Tectonophysics 622 (2014) 135–144

Contents lists available at ScienceDirect

Tectonophysics

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

Estimating concentrations of heat producing elements in the crust near the Sudbury Neutrino Observatory, Ontario, Canada

Catherine Phaneuf, Jean-Claude Mareschal *

GEOTOP, University of Quebec at Montreal, Montreal, QC, Canada

ARTICLE INFO

Article history:
Received 1 August 2013
Received in revised form 23 February 2014
Accepted 3 March 2014
Available online 11 March 2014

Keywords:
Heat flow
Crustal composition
Heat production
Meteorite impact
Sudbury
Geoneutrinos

ABSTRACT

Because the concentrations of uranium and thorium in the crust must be determined precisely for the future geoneutrino observations planned at the Sudbury Neutrino Observatory, we investigate whether airborne radiometric surveys can be used to constrain crustal radioactivity. The regional airborne surveys cover a wide area with high spatial resolution (<250 m), but are only sensitive to a very thin (25 cm) surficial layer. We calculate crustal heat production in the Sudbury region from airborne radiometric surveys and compare with measurements on outcrop and core samples, and with heat flow data. The concentrations of uranium, thorium, and potassium from radiometric surveys are correlated with geology, but heat production estimates are lower than values from rock samples. The radiometric surveys give a mean heat production of 0.8 ± 0.6 (σ) μW m^{-3} for more than 176,000 values. The outcrop samples collected along a transect in the Superior Province yield an average heat production of 2.9 ± 2.4 (σ) μW m^{-3} and core samples from drill holes yield an average of 2.5 ± 0.8 (σ) μW m^{-3}. The high heat production in the rock samples is consistent with surface heat flux measurements near Sudbury with a mean value that is 12 mW m^{-2} higher than the average Canadian Shield. The study shows that airborne aeromagnetic surveys give useful information on lateral variations in surface heat production but are unlikely to provide the reliable values of heat production needed to calculate the crustal geoneutrino flux. Crustal heat production will be best calculated from heat flux data complemented by heat production measurements on rock samples. The high mean heat production in Sudbury Igneous Complex samples (≈1.5 μW m^{-3}) suggests that the main source of the melt sheet was the very radioactive upper crust of the Superior Province or that the melt sheet was extremely enriched relative to a lower crustal source.

1. Introduction

1.1. The Sudbury Neutrino Observatory

The Sudbury Neutrino Observatory (SNOLAB) is located at a depth of 2000 m in the Creighton Mine, near Sudbury, Ontario. The facility has been upgraded and a new kiloton scale liquid scintillator detector (SNO+) has been installed and is due to become operational before the end of 2013. One of the experiments to be conducted by SNO+ will seek to detect geoneutrinos, i.e., anti-neutrinos produced by the decay of radioactive elements in the Earth (Dye, 2010; Dye and Guillian, 2008; Krauss et al., 1984). The main goal of geoneutrino studies is to determine the distribution of heat producing elements (HPE) in the Earth's mantle, which remains very poorly constrained. Because the mantle cannot directly be sampled, most estimates of the distribution of HPE in the mantle are based on geochemical and cosmochemical models (e.g., Hart and Zindler, 1986; Javoy, 1999; Lyubetskaya and Korenaga, 2007; McDonough and Sun, 1995; Palme and O'Neill, 2003). It is hoped that geoneutrino studies will provide new and robust constraints on the distribution of U and Th in the mantle. Recently, several reports from observatories in Japan (KamLAND) and Italy (Borexino) have demonstrated that constraints on the mantle radioactivity can indeed be obtained from geoneutrino studies (Borexino Collaboration Group (Bellini, G., 89 Collaborators), 2010; Enomoto, 2006; Enomoto et al., 2007; KamLAND Collaboration et al., 2005; KamLAND Collaboration et al., 2011). These results are remarkable because they come from observatories located in regions that are least favorable for geoneutrino studies. In order to measure the signal from the mantle, we must eliminate the noise (i.e., all the other sources of geoneutrinos). The two main sources of noise are nuclear reactors and the HPE in the Earth's crust (Fiorentini et al., 2005). The KamLAND site is close to several nuclear reactors that were in activity until 2011 when they were shut down following the great Tohoku earthquake. The small size of the Borexino detector limits the number of events that can be observed in a given time period. Because both sites are in tectonically active regions with complicated crustal structure, estimating the crustal composition is challenging. It is expected that the level of noise will be lower at Sudbury than at KamLAND. There are three nuclear power plants in Ontario with a total of eight reactors currently in operation. The Chalk River Laboratories are close (300 km) but

* Corresponding author. Tel.: +1 5149874080.
E-mail address: mareschal.jean-claude@uqam.ca (J.-C. Mareschal).

http://dx.doi.org/10.1016/j.tecto.2014.03.001
0040-1951/

they have a very low power output. It is expected that the signal from nuclear reactors will be significant but that it will not overwhelm the geoneutrino signal at SNOLAB (Chen, 2006).

It is commonly assumed that crustal heat production is uniformly low in shields and, therefore, the crustal "noise" will be low at Sudbury. However, heat flow studies from several continents have shown that heat production is not uniformly low, but quite variable in the shields (Jaupart and Mareschal, 1999, 2014; Perry et al., 2010). In particular, heat flow data from 10 sites in the Sudbury region show that the local heat production is higher than the average for the Canadian Shield (Perry et al., 2009). It is therefore important to determine precisely the concentrations of heat producing elements in the crust around Sudbury if the objective is to account precisely for the crustal contribution and calculate the mantle component of the geoneutrino flux that will be measured at SNOLAB.

