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# Imaging the Seattle Fault Zone with high-resolution seismic tomography

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**Abstract.**
The Seattle fault, which trends east-west through the greater Seattle metropolitan area, is a thrust fault that, around 1100 years ago, produced a major earthquake believed to have had a magnitude greater than 7. We present the first high resolution image of the shallow P wave velocity variation across the fault zone obtained by tomographic inversion of first arrivals recorded on a seismic reflection profile shot through Puget Sound adjacent to Seattle. The velocity image shows that above 500 m depth the fault zone extending beneath Seattle comprises three distinct fault splays, the northernmost of which dips to the south at around 60°. The degree of uplift of Tertiary rocks within the fault zone suggests that the slip-rate along the northernmost splay during the Quaternary is 0.5 mm $a^{-1}$, which is twice the average slip-rate of the Seattle fault over the last 40 Ma.

## Introduction

Although every year a large number of earthquakes occur beneath the Puget Lowland of western Washington state, most of these are deep, and associated with the subducting Juan de Fuca plate. No earthquakes within the crust with magnitude greater than 6 have been recorded west of the Cascade range [*Ludwin et al.,* 1991]. However, recent geological mapping of tsunami deposits and offsets in Quaternary sedimentary strata has revealed evidence of large prehistoric crustal earthquakes [*Gower et al.,* 1985; *Atwater and Moore,* 1992]. In particular, 7 m of uplift along part of the Seattle fault, an east-west oriented thrust in the greater Seattle metropolitan area, suggests that an earthquake with magnitude greater than 7 occurred around 900 A.D. [*Bucknam et al.,* 1992]. The realization that crustal earthquakes represent a major seismic hazard in the Puget Lowland has provided strong motivation for a number of recent studies, including this one, which are aimed at mapping subsurface structures, such as the Seattle fault, that threaten densely populated areas.

In 1998 the SHIPS (Seismic Hazards Investigation in Puget Sound) program acquired seismic reflection data through Puget Sound with the objective of delineating the crustal architecture in order to provide constraints on earthquake hazard analyses [*Fisher et al.,* 1999]. In this paper, we present a high-resolution velocity image obtained by tomographic inversion of the first arrivals recorded in reflection line PS-2, which crossed the Seattle fault zone in eastern Puget Sound near Seattle.

## Seattle Fault and Regional Stratigraphy

The Seattle fault zone trends east-west across the Puget Lowland, and separates the approximately 9 km-deep Seattle basin to the north from the Seattle uplift of Tertiary rocks to the south (Figure 1). The presence of the Seattle fault was first inferred from gravity data in 1965, and the fault zone was interpreted to comprise two steeply north-dipping normal faults with around 11 km of vertical displacement [*Danes et al.,* 1965]. Subsequent geological mapping led to the suggestion that the fault is a south-dipping thrust [*Atwater and Moore,* 1992; *Yount and Holmes,* 1992].

Data from high-resolution marine seismic reflection surveys in Puget Sound and Lake Washington locate the Seattle fault zone at several points along its length and indicate the existence of between three and five fault splays [*Johnson et al.,* 1994]. The dips of the faults are uncertain: dips as large as 70° have been proposed for one splay on the basis of offset patterns in the surface geology [*Bucknam et al.,* 1992]; a dip of between 45° and 60° has been proposed for part of the Seattle fault shallower than 4 km [*Johnson et al.,* 1994; 1999]; however, a dip as low as 20° was suggested for the fault at greater depth [*Pratt et al.,* 1997].

Interpretations of oil industry seismic sections and data from boreholes up to 3500 m deep show that the

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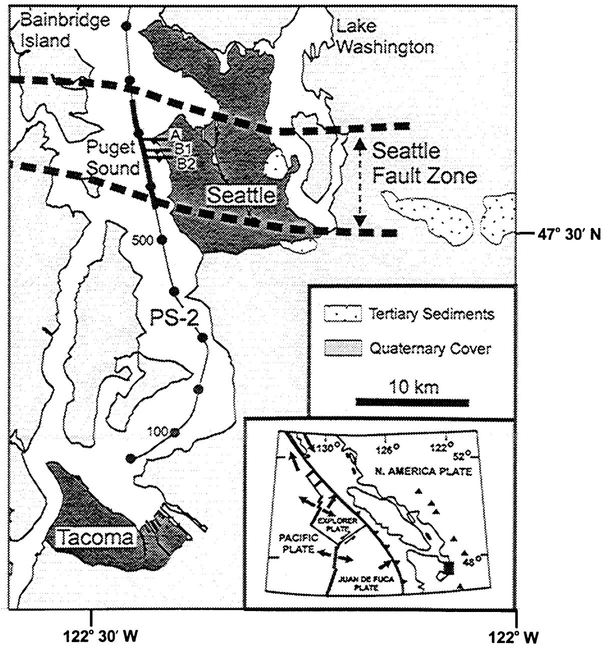


