Procurement and reprocessing of an industry marine seismic reflection profile from the Columbia River, Oregon and Washington

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ABSTRACT

The evolution of the tectonic style within the Portland Basin can have a profound impact on earthquake hazards of the region. Modern seismicity in the region and probabilistic hazards maps for the region show that the greatest regional risk for earthquakes lies in the upper crustal faults. A seismic reflection profile along the Columbia River through the Portland/Vancouver metropolitan area reveals new insights into the tectonic and depositional history of the Portland Basin. The basin contains 500 m of late Miocene to Recent fine to coarse-grained sediments that lie on top of Miocene-age Columbia River Basalts that tilt to the southwest. The Portland Basin appears to have two active basin margins, the Frontal Fault zone to the northeast, and the Portland Hills fault zone to the southwest. The Frontal Fault appears on the east-west and north-south seismic profiles, and if connected, suggest the fault may be regionally significant. The seismic reflection results document a fundamental shift in tectonic activity occured prior to the deposition of Plioence-age Troutdale gravels but after emplacement of Miocene-age Columbia River Basalts. The basin appears to have tilted westward, in part due to the uplift of the Cascade volcanic range less than 5 Ma. The Portland Hills fault zone acts as a backstop to the Cascade inflation and has produced more than 750 m of vertical offset. Fault activity continues on both the Frontal Fault and the Portland Hills Fault to accomodate the continued broad uplift to the east and clockwise crustal rotation. Vertical slip rates on the Frontal fault zone are roughly half that of the Portland Hills fault zone. Since the preexisting fault trends are oblique to the orientation of the Cascade Range, wrench-style faulting that appears along the southern portion of the Portland Hills fault may be related to Cascade uplift.

INTRODUCTION

In 1980, a 500 km long seismic reflection profile was acquired on the Columbia River from offshore to the confluence of the Snake River for the purposes of oil and gas exploration. A subset of this dataset extends through the Portland, Oregon and Vancouver, Washington metropolitan area and crosses the central portion and the northern and eastern margins of the Portland Basin. Recent high-resolution geophysical studies, in conjunction with an excavation trench, document fault-related deformation on modern sediments across the Portland Hills fault on the southwest margin of the Portland Basin, thus classifying the Portland Basin as active. Other studies suggest that the northeast basin margin may also be active, but no direct evidence to date appears. I reprocessed the seismic reflection profile to characterize the northeast margin of the Portland Basin and also to determine the structural and depositional style for the entire basin. Earthquakes from shallow crustal faults can produce severe ground shaking. Therefore, a detailed characterization of potentially active structures should help assess the hazards related to earthquakes in the Portland/ Vancouver metropolitan area.

GEOLOGIC AND TECTONIC SETTING

The Portland Basin lies at the center of Cascadia (Figure 1), an active convergent margin and volcanic arc in the Pacific northwest that is responding to oblique subduction of the Juan de Fuca plate beneath the North American plate. Within Cascadia, along-strike forearc blocks divide tectonic domains of varying crustal thickness. The Washington/Oregon border west of the Cascade volcanic arc roughly separates the Oregon forearc block to the south from the Washington forearc block to the north (Wells et al., 1998). The Oregon forearc block has rotated clockwise about 1.5

degrees/m.y. throughout the Cenozoic (Magill et al., 1982; Wells et al., 1998) and is underlain by a relatively thin crust (Trehu et al., 1994). The crustal thickness increases to the north below the Washington forearc (Trehu et al., 1994) with evidence of compression and uplift due to the Canadian Coast Mountain backstop inhibiting a northward block migration (Wells et al., 1998).

The Portland Basin is a northwest-trending structure that appears at the transition between the Oregon and Washington blocks. Past studies describe the region as a pull-apart basin that may have formed in response to the transfer of strain between basin bounding faults (Beeson et al., 1985; Yelin and Patton, 1991). Northwest-striking faults control the region that, on the basis of geologic relations, earthquake focal mechanisms, and potential field anomalies, have right-lateral strike-slip displacement (Beeson et al., 1985, 1989; Beeson and Tolan, 1990; Yelin and Patton, 1991; Blakely et al., 1995; 2000). In addition to strike-slip motion on regional faults, Yelin and Patton (1991) showed that the 1962 M_w 5.2 Portland earthquake, perhaps associated with a fault along the northeast basin margin, contained a significant extensional component. Madin and Hemphill-Haley (2001) and Liberty et al. (2003) documented significant shortening of modern sediments along the Portland Hills fault in Portland Basin (Figure 1). Beeson et al. (1985) showed that, based on geologic mapping and borehole information, the Portland Basin has been active prior to the emplacement of Miocene CRB volcanic rocks, thus burying and displacing the

