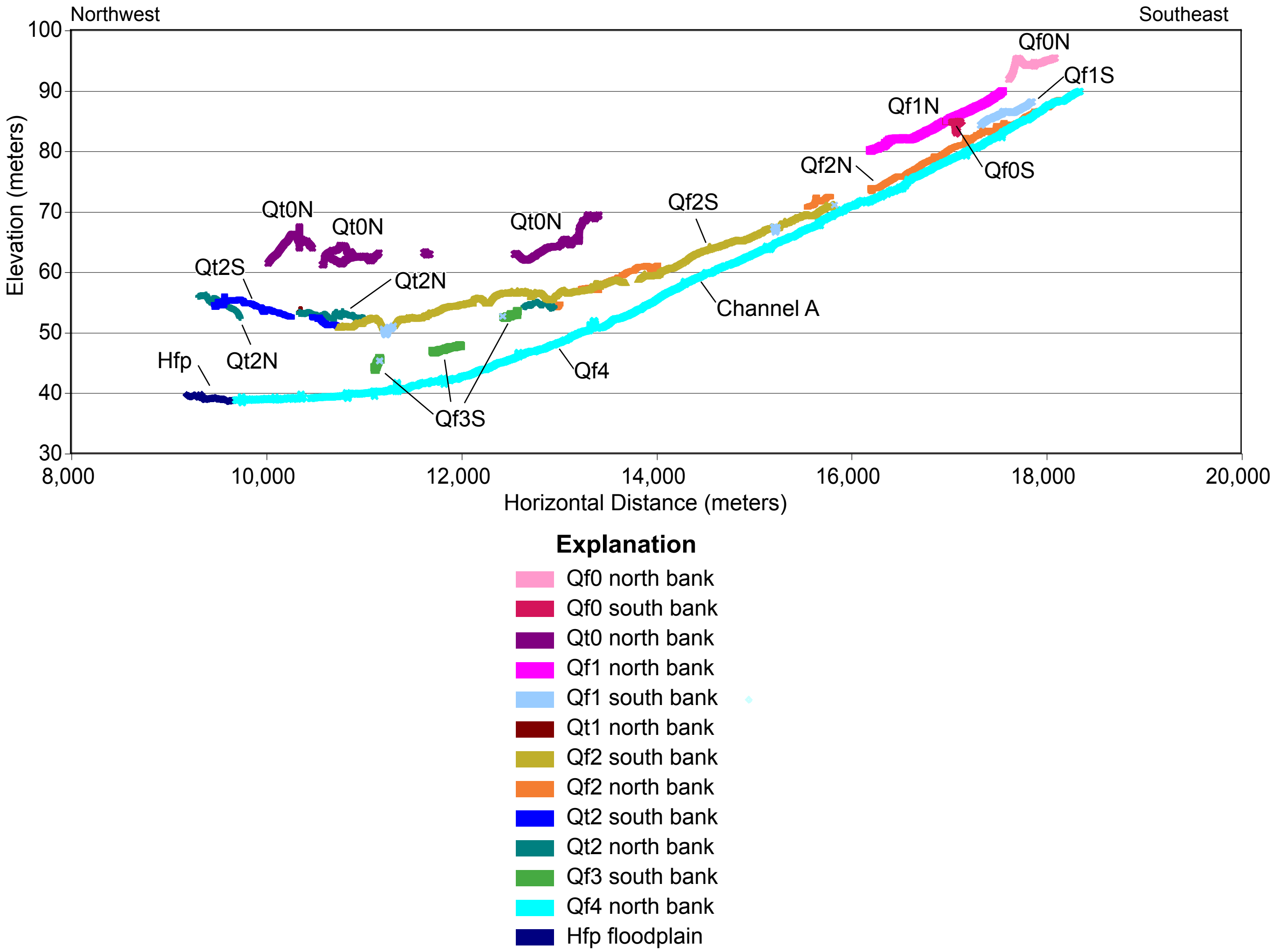
