ABSTRACT

The Portland metropolitan area historically is the most seismically active region in Oregon. At least three potentially active faults are located in the immediate vicinity of downtown Portland, with the Portland Hills fault extending directly beneath downtown Portland. The temporal and behavioral characteristics of these faults are poorly understood, and the surface geologic record does not provide the insight required to assess the hazards associatied with these faults. The limited geologic information stems from a surface topography that has not maintained a cumulative geologic record of faulting, in part, due to scouring and subsequent deposition of thick, young, catastrophic flood sediments and the probable dominant strike-slip component of the faults. We integrated multiple high- resolution geophysical methods, including seismic reflection, ground penetrating radar, and magnetic profiling with regional geological and geophysical surveys to determine that the Portland Hills fault is presently active, with a zone of deformation that extends at least 400 m. The style of deformation is consistent with at least 2 major earthquakes in the last 12-15 ka, as confirmed by a temporary excavation trench that we logged. High-resolution geophysical methods provide detailed images of the upper 100 m of deformation within an active fault zone and have been shown to be critical in assessing the hazards associated with earthquakes for this region.

INTRODUCTION

The Portland, Oregon and Vancouver, Washington metropolitan area is located in a seismically active region. Recent geological and geophysical studies indicate that several potentially active faults, including the Portland Hills, East Bank, Oatfield, and Frontal faults, are located in the immediate vicinity of downtown Portland and Vancouver, an urban corridor with a population of nearly 2 million people. Prior to this study, little was known about the earthquake potential and structural style of any of these faults, or even whether the identified faults were indeed active. The paucity of information regarding earthquake hazards beyond the historic record stems, in part, from the lack of geomorphic expressionof the faults. Three major events have shaped and continue to shape the topography of the region. First, 16.9-6 Ma Columbia River flood-basalt (CRB) flows blanketed the region, creating a regionally extensive, relatively flat plain (Hooper, 1982). The topography was again reconstructed during the 12-15 ka Missoula flood events (Waitt, 1985), where upwards of 40 catastrophic flood events reworked and regionally deposited up to 30 m of sediments. Finally, urbanization has reshaped and continues to shape the landscape, thus masking any surface topographic expression that may help in identifying active faulting. In addition to a reshaped surface topography, dominantly right-lateral, strike-slip displacement controls the northwest-striking faults that dominate the region (Beeson et al., 1985; Beeson and Tolan, 1990; Beeson et al., 1989; Yelin and Patton, 1991), thus minimizing any post-Missoula flood topographic relief that may indicate surface rupture from an active fault. The lack of geomorphic expression, extensive modern surface deposits, strike-slip displacement, and urbanization makes hazard assessment difficult with geologic mapping methods. Measuring fault displacement by correlating changing lithologies within nearby water wells is useful, but is limited due to the poorly-defined boundary that separates modern deposits from reworked older sediments, and the large variabilty in sediment types that comprise modern deposits. Large- scale geophysical methods (e.g., aeromagnetics, industry-scale seismic) are useful to locate faults, but do not provide the information needed to evaluate present-day earthquake hazard risks.

Subsurface mapping using near-surface geophysical methods is well suited for unraveling the neotectonic history of this region. The match between high-resolution geophysics and neotectonic studies in the Portland Basin and surrounding regions stems from the presence of a hard basalt basement, of known age, within a few hundred meters of the ground surfacestrong magnetization, and large seismic impedance contrast compared to overlying sediments. Deposits of Miocene-Recent age interbedded fine- and coarse-grained sediments also lie within the basin. The varying lithology within the sedimentary section enables high-quality seismic imaging while coarse-grained flood deposits within the upper few meters enables high-quality ground penetrating radar (GPR) imaging.

Our approach to assessing earthquake hazards in a highly urbanized region is to identify the approximate location of potentially active faults in a culturally quiet setting. We use existing geologic maps, regional geophysical data, and water well lithologies, then pinpoint stratigraphic offsets in the basalt basement and overlying younger sediments using seismic reflection and magnetic methods that focus on the upper few hundred meters below the ground surface. We then narrow our focus to image deformation in latest Pleistocene to modern sediments (upper 20 m) using both high-resolution seismic and GPR methods. This culiminates with documentation of individual surface rupture events exposed by exploratory trenching. Identifying clear evidence for earthquake related deformation in 12-15 ka sediments using both geophysics and a trench suggests that the fault is active and warrents further hazards investigations to understanding timing and magnitude of fault activity.

GEOLOGIC SETTING

Earthquakes in the Pacific Northwest (Figure 1) occur due to intraplate and interplate stresses related to active subduction of the Juan de Fuca plate and large-scale crustal block rotations within the North American plate (Figure 1). Although the largest earthquakes (M 8 or larger) have been documented along the subduction zone (Atwater and Hemphill-Haley, 1997; Atwater et al., 1995) and deep earthquakes occur within the Juan de Fuca plate (e.g., the 2000 Nisqually EQ), a significant hazard also exists from earthquakes in the upper crust of the North American plate. Upper plate earthquakes occur on crustal faults at relatively shallow depths (<25 km) and are of particular concern to the populated areas of western Oregon and Washington, where northwest-trending crustal faults have formed as a result of the breakup and rotation of the Cascade fore arc (Wells et al., 1998). Crustal faults are known to exist beneath most of the densely populated regions of western Oregon and Washington, and because of their shallow depth, crustal earthquakes can produce severe ground shaking (e.g., Wong et al., 2000).

The Portland area is the most seismically active region in Oregon in historical times. Based on the 150-year historic record, six earthquakes of Richter magnitude (ML) 5 or greater have occurred within the metropolitan area including the damaging 1962 ML 51/2 Portland and 1993 ML 5.6 Scotts Mills earthquakes (Bott and Wong, 1993), the latter causing $30 million in damage to buildings and infrastructure in a mainly rural setting (Madin et al., 1993; Wong et al., 1993).