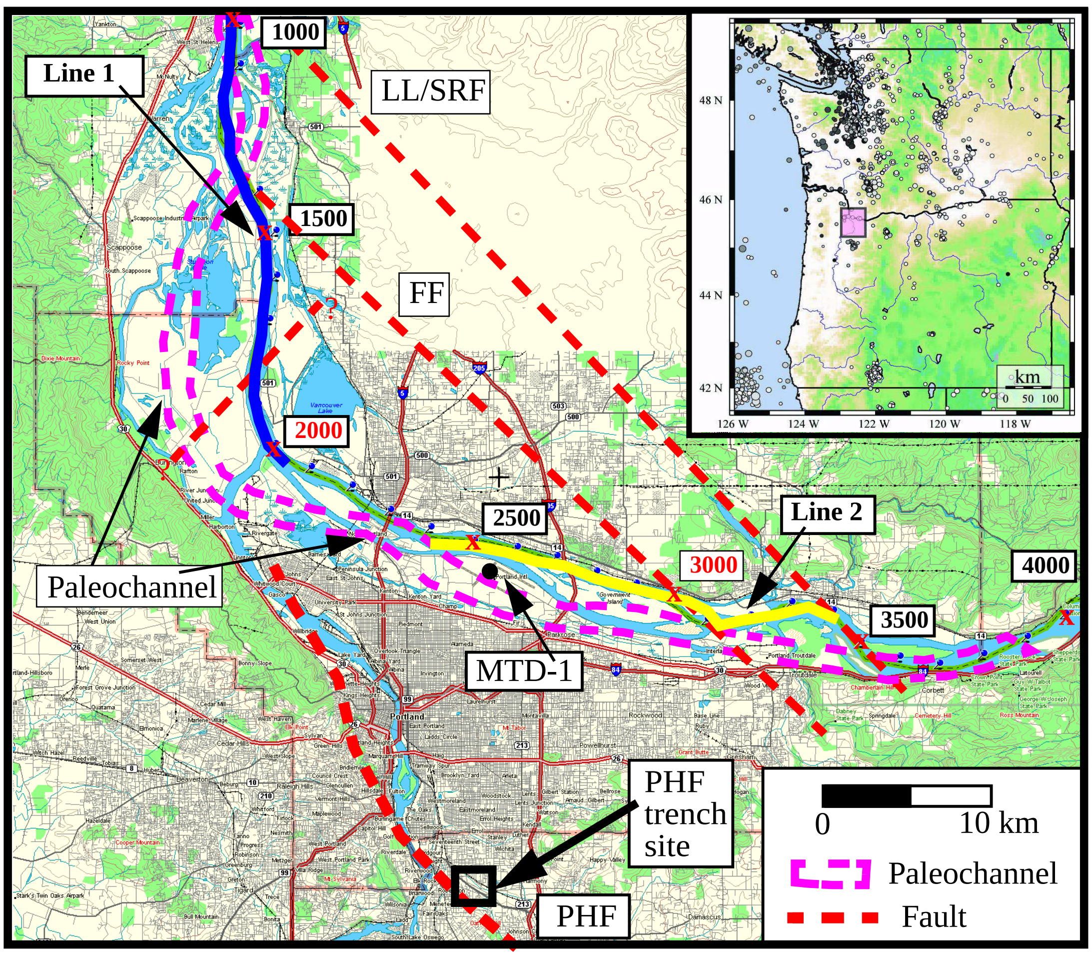

FIGURE 1. Topographic and cultural map from the Portland/Vancouver metropolitan area. Seismic Line 1 (blue) and Line 2 (yellow), Portland Hills Fault=PHF, FF=Frontal Fault, LL/SRF=Lackamas Lake/Sandy River Fault. Inset map- Topographic map of the Pacific northwest with seismicity since 1973.

Eocene accreted oceanic terrane rocks that form the basement of the region (Snavely et al., 1968). The observed structural style in the region is consistent with a complex tectonic system that has likely evolved from Eocene to the present.

The northeast boundary of the Portland Basin is likely controlled by the Sandy River-Frontal fault zone (e.g., Beeson et al., 1985; Yelin and Patton, 1991; Blakely et al., 1995), though offsets on this fault boundary have not previously been documented. The southwest boundary of the Portland Basin is controlled by the Portland Hills-Clackamas River fault zone (e.g., Beeson et al., 1985; Blakely et al., 1995; Wong et al., 2001) that may include the Oatfield and East Bank faults (e.g. Wong et al., 2000). Although much attention lately has been paid to the Portland Hills Fault (e.g., Blakely et al., 1995; Pratt et al. 2001; Wong et al., 2001) due its proximity to downtown Portland (Figure 1) and recent studies suggesting the fault is active (Madin and Hemphill-Haley, 2001; Liberty et al., 2003), little is known about the spatial and temporal characteristics of any of the mapped faults in the region and whether the mapped faults are the complete suite of seismic hazards for the region.

The surface topography of the region was reset with the introduction of more than 200 m of Miocene CRB volcanic rocks (Newton, 1969). The 16-12 Ma CRB flows blanketed the region after entering the Portland/Vancouver region along the ancestral Columbia River (Hooper, 1982; Beeson et al., 1985, Tolan et al., 1989). The basin then filled with more than 500 m of late Miocene to Pliocene age fine-grained sediments, Pliocene-Pleistocene age coarse-grained deposits, and modern coarse- and fine-grained channel fill and overbank flood deposits (e.g., Trimble, 1963; Swanson et al., 1993; Yeats et al., 1996). The late Miocene-Pliocene sediments are mostly fine-grained mudstones of the Sandy River Formation with interfingered sandstones and cemented gravels of the lower Troutdale unit dated at 12-4 Ma (Tolan and Beeson, 1984). The Sandy River mudstones are more predominant in the western portion of the Portland Basin, while the coarse-grained fluvial sediments appear more toward the eastern portion of the basin (Trimble, 1963), consistent with a lacustrine environment grading into a fluvial environment from west to east across the basin. Late Miocene and Pliocene sediments also appear on the adjacent Portland Hills at an elevation of 250 m above the basin surface. The upper Troutdale formation, dated at 4-2 Ma by Tolan and Beeson (1984), contains mostly volcaniclastic conglomerates shed from the Cascade Range and CRB deposits. Eruptions from the Boring lava (0.25-3 Ma) overlie the upper Troutdale gravels and appear throughout the Portland Basin with ages that young to the northwest (Fleck et al., 2002). The Portland Basin is capped with up to 30 m of reworked silts, clays, and sands that reset the surface topography during the 12-15 ka Missoula flood events (Waitt, 1985).

SEISMIC REFLECTION SURVEY

Data Acquisition and Processing

The seismic reflection data were acquired on an industry seismic vessel using 16 airguns totalling 600 cu in (4600 psi). A 25 m shot interval and a 24-channel streamer (20 hydrophones per group) with a 25 m group generated offsets from 255-830 m behind the airgun array. Both the airgun and streamer arrays were deployed at 6 m depth. Seismic data were recorded for 6 seconds at a 2 ms sample rate with a 5-128 Hz analog filter. Data quality from the shot gathers is highly variable. Although the relatively large airgun array should provide adequate energy to image bedrock depths of 500 m, a intermittent high-velocity water bottom associated with cemented Troutdale gravels limit recorded offsets and reduced subsurface imaging capabilities.

In a typical marine environment, a 24-channel streamer can adequately image the subsurface geology at a range of depths. Marine seismic generally is acquired with water depths of a few hundred meters and imaging targets of hundreds to thousands of meters below the water bottom. In this survey, 16 airguns and streamer offsets with 255-830 m should provide adequate depth and offset coverage to perform a reasonable velocity analysis for typical marine sediments. Unfortunately, the acquisition design was not ideally suited to image a basin containing relatively high-velocity sediments in the upper few hundred meters below a very shallow water bottom. Water depths along the Columbia River in the Portland/Vancouver metropolitan area range from 5-20 m. The primary imaging target for neotectonic studies is the geology of the upper 500 m of the Portland Basin containing both a sedimentary and volcanic rock sequence.

