Tectonophysics 608 (2013) 700–712

Contents lists available at ScienceDirect

Tectonophysics

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

3-D crust and mantle structure in southern Ontario, Canada via receiver function imaging

J. Zhang [1], A.W. Frederiksen *

Department of Geological Sciences, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada

ARTICLE INFO

Article history:
Received 6 May 2013
Received in revised form 4 August 2013
Accepted 6 August 2013
Available online 15 August 2013

Keywords:
Grenville Province
Receiver functions
Scattering tomography
Common conversion point stacking

ABSTRACT

A teleseismic data set from the POLARIS project is used to obtain 3-D images of southern Ontario using two imaging techniques: scattering tomography and common-conversion-point stacking. The resulting images reveal a layered crust, the layering being interrupted by discontinuities associated with major crustal-scale faulting. Breaks in crustal continuity and Moho deflections associated with the Ottawa-Bonnechère Graben indicate that the graben is associated with faulting on a whole crust scale. We also detect similar discontinuities across the Mississauga Domain, supporting the previous interpretation that the domain is bounded by crustal-scale faults. We locate discontinuous sub-lithospheric negative-polarity arrivals which indicate complex three-dimensional structures within the lithosphere and may be associated with subduction remnants or a mid-lithosphere discontinuity.

1. Introduction

In many regions of past tectonic activity, the depth extent of surface geology and the relationship between crust and mantle structures can be clarified through seismic imaging. With the proliferation of dense networks of earthquake seismographs, obtaining such images through passive rather than active seismology is an attractive option, particularly if such images can be produced in three dimensions. Through the POLARIS project (Eaton et al., 2005), a dense network was installed in southern Ontario beginning in 2002 (Fig. 1). Southern Ontario embraces part of the Grenville Province, a complex Proterozoic orogenic belt, cross-cut by normal faulting along the Ottawa-Bonnechère Graben; its crustal structure is believed to be strongly three-dimensional. Sufficient teleseismic data from the Ontario POLARIS data are now available to permit the use of 3-D imaging techniques applied to the *P* coda; in this paper, we apply common-conversion-point stacking and teleseismic scattering tomography to this collected data set, in order to examine the depth expression of major tectonic features and their relationship to mantle structure.

2. Tectonic and geophysical background

The Canadian Shield, the Precambrian core of North America, is an assemblage of tectonic provinces with very different ages and histories (Hoffman, 1988). One of these provinces is the Proterozoic Grenville Province, forming a belt ≈400–500 km wide along the southeastern margin of the Canadian Shield (Fig. 1, inset). In eastern Canada, the Grenville Province lies between the Archean Superior Province to the northeast and the Paleozoic Appalachian Orogen to the southeast, with some localized regions between the Superior and Grenville Provinces belonging to the Southern Province.

The Grenville Province is the result of the Grenvillian Orogeny, a complex orogeny occurring from 1.2 to 1.0 Ga along the southeast margin of the Laurentian continent during the assembly of Rodinia. As a result of the orogeny, material of various ages was overthrust onto the Superior basement, accompanied by exhumation of lower crustal material and extensive anorthositic intrusions (Easton, 1992; Ludden and Hynes, 2000). Within Ontario, the Grenville Province has traditionally been divided into two belts (Fig. 1) bounded by relatively narrow shear zones: immediately southeast of the Superior Province, the Central Gneiss Belt (CGB) is bounded to the northwest by the Grenville Front Tectonic Zone (GFTZ) and to the southeast by the Central Metasedimentary Belt Boundary Zone (CMBBZ), which is followed by the Central Metasedimentary Belt. A more recent subdivision by Carr et al. (2000) interprets the CGB as pre-Grenvillian Laurentia and its margin, and divides the CMB into the Composite Arc Belt (CAB; the portion of the CMB northwest of the Frontenac Terrane) and the Frontenac-Adirondack Belt (FAB; the Frontenac Terrane and regions to the southeast).

The CGB and CMB represent complex terrane assemblages of different compositions and metamorphic grades: the CGB consists largely of gneisses of igneous origin at upper amphibolite to granulite facies, while the CMB consists of mixed sedimentary and volcanic rocks intruded by plutons of varying age and composition and metamorphosed at grades ranging from greenschist to granulite facies (Easton, 1992).

---

* Corresponding author. Tel.: +1 2044749460.
E-mail addresses: jinling_zhang@sensorgeo.com (J. Zhang), Andrew.Frederiksen@umanitoba.ca (A.W. Frederiksen).

[1] Now at Sensor Geophysical Ltd., 1300, 736-6 Avenue SW, Calgary, Alberta T2P 3T7, Canada.

