Tectonophysics 624–625 (2014) 32–45

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

# The Wallula fault and tectonic framework of south-central Washington, as interpreted from magnetic and gravity anomalies

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ARTICLE INFO

*Article history:*
Received 28 May 2013
Received in revised form 23 September 2013
Accepted 3 November 2013
Available online 13 November 2013

*Keywords:*
Yakima fold and thrust belt
Earthquakes
Magnetic anomalies
Gravity anomalies
Crustal structure

ABSTRACT

The Yakima fold and thrust belt (YFTB) in central Washington has accommodated regional, mostly north-directed, deformation of the Cascadia backarc since prior to emplacement of Miocene flood basalt of the Columbia River Basalt Group (CRBG). The YFTB consists of two structural domains. Northern folds of the YFTB strike eastward and terminate at the western margin of a 20-mGal negative gravity anomaly, the Pasco gravity low, straddling the North American continental margin. Southern folds of the YFTB strike southeastward, form part of the Olympic–Wallowa lineament (OWL), and pass south of the Pasco gravity low as the Wallula fault zone. An upper crustal model based on gravity and magnetic anomalies suggests that the Pasco gravity low is caused in part by an 8-km-deep Tertiary basin, the Pasco sub-basin, abutting the continental margin and concealed beneath CRBG. The Pasco sub-basin is crossed by north-northwest-striking magnetic anomalies caused by dikes of the 8.5 Ma Ice Harbor Member of the CRBG. At their northern end, dikes connect with the eastern terminus of the Saddle Mountains thrust of the YFTB. At their southern end, dikes are disrupted by the Wallula fault zone. The episode of NE–SW extension that promoted Ice Harbor dike injection apparently involved strike-slip displacement on the Saddle Mountains and Wallula faults. The amount of lateral shear on the OWL impacts the level of seismic hazard in the Cascadia region. Ice Harbor dikes, as mapped with aeromagnetic data, are dextrally offset by the Wallula fault zone a total of 6.9 km. Assuming that dike offsets are tectonic in origin, the Wallula fault zone has experienced an average dextral shear of 0.8 mm/y since dike emplacement 8.5 Ma, consistent with right-lateral stream offsets observed at other locations along the OWL. Southeastward, the Wallula fault transfers strain to the north-striking Hite fault, the possible location of the M 5.7 Milton-Freewater earthquake in 1936.

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## 1. Introduction

Oblique subduction of the Juan de Fuca plate beneath North America (Fig. 1) accommodates most of the plate boundary motion along the Cascadia convergent margin. GPS velocities show that deformation of the upper plate is accommodated by regional clockwise rotation of crustal blocks at 0.2–0.7°/Ma about rotation poles to the east in Idaho, easternmost Oregon and Washington, and westernmost Montana (McCaffrey et al., 2007, 2013), similar to long-term (10–15 Ma) rotation rates determined from paleomagnetic studies (Wells et al., 1998). Northward motion of the rotating blocks against slower moving Canada puts much of Washington under margin-parallel compression, producing folds, reverse faults, and earthquakes from the Puget Sound to eastern Washington.

The most densely populated areas of the Pacific Northwest lie within lowland regions of the Cascadia forearc, where horizontal velocities, deformation, and seismicity are greatest due to large distance from the pole of rotation. Although closer to the pole of rotation, the backarc is seismically active as well, and was in fact the site of the largest shallow earthquake in Washington's recorded history, a M 6.8–7.4 event that occurred north of Wenatchee (Fig. 2A) in 1872 (Bakun et al., 2002). The backarc region has numerous population centers (e.g., Yakima, Wenatchee, Richland, Kennewick, Pasco, and Ellensburg) and supports a large infrastructure of Federal and municipal hydropower installations, an operating nuclear power plant, two large Federal irrigation projects, and the Hanford Site, where a processing facility is under construction to convert large volumes of stored high-level radioactive waste into a stable glass form for permanent disposal.