Figure 2a shows a 5 layer velocity model that is consistent with sediments overlying a volcanic basement. A large velocity step correlates with the top of the volcanic rock sequence at 450 m depth. Figure 2b shows a synthetic shot record calculated with a finite-difference acoustic algorithm (Kelly et al., 1976) ranging in offsets from 5-830 m and a peak frequency of 50 Hz. The

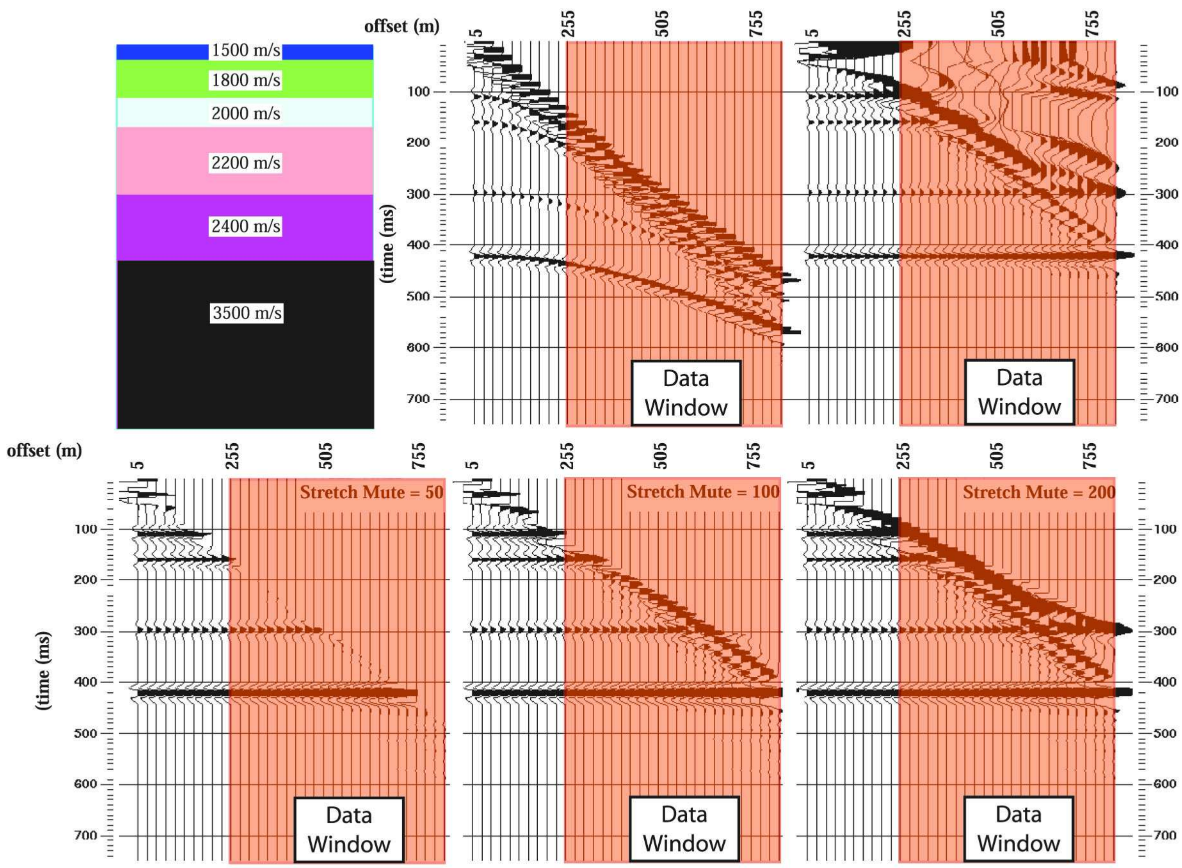

FIGURE 2. a) Seismic velocity model representing sediments from the Portland Basin. Interface at 450 m depth represents the sediment/CRB contact. b) Synthetic shot gather from (a). Highlighted area on b-f represent the recorded offsets from the reprocessed seismic data c) NMO corrected shot gather showing reflections and noise resulting from the NMO process. d) 50 percent stretch mute, e) 100 percent stretch mute, and f) 200 percent stretch mute. Note the trade-off between additional noise on the NMO gathers and muted reflections within the highlighted region.

highlighted area within Figure 2b shows the offsets consistent with the survey (255-830 m). Figure 2c shows the gather with normal moveout (NMO) corrections applied. Note that reflections in the upper 150 ms (100 m) do not appear within the highlighted region representing the recorded offsets of the seismic data and roughly half of the data window contains noise (NMO corrected head waves and numerical noise). Figure 2d shows the NMO corrected gather with a stretch mute of 50 percent applied to the shot gather after NMO corrections. Stretch mutes remove the effects of a changing wavelet produced by applying NMO corrections (Sheriff, 2002) and are required to avoid stacking traces with large variations in frequency content generated via data processing. Stretch mutes for a typical marine dataset range from 30 to 50 percent, but larger stretch mutes must be used if only long offsets are present (Yilmaz, 1987). In fact, long offsets may be beneficial to attenuate multiples. In the case of imaging targets within the Portland Basin where near offsets were not recorded, I retained the long offsets to include as much of the near-surface signal as possible, even though frequency distortion and low fold resulted in the upper few hundred meters of the stacked section. The stretch mute of 50 percent in Figure 2d shows that reflections in the upper 150 ms are not present. Figure 2e and 2f show the results of 100 and 200 percent stretch mutes respectively. Figure 2 shows that more reflection signal is included with an increase in percent stretch mute, but stretch mutes beyond 100 percent actually include more coherent noise in the NMO corrected gathers, do not provide additional reflection information in the upper 150 ms of the gather, and may actually degrade the final stack. I selected a stretch mute of 100 percent to retain the near-surface signal, with an understanding that a shift in frequency content and very low fold grades into a low confidence geologic region in the near-surface section.

I processed the seismic data using Landmark's ProMAX seismic data processing software. Due to the irregular shipping channel along the Columbia River in the Portland/Vancouver metropolitan area (Figure 1), I used a crooked line geometry to account for the variation in position of the airgun and streamer array along the Columbia River to provide a more accurate bin for velocity analysis and stacking. Since detailed positions of the streamer were not provided, I assumed the airgun and streamer position followed the ships path. A detailed velocity analysis, careful attention to mutes, and dip-moveout corrections followed. These steps proved critical to providing a high-quality seismic reflection stacked section. Next, I applied residual statics, bandpass filter, common mid-point (CMP) stack, FK migration, and true amplitude recovery to produce a stack.