The Portland/Vancouver region lies in a sedimentary basin at the northern terminus of the Willamette Valley. The Portland Basin contains Miocene age fine-grained sediments, Pliocene-Pleistocene age coarse-grained deposits, and late Pleistcene to Recent age coarse- and fine- grained flood deposits associated with Missoula flood events (e.g., Swanson et al., 1993; Yeats et al., 1996). Beneath the sedimentary cover, the stratigraphic section is dominated by Miocene and older volcanic and sedimentary units. The Portland Basin lies at the boundary between two crustal blocks that separate a compressional volcanic arc regime to the north and an extensional arc to the south

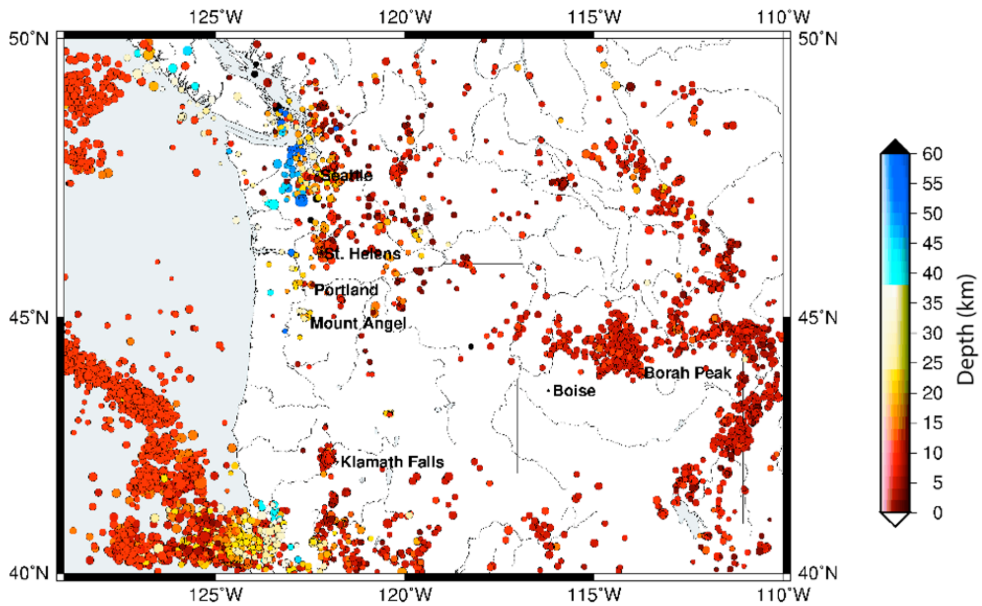

Figure 1a - Pacific Northwest schematic with seismicity since 1980. Circles represent earthquake epicenters, colors represent epicenter depth.

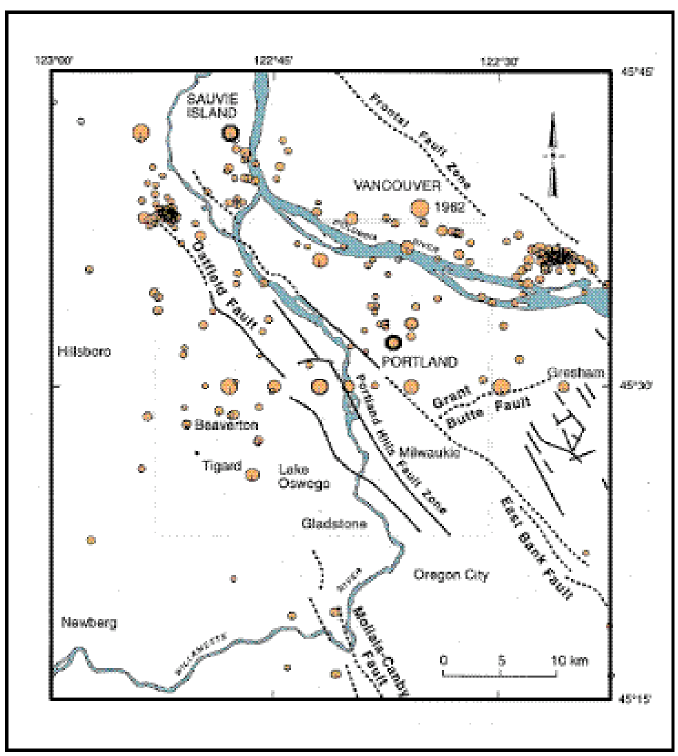

Figure 1b - Portland metropolitan area with historical seismicity since 1841. Figure from Wong et al. (2001).

(Magill et al., 1981; Wells, 1990) and may have formed in response to the transfer of strain between the basin bounding faults (Beeson et al., 1985; Yelin and Patton, 1991). The basin is controlled by northwest-striking faults that, on the basis of geologic relations, earthquake focal mechanisms, and potential field anomalies, have right-lateral, strike-slip displacement (Beeson et al., 1985; Beeson and Tolan, 1990; Beeson et al., 1989; Blakely et al., 1995; Yelin and Patton, 1991). The northeast boundary of the Portland Basin is controlled by the Sandy River and Frontal faults (e.g., Blakely et al., 1995; Walsh et al., 1987; Yelin and Patton, 1991). The southwest boundary of the Portland Basin is controlled by the Portland Hills fault (PHF) and perhaps also by the Oatfield and East Bank faults (e.g., Beeson et al., 1991; Blakely et al., 1995; Madin, 1990; Wong et al., 2001).

The three crustal faults that define the southwest boundary of the Portland Basin have been identified as potential sources for damaging crustal earthquakes of ML 61/2 or larger in the Portland region. An evaluation of earthquake recurrence based on the historical record suggests that crustal earthquakes of ML 6 or larger occur somewhere in the Portland region on average about every 1000-2000 years (Bott and Wong, 1993). Wong et al. (2000) showed that earthquakes from local faults present a greater risk than earthquakes associated with the Cascadia subduction zone. The PHF, extending through downtown Portland, has been identified as the greatest local hazard (Wong et al., 2000). In a moment magnitude (MW) 6.8 earthquake scenario on the PHF, calculated ground motions, as characterized by peak acceleration, exceeded 1g. Thus although in its 150-year existence, the Portland metropolitan area has gone relatively unscathed by damaging earthquakes, strong ground shaking generated by an earthquake on the PHF or nearby fault will have a major impact on the Portland area.

GEOLOGICAL AND GEOPHYSICAL STUDIES

Earthquake hazards studies in western Oregon and Washington often rely on geophysical methods to identify the location and characteristics of crustal faults, since a pronounced topographic expression from faulting does not appear on the surface. Numerous industry seismic reflection surveys from the region were acquired in the past in an interest for oil and gas deposits. Published results from these surveys (e.g., Liberty, 2002; Werner et al., 1992) document vertical offsets in the basement rocks and suggest that younger sediments are also offset. Regional aeromagnetic studies (Blakely et al., 2000; Blakely et al., 1995) have identified lineaments that correlate with crustal faults, including the PHF that extends below downtown Portland. Recent regional seismic reflection surveys that have focused on neotectonic studies (e.g. Liberty et al., 1999; Pratt et al., 2001; Wong et al., 2001) document offsets in Plio-Pleistocene age sediments above basement rocks. Prior to this study, Holocene-age disruption of sediments was inferred, but not directly documented.

