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Constraining fault interpretation through tomographic velocity gradients: application to Northern Cascadia

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Abstract

Spatial gradients of tomographic velocities are seldom used in interpretation of subsurface fault structures. This study shows that spatial velocity gradients can be used effectively in identifying subsurface discontinuities in the horizontal and vertical direc-

- tions. Three-dimensional velocity models constructed through tomographic inversion of active source and/or earthquake traveltime data are generally built from an initial 1-D velocity model that varies only with depth. Regularized tomographic inversion algorithms impose constraints on the roughness of the model that help to stabilize the inversion process. Final velocity models obtained from regularized tomographic inver-
- sions have smooth three-dimensional structures that are required by the data. Final velocity models are usually analyzed and interpreted either as a perturbation velocity model or as an absolute velocity model. Compared to perturbation velocity model, absolute velocity model has an advantage of providing constraints on lithology. Both velocity models lack the ability to provide sharp constraints on subsurface faults. An in-
- ¹⁵ terpretational approach utilizing spatial velocity gradients applied to northern Cascadia shows that subsurface faults that are not clearly interpretable from velocity model plots can be identified by sharp contrasts in velocity gradient plots. This interpretation resulted in inferring the locations of Tacoma Fault, Seattle Fault, Southern Whidbey Island Fault, and Darrington Devils Mountain fault much clearly. The Coast Range Boundary
- ²⁰ Fault, previously hypothesized on the basis of sedimentological and tectonic observations, is inferred clearly from the gradient plots. Many of the fault locations imaged from gradient data correlate with earthquake hypocenters indicating their seismogenic nature.





1 Introduction

Controlled source and earthquake traveltime data are commonly used for construction of tomographic velocity models for mapping crustal structure. Local and regional tomography models obtained from inversion of the traveltime data are useful in interpretation of lithology and subsurface structure. Subsurface structures that can be mapped by tomographic velocities are generally due to varying lithology across a fault, lithology difference across basin margins and basement surfaces, and varying compaction in rocks across the fault surfaces with in sedimentary units. Even though these contact/fault surfaces are in general sharp transitions in the subsurface, tomographic velocity models depict these surfaces by smooth velocity variation. This is due to the fact that the velocity models are constructed by applying smoothing constraints to overcome the ill conditioned nature of the tomographic inverse problem. Spatial gradients of the tomographic velocity model are seldom used in interpreting the velocity model. Results from an investigation of the applicability of velocity gradient analysis for structural

- interpretation of the upper crust, conducted using a previously constructed regional 3-D tomographic P-wave velocity model for northern Cascadia subduction zone (Ramachandran et al., 2006), are presented in this study. Information from horizontal gradients in X (east-west) and Y (north-south) directions define structural contacts much clearly than the tomographic velocity model. Some of the structural contacts identified from velocity gradient plots show correlation with relocated earthquake positions. This
- from velocity gradient plots show correlation with relocated earthquake positions. This correlation is not obvious in the velocity plots. The gradient in Z (depth) direction also shows correlation with earthquake clusters at some fault locations much clearly than the velocity plots.

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2 Data and methods

2.1 Tomography

First arrival Traveltime tomography using controlled source data from Seismic Hazards Investigation in Puget Sound (SHIPS) and regional earthquake data from British

- ⁵ Columbia, Canada and Washington State, USA resulted in a detailed velocity model for the northern Cascadia subduction zone (Ramachandran et al., 2006). Approximately 150 000 controlled source traveltime picks and 70 000 traveltime picks from nearly 3000 earthquakes were employed in constructing this velocity model. Traveltime data acquired in a three-dimensional experiment contain information about the spatial velocity structure in the subsurface. Even though minimum structure models
- implementing smoothness constraints are developed through tomographic inversion, structures which are needed to satisfy observed data are developed in the velocity model during regularized inversion. The smoothness constraints applied in the regularized tomographic inversion method are discussed in Ramachandran et al. (2005)
- and references there in. The smoothness constraints implemented in the inversion resulted in a final velocity model that has four times more smoothing in horizontal direction than in vertical direction. The starting model for the inversion is an 1-D model that has variations only in Z direction. Velocity reversals with depth were not used in the starting 1-D model. Velocity reversals with depth present in the final model are required by the data.

