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Mantle diapirism at convergent boundaries (*Sea of Japan*)

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Abstract

New data on geology, geochemistry, and isotope systematics of lavas in the East Sikhote-Alin area, along with earlier published evidence for the Sea of Japan, provide insights into the dynamics of back-arc basins and their role in the tectonic and magmatic history of continental margins. Right-lateral strike-slip faulting, the key event in the Cenozoic history of East Sikhote-Alin, apparently had no relation with the subduction in post-Eocene time. At that time, the Late Cretaceous subduction ended and oceanic asthenosphere with Pacific-type MORB isotope signatures injected into the subcontinental mantle through slab windows. The Sea of Japan opening began in the Eocene with formation of small rift basins in the Tatar Strait, which accumulated coastal facies. During the main Miocene phase of activity, the zone affected by oceanic asthenosphere moved eastward, i.e., to the modern deepwater Sea of Japan. The effect of oceanic asthenosphere on the continental margin ended in the Late Miocene after the Sea of Japan had opened and new subduction initiated east of the Japan Islands.

Keywords: tectonics; trace elements; isotopes; mantle geodynamics; Sea of Japan; East Sikhote-Alin

Introduction

The Western Pacific, which accommodates most of existing island arcs and more than 75% of back-arc basins, plays a key role in the Earth dynamics. Subduction and opening of back-arc basins are related processes but the origin and mechanism of this linkage remain unclear. Continental-margin rifting and opening of back-arc basins may result from (i) passive diapirism permitted by extension, (ii) active diapirism maintained by heat and fluids generated in the Benioff zone (Saunders and Tarney, 1984) or (iii) dynamic circulation involving secondary convection cells induced by subducting slabs (Karig, 1970; Martinez et al., 2007).

The latter model implies that convective motions in the mantle wedge induced by a cold oceanic slab sinking into a subduction zone force the trench and a part of an early volcanic arc to move oceanward (Elsasser, 1971; Moberly, 1972). The back-rolling trench, the arc, and the back-arc basin make a whole subduction system (Gill, 1981), which explains persistent signatures of depleted chemistry in island-arc volcanics due to the presence at their sources of mantle molten during basaltic back-arc crust generation (McCulloch and Gamble, 1991; Turner et al., 1997; Woodhead et al., 1993). However, there are other poorly understood issues of subduction magma generation, such as melting above cold slabs, high heat flow of > 2–3 HFU (heat flow unit, 1 HFU = 41.8 mW/m^2) (Watanabe et al., 1977), very high temperatures of island arc magmas (~1350 °C), low seismic velocities (Tatsumi, 2003) and presence of inclined 50 km wide hot regions in the mantle wedge. The hot regions called "hot mantle fingers" extend from deep mantle (>150 km) below the back-arc region towards shallower mantle beneath the volcanic front (Tamura et al., 2002).

Some of these issues are discussed below for the case of the Sea of Japan in which the structure and composition of sediments, and crust as a whole, are known better than in any other back-arc region.

Time and causes of opening of the Sea of Japan: historical background

The origin of the Sea of Japan basin by southeastward drift of lithospheric fragments, rifted off the eastern Asian margin, was first hypothesized in the early 1940s by T. Kobayashi and D. Bubnov proceeding from similarity in Mesozoic deposition and flora patterns shared by southern Primorye, Korea, and Japan (discovered by T. Kobayashi and A. Krishtofovich in the 1930s (Kropotkin and Shakhvarstova, 1965) and references therein). This similarity indicated that Japan was located much

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closer to the continent in the Mesozoic while the three areas formerly built a single landmass which subsided from time to time and became an accommodation basin for coastal and continental deposits.

The available data support the idea that Sikhote-Alin and Japan had a common Mesozoic geological history. Most of Japan consists of Jurassic and Early Cretaceous accretionary complexes (the Mino, Tamba, Ashio, Chichibu, Simanto, and other belts) which resemble and most likely continue those of Sikhote-Alin (Samarka and Taukhe terranes and their equivalents in the Amur basin). Suprasubduction Late Cretaceous volcanics occur along the Sikhote-Alin coast, on some submerged rises in the Sea of Japan, in Honshu Island, and in southeastern Korea (Golozubov, 2006; Martynov et al., 2006).

The rifting origin of Japan is consistent with paleomagnetic evidence of the Sea of Japan opening by differentiated clockwise and counter-clockwise rotation of southwestern and northeastern blocks, respectively (Kawai et al., 1962). The reconstruction of the Eurasian margin by Kropotkin and Shakhvarstova (1965) based on this discovery appears to be the earliest model of this kind followed by numerous later publications (Golozubov, 2006; Khanchuk, 2001).