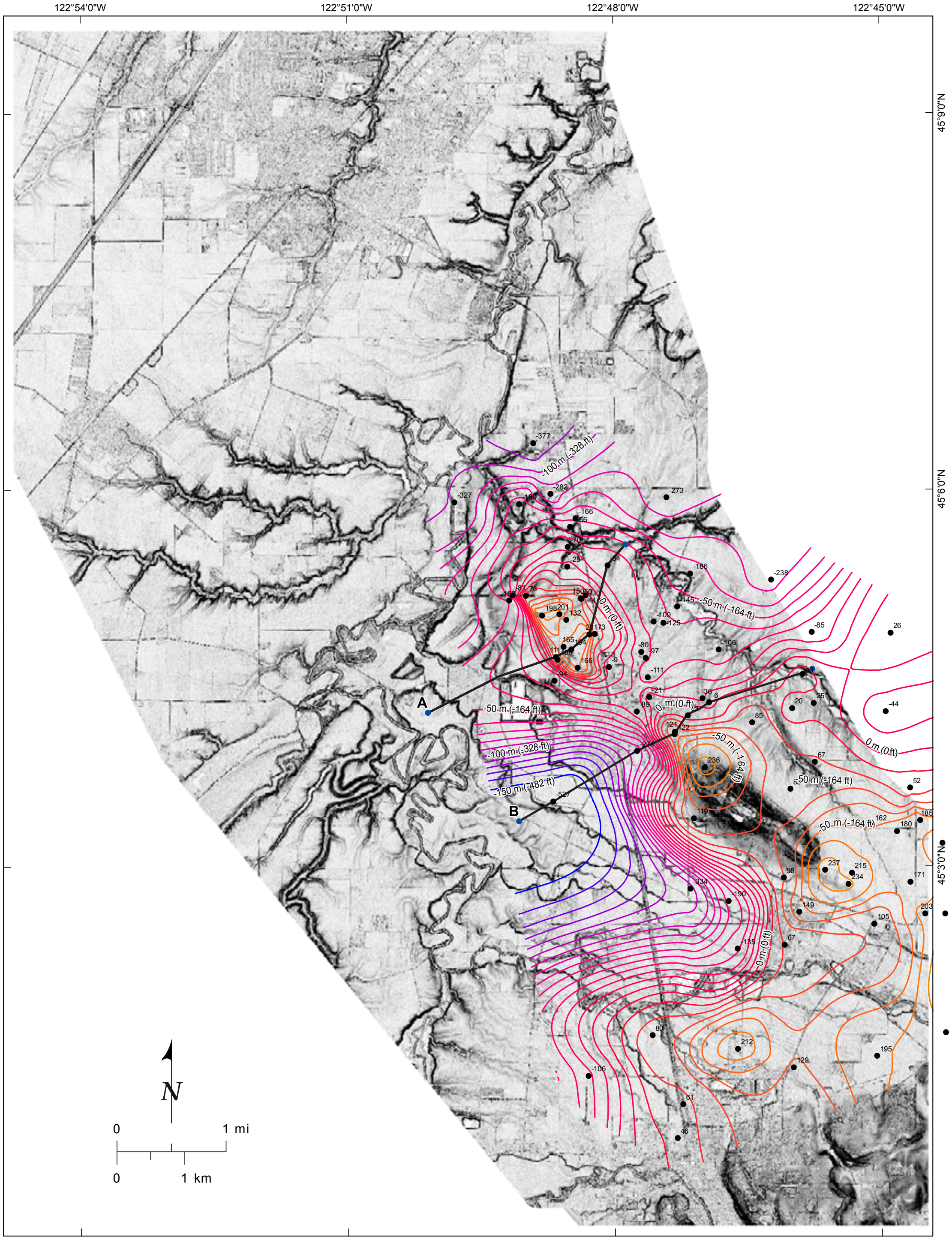