Prior to our investigation, the PHF had been identified and located only on the basis of large-scale geomorphic features such as the asymmetric anticline and fault line scarp of the Portland Hills (Madin, 1990) and from an aeromagnetic survey (Blakely et al., 1995). Blakely et al. (1995) identified a magnetic lineament associated with the PHF as a long-wavelength dominated signal to the east separating a short wavelength dominated signal that appears to the west (Figure 2). The absence of pronounced surficial features typically considered indicative of high slip rate fault activity, such as alluvial scarps, offset and aligned drainages and tonal, vegetation lineaments, does not preclude this fault from being a considerable seismic source. This can be attributed to surficial deposits that consist of 12 and 15 ka channel fill and overbank flood sediments associated with the draining of glacial Lake Missoula (Figure 3) (Waitt, 1985), a considerable amount of urban development, and the possibility that a significant portion of lateral slip occurs on the fault.

The principal objective of this investigation is to better locate and characterize the PHF and provide a site to fully characterize the temporal and behavioral characteristics with a geologic trench. The PHF is mapped for over 25 km, and possibly extends a considerable distance beyond its mapped boundaries. We focus our initial investigations at North Clackamas Park (NCP) to identify deformation of Miocene-age basalts (CRB) and younger sediments. This investigation also included identification of other potential investigation sites for more detailed fault studies. Our ultimate goal is to locate one or more sites suitable for exploratory trenching that might provide a chronology of surface rupture activity along the PHF.

NORTH CLACKAMAS PARK INVESTIGATION

The PHF is locally identified near NCP from regional aeromagnetic lineament (Blakely et al., 1995), Miocene-age basalts outcrop on a topographic high to the south (Madin, 1990) and water well lithologic logs that suggest more than 100 m of offset on the basalts across the county park (Figure 4). In addition to the location of the park with respect to the PHF, NCP extends for

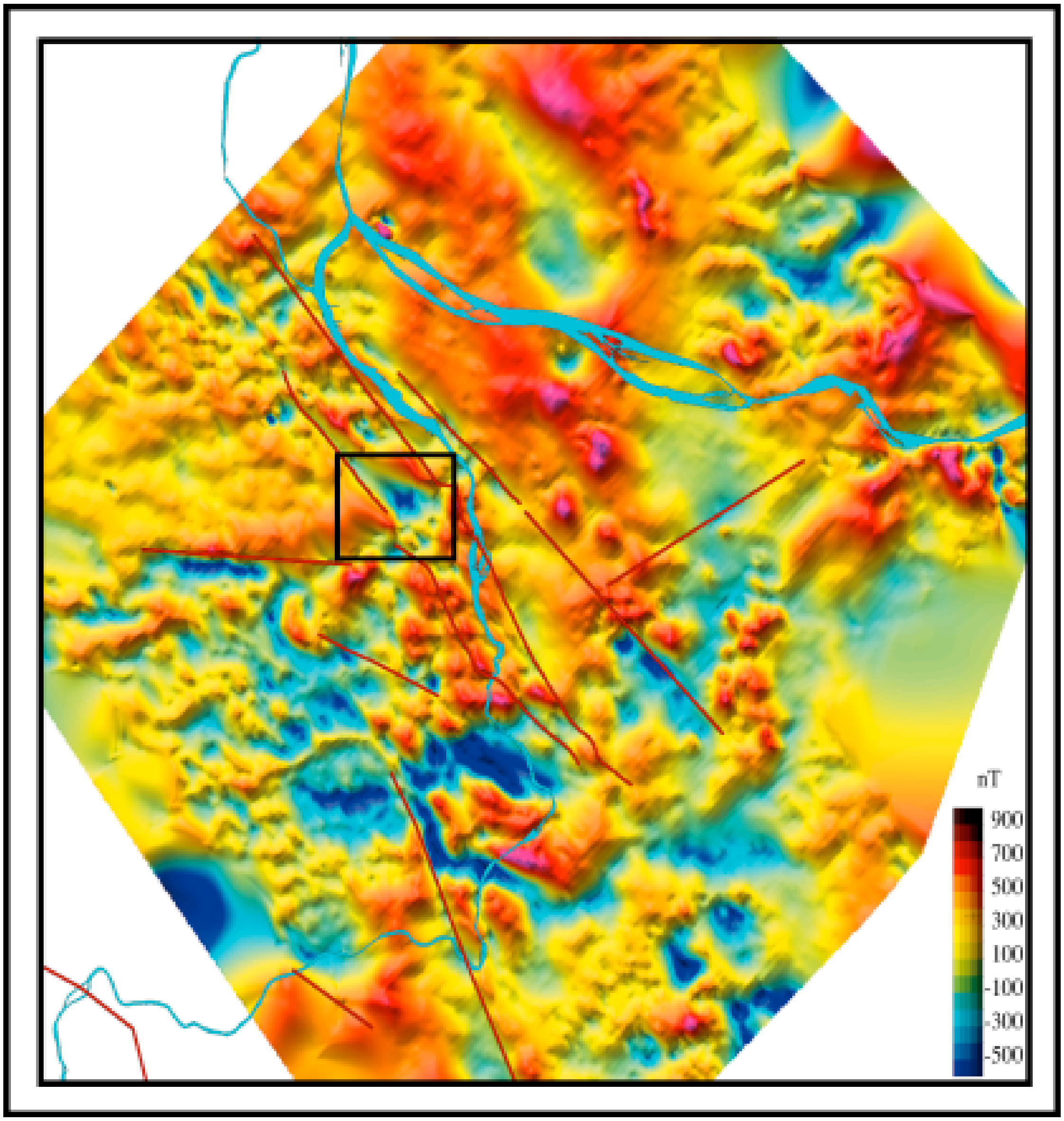

Figure 2 – Aeromagnetic anomaly map of the northern Willamette Valley (from Blakely et al. 1995). Color scale represents intensity of crustal magnetic field, expressed in nanoteslas (nT). High-amplitude anomalies probably related to Eocene oceanic basalt basement.

