Earth and Planetary Science Letters 472 (2017) 38–49

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

The uppermost mantle seismic velocity and viscosity structure of central West Antarctica

J.P. O'Donnell [a,b,*], K. Selway [c,1], A.A. Nyblade [a], R.A. Brazier [a], D.A. Wiens [d], S. Anandakrishnan [a], R.C. Aster [e], A.D. Huerta [f], T. Wilson [g], J.P. Winberry [f]

[a] Department of Geosciences, The Pennsylvania State University, University Park, PA 16802, USA
[b] School of Earth and Environment, The University of Leeds, Leeds, LS2 9JT, UK
[c] The Centre for Earth Evolution and Dynamics, The University of Oslo, 0316 Oslo, Norway
[d] Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63160, USA
[e] Department of Geosciences, Colorado State University, Fort Collins, CO 80523, USA
[f] Department of Geological Sciences, Central Washington University, Ellensburg, WA 98926, USA
[g] School of Earth Sciences, Ohio State University, Columbus, OH 43210, USA

ARTICLE INFO

Article history:
Received 17 March 2017
Received in revised form 11 May 2017
Accepted 13 May 2017
Available online xxxx
Editor: P. Shearer

Keywords:
West Antarctica
mantle viscosity
glacial isostatic adjustment
seismic low-velocity zone
seismology

ABSTRACT

Accurately monitoring and predicting the evolution of the West Antarctic Ice Sheet via secular changes in the Earth's gravity field requires knowledge of the underlying upper mantle viscosity structure. Published seismic models show the West Antarctic lithosphere to be ∼70–100 km thick and underlain by a low velocity zone extending to at least ∼200 km. Mantle viscosity is dependent on factors including temperature, grain size, the hydrogen content of olivine, the presence of partial melt and applied stress. As seismic wave propagation is particularly sensitive to thermal variations, seismic velocity provides a means of gauging mantle temperature. In 2012, a magnitude 5.6 intraplate earthquake in Marie Byrd Land was recorded on an array of POLENET-ANET seismometers deployed across West Antarctica. We modelled the waveforms recorded by six of the seismic stations in order to determine realistic estimates of temperature and lithology for the lithospheric mantle beneath Marie Byrd Land and the central West Antarctic Rift System. Published mantle xenolith and magnetotelluric data provided constraints on grain size and hydrogen content, respectively, for viscosity modelling. Considering tectonically-plausible stresses, we estimate that the viscosity of the lithospheric mantle beneath Marie Byrd Land and the central West Antarctic Rift System ranges from $\sim10^{20}$–10^{22} Pa s. To extend our analysis to the sublithospheric seismic low velocity zone, we used a published shear wave model. We calculated that the velocity reduction observed between the base of the lithosphere (∼4.4–4.7 km/s) and the centre of the low velocity zone (∼4.2–4.3 km/s) beneath West Antarctica could be caused by a 0.1–0.3% melt fraction or a one order of magnitude reduction in grain size. However, the grain size reduction is inconsistent with our viscosity modelling constraints, suggesting that partial melt more feasibly explains the origin of the low velocity zone. Considering plausible asthenospheric stresses, we estimate the viscosity of the seismic low velocity zone beneath West Antarctica to be $\sim10^{18}$–10^{19} Pa s. It has been shown elsewhere that the inclusion of a low viscosity layer of order 10^{19} Pa s in Fennoscandian models of glacial isostatic adjustment reduces disparities between predicted surface uplift rates and corresponding field observations. The incorporation of a low viscosity layer reflecting the seismic low velocity zone in Antarctic glacial isostatic adjustment models might similarly lessen the misfit with observed uplift rates.