Seismic Velocity Analysis

Figure 3 shows 4 CMP gathers (each with 2 adjacent gathers combined) and the NMO corrected product from selected locations along the profile. Although velocity information is very limited within each CMP gather (nominal 12 fold), first arrival and stacking velocities for deeper arrivals provide insight into the velocity structure for the Portland Basin and help increase the confidence of the geologic interpretations that I present. I have included 3 velocity values for each gather in Figure 3. The velocity value labeled in the upper left corner of each gather represents a near-surface velocity estimate calculated by the distance to the first channel (255 m) divided by the first motion of this trace. Although this velocity value is influenced by changing water depths, near-surface velocity variations (including hidden layers) and changing dips, the velocity value represents a first-order velocity estimate for near-surface sediments below water bottom and can help clearly identify velocity anomalies in the near-surface section that may be related to changing sedimentalogic and structural conditions. The other two velocity values that I display represent the head-wave velocity value for the first arrivals and the stacking velocity on the large-amplitude reflection that represents the base of the sedimentary section. Head wave first arrival velocities represent the velocity of the medium below the refractor, and with this survey design and geologic conditions represent depths that range from 30-50 m. The first arrivals may mask slower velocity layers that do not appear as a first arrivals, but do represent the velocity of the fastest layer encountered. Stacking velocities roughly represent a root mean square average of all geologic units above the reflected horizon. Note the large velocity variation when comparing selected gathers and within each gather. Gathers 1 and 2 show that fast velocities overlie slower velocities in the sedimentary section, as evidenced by a very fast head wave velocity compared to the stacking velocity on the reflection. Figure 3 shows a complex seismic velocity structure for the Portland Basin, but also provides valuable information regarding basin formation and lithologies.

The Portland Basin contains four dominant seismic velocity units that correlate with the geology discussed above. The most notable and widespread seismic boundary separates Neogene and younger sediments of the basin with the CRB volcanic rocks below. The depth to the upper CRB contact ranges from surface elevations to roughly 500 m below land surface with seismic velocities that exceed 3500 m/s. CRB depths are calibrated using both in nearby water well lithologies (e.g., Swanson et al., 1993; Koreny and Fisk, 2001), engineering well logs (Mabey and Madin, 1992), and also where volcanic rock exposures appear (Trimble, 1963). Beeson and Tolan (1990) estimate CRB thicknesses of 150 m below the Portland Basin and seismic boundaries are not

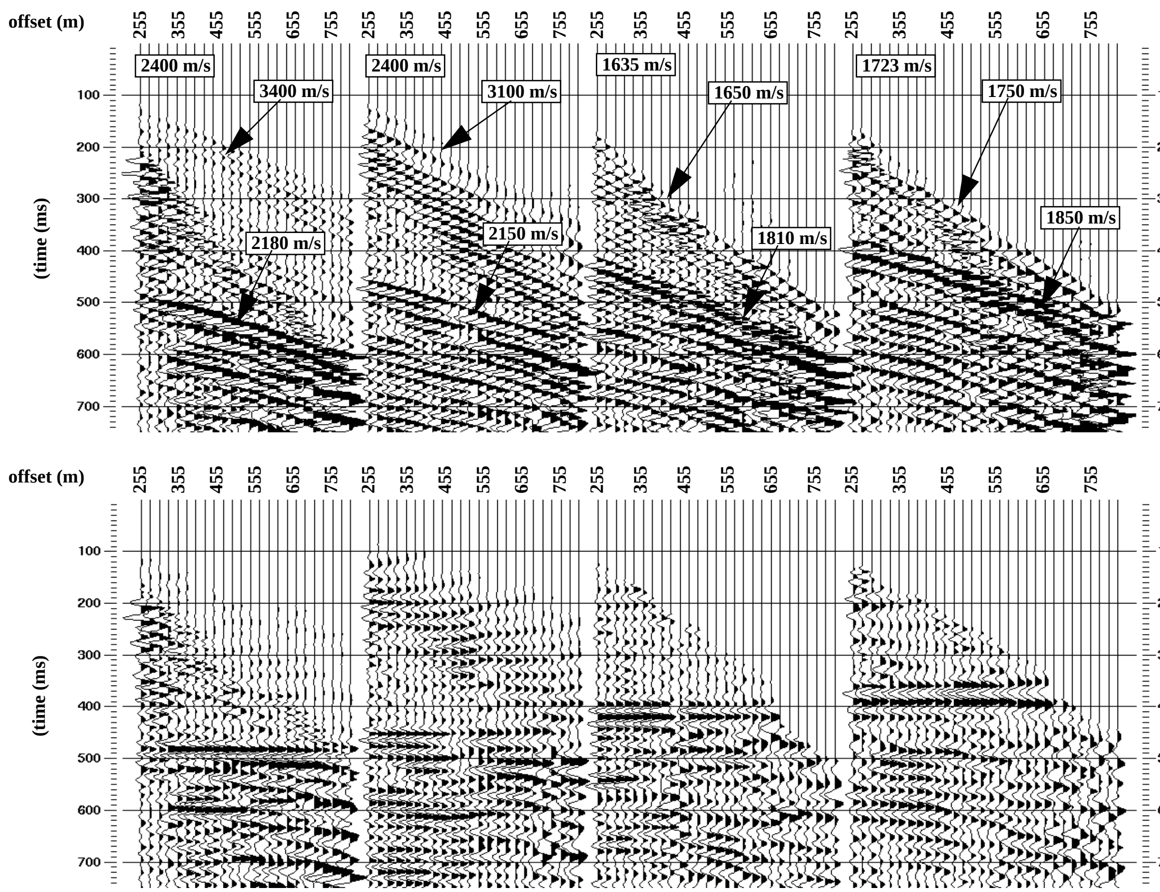

FIGURE 3. Unprocessed CMP (above) and NMO corrected gathers (below). Three velocity values appear on the upper gathers representing the near-surface velocity (near trace distance/first motion time), head wave velocity, and stacking velocity on the sediment/CRB contact. Note the large variation in seismic velocities (laterally and vertically) and the poor resolution above the basement reflection due, in part, to the acquisition geometry.

clearly observed below the upper CRB contact due to the acquisition parameters and the geologic conditions. Therefore, I present no seismic information below the upper CRB contact and I consider this contact acoustic basement. The cemented gravels of both the upper and lower Troutdale Formation appear as a relatively fast seismic velocity for sediments, often greater than 3000 m/s, thus defining the second observed velocity unit. Without detailed velocity control or geologic information, a reflection from the top of the CRB and the top of cemented gravels may be indistinguishable. Older sediments that are not lithified include sediments from the Sandy River mudstones and other unconsolidated sediments. The observed velocity of these sediments range from 1600-1800 m/s and may appear below the higher velocity Troutdale cemented gravels. The fourth seismic velocity unit includes the modern unconsolidated coarse-grained fluvial sediments with a slightly greater velocity than the velocity of the water column at 1500-1600 m/s. Water velocity for 15 degree C water at 0% salinity is calculated as 1465 m/s (Sheriff, 2002) and is used to correct velocity information along each profile (Figures 4 and 5).

