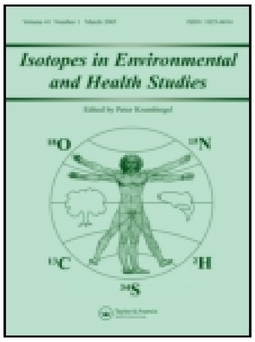


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oxygen-18 in the interstitial water increases which can cause the appearance the "lighter" hydrate gas water in a background of "heavy" interstitial water.

The calculations of fractionation coefficient showed that in nature it is higher than in laboratory conditions.

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# First Data on $^{10}$Be in Recent Volcanics of the Kurile-Kamchatka Island Arc System in Relation to Sediment Subduction

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*Concentrations of $^{10}$Be were measured in 23 lava samples representing historically and $^{14}$C dated eruptions of major Kurile and Kamchatka volcanoes. We report 2.2–7.9 · 10$^{6}$ at/g of $^{10}$Be for Kuriles and in most cases less than 1.2 · 10$^{6}$ at/g for Kamchatka. Thus Kurile segment of the Kurile-Kamchatka arc system features the same isotopic pattern as the Aleutians and some continental arcs like Central America and the Andes. The obtained results confirm previously drawn conclusion that the scale of sediment incorporation in Kurile magmas is not large though the process itself is quite real.*

*Es wurden $^{10}$Be-Konzentrationen in 23 Lavaproben gemessen, die historische und $^{14}$C-dadierte Eruptionen der größeren Kurilen und Kamtschatka-Vulkane representieren. Es wurden (2,2 ... 7,9) · 10$^{6}$ Atome/g von $^{10}$Be für die Kurilen und in den meisten Fällen weniger als 1,2 · 10$^{6}$ Atome/g für die Kamtschatkaproben bestimmt. Somit zeigt der Kurilenabschnitt des Kurilen-Kamschatka-Bogens dasselbe isotope Muster wie das der Alëuten und einiger Kontinentalbögen wie in Zentralamerika und den Anden. Die erhaltenen Ergebnisse bestärken frühere Schlußfolgerungen, wonach die Skala des Sedimenteintrages in das Kurilenmagma nicht groß ist, obwohl der Prozeß selbst ganz real abläuft.*

### Keywords

aleutian islands; amchitka island area; beryllium 10; continental crust; igneous rocks; volcanic regions; volcanoes

One of the fundamental questions of arc magmatism is the question of its sources. The key problem in relation to this is providing evidence whether oceanic slab is subducted beneath island arc, its components, sediments in particular, incorporated into magmatic melts or not [1–3].

It is known [4] that short-living (half life is 1.5 Ma) cosmogenic isotope $^{10}$Be accumulates in pelagic sediments where its concentrations are very high, greater than $10^9$ at/g. Concentration of $^{10}$Be in sediments is about 1000 times greater than in mid-ocean ridge and oceanic island basalts – other constituents of subducting oceanic plate, while in mantle ultramafics it is practically nil. If sedimentary component is involved in a process of arc magma generation one should expect that recent island arc lavas will be enriched in $^{10}$Be ($> 1 \cdot 10^6$ at/g) as compared with lavas originated in other geodynamic settings (oceanic islands, rift zones, etc). Specifically such phenomena is reported in some areas of plate convergence – Aleutian and partly Japanese Island Arcs, Central America and Peru-Chilean segment of the Andes. At the same time some arcs like Sunda, Mariana and Halmahera contain lavas with $^{10}$Be concentrations comparable with those in ocean island basalts and young platobasalts ($< 1 \cdot 10^6$ at/g). These facts are usually considered as indication of predominance of accretional processes causing sediment "piling" in the forearc region rather than their subduction.

Under the supervision of Profs. *J. Morris* and *F. Tera* in the Departament of Terrestrial Magnetism, Carnegie Institution of Washington, $^{10}$Be was measured in 23 lava samples from the Kurile – Kamchatka Island Arc system – representing historically and $^{14}$C dated eruptions. These are the first determinations of $^{10}$Be for that region, being the only one active island arc within the limits of the USSR. Measurements were carried out according to a technique described in *Tera* et al. [4] which included preliminary operations (sawing of the central unaltered part of the samples), chemical treating in order to extract Be and then tandem accelerator mass-spectrometry. The latter procedures were done in the University of Pennsylvania Tandem Accelerator Laboratory. Our study covered rocks of a wide petrographic range from basalts to rhyolites (Tab. 1).