1. Introduction

Warming Circumpolar Deep Water is eroding ice shelves that buttress the West Antarctic Ice Sheet (WAIS) (e.g., Jacobs et al., 2011). The stability of the WAIS is of particular concern because several large outflow glaciers such as Thwaites and Pine Island are thought susceptible to irrevocable ice loss through marine-ice sheet instability (e.g., Joughin et al., 2014). Satellite gravimetry

* Corresponding author.
E-mail address: j.p.odonnell@leeds.ac.uk (J.P. O'Donnell).
[1] Now at Department of Earth and Planetary Sciences, Macquarie University, Sydney, NSW 2109, Australia.

http://dx.doi.org/10.1016/j.epsl.2017.05.016
0012-821X/

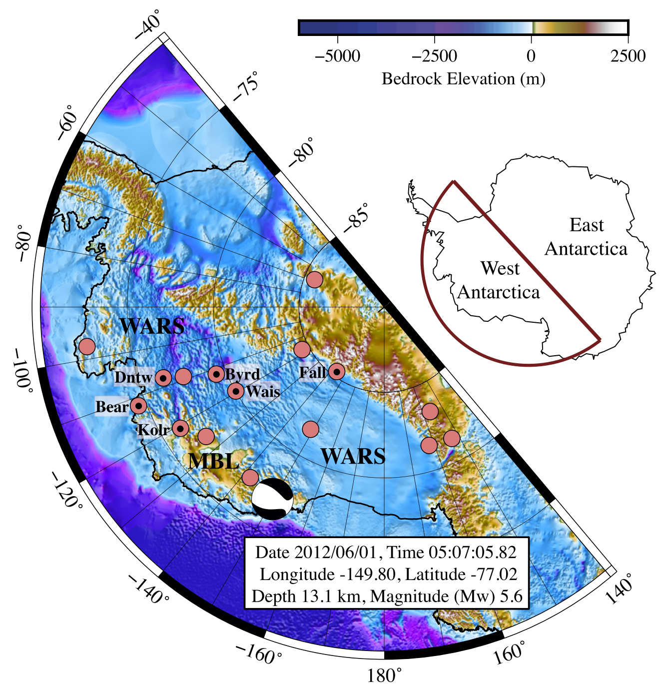

Fig. 1. Map showing the locations of POLENET-ANET stations (pink circles) that recorded the 2012 magnitude 5.6 intraplate Marie Byrd Land (MBL) earthquake. The hypocenter and origin time information is from the Global Centroid-Moment-Tensor catalogue. Full waveform modelling of seismograms from the labelled stations were used to infer crustal and upper mantle velocity information for MBL and the West Antarctic Rift System (WARS). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

theoretically offers an efficient means of monitoring WAIS mass change and hence quantifying its predicted contribution to sea level rise. In practice, the superimposed gravitational signal of glacial isostatic adjustment (GIA), the slow flow of the Earth's ductile mantle toward a new equilibrium following the advance or retreat of a significant surface ice load, must first be removed. The viscosity of the mantle means that the adjustment process can lag the instantaneous elastic response of the crust by hundreds or thousands of years. Thus, accurately modelling the GIA process necessitates knowledge of both the ice sheet history and the rheology of the Earth. Both tasks are challenging in a region with limited geological and geophysical data. These limitations are reflected in the disparities between surface uplift rates predicted by GIA models and corresponding field observations (e.g., Thomas et al., 2011).