2.2 Velocity gradient computation

The origin of the 3-D velocity model is at the top of the model in the northwest corner. Gradients of velocity in X, Y, and Z directions are computed using adjacent values in respective directions. Describing the velocity model in three dimensions by V(i, j, k),

²⁵ indices *i*, *j* and *k* corresponding to velocity node positions in X, Y and Z directions, the velocity gradients are computed as below:





Vx = [V(i+1, j, k) - V(i, j, k)]/node spacing,

 $V_{V} = [V(i, j+1, k) - V(i, j, k)]/\text{node spacing},$

Vx = [V(i, j, k+1) - V(i, j, k)]/node spacing.

A negative gradient in the X direction indicates a decrease in velocity from west to east and a negative gradient in the Y direction indicates a decrease in velocity from north to 5 south. A negative gradient in Z direction indicates a decrease in velocity with depth.

Results 3

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In general, earth's upper crust shows much lateral variation in composition and structure. Lateral variation in the upper crustal regions due to faulting and basin boundaries are mapped using plots of horizontal gradients of tomographic velocity model. Vertical gradients of tomographic velocity models are useful in identifying basement features. Practical case study using five vertical cross sections extracted from the 3-D tomographic velocity model along with gradients in X, Y, and Z directions is used to describe the strength of this interpretational method. Profiles AB, CD, EF, and GH (Figs. 2, 3, 4, and 5) are approximately E-W trending and profile IJ (Fig. 6) is in the SW-NE direction.

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Leech River Fault 3.1

The Metchosin Igneous Complex in southern Vancouver Island is the extreme northerly exposure of the Crescent Terrane, which includes the Crescent Formation and Coast Range Basalts of western Washington State and Oregon (Babcock et al., 1992). This complex dips approximately 30° to the north-northeast (Massey, 1986) and is bounded to the north by the Leech River Fault, which separates it from the Pacific Rim and Wrangellia terranes. The Leech River Fault has been imaged by seismic reflection





as a thrust fault dipping 35° - 45° to the northwest and extending to a depth of 10 km (Clowes et al., 1987).

The Leech River Fault and the outline of Metchosin Igneous Group in the near subsurface are identified on profiles AB and CD. The Leech River Fault that separates the Metchosin Igneous Complex rocks from Pacific Rim meta sedimentary rocks is mapped at 60 km position on profile AB and at 80 km position on profile CD as sharp gradient changes on the X and Y gradients. Since the profiles are oblique to the fault separating units with different velocities, the velocity gradient at the profile-fault intersection is observed on both X and Y gradient plots. The contact of Metchosin Igneous Rocks with the sediments in the Strait of Juan de Fuca is identified on the X and Y gradients at 30 km location on profile AB. The features discussed above are not interpretable as clearly from the velocity model plots alone.

3.2 Outer Island Fault

The Outer Islands Fault is a large extensional fault that down-drops the Cretaceous sediments in the Watcom depocenter of the Georgia basin by 3 km below the Tertiary sediments (England and Bustin, 1998). At 150 km on profile AB (Fig. 2), the Outer Island Fault is identified on the X, Y, and Z gradient plots. The sharp contact and increasing velocity gradients to the northeast in the Z gradient plot at 150 km location indicates that the younger sediments extend much deeper in the basin.

20 3.3 Southern Whidbey Island Fault

Johnson et al. (1996) have described the Southern Whidbey Island fault (SWIF) (Fig. 1) as a broad (6–11 km) transpressional zone comprising three main splays. In this zone, the Eocene marine basaltic basement on the south and southwest is juxtaposed with heterogeneous pre-Tertiary basement in the northeast. The southern Whidbey Island Fault is a potential seismogenic structure below the eastern Strait of Juan de Fuca

²⁵ Fault is a potential seismogenic structure below the eastern Strait of Juan (Johnson et al., 1996; Fisher et al., 2005; Sherrod et al., 2008).