**Figure 1.** SHIPS seismic reflection profile PS-2 superimposed on the geology of the Puget Lowland region around Seattle. Darker areas represent the cities of Seattle and Tacoma. Dots indicate every hundredth shot point along the seismic line. The thicker line corresponds to the sections presented in Figures 2 and 3. The location of the Seattle fault zone is approximate and based on previous seismic reflection studies. Letters, which correspond to the notation of *Johnson et al.* [1999], indicate the locations of thrust fault splays interpreted in Figure 3. The position of the survey area with respect to the Cascadia convergent margin is shown by the black rectangle in the inset location map.

Seattle basin is floored by volcanics of the Eocene Crescent terrane, and attains a depth of approximately 9 km close to the Seattle fault [*Johnson et al.,* 1994; *Pratt et al.,* 1997]. In the deepest part of the basin, the Crescent terrane is overlain by approximately 2100 m of mainly mid-Eocene sediments, 3800 m of the marine Late Eocene to Oligocene Blakeley formation, 3000 m of the non-marine Miocene Blakeley Harbor formation, and 1000 m of Quaternary sediments [*Johnson et al.,* 1994]. Seismic reflection data show that the shallowest Tertiary rocks are characterized by high amplitude parallel reflections, which are separated from the lower amplitude, discontinuous hummocky reflections of the overlying Quaternary units by either a disconformity or, where the Tertiary units are folded, by an angular unconformity [*Johnson et al.,* 1999]. The correlation in these previous interpretations of specific geological units with seismic reflection character allows us to date many of the structures that we observe in our data.

## Seismic Data

SHIPS seismic reflection line PS-2 was shot using a 13-gun tuned airgun array with a total volume of 79 l. (4838 in.$^3$). The data were recorded by a 96-channel hydrophone streamer with 25 m group interval and 2575 m far offset. The 50 m shot point (SP) interval yielded a nominal 24-fold stacked reflection section. Data from the hydrophone group at 2100 m shows that, despite occasionally elevated levels of environmental noise, the first arrivals can be clearly identified (Figure 2). Low quality recording channels and bad shots were removed, and the first arrivals picked on every shot to an accuracy of ±8ms. These first arrival times were input to an iterative two-dimensional tomographic inversion algorithm based on a finite-difference solution to the Eikonal equation [*Aldridge and Oldenburg,* 1993], which was modified to allow the water layer velocity to be fixed at 1488 ms$^{-1}$. A simple 1-D three-layer starting model was estimated from a few trial inversions. 21 iterations were computed, which reduced the root-mean-square residual traveltime error from 124.3 ms to 8.8 ms. The model flatness constraints and the 125 m x 125 m smoothing operator applied during the inversion were set equal in horizontal and vertical directions to minimize any directional bias in the final velocity model. In this paper, we present a section across the Seattle fault zone from the tomographic inversion of line PS-2.

## Imaging the Fault Zone

Away from the Seattle fault zone, the derived subseafloor P-wave-velocity model reveals an undulating bedrock unit, in which the velocity increases quickly with depth; bedrock is overlain by a low velocity fill (Figure 3a). Our inversion shows that velocities in the upper unit range from 1500-1800 ms$^{-1}$, which compares well with velocities of 1500-2000 ms$^{-1}$ estimated for Pleistocene rocks using sonic logs [*Brocher and Ruebel,* 1998]. Hence we interpret this unit to comprise Quaternary sediments. In the lower unit, velocities increase quite sharply from 2000 ms$^{-1}$ to around 3000 ms$^{-1}$ over a 300 m depth range. These rocks are interpreted to be mostly Oligocene Blakeley formation, which is exhumed within the Seattle fault zone at Alki Point 1 km to the east of the seismic line. Although not found at Alki Point, Miocene Blakely Harbor formation is ex-