Figure 10. A) Location map and B) longitudinal profiles along the channel C of Abiqua Creek. Detailed mapping shown on Plate 1. Black lines mark locations of terrace profiles.



Explanation

DOGAMI boring log compilation Marion County, Oregon (elevations listed are in feet)

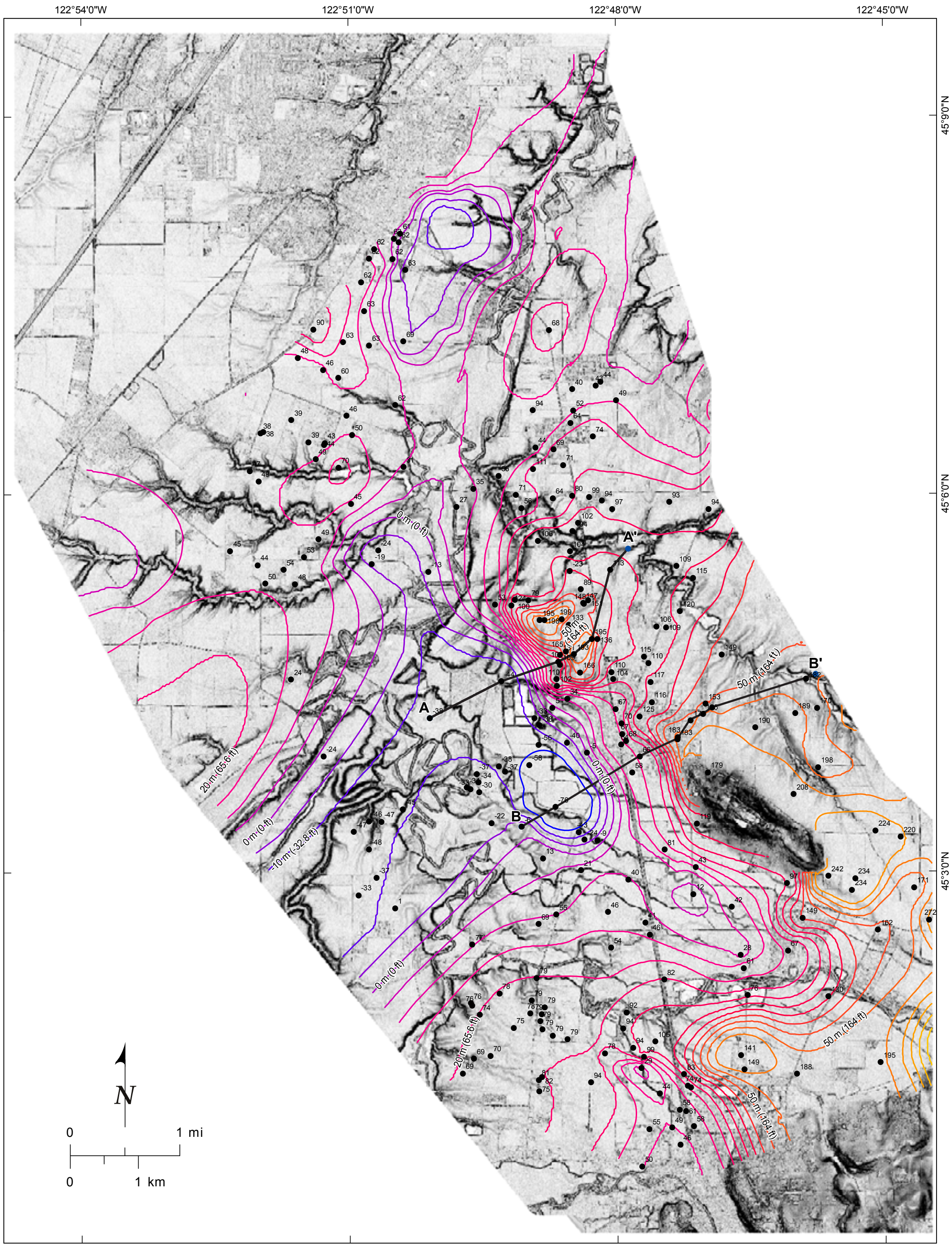
Geologic cross section (Figures 14 and 15)

Top of Columbia River Basalt Structure Contours

80 m (262.4 ft.)

-15 m (-49.2 ft.)

Figure 11. Structure contour map of the top of Columbia River Basalt. Contour interval is 5 meters.



Explanation

75 • DOGAMI boring log compilation Marion County, Oregon (elevations listed are in feet)