INTERPRETATION

To interpret the seismic reflection data from the Columbia River, I created two profiles. I define Line 1 as the north-south segment that extends from St. Helens, Oregon to the confluence of the Willamette River (Figure 1). Line 2 extends west to east from the confluence of the Willamette River beyond the eastern extent of the Portland Basin near Corbett (Figure 1). Line 1 trends approximately 40 degrees from both major regional faults and the basin orientations and Line 2 extends from an along strike orientation on the western portion of the profile to approximately 35 degrees from the associated basin structures along the eastern basin margin.

The processed seismic reflection data show the general shape of the Portland Basin contained by a strong amplitude basement reflection that correlates to the top of the CRB volcanic stratigraphy (Figures 4 and 5). This reflection from acoustic basement has an apparent basinward dip of less than 1 degree for much of the two profiles and appears flat lying along the western portion of Line 2 where the profile is orientated subparallel to the basin axis (Figure 1). No major offsets in the CRB reflector appear outside the basin margins and suggests the Portland Hills fault zone does not extend east of the Columbia River. One minor offset in the CRB reflector appears at CMP 1750 (Figure 4). This CRB step coincides with a near-surface velocity anomaly (Figure 4) that would place an offset of 30 m (depth corrected @ 1800 m/s) on this horizon. If this structure is fault related, a northeast trend must account for this structure, since a similar feature is not observed on Line 2 (Figure 5). Blakely et al. (personal comm.) mapped a northeast-trending magnetic lineament that crosses the river in this region and may further support evidence for a previously unmapped fault. Northeast trending faults are mapped in the region (e.g., Beeson et al., 1991), but do not appear regionally extensive.

The CRB reflection has a rugged topography along much of Line 1 (Figure 4) and a very smooth topography along Line 2 (Figure 5). This contrasting reflection character may represent both the ship and streamer orientation with respect to CRB deposition and also the CMP location with respect to the ancestral Columbia River. An east-west CRB flow direction in the Portland Basin (Hooper, 1982; Tolan and Beeson, 1984) suggests the east-west segment of the seismic profile would follow the in-situ flow directions and the topography would appear relatively flat. With a north-south river orientation, the seismic data extend across individual basalt flows and a more rugged topography appears. The geometry of the basement reflection suggests local CRB flow

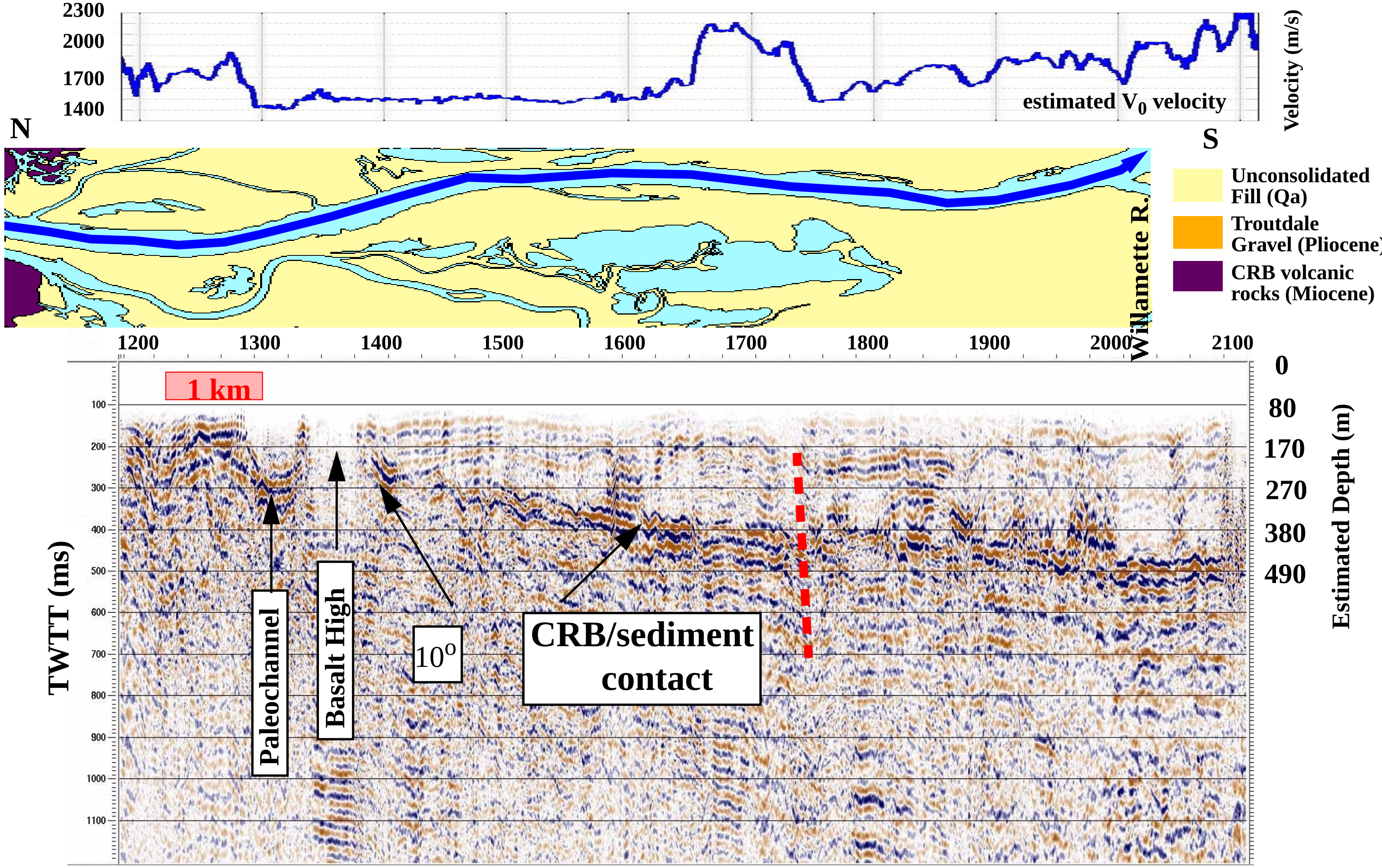

FIGURE 4. Unmigrated seismic Line 1 with near-offset velocity profile and generalized geologic map. Note the basin margin at 1400 is roughly 2 km south of the nearest CRB outcrop. Velocity profile represents the near-trace (255 m)/first motion travel time.