On profile CD (Fig. 3), between 95 and 105 km location, the Southern Whidbey Island fault zone is identified on X and Y gradient plots as sharp contrasts. At 105 km location on profile CD (Fig. 3), a discontinuity in gradient is observed on X and Y gradient plots, coinciding with a line of earthquake hypocenters indicating that this is an active fault. On the SW-NE oriented profile IJ (Fig. 6), SWIF can be seen in the Y gradient plot at

3.4 Darrington-Devils Mountain Fault

Near the eastern strait of Juan de Fuca, the Darrington-Devils Mountain Fault (DDMF) strikes nearly east-west from the Cascade Range to Vancouver Island (Fig. 1), dips 45°–75° to the north, and forms the northern boundary of the onshore Everett Basin. This fault is active as indicated by high-resolution seismic reflection sections, which show that Quaternary strata are faulted and/or folded (Johnson et al., 2001).

This fault is identified on profile CD (Fig. 3), at 140 km location on the X and Y gradient plots; the signature of this fault is not visible in the velocity plot. On the SW-NE
oriented profile IJ (Fig. 6), the Y gradient plot shows the signature of DDMF at 110 km location in terms of varying gradients across the fault, correlating with earthquake locations.

3.5 Hood Canal Fault

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110 km location.

Based on surface geology, gravity data and limited magnetic observations, Danes et
al. (1965) concluded that an unnamed, major active fault separates the Puget Lowlands from the Olympic Mountains and noted that northern Hood Canal developed along this fault. The Hood Canal fault zone is a northerly trending feature that is defined largely by geophysical anomalies and seismic-reflection data that collectively suggest the feature is a major active fault zone (e.g., Brocher et al., 2001; Dragovich et al., 2002; Blakely
et al., 2002).





On profile EF (Fig. 4), the Hood Canal Fault appears as a smooth transition at 30 km location in the velocity model. However, this fault can be identified by sharper discontinuities on the X, Y, and Z gradient plots at approximately 30 km location. To the south, this fault can be identified on profile GH (Fig. 5), at 20 km location on the X and Y gradient plots.

3.6 Seattle Fault

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In Puget Lowland, the Settle basin is bounded to the south by the Seattle fault zone. The Seattle fault zone is made up of several east-west trending fault segments (e.g., Johnson et al., 1994; Pratt et al., 1997; Wells et al., 1998). South of the Seattle fault, Crescent basement lies close to the surface (e.g., Pratt et al., 1997). Reverse displacement on the Seattle fault has resulted in both subsidence of the Seattle basin north of the fault and uplift of the basement south of the fault (Johnson et al., 1994, 1999; Pratt et al., 1997).

On profile IJ (Fig. 6), Seattle fault zone is inferred between 65 and 75 km location on the Y and Z gradient plots. The Z gradient plot has a sharp discontinuity at about 75 km location on this profile, coinciding with a near vertical location of earthquake hypocenters. Such a sharp feature is not readily visible in the velocity plot. North of this location the Z gradient map shows higher gradients extending deeper; this indicates that the sedimentary column extends probably down to 10 km depth.

20 3.7 Tacoma Fault

Based on gravity, a bounding fault on the north side of the Tacoma basin was proposed by Danes et al. (1965). Gower et al. (1985) proposed this fault based on gravity and aeromagnetic anomalies. Brocher et al. (2001) interpreted this boundary as a northdipping reverse fault, designated the Tacoma fault, from smooth tomographic velocity model and from documented uplift at two localities north of the Tacoma basin (Bucknam et al., 1992; Sherrod, 1998). This fault is identified on profile IJ (Fig. 6), at 40 km





distance on the Y gradient plot. From the Y and Z gradient values at 20 km location on this profile it can be inferred that the basement is approximately at 8 km depth.