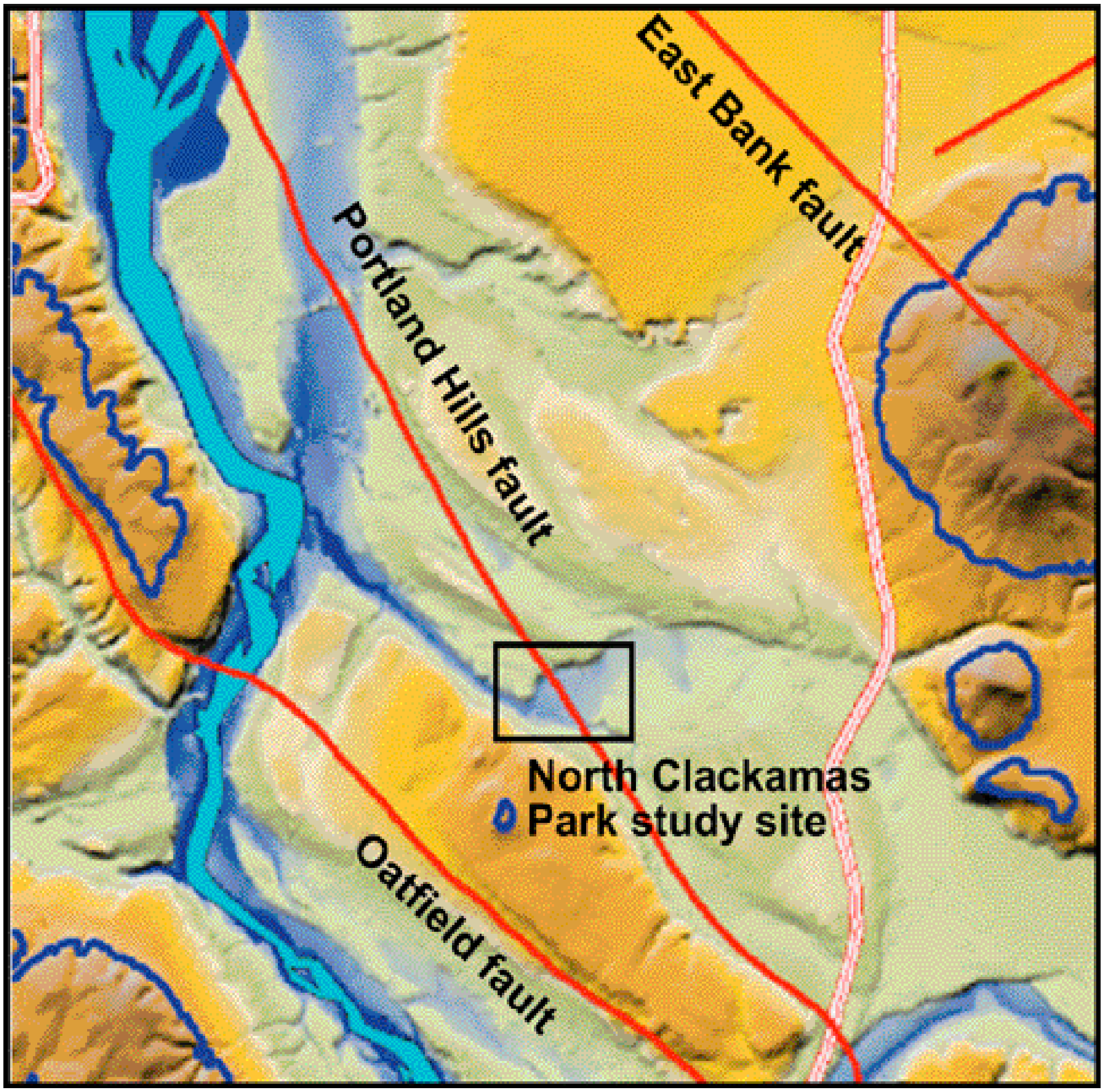

Figure 3 – Shaded topographic map of the Portland Metropolitan and surrounding areas. The approximate location of faults is based on Madin (1990). The North Clackamas Park (NCP) study site is shown in the black rectangle. Bold blue line depicts the approximate high strand line for the Missoula Floods at about elevation 300 ft. Much of the contemporary topography below this elevation is related to resculpturing by the floods.

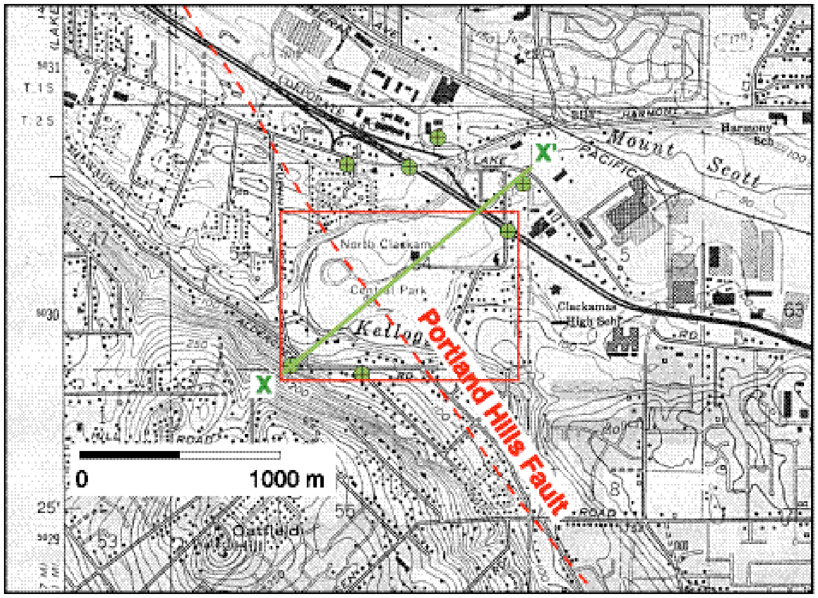

Figure 4a – Topographic map showing the distribution of water wells in the vicinity of North Clackamas Park. Red box indicates location of Figure 3. No well data were recovered from within the park. The wells span the Park and provide constraints for the location of the Portland Hills fault. The westernmost well, drilled to a depth of approximately 30 ft is located entirely within Columbia River basalt (CRB).