Progression from the use of global average 1D radial viscosity profiles in GIA modelling to 3D viscosity models informed by global and continental scale seismic tomography models (e.g., van der Wal et al., 2015) has lessened the misfit. As seismic wave propagation is particularly sensitive to thermal variations, and viscosity to temperature, seismic velocity models can help constrain viscosity structure. Recently developed higher resolution seismic models showing crustal and upper mantle heterogeneity beneath West Antarctica can help in this regard. For example, Heeszel et al. (2016) model the West Antarctic lithosphere as being ∼70–100 km thick and underlain by a low velocity zone extending to at least ∼200 km. Such studies circumvent the relative seismic quiescence of the Antarctic continent by relying on teleseismic surface wave and ambient noise analyses to probe the underlying absolute velocity structure. However, these techniques lend themselves to the determination of shear wave velocity (V_S) structure; compressional wave velocity (V_P) information is generally unforthcoming. This is unfortunate because the combination of V_P and V_S data can further inform rock type and the presence of partial melt, both of which influence viscosity. In 2012, a magnitude 5.6 intraplate earthquake in Marie Byrd Land (MBL) was recorded on an array of POLENET-ANET seismometers deployed across West Antarctica (Fig. 1). Many of the seismograms recorded a Pnl wave. This is a long-period body wave observable at regional distance representing a superposition of upper mantle head wave (Pn) and partially trapped crustal (PL) energy (e.g., Helmberger and Engen, 1980). In conjunction with the recorded Rayleigh wave, this afforded us the opportunity to probe the V_P and V_S structure of the crust and uppermost mantle across MBL and the central West Antarctic Rift System (WARS).

In addition to temperature and melt, viscosity also depends on factors such as grain size and the hydrogen content of nominally anhydrous minerals (e.g., Hirth and Kohlstedt, 2003) which are not well constrained across West Antarctica and not so readily extractable from seismic velocity measurements. To this end we combined the seismic information obtained from modelling the MBL earthquake waveforms with magnetotelluric, petrological and mineral physics data to infer realistic values for temperature, grain size, hydrogen content and melt fraction in order to estimate realistic viscosity bounds for the West Antarctic lithospheric mantle. As GIA is thought especially sensitive to upper mantle viscosity structure (e.g., Whitehouse et al., 2012), and because our new seismic model does not extend below the lithosphere, we extended our analysis to the sublithospheric mantle using the shear wave model from Heeszel et al. (2016). We estimated an average viscosity for the central West Antarctic sublithospheric mantle based on the corresponding average velocity structure inferred by Heeszel et al. (2016). The sublithospheric low velocity layer imaged by Heeszel et al. (2016) beneath much of West Antarctica shares many of the attributes of the global seismic low velocity zone (LVZ) that exists beneath most continental areas (Thybo, 2006, and references therein). The global LVZ is generally attributed to either a small amount of partial melt (e.g., Anderson and Spetzler, 1970) or solid-state mechanisms which affect the elastic properties of solid peridotite (e.g., Karato and Jung, 1998). We examined the feasibility of these hypotheses to account for the LVZ beneath West Antarctica and compared them in terms of their viscosity implications.

2. Data and method

The third International Polar Year 2007–2008 motivated the first deployment of broadband seismometer arrays in the interior of the Antarctic continent. In particular, across West Antarctica an array of seismometers was deployed as part of the POLENET-ANET project (www.polenet.org) to probe the structure of the WARS. The instruments deployed were a mixture of cold-rated Güralp CMG-3T (120 s) and Nanometrics T240 (240 s) seismometers sampling at 1 and 40 samples per second (sps). 16 of these recorded the June 1st 2012 M5.6 MBL event, an intraplate extensional earthquake estimated to have occurred at a depth of ∼13 km (Fig. 1).

At the given epicentral distances of ∼175 to 1500 km, the first energy to arrive at the POLENET-ANET seismometers was the Pn seismic phase. This is the portion of the seismic energy that transits the majority of the path between the earthquake hypocenter and seismometer as a compressional head wave in the lithospheric mantle. At these distances, the energy transiting entirely within comparatively lower velocity crustal rock arrived later. The precise arrival time of the Pn wave was readily identifiable on the seismograms and allowed us to infer associated travel times using the hypocenter and origin time reported in the Global Centroid-Moment-Tensor (CMT) catalogue. Analysis of the Pn travel times as a function of epicentral distance points to a consistent regional lithospheric mantle V_P of ∼7.95 km/s beneath the WARS and MBL (Fig. 2). The Sn wave arrival, by comparison, was not reliably identifiable on the seismograms. To extract additional crustal and litho-