3.8 Coast Range Boundary Fault

Beneath Puget Sound, the Coast Range Boundary Fault (CRBF) forms the eastern
⁵ boundary of the Eocene volcanic rocks (Johnson, 1984, 1985; Johnson et al., 1996).
CRBF is inferred mainly from tectonic and sedimentologic evidence to lie beneath the eastern Puget Lowland where it strikes approximately N–S (Van Wagoner et al., 2002).
Northward motion of the Cascadia forearc region during the early Tertiary may have been accommodated along the proposed Coast Range Boundary fault (CRBF), a right10 lateral strike-slip fault which presumably separates rocks of the Coast Range terrane from the pre-Tertiary basement of the Cascades (Johnson, 1984, 1985; Johnson et al., 1996).

There is no direct evidence for the presence of this fault from the tomographic velocity models constructed by Symons and Crosson (1997), Brocher et al. (2001) Van ¹⁵ Wagoner et al. (2002), and Ramachandran et al. (2006). This fault could not be inferred previously from the tomographic velocity models due to the smooth nature of the velocities. However, CRBF can be inferred clearly on profile EF (Fig. 4) at 85 km location on the X gradient plot and on profile GH (Fig. 5) at 95 km location on the X gradient plot.

- Johnson et al. (1999) identified a zone of active or potentially active north-trending strike-slip and normal faults, a few kilometers west of and parallel to the Coast Range Boundary Fault, representing a portion of a regionally distributed shear zone along which the Washington Coast Range is moving northward relative to the eastern Puget Lowland and Cascade Range. Approximately 10 km east of the CRBF locations iden-
- ²⁵ tified on profiles EF and GH, there is a near vertical line of earthquake locations that correlate with faults paralleling CRBF discussed by Johnson et al. (1999).





4 Conclusions

Conventional tomographic velocity model interpretation relies on absolute velocity interpretation or perturbation velocity interpretation. In this study it is shown that spatial gradients of tomographic velocities provide excellent constraints on locating horizontal

- ⁵ discontinuities such as faults and basin margins, and vertical discontinuities such as sediment-basement contact. Even though velocity models possess inherent gradient information, it is not explicitly visible in velocity model plots making it difficult to interpret geological discontinuities. Application of velocity gradients interpretation approach to the tomographic velocity model from northern Cascadia resulted in mapping of the sig-
- nificant faults with better clarity. The gradient plots also depict the closeness of some of these faults to seismicity in a much clear fashion. The Coast Range Boundary Fault, which has not been mapped from tomographic velocity models earlier, was clearly identified from the gradient plots. It is recommended that tomographic velocity model interpretation studies be accompanied by interpretation of spatial velocity gradients to obtain better structural information chaut subsurface discontinuities.
- ¹⁵ obtain better structural information about subsurface discontinuities.

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Fig. 1. Location map showing the study area. Vertical cross-section of velocities and spatial gradients of velocities along profiles AB, CD, EF, GH and IJ are shown in Figs. 2–6. CFTB-Cowichan Fold and Thrust Belt; CH-Chuckanut sub-basin; CLB-Clallam basin; CPC-Coast Plutonic Complex; CRBF-Coast Range boundary fault; CR-Crescent terrane; DDMF-Darrington-Devils Mountain fault; EB-Everett basin; HCF-Hood Canal fault; HRF-Hurricane Ridge fault; KA-Kingston Arch; LIF-Lummi Island fault; LRF-Leech River fault; B-Muckleshoot Basin; NA-Nanaimo sub-basin; OF-Olympia fault; OIF-Outer Islands fault; PB-Possesion Basin; PR-Pacific Rim terrane; PTB-Port Townsend basin; SB-Seattle basin; SF-Seattle fault; SU-Seattle up-lift; SWIF-southern Whidbey Island fault; TB-Tacoma basin; TF-Tacoma fault; WA-Whatcom sub-basin.









































