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Enhanced crustal geo-neutrino production near the Sudbury Neutrino Observatory, Ontario, Canada

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ABSTRACT

The geo-neutrino flux at the Sudbury Neutrino Observatory depends on the local level of crustal radio-activity, which is best estimated from surface heat flux data. The surface heat flux records average crustal radio-activity over the whole crustal column and is unaffected by small-scale heterogeneities. We show how the contribution of crustal heat sources to the geo-neutrino flux can be calculated from knowledge of the surface heat flux. We present new heat flux data from two very deep holes (>2000 m) in the Sudbury structure as well as measurements of U, Th, and K concentrations in the main geological units of the area. With all available data, the average heat flux in the Sudbury basin is $\approx$53 mW m^{-2}, higher than the mean value of 42 mW m^{-2} for the entire Canadian Shield. The elevated heat flux is due to high heat production in the shallow crust and implies an at least 50% increase of the local crustal component of the geo-neutrino flux relative to that expected for the average crustal composition of the shield.

1. Introduction

Current estimates of the total heat production of the Earth depend on geochemical models such as the bulk silicate earth (McDonough and Sun, 1995; Palme and O'Neill, 2003), but the heat production of the mantle is not directly constrained (Jaupart et al. 2008). In principle, geo-neutrinos generated by the decay of Uranium, Thorium and Potassium in the Earth will permit a direct determination of the contribution of mantle radio-activity to the Earth energy budget (Fiorentini et al., 2005b; Enomoto et al., 2007). The main source of geo-neutrinos, however, is the continental crust in the vicinity of the detector, and only a small fraction ($\approx$20%) of the geo-neutrinos comes from the mantle (Chen, 2006). So far, geo-neutrinos have indeed been detected at the KamLAND neutrino observatory in Japan but the errors remain too large to usefully constrain the mantle heat production (Fiorentini et al., 2005a). In order to properly determine the contribution of the mantle to the neutrino flux, it is necessary to determine as precisely as possible the local crustal component.

The Sudbury Neutrino Observatory (SNO) has been in operation since November 1999. The upgrade of the facility to SNO+ in the coming year will permit the detection of neutrinos of lower energy, including geo-neutrinos (Chen, 2006). This observatory is installed at a depth of 2000 m in the Creighton mine, operated by Vale INCO at the edge of the Sudbury impact structure. The structure is known for its numerous mineral deposits and has been mined for nickel since the 1920s. It straddles the boundary between the Archean Superior Province and the PaleoProterozoic Southern Province (Fig. 1). It is elliptical in shape with its major axis lying along the continuation of the contact between the Archean basement and the PaleoProterozoic Huronian sediments. The WSW–ENE trending Grenville front passes some 20 km to the south. The structure comprises an igneous complex of mostly norite and granophyre, overlain by a sequence containing the breccias of the Onaping formation and the sedimentary units of the Whitewater supergroup. The rocks of the igneous complex have been dated at 1850 ± 1 Ma (Krogh et al., 1984). The structure has been deformed into its present asymmetric shape by Proterozoic collisional orogens that took place at the southern margin of the Archean craton between 1.85 and 1 Ga. The basin has been the focus of numerous geological and geophysical studies, and its deep structure has been imaged by the seismic reflection profiles obtained by LITHOPROBE (Milkereit and Green, 1992; Boerner et al., 2000). With these data, the 3-D geometry of the Sudbury structure is well-known with one important exception. The geophysical model shows that the structure was folded back on itself by reverse thrusting. The interpretation of the structure near the SNO facility remains ambiguous. Below the granophyre and Onaping formation that can be traced to $\approx$5 km depth, a 4 km-thick zone remains undefined. This zone might be comprised of tectonically thickened granophyre and Onaping rocks (McGrath and Broome, 1994). Such an ambiguity makes the forward calculation of the crustal neutrino flux highly uncertain. With heat flow data, the heat production (and therefore the U, Th, K content) can be determined directly regardless of the ambiguous geological interpretation.

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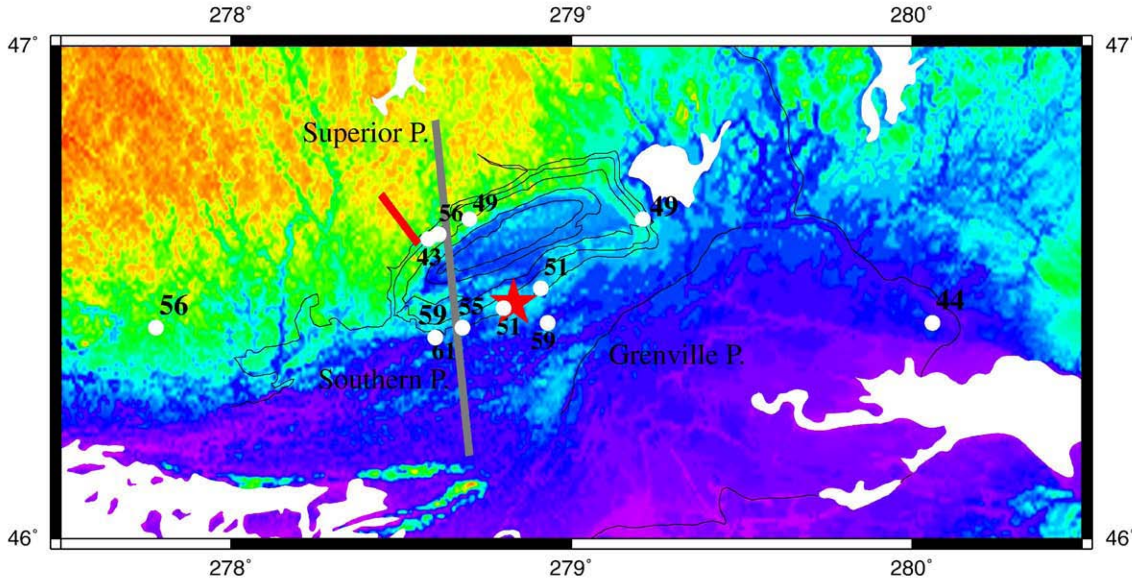