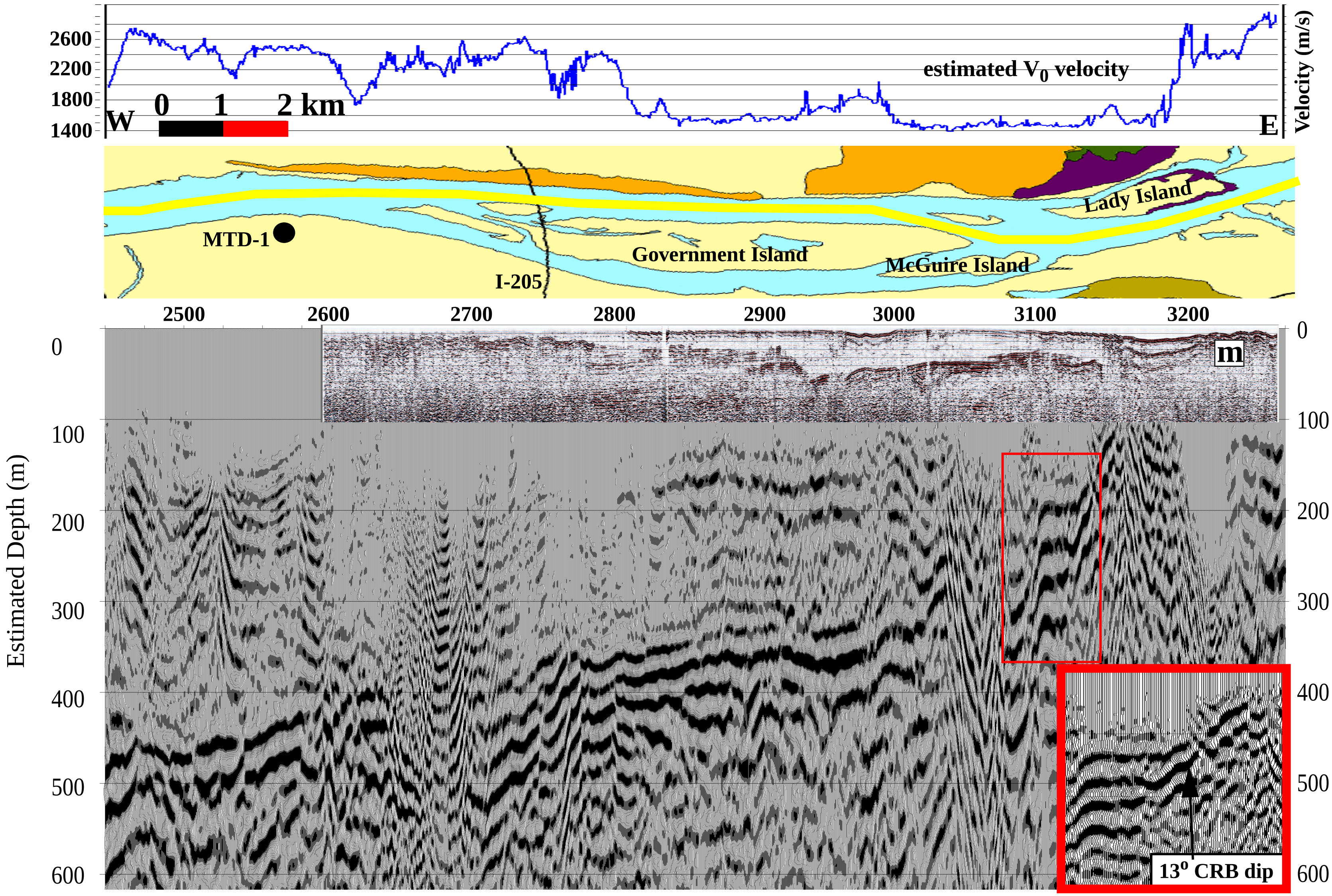

FIGURE 5. Migrated, true amplitude, and depth corrected seismic Line 2 (bottom) with the projected uniboom data (Pratt et al., 2001) above. The generalized geologic map, line location, and first arrival, near-offset velocity profile appear above. When the high-velocity cemented gravels appear near water bottom depths (2450-2800), seismic data quality suffers. Multiples (m) appear at 3150-3200 on the uniboom data and correlate with the location of CRB outcrop on Lady Island. Geology is summarized on Fig. 4. Frontal Fault region blowup appears in lower right corner

widths of 150 m and flow heights of 15 m. In addition to the orientation of the river with respect to flow directions, high-energy cemented gravels of the Troutdale gravel directly overlie CRB rocks along portions of the Portland Basin (e.g., Trimble, 1963; Swanson et al., 1993), thus providing an erosional agent to remove the CRB flow tops. An eroded upper CRB contact along the river is consistent with engineering borehole MTD-1 at 426 m depth (Figure 1), where vesicular basalt textures typical of flow tops are missing from the CRB surface (Wilson, 1997). Other deep boreholes in the Portland Basin that penetrate the volcanic stratigraphy away from the inferred location of the ancestral Columbia River document intact flow tops (Wilson, 1997) and suggests the CRB topography is largely controlled by the late-Miocene age ancestral Columbia River.

Along the northern and eastern basin margins, an approximate 10 degree and 13 degree dip appears on the CRB reflection near positions 1400 and 3100 (Figure 4 and 5) respectively that drops the CRB top more than 200 mto the southwest. Since the orientation of both profiles are oblique to the mapped northwest trend of the major basin-related structures (Figure 1), actual dips for this horizon may be steeper. This drastic change in CRB dip and depth at the basin margins is consistent a basin-bounding fault both to the north and east of the Portland Basin that I refer to as the Frontal fault. Yelin and Patton (1991) defined the Frontal fault zone along the eastern margin of the Portland Basin to account for the both a pull-apart tectonic style and to account for the 1962 ML 6.2 Portland event. The eastern portion of this fault zone has been connected to the Sandy River and Lackamas Lake faults (Walsh et al., 1987; Yelin and Patton, 1991; Blakely et al., 1995), but no basinward fault has been mapped. The similar deformation observed on the CRB horizon along both Lines 1 and 2 along the northeast boundary of the basin and the northwest projection observed in many other regional faults (e.g., Blakely et al., 1995; Beeson and Tolan, 1990) suggest that the fault segments observed on the two seismic profiles may be related. Evidence for the Frontal Fault acting as an active northeast basin bounding fault stems from the following: Results from a recent uniboom high-resolution seismic survey (Pratt et al, 2001) show a down to the west step in a reflection near CMP 3100 (Figure 5) that correlates to a modern erosional channel. Yelin and Patton (1991) suggest that a fault projected to the surface location of the Frontal Fault likely accounts for the 1962 Portland ML 5.2 earthquake (Figure 1) and Bet and Rosner (1993) document evidence for a northwest-trending fault south of McGuire Island that is down to the west. Evidence for this fault stems from well logs, geophysical logs, and from an outcrop exposure that shows conjugate fault sets in a gravel surface that is likely younger than the Troutdale gravels (late Pleistocene?). Each of the three independent lines of evidence, combined with my results, support the Frontal fault crossing the Columbia River east of Government Island, extending south of the river (Bet and Rosner, 1993), and north of the river (Yelin and Patton, 1991) and perhaps across the entire basin. If the Frontal fault is responsible for the observed step in the river's modern erosional surface (Pratt et al., 2001; Figure 5) and for the 1962 ML 6.2 Portland earthquake (Yelin and Patton, 1991), the fault is active.

