Earth and Planetary Science Letters 407 (2014) 196–204

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Heat flow anomaly on the seaward side of the Japan Trench associated with deformation of the incoming Pacific plate

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ARTICLE INFO

Article history:
Received 8 June 2014
Received in revised form 13 September 2014
Accepted 17 September 2014
Available online 23 October 2014
Editor: P. Shearer

Keywords:
Japan Trench
Pacific plate
heat flow
thermal structure
subduction zone
hydrothermal circulation

ABSTRACT

Extensive heat flow measurements were conducted on the seaward side of the Japan Trench for investigation of the extent and the origin of high heat flow previously found on the incoming Pacific plate. The obtained data combined with the existing data showed that high and variable heat flow values are pervasively distributed seawards of the northern half of the trench and within about 150 km of the trench axis. In this anomalous zone, the average heat flow is 60 to 70 mW/m^2, appreciably higher than the value typical for the seafloor age of about 135 m.y. The occurrence of the anomalous heat flow along the trench indicates that it results from processes closely related to deformation of the incoming plate. Heating by intra-plate "petit-spot" volcanism and/or fluid flow along normal faults developed on the trench slope may yield local heat flow peaks but cannot raise regional average heat flow. The most probable cause of the observed widespread anomalous heat flow is efficient vertical heat transport by hydrothermal circulation in a permeable layer in the oceanic crust, which is gradually developed by fracturing due to plate bending. Similar heat flow and temperature structure anomalies on the seaward side of the trench may exist in other subduction zones.

1. Introduction

Recent studies showed that the Pacific plate subducting along the Japan Trench may not be uniformly cold as inferred from its old age, over 100 m.y. Yamano et al. (2008) conducted heat flow measurements on the seaward slope and the outer rise of the Japan Trench along a parallel of 38°45′ N and found the existence of heat flow anomaly. High heat flow values, 70 to 110 mW/m^2, were obtained at many stations, while values normal for the seafloor age, about 50 mW/m^2, were also observed at some stations. It suggests that the upper part of the incoming Pacific plate has anomalous temperature structure at least at this latitude.

Another finding is a peculiar type of intra-plate volcanism around the outer rise of the Japan Trench, called "petit-spot" (Hirano et al., 2001; Hirano, 2011). Basaltic rocks with radiometric ages ranging from 1.8 to 8.5 m.y. were collected on the seaward slope of the trench and even younger rocks (younger than 1 m.y.) were sampled on the eastern edge of the outer rise. The magmas that produced the petit-spot volcanoes, regardless of their origin, must have heated the oceanic crust and the underlying mantle of the Pacific plate to some extent.

These results indicate a possibility that the uppermost part of the Pacific plate subducting along the Japan Trench may be anomalously warm for its age. The thermal structure of the incoming plate is one of the key factors controlling the temperature distribution around the subduction plate interface. Subduction of the warmer Pacific plate would therefore result in an anomalous temperature structure along the plate interface, the seismogenic zone of large thrust earthquakes off Tohoku (NE Japan).

The Japan Trench area is one of the best studied subduction zones and extensive seismological studies have been conducted on the interplate seismogenic zone. They showed the nature of the seismogenic zone, such as seismicity, size of asperities and coupling of the plates, significantly varies along the trench (e.g., Fujie et al., 2002; Nishimura et al., 2004; Yamanaka and Kikuchi, 2004). The devastating 2011 Tohoku-oki earthquake demonstrated that seismogenic process along this plate interface is even more complicated both in space and in time (e.g., Tajima et al., 2013). For better understanding of the complex process, information on the temperature structure along the plate interface is indispensable, since mechanical properties of the subduction plate interface are

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http://dx.doi.org/10.1016/j.epsl.2014.09.039
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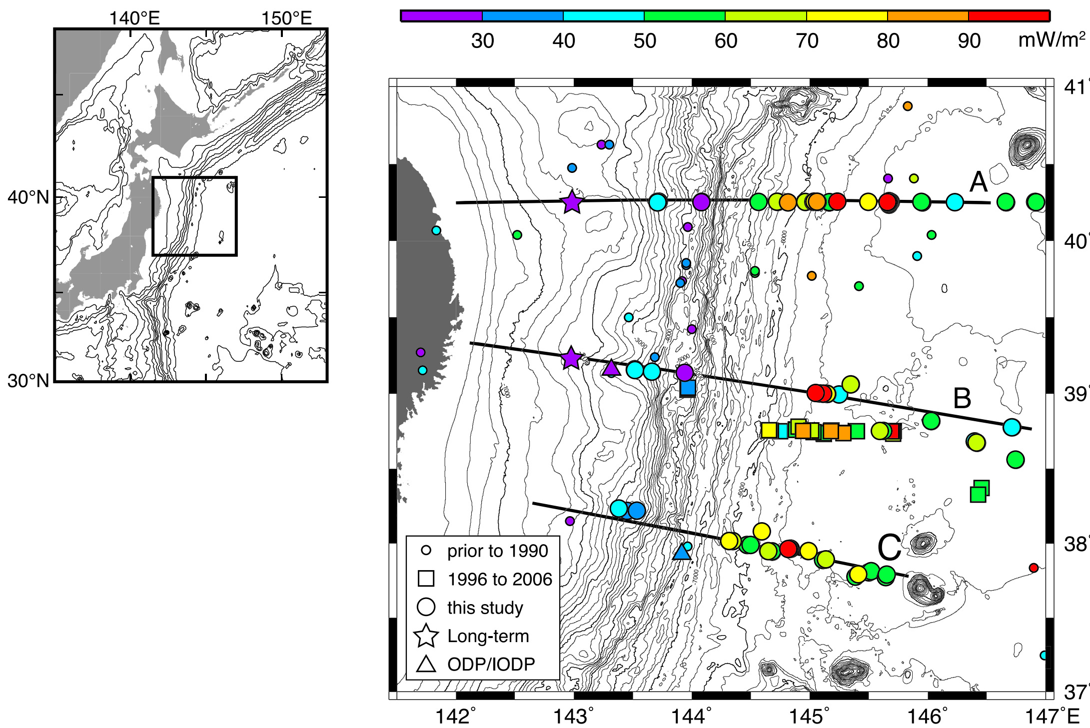

