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Finite-frequency P-wave tomography of the Western Canada Sedimentary Basin: Implications for the lithospheric evolution in Western Laurentia

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ABSTRACT

The lithosphere beneath the Western Canada Sedimentary Basin has potentially undergone Precambrian subduction and collisional orogenesis, resulting in a complex network of crustal domains. To improve the understanding of its evolutionary history, we combine data from the USArray and three regional networks to invert for P-wave velocities of the upper mantle using finite-frequency tomography. Our model reveals distinct, vertically continuous high (>1%) velocity perturbations at depths above 200 km beneath the Precambrian Buffalo Head Terrane, Hearne craton and Medicine Hat Block, which sharply contrasts with those beneath the Canadian Rockies (<−1%) at comparable depths. The P velocity increases from −0.5% above 70 km depth to 1.5% at 330 km depth beneath southern Alberta, which provides compelling evidence for a deep, structurally complex Hearne craton. In comparison, the lithosphere is substantially thinner beneath the adjacent Buffalo Head Terrane (160 km) and Medicine Hat Block (200 km). These findings are consistent with earlier theories of tectonic assembly in this region, which featured distinct Archean and Proterozoic plate convergences between the Hearne craton and its neighboring domains. The highly variable, bimodally distributed craton thicknesses may also reflect different lithospheric destruction processes beneath the western margin of Laurentia.

1. Introduction

1.1. Overview

Cratons are ancient cores of continents that have survived secular tectonic evolution since the Precambrian (Jordan, 1975; Pollack, 1986; Hoffman, 1988; King, 2005). Their longevity and stability have been largely attributed to the presence of a thick (>300 km), cold and chemically depleted boundary layer (i.e., tectosphere) that resists the convective disruption from the underlying mantle over billions of years (Jordan, 1975, 1979, 1988; Carlson et al., 2005; Sleep, 2005; Griffin et al., 2009). Although the mechanisms for the formation and growth of cratons have been a subject of active debate, existing theories generally favor three possible origins (Lee et al., 2011; Gerya, 2014): hot plume (Boyd, 1989; Griffin et al., 2003; Arndt et al., 2009), slab subduction (Helmstaedt and Schulze, 1989; Hoffman, 1990; Sambridge and Drijkoningen, 1992; Bostock, 1998; Canil, 2004; Pearson and Wittig, 2008; Snyder et al., 2015) and continental collision (Jordan, 1978; Cooper et al., 2006; Gray and Pysklywec, 2010). Since their formation in the Precambrian, the majority of continental cratons have remained relatively stable, although the underlying lithospheric keels may have undergone considerable modifications through episodic growth and destruction associated with major tectonic events (Gao et al., 2002; Carlson et al., 2004; Foley, 2008; Lee et al., 2011).

Laurentia, the cratonic core of North America, has witnessed protracted lithospheric accretion (Hoffman, 1988, 1989; Villeneuve et al., 1993; Foster et al., 2006; Whitmeyer and Karlstrom, 2007; Pearson and Wittig, 2008; Corrigan et al., 2009; Yuan and Romanowicz, 2010; Darbyshire et al., 2013) and reworking (Ross et al., 1991; Davis et al., 2003; Carlson et al., 2004; Mercier et al., 2009; Frederiksen et al., 2013; Bao and Eaton, 2015; Humphreys et al., 2015; Boyce et al., 2016; Liu et al., 2016) during its extensive evolutionary history dating back to >3 billion years ago (Hoffman, 1988; Hammer et al., 2011). The western margin of this ancient continent, where is currently overlain by the Paleozoic strata in the Western Canada Sedimentary Basin (WCSB), has exhibited evidence of rifting, subduction, collisional orogenesis and melting during the Precambrian (Ross et al., 1991; Villeneuve et al., 1993). These tectonic processes and the associated tectonothermal events may have considerable implications for the stabilization and modification of the mantle lithosphere beneath this region (Ross et al., 1991; Ross, 2002).