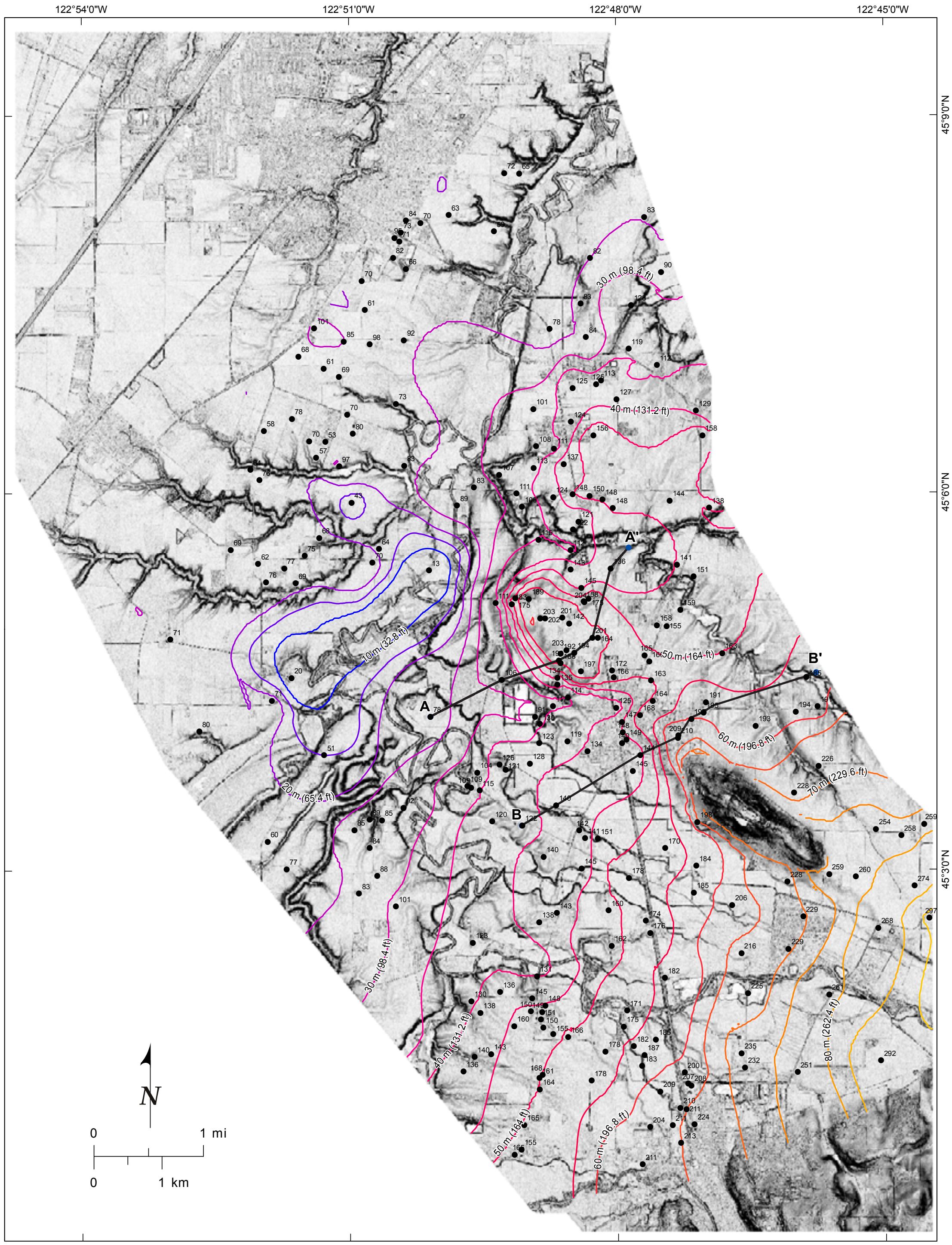
Geologic cross section (Figures 14 and 15)

Base of Gravel
Structure Contours

80 m (262.4 ft.)

-15 m (-49.2 ft.)

Figure 12. Structure contour map of the base of gravel. Contour interval is 5 meters.



Explanation

182 ● DOGAMI boring log compilation Marion County, Oregon (elevations listed are in feet)

●—● Geologic cross section (Figures 14 and 15)

Top of Gravel
Structure Contours

90 m (295.2 ft.)

10 m (32.8 ft.)

Figure 13. Structure contour map of the top of gravel. Contour interval is 5 meters.