Prominent folds and faults throughout the backarc regions of central and eastern Washington testify to long-term deformation most prominently displayed in the Yakima fold and thrust belt (YFTB) of south-central Washington (Fig. 2). Folds and faults of the YFTB fan westward into the Cascade Range and likely continue into populated regions of the Puget Lowland and Willamette Valley (e.g., Blakely et al., 2011). A northwest-striking domain of the YFTB comprises one segment of the Olympic–Wallowa lineament (OWL), a physiographic alignment extending northwestward ~500 km from northeastern Oregon to Vancouver Island, British Columbia (Fig. 2). The OWL was first recognized nearly 70 years ago as a topographic lineament (Raisz, 1945),

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0040-1951/$ – see front matter. Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.tecto.2013.11.006

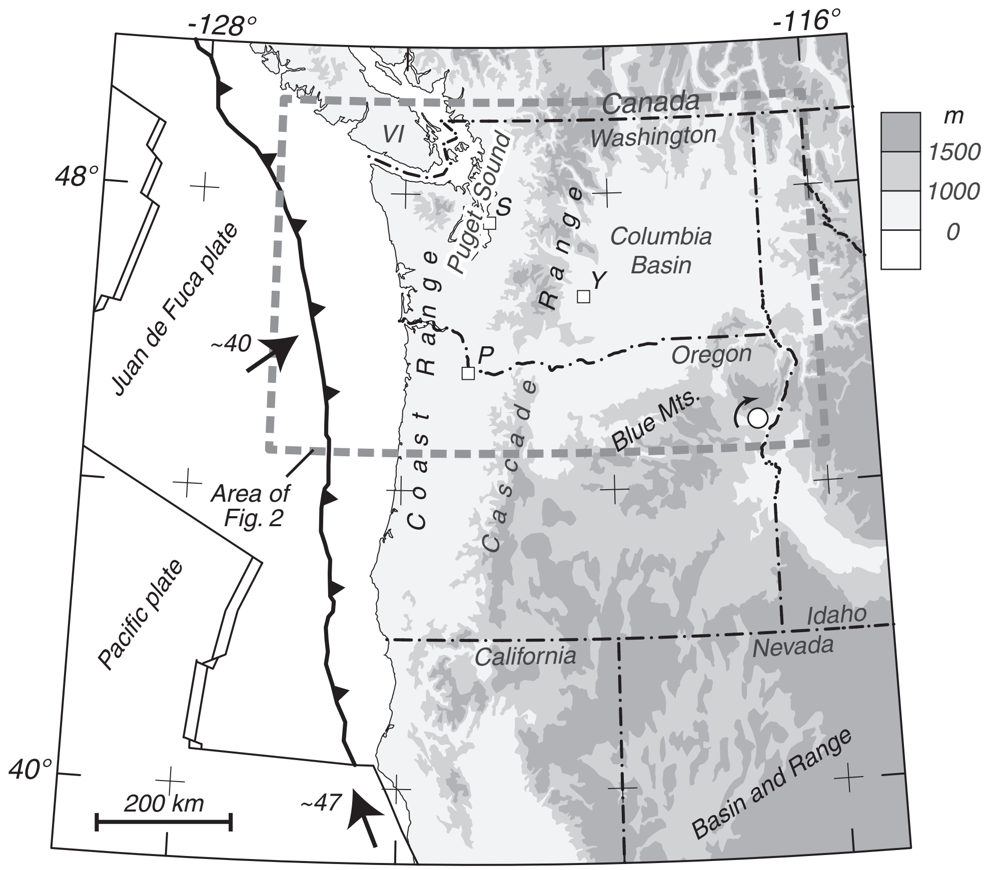


**Fig. 1.** Cascadia subduction zone, Pacific Northwest. Gray shades indicate topography. Dashed rectangle is area of Fig. 2. Arrows and accompanying numbers indicate motion of Juan de Fuca and Pacific plates with respect to North America in mm/y. White circle is modern pole of rotation for the Oregon Coast Range relative to North America; rotation rate 0.67°/my (McCaffrey et al., 2013). Note that the YFTB pole of rotation is located just east of Idaho and outside map area (McCaffrey et al., 2013). VI, Vancouver Island; S, Seattle; P, Portland; Y, Yakima.