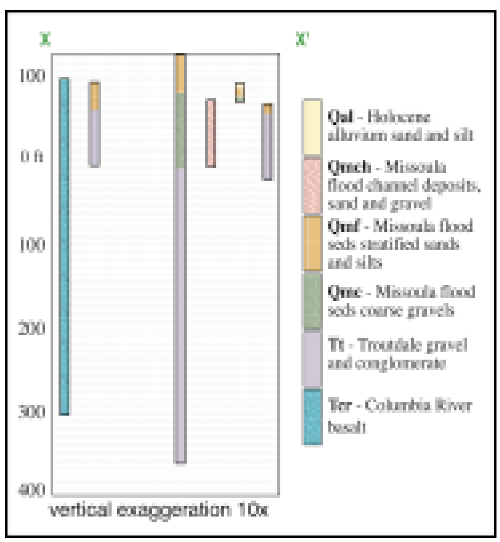

Figure 4b – Cross-section of well data across the Portland Hills fault near NCP.

approximately 1 km across strike in a culturally quiet area, and NCP is located in a topographic depression that lies within a meter of the seasonally-high water table. Although park records suggest that the upper meter of the park lands culturally may have been disturbed in recent times, the high water table elevation precluded a major sediment disturbance at depth. The NCP site is not an ideal location to confirm Holocene deformation with a trench due to the high water level and the possible removal of the youngest sediments, but alternating fine- and course-grained saturated sediments to CRB depths and a culturally quiet setting provide ideal conditions for our initial seismic investigation to identify the location and long-term deformational style of the PHF.

To locate our seismic lines, we initially acquired a ground magnetic profile that extends from the CRB outcrop to the southwest to US Hwy 224 to the northeast (Figure 5). We acquired the magnetic data with a Geometrics cesium magnetometer with a sensor located 2 m above ground surface. The magnetic profile shows a variation in magnetic intensities of more than 2500 nT across the section (Figure 6). Where CRB appears at the surface, we observe a magnetic high and an associated short wavelength signal (Figure 6). The profile contains a long wavelength (~500 m), large amplitude anomaly along the southwest portion of the profile, with a relatively flat signature to the northeast. We associate the observed long wavelength anomaly with variations in topography on the top of the CRB which matches the signal characteristics of the regional aeromagnetic survey. The changing depth to CRB inferred from the magnetic signature is confirmed with lithologic well logs from the region (Figure 4). Figure 6 also shows the calculated 240 m elevation upward continued anomaly that would correlate with the Blakely et al. (1995) survey and the observed anomaly from this same survey. Although the observed and calculated anomalies from the airborne survey are not identical, in part due to the coarse sampling of the aeromagnetic data, the ampliutude and wavelengths of the anomalies are similar.

Once we identified the magnetic anomaly that we infer to be topography of CRB ,we acquired two split spread P-wave seismic profiles, that extend approximately 1.0 km and 0.5 km respectively, across the PHF. We used an airless jackhammer, also described as a vertical slide hammer, as a seismic source and we vertically stacked 10-16 times per station. We acquired the seismic data with a 120-channel Geometrics 24-bit seismograph with 1.0 m station spacing to focus on the upper 100 m below land surface. We acquired shots at each 1/2 station (1 m interval) to

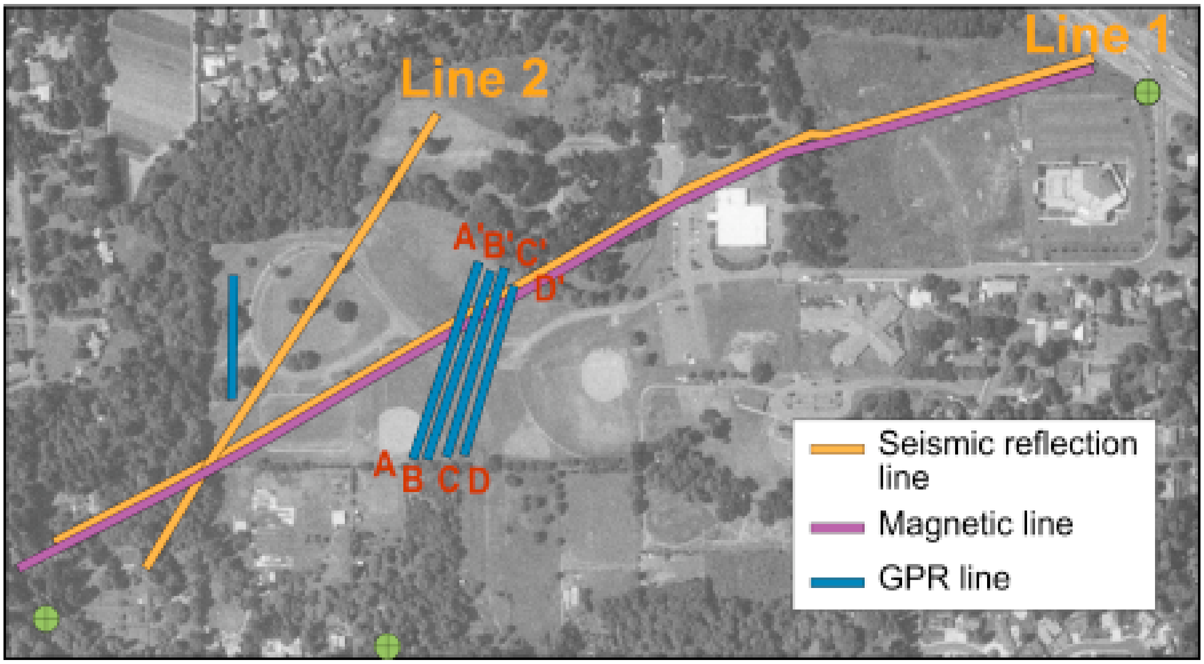

Figure 5 – Locations of geophysical studies within the NCP study area. Two small green circles depict the locations of two southern wells shown in Figure 4a.

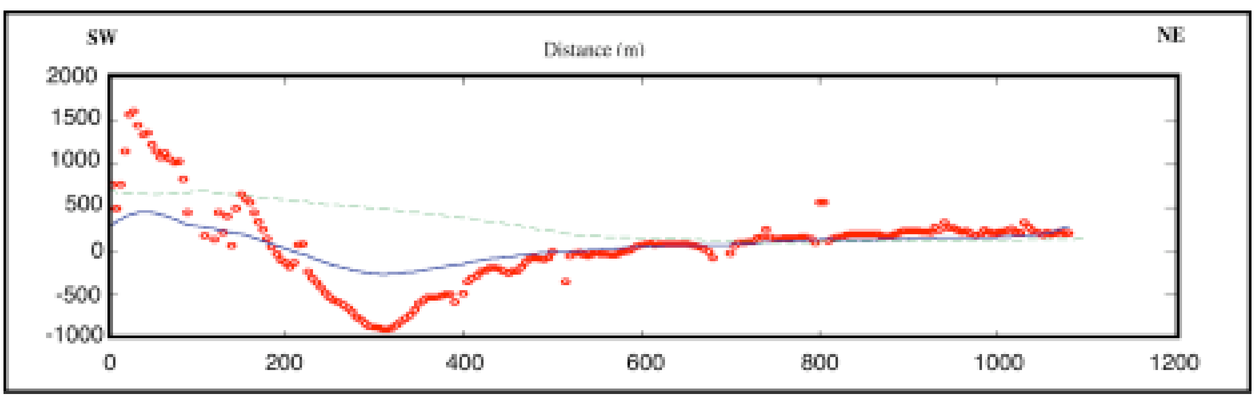

Figure 6 – Ground-based magnetometer survey results (see Figure 5 for location of transect). Red circles along magnetometer survey denote observed ground-based values, blue line is the upward continued anomaly to 240 m above land surface, and green dashed line represents the observed values interpolated from Blakely et al. (1995) 240 m elevation aeromagnetic survey.

provide nominal 60-fold seismic reflection images with a common mid-point (CMP) spacing of 0.5 m. We recorded the data with a 0.5 ms sample rate using 10-Hz geophones.