0040-1951/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tecto.2013.08.011

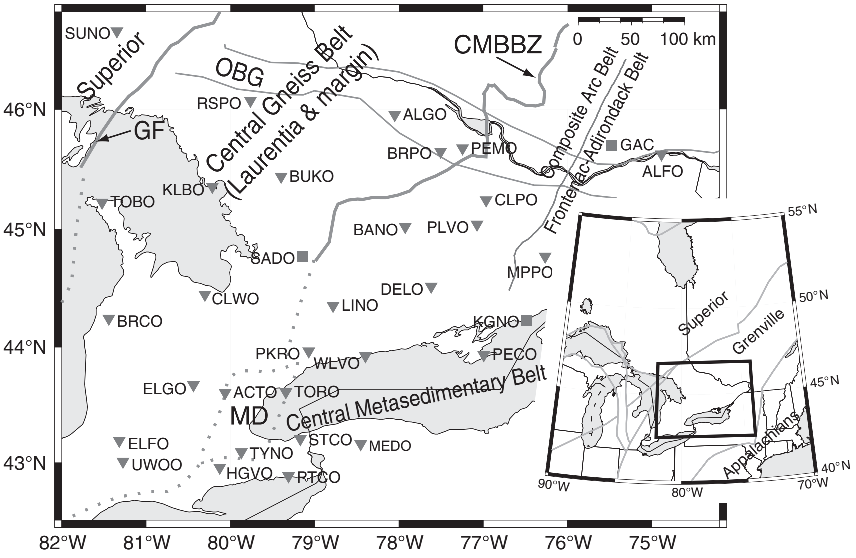

Fig. 1. Station set used in this experiment, overlaid on a map of the major tectonic divisions of eastern Ontario (after Ludden and Hynes, 2000). Triangles indicate POLARIS instruments, while squares indicate permanent CNSN stations. Heavy gray lines indicate major tectonic divisions, while thin gray lines indicate the bounds of the Ottawa-Bonnechère Graben (OBG) and the internal division of the CMB introduced by Carr et al. (2000). Dashed lines indicate interpreted boundaries beneath sedimentary cover. Major boundaries include the Grenville Front (GF) and the Central Metasedimentary Belt Boundary Zone (CMBBZ); the region denoted MD is the Mississauga Domain. The inset map indicates the location of the study area (rectangle) in relation to eastern North America and its major tectonic provinces (boundaries after Hoffman, 1988).

Later rifting on the Ottawa-Bonnechère Graben (OBG) cuts both belts at a high angle (Fig. 1) and its associated faults remain seismically active (Rimando, 1994).

The Grenville Province and environs have been investigated in a number of previous geophysical studies. The Grenville and OBG were notably examined by a 1982 COCRUST refraction/wide-angle reflection profile (Mereu et al., 1986), which detected crustal thickening beneath the GFTZ, a Moho step at the CMBBZ with thicker crust on the CMB side, and a disturbed Moho at the OBG; all of these observations indicate that the major tectonic boundaries of southern Ontario are crustal-scale features. Extensive reflection and refraction work was performed as part of the Lithoprobe Abitibi-Grenville Transect (see e.g. White et al., 2000), determining that the GFTZ and CMBBZ dip to the southeast at depth, ending at a décollement at ca. 25–30 km.

Passive seismic studies of southern Ontario took place as part of the POLARIS project (Eaton et al., 2005). The thickness and *P*–*S* velocity ratio of the crust were studied using receiver functions (Eaton et al., 2006), finding that the crustal thickness ranges from 34 to 52 km across the area. The mantle was examined using travel-time tomography by Aktas and Eaton (2006) and using surface waves by Chen and Li (2012), though neither of these methods was capable of resolving fine upper mantle layering. Single-station receiver-function work by Frederiksen et al. (2006) revealed a complex and laterally-varying pattern of upper-mantle layering, but did not image the layering in three dimensions.

3. Data and processing

The Canadian National Seismograph Network (CNSN), a project of the Geological Survey of Canada, has been operating two broadband seismometers in the study area for over a decade: GAC (Glen Almond, Québec) was installed in 1992, and SADO (Sadowa, Ontario) in 1993. An additional station (KGNO, in Kingston, Ontario) was installed in 1999. Beginning in 2002, a network of broadband instruments has been operating in southern Ontario as part of the POLARIS project (Eaton et al., 2005). For this project, all 36 broadband stations in the study area were used (Fig. 1), forming a network of instruments spaced ≈50–60 km apart. Teleseismic events in the following time periods were analyzed: 03/2002–04/2005 for the POLARIS stations, 01/1994–05/2005 for GAC, and 11/1996–04/2005 for SADO (Fig. 2).

In order to remove the effects of varying source time functions and source-side structure, a variant of receiver-function deconvolution was performed. We employed a method similar to that of Bostock (1998): the free-surface transform was used to improve separation of the *P*, *SV* and *SH* components, after which damped deconvolution was performed. Redundancy of data was exploited by binning events in back-azimuth/slowness windows, under the assumption that events with similar incidence angles would exhibit similar structural responses, and the binned events were deconvolved simultaneously (Frederiksen et al., 2006). Slowness bins were spaced 0.002 s/km apart, while back-azimuthal bins were spaced 20° apart; final receiver functions were filtered in the 0.05–0.5 Hz passband.

Gathers of processed receiver functions for two stations are shown in Figs. 3 and 4. SADO (Fig. 3) is a high-quality permanent CNSN station with a long data record, while PEMO is a temporary POLARIS instrument; this difference is reflected in the larger stacking fold and broader back-azimuth distribution of the SADO data. Both data sets show *SV* arrivals at ≈5 and 15 s after the *P* arrival, corresponding to the Moho *Ps* conversion and *Ppps* multiple, respectively. Coherent arrivals prior to the Moho conversion are constrained to be the result of crustal structure, as any *Ps* energy converting below the Moho would occur after the Moho *Ps*. Coherent energy between 5 and 15 s may represent either multiples from crustal structure, or conversions occurring in the uppermost mantle, though in the former case there should be a corresponding converted arrival prior to 5 s.

For a layered, isotropic Earth, incident *P* energy can generate only *SV*-polarized *S* waves by mode conversion. The frequent presence of coherent energy on the *SH* component (e.g. Figs. 3 and 4) is therefore strong evidence that anisotropy, 3-D structure, or both are present beneath southern Ontario. A visual fit to much of the *SH* energy was previously obtained assuming anisotropic layering at selected single stations (Frederiksen et al., 2006), although the resulting structures were inconsistent from station to station — over the breadth of the array, significant lateral variation must be present. Using typical crustal property values from Eaton et al. (2006) (a thickness of 40 km, a *P* velocity of 6.39 km/s, and an *S* velocity of 3.69 km/s), we find that for a