and its tectonic significance remains a matter of discussion today. The tectonic relevance of the OWL, particularly the degree to which horizontal shear has contributed to its evolution, is an important element in assessing the kinematic connection between Cascadia backarc and forearc regions, and the consequent seismic hazard it poses to the region, including the greater Puget Sound area and south-central Washington. Past workers have come to rather different conclusions, suggesting sinistral (Swanson et al., 1976), dextral (Hooper and Conrey, 1989; Pratt, 2012), and no (Hutter, 1997; Reidel et al., 2002) horizontal displacement on the OWL.

Here we describe gravity and magnetic anomalies over the eastern limits of the YFTB, where multiple, broadly separated folds and faults converge eastward into the relatively narrow Wallula fault zone. We develop a model to explain the evolution of this eastward convergence, provide new constraints on long-term horizontal shear of the Wallula fault zone, and discuss implications for seismic hazards of south-central Washington.

## 2. Geologic setting

Our study area (Figs. 3 and 4) is located within the Columbia Basin, a broad, topographically low-lying region of the Cascadia backarc. Flood basalt of the CRBG dominates the landscape and covers the entire Columbia Basin (Fig. 3). CRBG lava flows erupted from 17.5 to 6.0 Ma, mostly from vents in southeastern Washington and northeastern Oregon well east of the study area, sometimes flowing all the way to the Pacific Ocean. CRBG flows together comprise 174,000 km$^3$ and cover 163,700 km$^2$ of Oregon and Washington (Tolan et al., 1989, 2009). CRBG production was not uniform; the Grande Ronde Basalt, for example, comprises ~85% (by volume) of the CRBG, erupted over a period of less than 2 million years (17.0 to 15.6 Ma), and underlies the entire Columbia Basin. Although Grande Ronde Basalt exposures are limited in the study area (Hutter, 1997; Schuster et al., 1997), these rocks undoubtedly comprise a large part of the CRBG section at depth. Grande Ronde Basalt is overlain by Wanapum (15.6 to 14.5 Ma) and Saddle Mountains Basalt (14.5 to 6.0 Ma), both exposed in the study area. CRBG in the study area is mostly concealed at the surface by Miocene–Pliocene continental sediments and younger dune sands, loess, and flood deposits (Schuster et al., 1997).

Most CRBG basalts flowed into the study area from the east. In the waning stages of CRBG eruptions, however, intrusions narrowed to a northwest-striking zone in the central part of the study area (Fig. 3A; Tolan et al., 1989). These northwest-striking dikes and laterally restricted flows comprise the Ice Harbor Member of the CRBG, emplaced ~8.5 Ma (Swanson and Helz, 1979; Swanson et al., 1975) near the end of Saddle Mountains Basalt eruptions. Swanson and Helz (1979) divided the Ice Harbor Member into three units with different magnetic polarities (Choiniere and Swanson, 1979): from oldest to youngest, the basalt of Basin City (normal), basalt of Martindale (reversed), and basalt of Goose Island (low-latitude normal).

Rocks older than CRBG are not exposed in the study area, but one deep borehole provides a glimpse of sub-CRBG lithologies. The Shell Darcell 1-10 borehole (Fig. 2) encountered the base of CRBG at 2382 m depth, passed through 175 m of Eocene sediments, reached basement at 2557 m depth (Reidel et al., 2002; Wilson et al., 2008), and continued another 50 m to a total depth of 2607 m. Basement encountered in Darcell 1-10 was metasedimentary rock of Precambrian to Paleozoic age interpreted as continental craton (Kuehn, 1995; Reidel et al., 1994, 2002). Partly on the basis of the Darcell 1-10 borehole and gravity data, Reidel et al. (1994; 2002, Fig. 2.2) concluded that the