We processed the seismic data with Landmark's ProMAX seismic processing software. Figures 7 and 8 show the seismic reflection stacks with processing steps that include a bandpass filter, elevation statics, and trace mutes to remove ground roll, air wave, and refraction energy, detailed velocity analyses, dip moveout, and deconvolution, and migration.

The seismic profiles at the NCP site (Figures 7 and 8) provide detailed images of the upper 100 m of the stratigraphic section, and identify significant offset in the Miocene-age Columbia River basalts (CRB) and overlying sediments. Seismic Line 1 (Figure 7), magnetics (Figure 6), and well log information (Figure 4) indicate that basalts dip to the northeast and are observed at depths greater than 100 m to the north of the site. Line 1 shows a strong amplitude, steeply dipping (~25 degrees) horizon that correlates with the CRB/sediment contact (Figure 7). Reflections from younger sediments, dominately Plio-Pleistocene sands and gravels to Latest Pleistocene and modern Missoula flood deposits, also appear deformed to the 400 m position along Line 1. To the northeast (> 400 m position), reflections associated with young sediments (within 10 m of the surface) appear flat lying. Although our seismic source did not have adequate energy and/or proper acquisition parameters to image the CRB reflector to the northeast, we suspect that the depth to the CRB horizon does not significantly vary. We base this on the ground magnetic survey that shows no major magnetic anomaly east of the 400 m location along our profile (Figure 6) and nearby well log information (Figure 4).

We acquired Line 1 slightly oblique to the dip of the PHF to obtain a profile that extends across the PHF for more than 1 km. We also acquired a short dip profile (Line 2) that crosses the PHF, but does not show the undisturbed sediments to the northeast of the fault zone. Line 2 shows very similar features at the CRB/sediment contact reflection (Figure 8); a primary reflection that dips to the southwest at roughly 25 degrees, with a sequence of reflections that appear folded above the dipping CRB reflection. Two prominent antiformal structures appear to deform Pliocene and younger sediments within the section (Figure 8). Since Line 2 appears as the dip profile, the observed structures on this profile better represent the subsurface structure below NCP.

A difficulty with the NCP site is that the site lies on a topographic low that contains saturated sediments within one meter of the surface. We constructed four GPR transects across

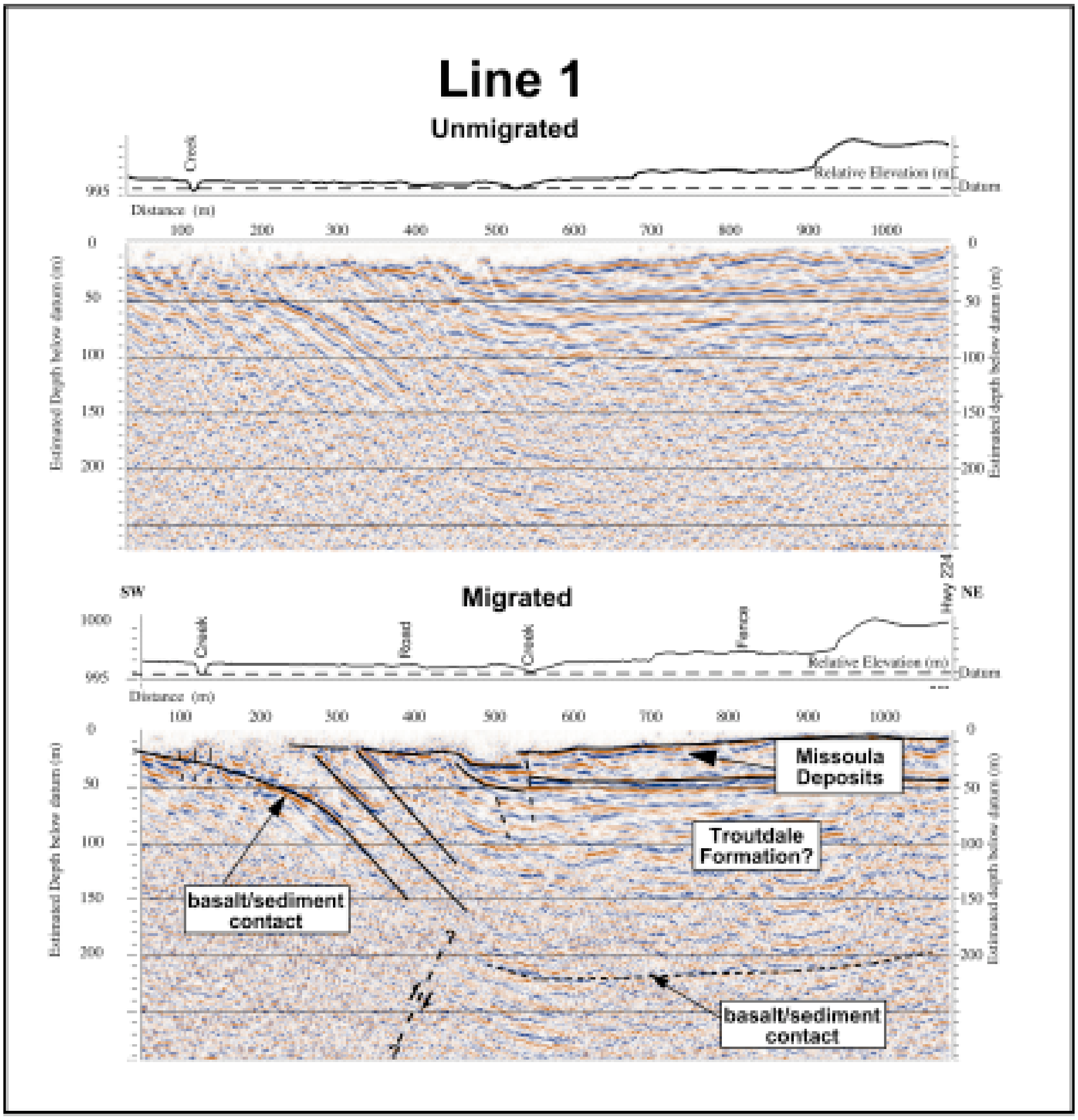

Figure 7 – Unmigrated and migrated results from seismic reflection Line 1 (see Figure 5 for transect location). Reflections dip approximately 25 degrees to the northeast on the southwest portion of the profile while reflections are flat lying to the northeast. Note the abrupt change in reflection character at 400 m distance. Basalt/sediment contact is inferred from geologic outcrop and water wells.