Further paleomagnetic research (Hirooka, 1988; Nishitari and Tanone, 1988; Otofuji et al., 1985; Tosha and Hamano, 1988) constrained the age of the main opening phase as the earliest Middle Miocene (~15 Ma). These estimates agree with marine fauna changes found at this level in cores retrieved by legs 31 (*Glomar Challenger*) and 127–128 (*JOIDES Resolution*) of the ocean drilling program (ODP), as well as with isotope data from the NW Honshu and SW Hokkaido basalts (Kurasawa and Konda, 1986; Nohda et al., 1988; Shuto et al., 1992). However, they are at odds with isotope ages of > 20 Ma corresponding to older crust production (Tamaki, 1986; Yamano, 1985), while biostratigraphic and isotope (K–Ar, Ar–Ar) data for ODP sites 797, 795, and 794 indicate an interval of 17–24 Ma (Early Miocene).

Having synthesized the results of drilling and geophysical experiments during ODP legs 127 and 128, Tamaki et al. (1992) suggested a tectonic scenario for the evolution of the Sea of Japan. Its tectonic history was divided into eight discrete phases:

(1) relatively slow initial thermal subsidence between 32 Ma and 23 Ma;

(2) rapid subsidence to bathyal depths apparently accompanied by rapid spreading, back-arc extension, and arc rotation between 23 Ma and 19 Ma;

(3) slow thermal subsidence between 19 Ma and 15 Ma;

(4) a second phase of rapid mechanical or fault-controlled subsidence between 15 Ma and 12.5 Ma;

(5) a return to slow thermal subsidence between 12.5 Ma and 10 Ma;

(6) initiation of widespread uplift and onset of a compression regime between 10 Ma and 7 Ma;

(7) acceleration of uplift and deformation along the margins of the Sea of Japan about 5 Ma; and

(8) major compression deformation and topographic reorganization of large areas of the Sea of Japan and adjacent insular and continental margins accompanied by extremely high rates of uplift (~ 500 m/myr) between 2 Ma and 0 Ma.

Two phases of rapid fault-controlled subsidence (2 and 4), at 23–19 and 15.0–12.5 Ma, respectively (Jolivet and Tamaki, 1992; Tamaki et al., 1992), fit an earlier model of Lallemand and Jolivet (1985) that interpreted the Sea of Japan as a pull-apart basin opened between two right-lateral strike-slip fault zones.

Mantle plumes were suggested to have been another agent in the Sea of Japan opening (Bersenev et al., 1987; Deng et al., 1998; Maruyama et al., 2007; Yemeliyanova and Lelikov, 2013), in addition to tectonic forcing. The plume model is in line with thick crust beneath the Yamato basin (Hirata et al., 1989), though heat flow data (Langseth and Tamaki, 1992) better agree with simple slab cooling.

Note that the cessation of subduction during back-arc basin opening was not discussed in earlier publications (Okamura et al., 2005).

Sea of Japan opening in the context of Cenozoic tectonic changes at the eastern Asian margin

The Jurassic and Cretaceous history of the eastern Asian margin was controlled by interaction between stable Eurasia and the Izanagi (Kula) plate east of it moving rapidly north- and northwestward (Engebretson et al., 1985). As a result, the Sikhote-Alin belt striking generally in the ENE direction at ~30° experienced large-scale left-lateral strike-slip faulting both along the ocean-continental boundary and in the adjacent landmass (Golozubov, 2006). In the Late Cretaceous, the East Sikhote-Alin volcanic arc was part of an Andean-type active margin subject to SE–NW compression (Golozubov, 2006; Khanchuk, 2006). Note that left-lateral strike-slip faulting remained active through the Late Cretaceous in the N–S East Bureya area located nearby in the north (Golozubov, 2006) (Fig. 1).

The setting changed dramatically in the Eocene, when deposition and volcanism were largely controlled by dextral strike-slip motions along N–S fault zones, especially along the Hokkaido–Sakhalin system (Fournier et al., 1995; Golozubov et al., 2012; Jolivet and Tamaki, 1992; Kirillova, 2004; Lallemand and Jolivet, 1985; Rozhdestvensky, 1969, 1997). The motions occurred under NE compression (30°–45°) discordant with the direction of push from the Pacific plate which kept moving north- and northwestward (Engebretson et al., 1985), possibly, as a far effect of the India–Eurasia collision (Flower et al., 1998; Jolivet et al., 1990; Worral et al., 1996).

According to the Sea of Japan opening model of Lallemand and Jolivet (1985) based on these ideas, rift zones appeared in the Eocene at the junction between the Hokkaido–Sakhalin and Tsushima right-lateral shear systems. This model does not contradict the Eocene–Oligocene sedimentation and volcanism in the Sea of Japan (Kirillova, 2004). Namely, Eocene clastics (earlier continental and later coastal facies) occur in the northern part of the back-arc basin along the Hokkaido and Sakhalin coasts while Oligocene sediments are widespread in