It was found that Kurile lavas contain 2.2–7.9 · $10^6$ at/g of $^{10}$Be, whereas in Kamchatka its concentrations are much lower 0.0–3.7 · $10^6$ at/g, only two out of eight Kamchatka volcanoes: Opala and Krasheninnikov giving values higher than 1.2 · $10^6$ at/g – correspondingly 2.5 and 3.7 · $10^6$ at/g. Note that according to many authors Kurile segment of the arc system do not terminate in the Northern Kuriles but stretches further north into Kamchatka peninsula taking its southern part up to the so-called Nachiki block-folded transverse zone. In the similar fashion in the south, Kurile segment of the arc includes most part of Hokkaido Island. Thus one of the "high" figures: 2.5 · $10^6$ at/g of $^{10}$Be for Opala volcano may well be considered as yet referring to the Kurile segment of the Kurile-Kamchatka arc system though the volcano itself in geographical sense is located within Kamchatka Peninsula.

Analysing the obtained results we can notice definite decrease in $^{10}$Be concentrations towards northern and southern flanks of the Kurile segment where the arc comes across more consolidated structures (Fig. 1). However near its junction with the Honshu Arc $^{10}$Be concentrations in Frontal zone lavas abruptly increase [4]. Thus in the south-east end of Hokkaido $^{10}$Be contents continually

Tab. 1. $^{10}$Be and $^{9}$Be in recent lavas of Kuriles, Kamchatka and Northern Japan

| Volcano, Island | Eruption date | Rock | Zone | $^{10}$Be $10^6$ at/g | $^{9}$Be ppm |
|---|---|---|---|---|---|
| **Kuriles** | | | | | |
| Tiyatiya, Kunashir Isl. | 1973 | Bas. | F | 2.2 | 0.40 |
| Medvezhiy, Iturup Isl. | 1883 | And. | F | 7.9 | 0.26 |
| Berg, Urup Isl. | 1937 | And. | F | 4.1 | |
| Chernogo, Chirpoy Isl. | 1857 | And. | F | 5.2 | 0.44 |
| Zavaritsky, Simushir Isl. | 1957 | And. | F | 5.4 | |
| Sarichev, Matua Isl. | 1976 | Bas.-And. | F | 3.4 | 0.46 |
| Chirinkotan, Chirinkotan Isl. | 1980 | And. | B | 6.7 | 0.83 |
| Krenitsin, Onekotan Isl. | 1952 | And. | F | 2.6 | |
| Alaid, Atlasova Isl. | 1934 | Bas. | B | 3.6 | |
| Alaid, Atlasova Isl. | 1972 | Bas. | B | 3.7 | 0.69 |
| Alaid, Atlasova Isl. | 1972 | Bas. | B | 3.2 | |
| Alaid, Atlasova Isl. | 1981 | Bas. | B | 4.2 | 0.69 |
| **Kamchatka** | | | | | |
| Opala | 500*) | Rhyol. | B | 2.5 | |
| Avachinski | 1938 | Bas.-And. | F | 0.8 | 0.35 |
| Karimski | 1976 | Bas.-And. | F | 1.2 | 0.70 |
| Krasheninnikov | 1400*) | Dac. | F | 3.7 | |
| Tolbachik | 1975 | Bas. | B | 1.0 | 0.41 |
| Tolbachik | 1975 | Bas. | B | 0.0 | |
| Bezimianny | 1977 | And. | F | 1.0 | |
| Klychevskoi | 1932 | Bas.-And. | F | 0.4 | |
| Klychevskoi | 1983 | Bas.-And. | F | 0.4 | 0.67 |
| Shiveluch | 1980 | And. | F | 0.6 | 0.69 |
| **Northern Japan [4]** | | | | | |
| Rausudake, Hokkaido Isl. | ? | ? | F | 2.5 | |
| Meakan, Hokkaido Isl. | ? | ? | F | 2.2 | |
| Takachi, Hokkaido Isl. | ? | ? | B | 2.2 | |
| Turumai, Hokkaido Isl. | ? | And. | F | 0.5 | |
| Usu, Hokkaido Isl. | 1978 | And. | F | 0.2 | |