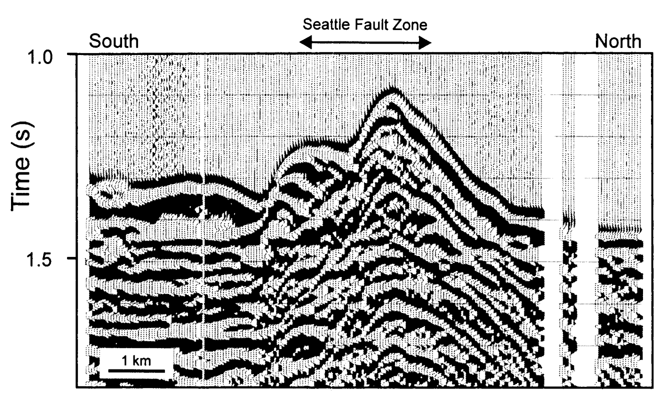


**Figure 2.** A common offset gather from line PS-2 near the Seattle fault zone; the source-receiver offset is 2100 m. First arrivals, which can be identified as the first strong arrivals on the section, are up to 300 ms earlier over the fault zone than elsewhere due to high velocity rocks close to the seafloor.

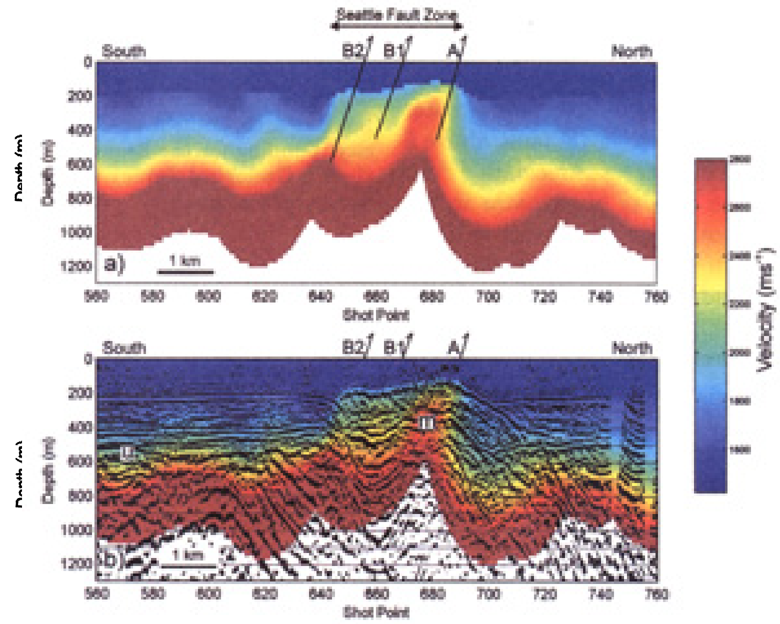


**Figure 3.** P wave velocity variation across the Seattle fault zone: a) velocity model derived from tomographic inversion of first arrival times with the position of the interpreted fault splays indicated; b) velocity model superimposed on the corresponding depth migrated seismic reflection section. The velocity model is not shown beneath the maximum depth to which rays propagated in the final tomography iteration. Arrows indicate the surface locations into which the interpreted faults project. A 700 m-wide zone of uplifted high-velocity rocks exists just beneath the seafloor south of fault A, while two narrower zones of elevated velocity can be identified just south of B1 and B2. With the exception of the seafloor multiple (m), few reflections can be seen within the fault zone. Folded high velocity Tertiary strata can be observed to the south of the fault zone beneath an angular unconformity (u), above which there are lower velocity Quaternary sediments. The vertical exaggeration is 3:1.

posed in the fault zone on Bainbridge Island 4 km to the west, and may also be present. The velocity model shows that the Seattle fault zone coincides with a 2.5 km-wide block of these uplifted higher-velocity Tertiary rocks. Rocks with velocities of 2000 ms$^{-1}$ are exposed at the seafloor, and the uplift zone is cored by rocks with velocities as high as 2600 ms$^{-1}$ that are just 170 m below the seafloor. Such high velocity rocks within the uplifted block are restricted to a narrow zone that is 700 m wide (south of "A" in Figure 3a). Two other regions of elevated velocity can be identified within the fault zone, just south of locations B1 and B2.