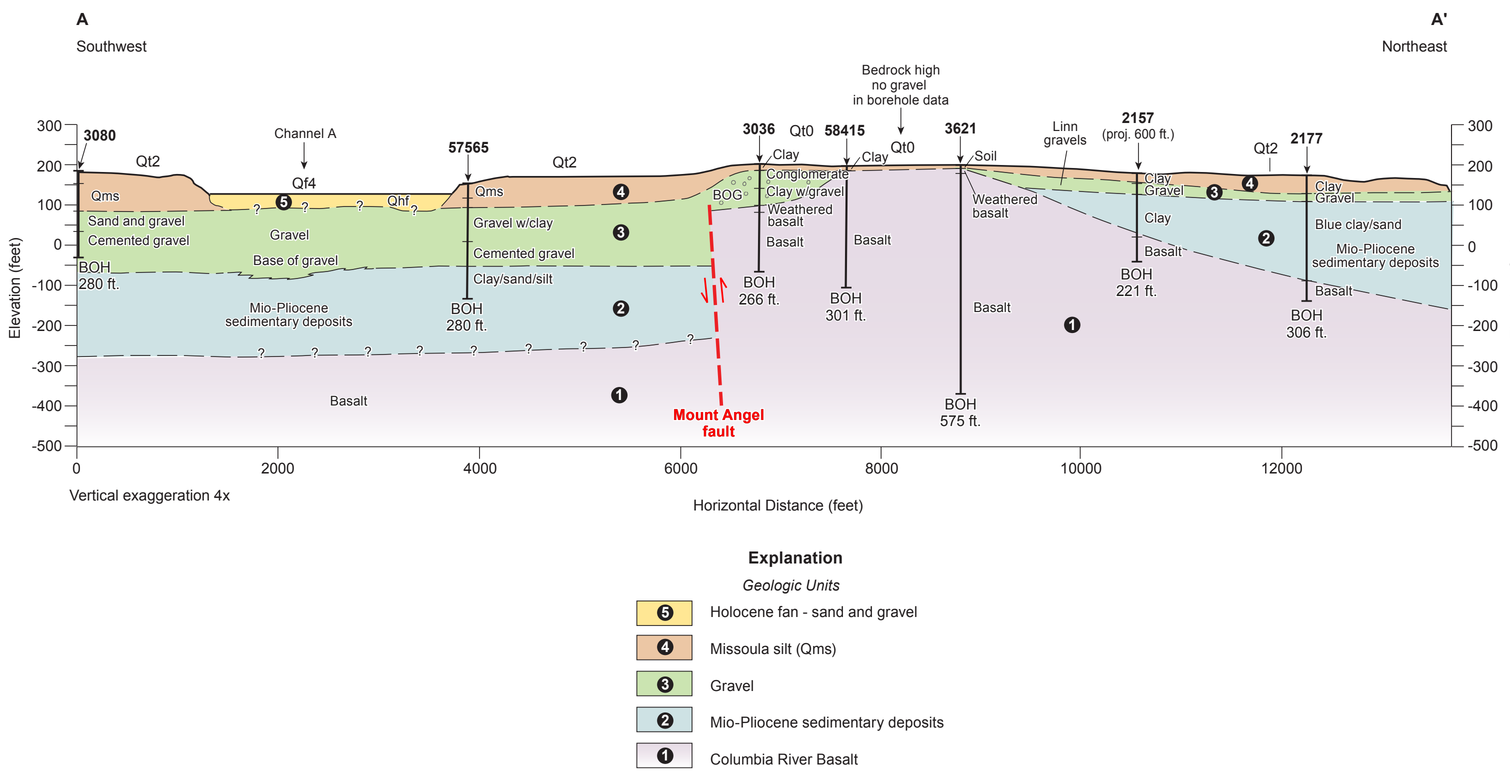


Figure 14. Geologic cross section A - A' across the Mount Angel fault (Plate 1). Water well logs from the Oregon Department of Water Resources by Madin and Wang (2001) and this study.