In this study we take advantage of recently developed regional seismic arrays in Alberta, in conjunction with the USArray Transportable

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Array (TA) deployed to the south of the WCSB, to map the mantle P-wave velocities. Our focuses are the integrity and characteristics of the lithospheric mantle, which enable an updated appraisal of both the existing tectonic framework and the Precambrian evolutionary history of western Laurentia.

1.2. Geological setting

The WCSB consists of the eastern Canadian Cordillera, a strongly deformed thrust and fold belt overlying the western margin of the Precambrian basement, and two major sedimentary basins (i.e., the Williston and Alberta basins; Wright et al., 1994) near the western margin of the ancestral North American craton. The Precambrian basement of the WCSB, presently buried beneath the thick Phanerozoic sedimentary layers, is a network of the Archean continental fragments assembled along the Proterozoic orogenic belts during a relatively short geological period ca. 2.0–1.8 Ga (Ross et al., 1991). These domains are bounded to the east by the Trans-Hudson Orogen (THO), a Himalayan-scale Paleoproterozoic collisional orogenic belt, and to the west by the accreted terranes of the Phanerozoic Cordillera that overthrusted onto the western margin of Laurentia after the Jurassic period (Dickinson, 2004). Our study region consists of the Archean Rae, Hearne, Medicine Hat Block (MHB) and Wyoming provinces, four microcontinents separated by potential structural discontinuities known as the Snowbird Tectonic Zone (STZ), Vulcan Structure (VS) and Great Falls Tectonic Zone (GFTZ), respectively (Fig. 1).

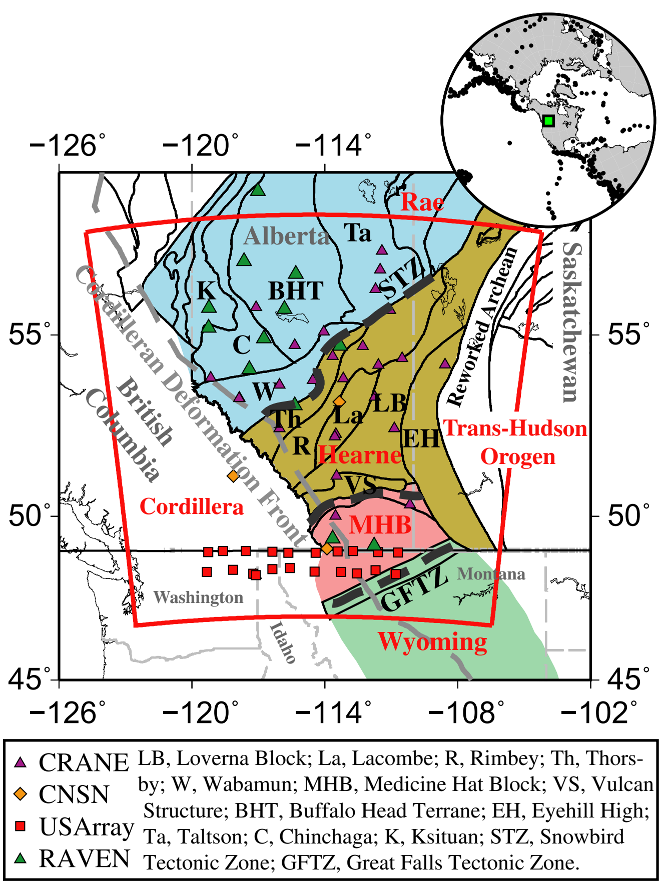

Fig. 1. The tectonic domains in western Laurentia. The red lines mark the boundaries of our velocity model. The black and grey dashed lines indicate the respective locations of major structural discontinuities (i.e., the STZ, VS and GFTZ) and the Cordilleran Deformation Front. The various symbols denote the stations used in this study. The earthquake epicenters are shown in the map inset and the green square marks the region of this study.