The history of the Frontal fault can be further established based on reflections that overlie the CRB horizon on Line 2. Figure 5 shows the CRB reflection along the eastern basin margin to Lady Island, where CRB volcanic rocks are mapped at the land surface (Figure 5; Trimble, 1963). Above the CRB contact, a reflection appears near flat lying at 180 m depth, compared to the 13 degree apparent dip of the CRB reflector. Wilson (1998) calculated a 0.03 - 0.05 mm/yr deposition rate for the Portland Basin, placing the age of this boundary between 3.6 - 6 Ma. This change in dip is consistent with nearby borehole information (e.g., Bet and Rosner, 1993; Swanson et al., 1993) and suggests that a change in tectonic style occurred before deposition of the Pliocene-age Troutdale sands and gravels and after 12 Ma CRB emplacement. A similar change in reflection dip appears on Line 1 at position 1400 (Figure 4).

Beyond the 13 degree apparent dip observed near the Frontal Fault, the CRB horizon appears to dip basinward approximately 0.5-1.0 degrees along Line 2 (Figure 5). Overlying reflections on Line 2 also appear with similar dips (Figure 5), suggesting that a southwest tilt of the Portland Basin occurred during or after deposition of the shallowest reflections observed on the airgun survey. I have included unpublished Columbia River uniboom data from Pratt et al. (2001) on Figure 5 to better characterize reflections from the upper 100 m related to Troutdale sediments. Reflections between 30-100 m depth on the uniboom show similar westward dips that range from 0.3-0.7 degrees. Nearby borehole information (Bet and Rosner, 1993; Korney and Fisk, 2001) confirm the dip observed on the seismic data matches the lithology of the upper and lower Troutdale gravels. Tolan and Beeson (1984) identified the lower contact of the upper Troutdale unit at an elevation of 240 m above sea level 20 km east of the Frontal Fault at Bridal Veil (Figure 1). Bet and Rosner (1993) identify this same contact at sea level near the Frontal Fault and Wilson (1997) identify the this boundary at more than 150 m depth at MTD-1 in the basin center.

This regional dip observed in both Troutdale and CRB reflections is not likely due to the river's modern gradient (roughly 7 m in 20 km or 0.02 degrees), but may, in part, reflect a rising sea level change. Since the Columbia River is at sea level throughout the Portland region, sea level changes may play a role in the observed depositional dip in the Portland Basin. Peterson and Phipps (1992) report a sea-level change of more than 55 m over the past 10 ka at nearby Grays Harbor, Washington. Tolan and Beeson (1984) tie the termination of the Troutdale gravels (at 2 Ma) and subsequent elevation change at Bridal Veil to an abrupt Cascadian uplift beginning 2-3 Ma. Priest (1990) and Sherrod (1986) suggest that rapid uplift of the western Cascades east of the Willamette Valley occurred between 5-6 Ma and 3 Ma. The broad tectonic tilt cannot fully be accounted for by changing sea level conditions due to the magnitude of the regional elevation change and suggests Cascadia inflation may, in part, be responsible for the tectonic tilt observed across the Portland Basin.

Mapped deposits of Sandy River mudstones and Troutdale Formation on the Portland Hills at 250 m elevation west of the basin (Trimble, 1963; Beeson et al., 1991) suggest not only was the topography of the region reset by emplacement of CRB volcanic rocks, but also that vertical slip rates across the PHF west of the Portland Basin remained relatively small throughout late Miocene and perhaps into Pliocene to account for the 800 m elevation change across the PHF. The Columbia River continued to flow into the present-day Portland Basin from the east (south of its modern coarse) and eroded the flow tops along portions the modern east-west river channel. Since the topography across the PHFZ did not exist in late Miocene, the north-south turn in the Columbia River did not occupy its present-day river channel, but likely flowed west of it's present coarse. The Frontal Fault and perhaps associated faults deformed the youngest CRB volcanic rocks estimated at 12 Ma, although with erosion the upper CRB contact may be older. This deformational style of the Frontal Fault changed prior to emplacement of late Miocene to Pliocene Troutdale deposits. During or after emplacement of late Miocene to Pliocene Troutdale deposits, the basin began to tilt to the west, in part as a result of Cascadia inflation. The preexisting PHF zone acted as a backstop to continued westward tilt of the western Cascades and normal faulting accomodated the tectonic tilt. Assuming the onset of Cascadia inflation began at 8 Ma, a 0.1 mm/yr uplift rate for the PHFZ is consistent with 1.5 m of vertical offset since Missoula Flood sediments (15 ka) were deposits in the basin. The north-south orientation of the Cascade volcanoes, the preexisting northwest orientation of the steeply dipping PHFZ, and the continued clockwise crustal rotation all suggest we may observe a complex tectonic style from north to south across the basin. These complexities may account for the shortening observed in 12-15 ka sediments across the Portland Hills fault (Madin and Hemphill-Haley, 2001; Liberty et al., 2003) along the southern portion of the PHFZ and may affect the interplay between the PHF and the Frontal Fault zone.

REFERENCES

Beeson, M.H., and Tolan, T.L., The Columbia River Basalt Group in the Cascade Range A mid-Miocene reference datum for structural analysis, Journal of Geophysical Research, 95 (12), 19547-19559, 1990.

Beeson, M.H., Fecht, K.R., Reidel, S.P., and Tolan, T.L., Regional correlations within the Frenchman Springs Member of the Columbia River Basalt Group: New insights into the middle Miocene tectonics of northwestern Oregon, Oregon Geology, 47 (8), 87-96, 1985.

Beeson, M.H., Tolan, T.L., and Anderson, J.L., The Columbia River Basalt Group in western Oregon: Geologic structures and other factors that controlled flow emplacement patterns, Geological Society of America Special Paper 239, 223-246, 1989.

Beeson, M.H., Tolan, T.L., and Madin, I.P., Geologic map of the Portland Quadrangle, Multnomah and Washington counties, Oregon and Clark County, Washington, Oregon Department of Geology and Mineral Industries Series, GMS-75, scale 1:24,000, 1991.

Bet, J.N., and M.L. Rosner, Geology near Blue Lake County Park, eastern Multnomah County, Oregon, Oregon Geology, 55, 59-69, 1993.