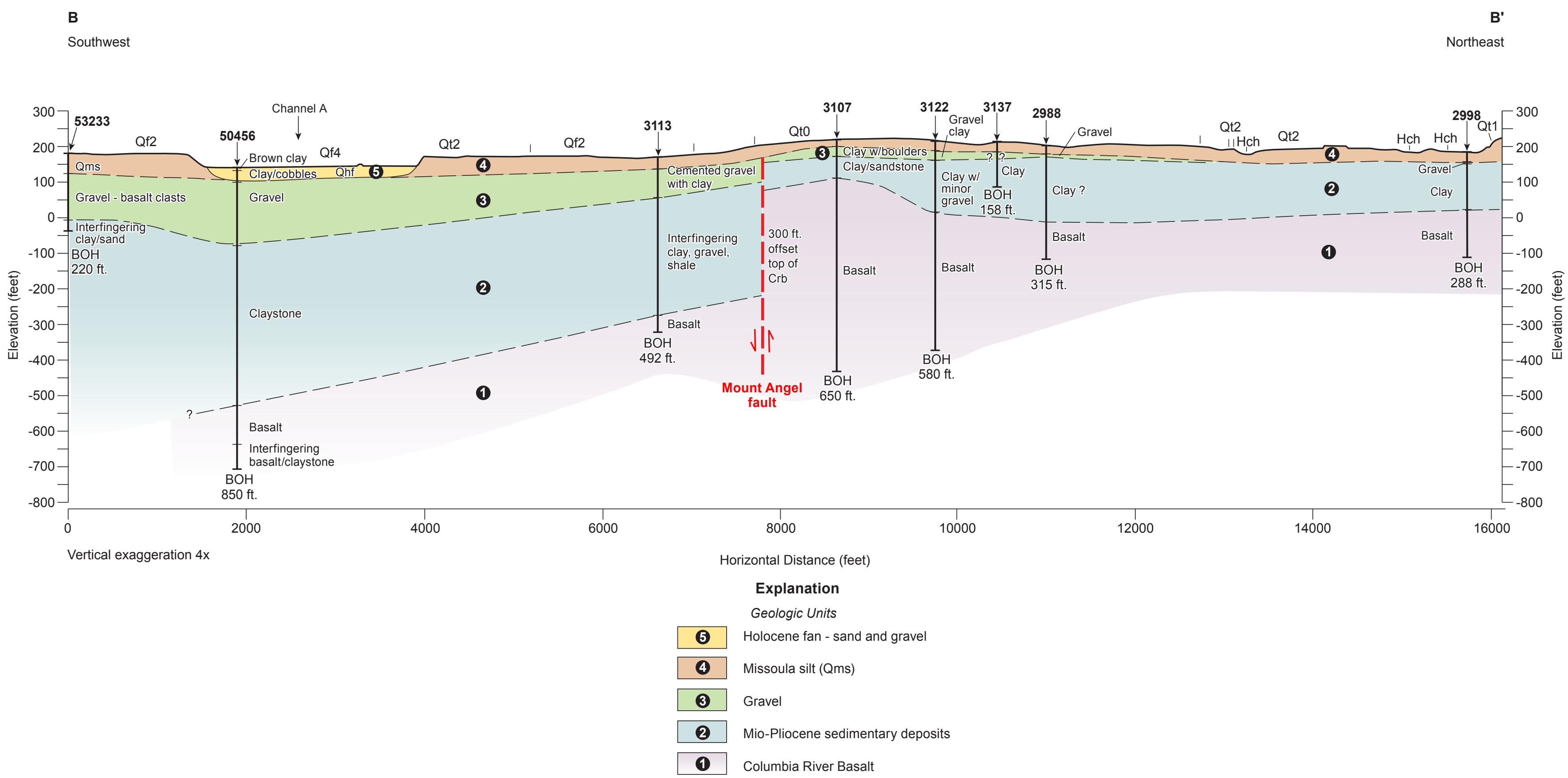


Figure 15. Geologic cross section B - B' across the Mount Angel fault (Plate 1). Water well logs from the Oregon Department of Water Resources by Madin and Wang (2001) and this study.