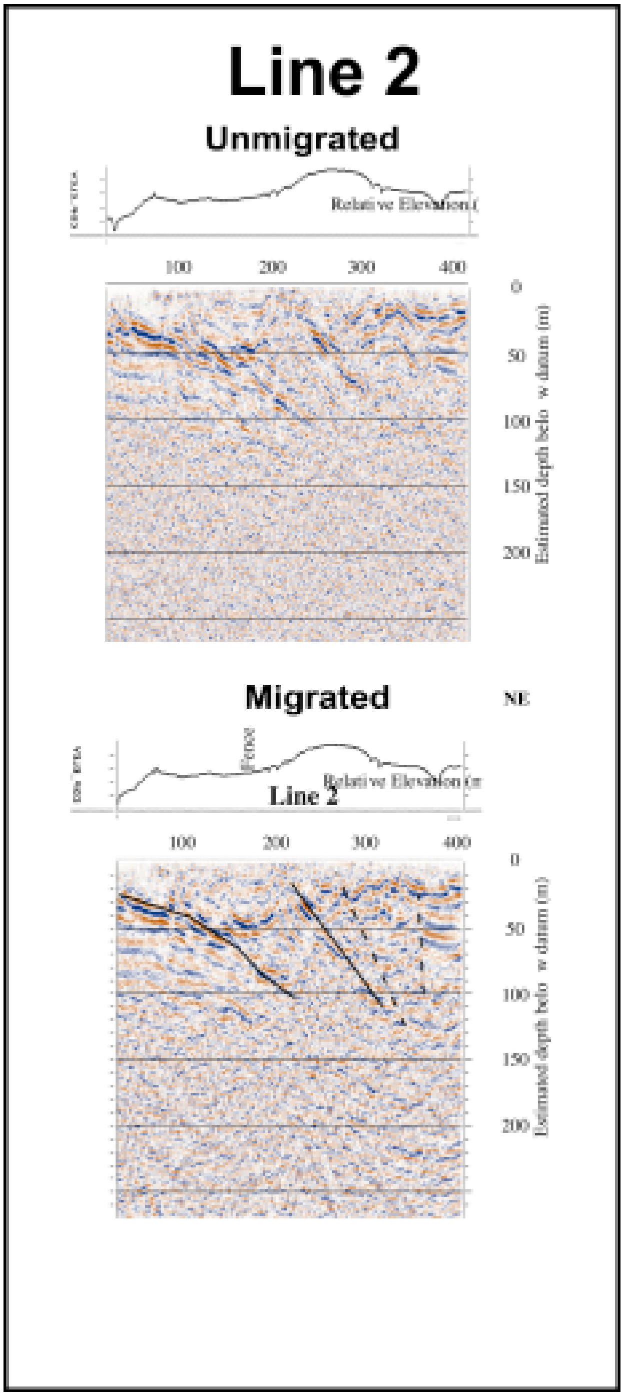

Figure 8 – Line 2 seismic reflection dip profile (see Figure 5 for transect location). This profile shows apparent compressional deformation within 10 m of the surface.

seismic line 1 at the location of suggested major offest along the PHF (Figure 3). However, the ground surface is highly conductive, and thus GPR surveying for very shallow imaging was not successful. Althought we could identify a relatively large-scale feature such as a buried alluvial channel at a depth of between 2 and 5 m (Figure 9) we were unable to identify deformation-related features. Also, we could not confidently determine from well-based lithologic logs (Figure 4) that Holocene sediments appear at this site.

It does appear that, at NCP, based on the geological and geophysical information, significant shortening of Plio-Pleistocene age sediments appears along the PHF and that the fault zone extends at least 400 m (possibly deformation extends into the basalt stratigraphy to the southwest). We were unable to identify direct evidence for Holocene deformation at the NCP site.

DISCUSSION

Prior to this study, little was known about the temporal and behavioral characteristics of the Portland Hills fault. However, during our investigation, we conducted high-resolution geophysical surveys to document more than 100 m of offset and and tilting of Miocene-age basalts and folding and faulting of probable Pliocene and younger aged sediments.

Three high-resolution geophysical methods that follow regional geophysical and geological surveys have shown significant value in uncovering buried active faults in the Portland/Vancouver metropolitan area. Ground-based magnetic surveys, in conjunction with the regional aeromagnetic counterpart, help clearly identify the magnetic signature associated with offsets in Miocene-age and older volcanic rocks. The regional aeromagnetic survey clearly identifies the PHF from a lineament that correlates with the mapped location of the PHF, although the dominant source of the aeromagnetic lineament is not likely from offset CRB, but from offsets of deeper magnetic sources (Eocene-age volcanic rocks) with a greater vertical offsets (Blakely et al., 2000; Liberty et al., 1999). The high-resolution ground-based magnetic surveys contain considerably greater detail for zone of deformation for a fault, and the amplitude and wavelengths associated with the high-resolution surveys more likely represents the magnetic signal from offsets in the top of the CRB at depths of less than a few hundred meters. Magnetic methods help identify the location of potentially active faults, but the deformational style and timing of faulting is not included in the magnetic signal.