Fig. 1. Heat flow data in the northern Japan Trench area color coded by heat flow value. Large circles and stars: this study, squares: Yamano (2004), Yamano et al. (2008), small circles: measurements before 1990 (Yamano, 2004), triangles: measurements in ODP/IODP holes (Shipboard Scientific Party, 2000; Fulton et al., 2013). A, B, and C are lines on which heat flow data are projected in Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

strongly controlled by the temperature condition (e.g., Oleskevich et al., 1999; Moore and Saffer, 2001).

We conducted heat flow measurements in the northern part of the Japan Trench area for further research on the heat flow anomaly on the incoming Pacific plate reported by Yamano et al. (2008). Investigation of the extent and the origin of the heat flow anomaly should provide essential information for estimating the thermal structure of the interplate seismogenic zone. In the following, we report the results of the heat flow survey, delineate features of the heat flow anomaly seaward of the Japan Trench, and discuss possible causes of the anomaly.

2. Heat flow measurements

Heat flow measurements were made in the northern part of the Japan Trench area (Fig. 1) on research cruises conducted in 2007 to 2010. The seafloor age of the incoming Pacific plate in this area is around 135 m.y. (Nakanishi and Winterer, 1998). Bending of the Pacific plate associated with subduction formed prominent topographic structures seaward of the trench (e.g., Kobayashi et al., 1998; Nakanishi, 2011). The trench outer rise is well developed and extends to about 300 km east of the trench axis (Figs. 1 and 3). To the west of the crest of the outer rise, which is located about 100 km from the trench axis, the plate surface is highly disrupted by normal faulting as demonstrated by seismic reflection surveys (e.g., Tsuru et al., 2000). The fault throw increases toward the trench and the outer slope of the trench is characterized by pervasive escarpments forming horst and graben structures.

We chose three survey lines for the thermal structure across the northern Japan Trench (lines A, B, and C in Fig. 1), along which seismic refraction and reflection surveys were made (Tsuru et al., 2000; Ito et al., 2004; Miura et al., 2005; cf. Fig. 2). The three lines go through regions with different degrees of seismic coupling on the plate interface. Around 40° N and 38° N, where the lines A and C lie respectively, large subduction thrust earthquakes have occurred repeatedly, while occurrence of large earthquakes has not been reported around 39° N (line B) (e.g., Yamanaka and Kikuchi, 2004). Interplate coupling estimated from GPS observations is also stronger around line C than around line B (e.g., Nishimura et al., 2004). Tanioka et al. (1997) showed that the height of escarpments on the seaward trench slope varies along the trench and suggested that the rough surface region may be correlated with weaker seismic coupling.

Our principal target was the Pacific plate seaward of the trench and most of the measurements were conducted on the seaward trench slope and the outer rise, up to 250 km away from the trench axis. As the line B is close to the data obtained by Yamano et al. (2008) along 38°45′ N (Fig. 1), we focused mainly on the lines A and C rather than the line B. Some measurements were made on the landward side of the trench as well, since heat flow data on the overriding plate can be important constraint on thermal modeling of the subduction zone for estimation of the temperature distribution around the seismogenic zone. In total, we obtained 147 heat flow data in the study area (Fig. 1; Table 1 in the supplementary material), 121 of which are on the seaward side of the trench.

We used ordinary deep-sea heat-flow probes that are 3.0 or 4.5 m long and have seven temperature sensors. Temperature profile measurements were made with a piston core sampling system as well using temperature sensors mounted on the core barrel. At most of the stations, the probes and corers penetrated into sediments by 1.5 to 3 m, while at some stations, the probes fell down or the penetration depth was very small probably due to volcanic ash layers at shallow depths. Four measurements were made with a short (60 cm long) temperature probe for submersibles (SAHF) (Kinoshita et al., 2006) during dives of a remotely operated vehicle. Except for the stations with water depth of less than 2500 m and the penetrations with only two temperature sensors in mud, which were discarded as less reliable data, the obtained temperature profiles are linear. It indicates that these measurements were not appreciably affected by temporal variation in the bottom water temperature.