1793 Mount Angel Fault

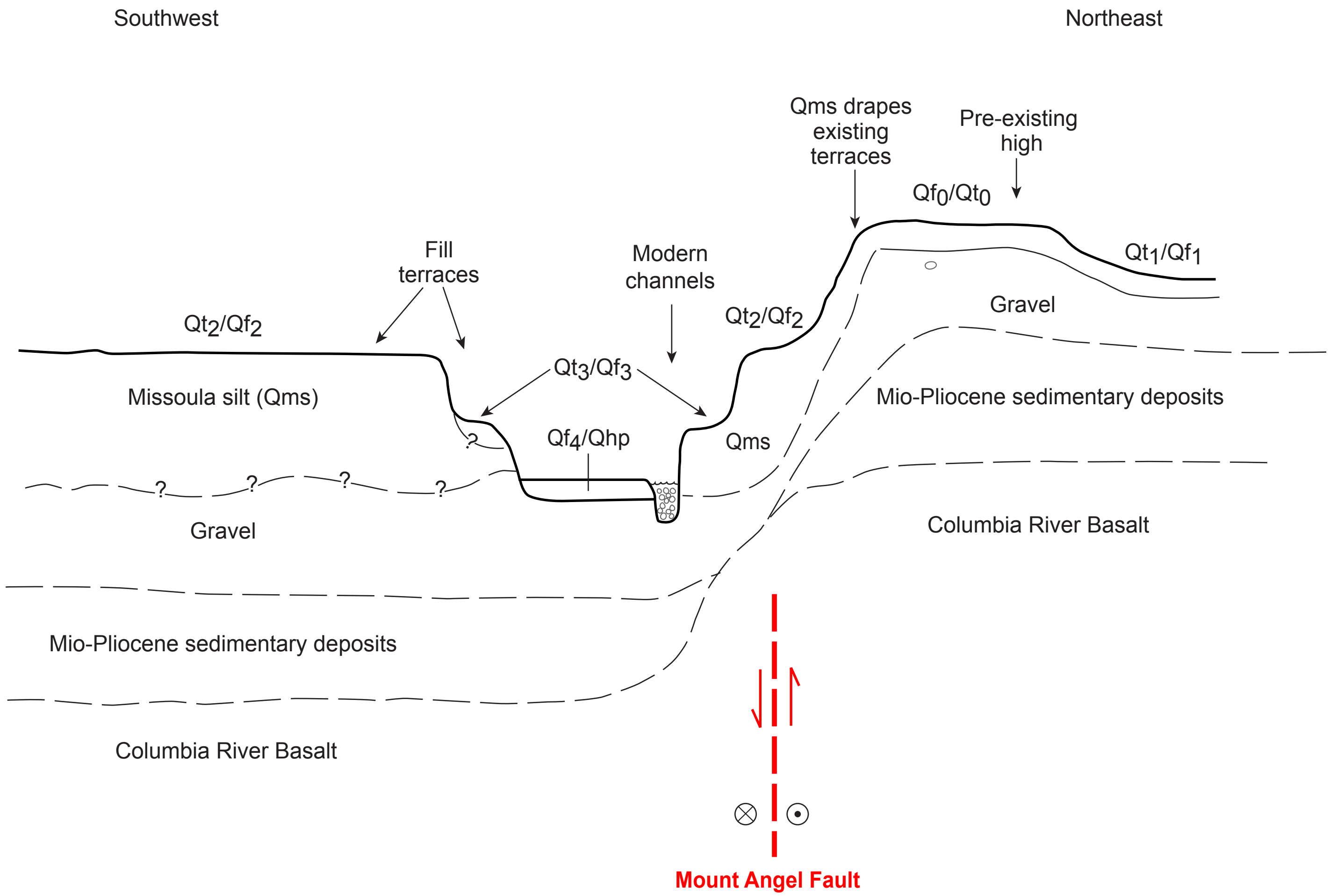


Figure 16. Schematic illustrating stratigraphic and geomorphic relationships between major geologic/geomorphic units in the Mount Angel map area.