The aforementioned structural discontinuities play a significant role in the interpretation of the regional tectonic history. The STZ can be traced from the exposed portion of the Canadian Shield from northern Saskatchewan to the subsurface in central Alberta, where its delineation is primarily based on potential field anomalies (Ross et al., 1991; Villeneuve et al., 1993). A popular theory attributes its origin to a Proterozoic intercontinental suture (Hoffman, 1988; Berman et al., 2007), resulting from the subduction of an oceanic basin (the Thorsby domain) and the subsequent continent-continent collision between the Archean Rae and Hearne provinces. In this scenario, the Rimbey domain to the southeast of the STZ, which contains 1.79–1.85 Ga old biotite granites, could be associated with a magmatic belt formed during the subduction (Ross et al., 1991; Ross, 2002). Alternative interpretations of the STZ accentuate intracontinental origins such as a shear zone (Hanmer et al., 1995) or an incipient rift (Flowers et al., 2006) based on major metamorphic events (~1.9 Ga) in this area.

The VS in southern Alberta and the GFTZ in northern Montana are equally debated in recent literature. The east-west trending VS is visible from magnetic and gravity observations, separating the Loverna Block (LB), the ancient core of the Hearne craton, from the Archean MHB in the south (Lemieux et al., 2000; Ross, 2002). It was initially proposed to be a rift zone (Kanasewich et al., 1969) but, more recently, a collisional suture according to geophysical analyses (Eaton et al., 1999a; Lemieux et al., 2000). The direction of the dip (north or south; Eaton et al., 1999a; Lemieux et al., 2000) and the age of collision (Archean or Proterozoic; Lemieux et al., 2000; Clowes et al., 2002; Gorman et al., 2002) along the VS remain debated. A similarly controversial structure is the GFTZ, a northeasterly trending potential field anomaly that marks the boundary between the MHB and Wyoming province. While it is more commonly suggested as a convergent margin (Clowes et al., 2002; Gorman et al., 2002; Mueller et al., 2002; Mueller and Frost, 2006), an intracontinental origin cannot be ruled out based on geochemical (Buhlmann et al., 2000) and magnetotelluric observations (Boerner et al., 1998; Meqbel et al., 2014).

1.3. Previous geophysical studies

Potential field data and analyses of U-Pb geochronology of drill core samples of the crystalline basement provided first-order constraints on the configuration of tectonic elements of the WCSB (Ross et al., 1991; Villeneuve et al., 1993). Further refinements to the basement structure were made through multi-disciplinary studies from the Alberta Basement Transects of Lithoprobe (Clowes et al., 1995, 2002; Ross et al., 1995, 2000; Boerner et al., 2000; Ross, 2002), a milestone trans-Canada geophysical experiment. A synopsis of the results from these transects (Eaton et al., 1999a; Lemieux et al., 2000; Ross et al., 2000; Bouzidi et al., 2002) shaped the present-day understanding of the tectonic history of the WCSB, particularly those from the Central Alberta Transect (CAT; Ross et al., 1995, 2000; Eaton and Cassidy, 1996), the Peace River Arch Industry Seismic Experiment (PRAISE) in northern Alberta (Eaton et al., 1999b) and the Southern Alberta Lithospheric Transect (SALT; Eaton et al., 2000; Lemieux et al., 2000; Clowes et al., 2002).

Seismic reflectivity on these transects, in combination with other geophysical observations (e.g., seismic velocity, electrical resistivity and potential fields; Boerner et al., 2000; Hope and Eaton, 2002; Gu and Shen, 2015), played a fundamental role in elucidating the tectonic evolutionary history of central-southern Alberta (Ross, 2002). CAT highlighted the role of the STZ as a collisional boundary (Ross et al., 1995; Eaton and Cassidy, 1996) and revealed thrust-imbricated crust beneath the Hearne province (Ross et al., 1995, 2000). These seismic observations, together with increased mantle conductivity (Boerner et al., 1999; Boerner et al., 2000), led to the “tectonic vise” model in central Alberta (Ross et al., 2000; Ross, 2002), where the Hearne province was suggested to be trapped between oceanic subduction along the STZ in