Fig. 1. Heat flux values over color coded topography, outline of the structure and geological boundaries in the Sudbury region. The large red star marks the location of the Sudbury neutrino observatory. The thick red line shows the location of a transect of heat generation measurements (Schneider et al., 1987). The thick grey line shows the location of the cross-section (Fig. 4). A value of 60 mW $m^{-2}$was measured at Elliot Lake ≈20 km to the west of the map limit.

In this report, we discuss the relationship between crustal heat production, surface heat flux, and the geo-neutrino flux. We show that the best method to estimate the bulk crustal radio-activity is through heat flux measurements. We study the distribution of heat flux and heat production in the Sudbury region. We rely on available data by Misener et al. (1951), Jessop and Lewis (1978), and Pinet et al. (1991) and add two new heat flux measurements in very deep boreholes. The single entry for Sudbury in the report of Jessop and Lewis (1978) was obtained by averaging seven individual measurements within a 25×25 km area, and has been reanalyzed here. In addition, we have determined U, Th and K concentrations, as well as radiogenic heat production in the main units of the Sudbury structure. Combined with previously available data, these new measurements provide the robust constraints on the distribution of radio-elements required to calculate the crustal contribution to the flux of geo-neutrinos at SNO.

2. Heat flux, crustal heat production, and the geo-neutrino flux

Two approaches have been used so far to calculate the crustal component of the geo-neutrino flux. One relies on global crustal models such as Crust2.0 (Mooney et al., 1998) and on assumptions about crustal heat production (Mantovani et al., 2004; Fiorentini et al., 2005b). Continental crust is split into upper, middle and lower layers, with each layer assigned average U, Th and K concentrations from global geochemical compilations such as Rudnick and Fountain (1995). This procedure glosses over the important variations of crustal composition that occur between geological provinces (Jaupart and Mareschal, 2003; Perry et al., 2006). The bulk crustal heat production contributes a large fraction of the heat flux at Earth's surface and can be estimated from heat flux data. When averaged over large continental areas, estimates from geochemical and heat flux models are consistent with one another (Rudnick and Gao, 2003). In fact, some geochemical models rely on heat flux data for estimates of U, Th and K concentrations in the lower crust (Taylor and McLennan, 1985). The great advantage of heat flux measurements is that they allow constraints on the local crustal heat production near each measurement site and on lateral variations due to changes of geological structure. Thus, in principle, the global map of predicted geo-neutrino flux should mirror that of the surface heat flux. This not so, however. For instance, the map of Fiorentini et al. (2005b) predicts larger than average number of neutrino events in the Baltic Shield, where the heat flux and crustal heat production are very low. This global model almost invariably predicts the neutrino flux to be higher where the crust is thicker. We expect, however, a more complicated distribution because of the scale of crustal heterogeneities. Another approach to calculate the crustal geo-neutrino flux relies on a direct summation of the individual contribution of all the geological units (Enomoto et al., 2007). This requires very extensive sampling combined with geophysical data for the location and extent of geological units below Earth's surface. We show below that available geophysical data at Sudbury are not sufficient for such a forward crustal model.

On average, the ratio of the concentration of the main heat producing elements in the Earth, U, Th, and K, is constant with Th/U≈4 and K/U≈12,000 (e.g., McDonough and Sun, 1995; Jaupart and Mareschal, 2003). The rate of heat generation H and the rate of geo-neutrino production H' ($m^{-3}s^{-1}$) are therefore proportional: $H' = \gamma H$. At the Earth surface, the vertical component of the heat flux q_z due to heat generation in the crust is given by:

$$q_z = \frac{1}{2\pi}\int\int\int \frac{z' H(x',y',z')dx'dy'dz'}{((x-x')^2 + (y-y')^2 + (z-z')^2)^{3/2}} \quad (1)$$

where the integral is taken over the half space $z>0$. For the crustal contribution, the region of integration is the slab $0<z<z_m$, where z_m is the crustal thickness. In principle, the inverse problem of determining the crustal heat production from heat flux measurements is non-unique. However, different arguments suggest that the variations in heat flux originate in the shallow part of the crust and that the lower crust is depleted in radioactive elements (Rudnick and Fountain, 1995; Mareschal and Jaupart, 2004). Note also that the heat flux decreases as r^{-3} with r distance to the source, so that it mostly records local variations in heat production. The geo-neutrino flux Φ observed at the origin of the coordinate system will be given by:

$$\Phi = \frac{\gamma}{4\pi}\int\int\int \frac{H(x',y',z')dx'dy'dz'}{(x'^2 + y'^2 + z'^2)} \quad (2)$$

where we have neglected the neutrino survival probability which is 1 for the short distances of interest here (Fiorentini et al., 2005b). The factor 2 difference between Eqs. (2) and (1) is due to the boundary condition that the temperature must equal 0 on the surface $z=0$. The difference in the kernel of the integral is due to the fact that the heat flux is vertical at the surface while the neutrino detector records