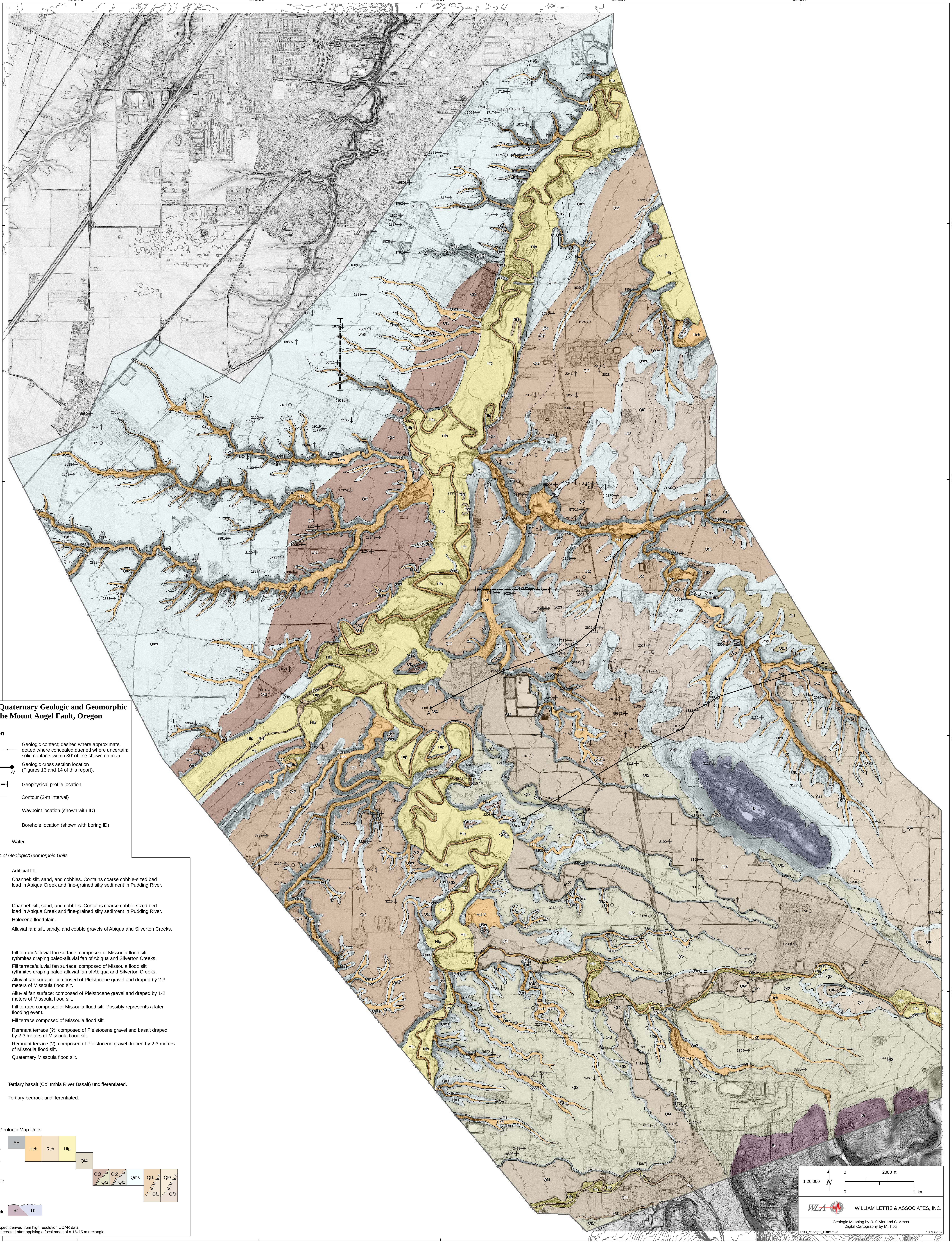


Plate 1: Quaternary Geologic and Geomorphic Map of the Mount Angel Fault, Oregon

Explanation

Geologic contact; dashed where approximate, dotted where concealed,queried where uncertain; solid contacts within 30' of line shown on map.

A — A' Geologic cross section location (Figures 13 and 14 of this report).

Geophysical profile location

Contour (2-m interval)

107 Waypoint location (shown with ID)

3052 Borehole location (shown with boring ID)

W Water.

Description of Geologic/Geomorphic Units

HISTORICAL

- AF — Artificial fill.
- Rch — Channel: silt, sand, and cobbles. Contains coarse cobble-sized bed load in Abiqua Creek and fine-grained silty sediment in Pudding River.

HOLOCENE

- Hch — Channel: silt, sand, and cobbles. Contains coarse cobble-sized bed load in Abiqua Creek and fine-grained silty sediment in Pudding River.
- Hfp — Holocene floodplain.
- Qf4 — Alluvial fan: silt, sandy, and cobble gravels of Abiqua and Silverton Creeks.

LATE PLEISTOCENE

- Qf3 — Fill terrace/alluvial fan surface: composed of Missoula flood silt rythmites draping paleo-alluvial fan of Abiqua and Silverton Creeks.
- Qf2 — Fill terrace/alluvial fan surface: composed of Missoula flood silt rythmites draping paleo-alluvial fan of Abiqua and Silverton Creeks.
- Qf1 — Alluvial fan surface: composed of Pleistocene gravel and draped by 2-3 meters of Missoula flood silt.
- Qf0 — Alluvial fan surface: composed of Pleistocene gravel and draped by 1-2 meters of Missoula flood silt.
- Qt3 — Fill terrace composed of Missoula flood silt. Possibly represents a later flooding event.
- Qt2 — Fill terrace composed of Missoula flood silt.
- Qt1 — Remnant terrace (?): composed of Pleistocene gravel and basalt draped by 2-3 meters of Missoula flood silt.
- Qt0 — Remnant terrace (?): composed of Pleistocene gravel draped by 2-3 meters of Missoula flood silt.
- Qms — Quaternary Missoula flood silt.

TERTIARY BEDROCK

- Tb — Tertiary basalt (Columbia River Basalt) undifferentiated.
- Br — Tertiary bedrock undifferentiated.

Correlation of Geologic Map Units

Historical: AF
Holocene: Hch, Rch, Hfp, Qf4
Late Pleistocene: Qt3/Qf3, Qt2/Qf2, Qms, Qt1/Qf1, Qt0/Qf0
Tertiary Bedrock: Br, Tb

Base map: slope aspect derived from high resolution LiDAR data.
Contours were were created after applying a focal mean of a 15x15 m rectangle.

1:20,000 N

0 2000 ft

0 1 km

WILLIAM LETTIS & ASSOCIATES, INC.

Geologic Mapping by R. Givler and C. Amos
Digital Cartography by M. Ticci

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