Blakely, R.J., Wells, R. E.,Tolan, T. L., Beeson, M. H., Trehu, A. M., Liberty, L. M., New aeromagnetic data reveal large strike-slip (?) faults in the northern Willamette Valley, Oregon, Geological Society of America Bulletin, 112 (8), 1225-1233, 2000.

Blakely, R.J., Wells, R.E., Yelin, T.S., Madin, I.P., and Beeson, M.H., Tectonic setting of the Portland-Vancouver area, Oregon and Washington: Constraints from low-altitude aeromagnetic data, Geological Society of America Bulletin, 107 (7), 1051-1062, 1995.

Bott, J.D.J., and Wong, I.G., Historical earthquakes in and around Portland, Oregon, Oregon Geology, 55 (5), 116-122, 1993.

Fleck, R.J., R.C. Evarts, J.T. Hagstrum, and M.J. Valentine, The Boring volcanic field of the Portland, Oregon area; geochronology and neotectonic significance, in Geological Society of America, Cordilleran Section, pp. 33-34, Geological Society of America, Corvallis, Or, 2002.

Hooper, P.R., The Columbia River Basalts, Science, 215, 1463-1468, 1982.

Kelly, K.R., R.W. Ward, S. Treitel, and R.M. Alford, Synthetic seismo-grams: a finite-difference approach, Geophysics, 41, 2-27, 1976.

Koreny, J.S. and Fisk, T.T., 2000, Hydraulic continuity of the Portland Basin deep aquifer system, Environmental and Engineering Geoscience, v. 6, no. 3, pp. 279-292.

Liberty, L. M., Hemphill-Haley, M.A.,and Madin, I.P., 2003, The Portland Hills fault: uncovering a hidden fault in Portland, Oregon using high-resolution geophysical methods, *Tectonophysics. in press*.

Mabey, M.A., and I.P. Madin, Shear wave velocity measurements in the Willamette Valley and the Portland Basin, Oregon, Oregon Geology, 54, 51-53, 1992.

Madin, I.P., Earthquake-hazard geology maps of the Portland metropolitan area, Oregon, pp. 21, Oregon Department of Geology and Mineral Industries, 1990.

Madin, I.P., and Hemphill-Haley, M.A., The Portland Hills fault at Rowe Middle School, Oregon Geology, 63 (2), 47-49, 2001.

Magill, J.R., Cox, A.V., and Duncan, R.A., Tillamook Volcanic Series - Further evidence for tectonic rotation of the Oregon Coast Range, Journal of Geophysical Research, 86, 2953-2970, 1981.

Newton, V.C.J., Subsurface geology of the lower Columbia and Willamette Basins, Oregon, in Oregon Department of Geology and Mineral Industries, Oil and Gas Investigations, pp. 121, 1969.

Peterson, C.D., and J.B. Phipps, Holocene sedimentary framework of Grays Harbor Basin, Washington, USA, SEPM Special Publication No. 48, Quaternary Coasts of the United States: Marine and Lacustrine Systems, 273-285, 1992.

Pratt, T.L., Odum, J., Stephenson, W., Williams, R., Dadisman, S., Holmes, M., and Haug, B., Late Pleistocene and Holocene tectonics of the Portland Basin, Oregon and Washington, from high-resolution seismic profiling, Bulletin of the Seismological Society of America, 91 (4), 637-650, 2001.

Priest, G.R., Volcanic and tectonic evolution of the Cascade Volcanic Arc, central Oregon, Journal of Geophysical Research, 95 (B12), 19,583-19,600, 1990.

Sheriff, R.E., Encyclopedic dictionary of applied geophysics, Society of Exploration Geophysicists, Tulsa, Ok, 2002.

Snavely, P.D., Jr., MacLeod, N.S., and Wagner, H.C., Tholeiitic and alkalic basalts of the Eocene Siletz River Volcanic, American Journal of Science, 266, 454-481, 1968.

Swanson, R.D., McFarland, J. B. ,Gonthier, J. B., and Wilkinson, J.M., A description of hydrogeologic units in the Portland basin, Oregon and Washington, pp. 56, U.S. Geological Survey Water Resources Investigation Report, 1993.

Tolan, T.L., and M.H. Beeson, Intracanyon flows of the Columbia River Basalt Group in the Columbia River Gorge and their relationship to the Troutdale Formation, Geological Society of America Bulletin, 95 (4), 463-477, 1984.

Tolan, T.L., S.P. Reidel, M.H. Beeson, K.R. Fecht, J.L. Anderson, and D.A. Swanson, Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group, in Volcanism and Tectonism in the Columbia River Flood-Basalt Province, S.P. Reidel and P.R. Hooper eds., pp. 1-20, Special Paper to the Geological Society of America, 1989.

Trehu, A.M., I. Asudeh, T.M. Brocher, J. Luetgert, W.D. Mooney, J.L. Nabelek, and Y. Nakamura, Crustal architecture of the Cascadia forearc, Science, 265, 237-243, 1994.

Trimble, D.E., Geology of Portland, Oregon and adjacent areas, U.S. Geological Survey Bulletin, 1119, 119, 1963.

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

Wells, R.E., Paleomagnetic rotations and the Cenezoic tectonics of the Cascade arc, Washington, Oregon, and California, Journal of Geophysical Research, 95, 19,409-19,417, 1990.

Wells, R.E., Weaver, C.S., and Blakely, R.J., Fore-arc migration in Cascadia and its neotectonic significance, Geology, 26 (8), 759-762, 1998.

Wilson, D. C., Post Middle-Miocene geologic history of the Tualitan Basin, Oregon with hydrogeologic implications [Dissertation thesis]: Portland State University, 321 p., 1997

Wilson, D.C., Post-middle Miocene geologic evolution of the Tualatin basin, Oregon, Oregon Geology, 60, 99-116, 1998.

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

Wong, I.G., Hemphill-Haley, M.A., Liberty, L.M., and Madin, I.P., The Portland Hills fault: an earthquake generator or just another old fault?, Oregon Geology, 63, 39-50, 2001.

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

Yelin, T.S., and Patton, H.J., Seismotectonics of the Portland, Oregon, region, Seismological Society of America Bulletin, 81, 109-130, 1991.

Yilmaz, O., Seismic data processing, 526 pp., Society of Exploration Geophysicists, Tulsa, OK, 1987.

FY2002 publications resulting from this grant

Liberty, L.M., The Portland Basin as Imaged by a Reprocessed Industry Seismic Profile on the Columbia River: Implications for Earthquake Hazards, *Seismological Research Letters*, 73 (2), 249, 2002.

Liberty, L.M., Seismic Reflection Imaging of the Portland Basin: Implications for Seismic Hazards, *Eos Trans. AGU*, 83 (47), Fall Meet. Suppl., Abstract S22B-1037, 2002.