Strong lateral velocity variations, such as observed across the Seattle fault zone, can distort the geometry of seismic reflection images and result in erroneous depth estimates. However, we have solved this problem by depth migrating reflection profile PS-2 using the P wave velocities obtained from the tomographic inversion of the first arrivals (Figure 3b). The depth migrated section shows that reflections in the Quaternary section, such as those at 500 m depth, truncate against the higher velocity rocks that are uplifted within the fault zone. On the north side of the fault zone these reflections have been folded upward. Shallow reflections within the fault zone are chaotic. This character is consistent with geological mapping that shows steep overturned dips in Oligocene strata at Alki Point [*Yount and Gower,* 1991], close to line PS-2, because seismic reflection imaging of such geometries is rarely possible. The strong reflection that extends across the fault zone at 300-500 m depth is the first seafloor multiple ("m" in Figure 3b), and is not representative of subsurface structure.

We interpret the highest velocity, 2600 ms$^{-1}$, rocks in the Seattle fault zone to be a single sheet of Tertiary sedimentary rocks thrust along fault A, the northernmost fault of the Seattle fault zone [*Johnson et al.,* 1999], and over the low velocity Quaternary sediments that fill the upper part of the Seattle basin. We also interpret the velocity variations within the southern part of the 2.5 km-wide fault zone to indicate the presence of two other thrust sheets, with velocities in the range of 2100-2300 ms$^{-1}$, and separated by faults, B1 and B2. Undulations in the 2000-3000 ms$^{-1}$ velocity contours south of the Seattle fault zone at 600 m depth result from folding of the Tertiary strata, and the truncation of those strata at the Tertiary-Quaternary angular unconformity ("u" in Figure 3b). *Johnson et al.* [1999] interpreted a fourth fault splay, C, 1600 m south of splay B2; however, our results indicate that the structure identified by *Johnson et al.* [1999] lies within the Tertiary section, and that the continuity of the overlying Quaternary strata precludes any active faulting here.

Under the assumption that the location of the sudden lateral transition from high velocity to low velocity marks the position of a thrust fault, we are able to estimate the dip of fault A to be around 60° from the slope of the 2500 $ms^{-1}$ isovelocity contour. This value is comparable to dips interpreted from shallow penetration seismic data [*Johnson et al.,* 1999], and greater than the 45° dip inferred for the Seattle fault above 5 km depth from gravity and industry seismic data [*Pratt et al.,* 1997]. However, the density of raypaths in the final velocity model suggests that the model is likely only well constrained down to around 400 m depth in the vicinity of fault A, and that the accuracy of any dip estimate may not be high. In fact repeated runs of the inversion with different constraints in the horizontal and vertical directions have produced dip values between 40° and 80°. Therefore our final estimate of the dip of fault A is 60° ± 20°.

*Johnson et al.* [1999] estimated slip-rates of 0.4-0.9 mm $a^{-1}$ at various points along the Seattle fault with much of the variation in slip-rate attributable to differences in the age of the deepest Quaternary strata, which may be no older than 1 Ma due to the effects of several glaciations during the Quaternary. The final velocity model shown in Figure 3 indicates that Tertiary rocks lie as shallow as 170 m below sea level just south of thrust A. At SP 720 north of the fault zone and where the velocity model appears to be well-constrained, the Tertiary-Quaternary unconformity occurs at 590 m below sea level, suggesting that vertical uplift of around 420 m has occurred across fault A during the Quaternary. This uplift would be produced by a displacement of around 485 m along a 60°-dipping fault, and, assuming that no Quaternary strata older than 1 Ma are preserved, implies a slip rate of around 0.49 mm $a^{-1}$. With the broad range of fault dips we previously estimated, we calculate the slip-rate along thrust A over the last 1 Ma to be 0.42-0.65 mm $a^{-1}$ in eastern Puget Sound. Our calculated slip-rate is consistent with the values of *Johnson et al.* [1999], but twice the long-term slip-rate of 0.25 mm $a^{-1}$ for the Seattle fault over the last 40 Ma [*Pratt et al.,* 1997].

## Conclusions

We have presented the first high-resolution images of the shallow velocity structure across the Seattle fault zone obtained by tomographic inversion of a very dense dataset of first arrivals recorded in a marine seismic reflection profile. The resulting velocity model is sufficiently detailed that individual fault splays can be identified. The Seattle fault zone adjacent to the Seattle metropolitan area comprises three splays: a northernmost fault, along which Tertiary rocks are being thrust northward over the Quaternary sediments of the Seattle basin at a rate of approximately 0.5 mm $a^{-1}$, plus two secondary, less well-defined thrusts 1-2 km further south. The dip of the northernmost thrust is not particularly well resolved, but appears to be around 60°.

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