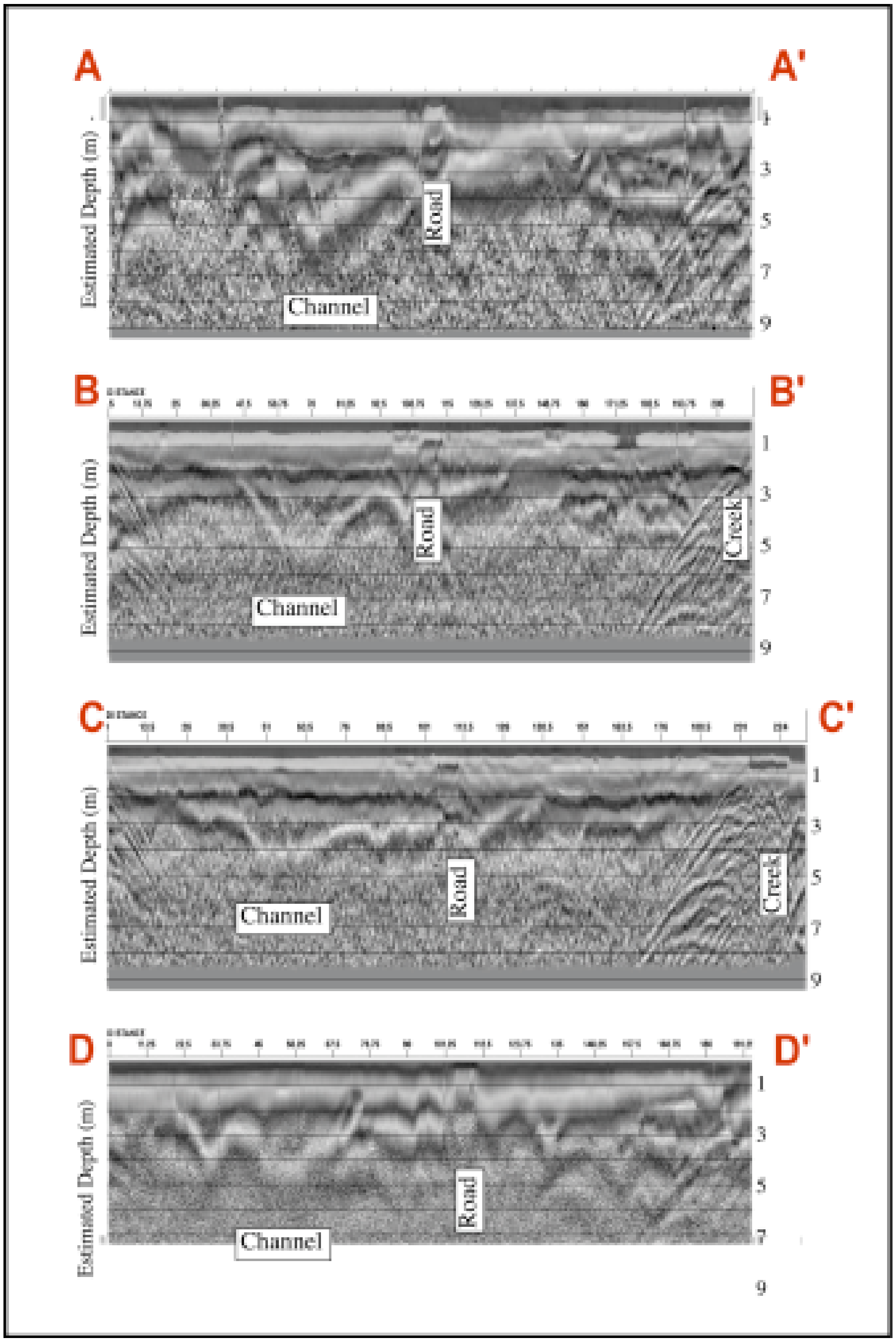

Figure 9 – Ground penetrating radar profiles constructed across the projection of the Portland Hills fault (see Figure 5 for location of profiles). Estimated depth of penetration typically does not exceed 5 to 7 m. Some large scale features such as a buried channel can be imaged in all four profiles. Image resolution is not reliable to estimate offset of meter scale features such as fault offset.

Our seismic reflection results clearly identify deformation of sediments and basalt within the Portland Basin. A scale-based approach to seismic imaging has provided detailed images of the upper 10-100 m below land surface at NCP, followed by a more focused seismic experiment that clearly images detailed deformation in the upper 20 m, a zone that is not clearly imaged with traditional seismic reflection methods (e.g., Steeples and Miller, 1998). Our success with seismic reflection methods starts with loctating the seismic profiles in a culturally quiet setting that contains the appropriate geologic target. Regional geophysical and geological surveys provide the initial site selection, followed by a ground canvas to identify the best suited locales. To provide significant detail when imaging the upper 100 m, we opt for high-density, high nominal fold surveys to provide detailed velocity information at a range of depths. Strong surface wave energy and slow seismic velocities limit the optimum window for P-wave reflections (Hunter et al., 1984). We use surface wave and normal moveout stretch mutes when processing, thus temporal fold varies from nominal fold for high-resolution seismic reflection surveys. To maintain adequate velocity information for all target depths and provide confidence that P- wave seismic energy dominates the stack, high nominal fold provides reasonable temporal fold at all targets.

As the magnetic profile, well logs, and ground truthing suggests, basalts associated with the Columbia River Basalt (CRB) sequence crop out near the southwest portion of the NCP site. Seismic, magnetics, and well log information confirm that the basalts dip to the northeast and are observed at greater than 100 m to the north. The seismic data show a strong amplitude, steeply dipping horizon that is likely the top of the CRB sequence. Reflections from younger sediments (Tertiary Troutdale to Latest Pleistocene Missoula flood deposits) also appear to steeply dip, and are highly deformed. To the northeast of the fault zone, all reflections associated with young sediments appear flat lying. The seismic and magnetic data also suggest that away from the fault zone basalt appears at depth and the surface does not significantly vary. This suggests that the Portland Hills fault zone extends at least 400 m with a style of deformation that is consitent with a strike-slip fault with a minor dip-slip component. Although the Portland Basin appears as a pull-apart basin, strike-slip extension appears to control the basin formation.

CONCLUSIONS

We integrated surface and airborne magnetic, seismic, and GPR surveys, with well logs, and geologic maps to identify the Portland Hills fault in late Tertiary and possibly younger sediments at North Clackamas Park. Although we were unable to conclusively document latest Pleistocene or Holocene deformation at this single investigation site we are encouraged by the promising results from the combined geological and geophysical data. We can now demonstrate that, in addition to substantial vertical separation of Miocene CRB flows, there has been significant deformation of post-CRB deposits. Based on the geometric properties of the fault, as imaged by high-resolution seismic reflection, we can also suggest that, at NCP, a portion of the vertical separation appears to be due to contraction along a high-angle fault.

We intend to continue our investigations by using high-resolution geophysical surveys at additional sites to better determine style and location of faulting, and to locate potential exploratory trench sites. The trench information will be used to construct a chronology of surface rupture. Finally, we can integrate all information to determine the regional extent of deformation and interaction with other regional faults.

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