In this paper, we examine whether airborne radiometric surveys can be used to estimate the concentrations of radioactive elements in the crust near SNOLAB. To assess the usefulness of the radiometric surveys we shall estimate heat production from these data and compare the results with those of measurements made on outcrop and core samples from mining exploration drill holes, and with heat flow data.

1.2. The Sudbury Structure

Sudbury is located in the province of Ontario, ≈55 km due north of the shore of Georgian Bay, in Lake Huron. SNOLAB was installed 2040 m below the Earth's surface in the Creighton Nickel Mine owned and operated by Vale INCO. The Creighton Mine is located at 46.475°N and 81.201°W on the south range of the Sudbury impact structure, the world's largest preserved impact melt sheet (Boerner et al., 1994, 2000; Grieve et al., 1991, and references therein). The melt sheet forms the Sudbury Igneous Complex (SIC), which is the host of important nickel and other mineral deposits (Ames et al., 2008; Grieve, 2005).

The Sudbury Structure straddles the boundary between the Archean Superior Province to the North, and the Paleoproterozoic Southern Province to the east and south (Fig. 1). The origin of the structure remained enigmatic until Dietz (1964) suggested that it is the consequence of a meteoritic impact. The impact occurred at ca 1850 Ma (Krogh et al., 1984). It is thought that, at that time, that the Southern Province was the passive margin of the Superior craton. The initially circular structure was subsequently deformed during the Penokean (ca 1800 Ma) and Grenville (ca 1100 Ma) orogenies, which gave the Sudbury basin its present elliptical shape (Shanks and Schwerdtner, 1991a,b). The Grenville front, which separates the Superior and Southern Provinces from the Grenville Province, passes about 15 km southeast of the structure.

The Sudbury Structure is comprised of a central basin, the Whitewater group which filled the central depression and is underlaid by the Sudbury Igneous Complex, and the breccia rocks of the footwall surrounding the SIC (Boerner et al., 2000, and references therein). The Whitewater Group is composed of three sedimentary formations and the Sudbury Igneous Complex mostly consists of granophyre on top and norite-gabbro on the bottom, with a total thickness of ≈3 km. The footwall is made up of Archean and Proterozoic rocks that have been fractured, brecciated and partially melted following the meteoritic impact. The structure is in contact with the Archean (Levack) gneiss of the Superior Province to the north and with the low grade metamorphosed sediments of the Southern Province to the South (Fig. 1).

The Sudbury Structure coincides with an anomalously high heat flux and heat production region (Perry et al., 2010). The mean of the heat flux values in the Sudbury region is 53 mW m^{-2} $\pm$ 6(σ) compared to a mean of 41 mW m^{-2} $\pm$ 8(σ) for the Superior Province, as well as for the entire Canadian Shield (Table 1, Fig. 2 and 3). A Student's t test (Press et al., 1992) shows that the means are different with a significance <0.02 (i.e., the probability that the difference is due to chance is less than 2%). Variations in heat flux in the Canadian Shield are due to local variations in abundance of HPE in the upper crust (Jaupart and Mareschal, 2014) and the high heat flux in the Sudbury region must coincide with an enrichment in radioactive elements.

2. Surface heat flux, crustal heat production and geoneutrino flux

2.1. Constraining the crustal radioactivity and geoneutrino flux

Determining accurately the mantle component in the very faint geoneutrino signal requires precise accounting of the crustal contribution. In continents, the largest part, about 80%, of the crustal geoneutrino flux comes from the continental crust within a 1000 km radius from the observatory, and the remaining 20% from the far field (Chen, 2006). Two complementary approaches have been taken to estimate the crustal field: one relies mostly on global crustal models based on geological type and/or seismic information when available, such as CRUST2.0 (Chulick et al., 2002; Mooney et al., 1998); the other relies on direct estimates of the crustal heat production from heat flux data. The former approach has been used by Fiorentini et al. (2005) and by Huang et al. (2013) to predict the geoneutrino flux globally. The latter has been

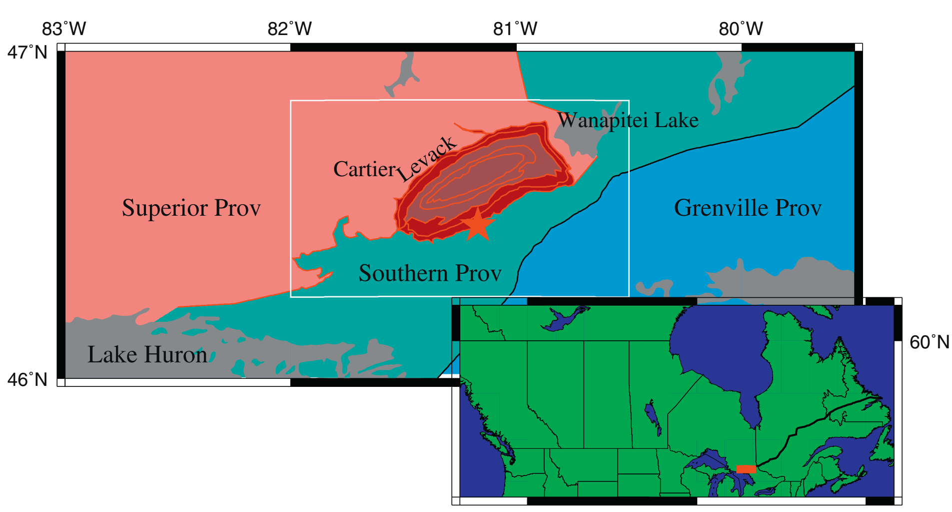

Fig. 1. Geological map of the Sudbury region with a geographic location inset. The red star marks the location of the Creighton Mine where the Neutrino Observatory is located. The white rectangle marks the limits of the maps shown in Figs. 4, 7, and 10. Approximate locations of the Cartier Batholith and the Levack gneiss are indicated.