*) $^{14}$C age; F – Frontal, B – Back-Arc zones

decrease from the volcanic front towards the Back-Arc structural zone: 13.5 · $10^6$ at/g for Esan, 4.4 · $10^6$ at/g for Komagataki and 1.5 · $10^6$ at/g for Oshima-Oshima volcanoes, i.e. there we have a well-defined transverse isotopic zonation. It is interesting to note that further south $^{10}$Be concentrations again become lower and in Honshu Island for Funagata and Fuji volcanoes are less than $10^6$ at/g., i.e. fall within the same range as for the most Kamchatka volcanoes. We believe that such patterns of $^{10}$Be distribution could be governed by some large-scale processes upon which smaller scale events are superimposed. For instance, interaction of two streams of oppositely directed oceanic currents can well lead to increase in sediment accumulation rate on the ocean floor near Hokkaido resulting in faster deposition of $^{10}$Be enriched piles of pelagic sediments which upon subduction could have caused the above defined isotopic trend. No question that of special importance also were geodynamic parameters of subduction itself: inclination and subsidence rate of subducting slab in different parts of the Kurile-Kamchatka arc system, occurrence of lateral tectonic dislocations in the vicinity of the Trench, composition and thickness of sediments covering the Pacific plate, etc.

We must also note higher amounts of $^{10}$Be (6.7 · $10^6$ at/g for two samples) in lavas of Chirinkotan volcano in the Back-Arc zone of the Northern Kuriles. Lavas of Krenitsin (Onekotan Isl.) and Sarichev (Matua Isl.) volcanoes located correspondingly in 70 and 100 km to the north and to the south of Chirinkotan latitude and in the Frontal zone of the arc contain only 2.6; 3.4. $10^6$ at/g of $^{10}$Be. Hardly should we look for explanation of these facts from the viewpoint of greater sediment incorporation in the Back-Arc zone magmatic reservoires as compared to the Frontal zone ones. As we know Chirinkotan volcano is approximately in 250 km from the trench axis, the distance to a seismic zone being about 190 km [5]. According to basics of plate tectonics it seems hardly probable that the degree of sediment contamination of island arc magmatic sources will increase with the increasing distance from the converging plate boundaries and greater depth to Benioff zone. That is why we assume that occurrence of rocks relatively enriched in $^{10}$Be in the Back-Arc zone of the Kuriles just as in any other island arc of the World Ocean, e.g. Bogoslof Isl. in the Aleutian Arc (15.3 and 5.2 · $10^6$ at/g of $^{10}$Be [4]) most probably is the result of random phenomena, in some cases possibly due to existance of tectonic grabens near the bend of the subducting slab where thickness of the young sediment pile and consequently total inventory of $^{10}$Be are abnormally high. Such tectonic structures were documented lately in Japanese and Mid-America Trenches [6]. This conclusion is supported by distribution patterns of $^{10}$Be in lavas of the north-eastern Honshu. There, as noted above, in between two areas of low concentrations of $^{10}$Be (in the Frontal zone both to the north and to the south of the south-western end of Hokkaido) stretches rather narrow transverse zone where concentrations of $^{10}$Be are continually decreasing from the volcanic front towards the arc rear.

Patterns of the Kurile-Kamchatka along-the-arc $^{10}$Be isotopic zonation to some extent follow patterns of Sr-isotopic zonation. According to the data available [7] average $^{87}$Sr/$^{86}$Sr ratios in recent lavas of the Central part of the Kurile segment are 0.70316 for the Frontal and 0.70298 for the Back-Arc zones, while near Kamchatka and Hokkaido these ratios get somewhat higher – correspondingly: 0.70338 (Frontal zone) – 0.70315 (Back-Arc zone) and 0.70350 (Frontal zone) – 0.70330 (Back-Arc zone). In a whole Kurile segment of the Kurile-Kamchatka Island Arc system seems totally compatible with such modern arcs as the Aleutian and Central American (Guatemala, Nicaragua) where earlier [4] sediment involvement in magmatic processes was proved (Fig. 2). At the same time the amount of $^{10}$Be in Kamchatka lavas with the exception of the cases mentioned above, matches that in rocks of Sunda, Mariana and Halmahera arcs, abyssal tholeiites and young platobasalts (traps) never greater than 1.2 · $10^6$ at/g.

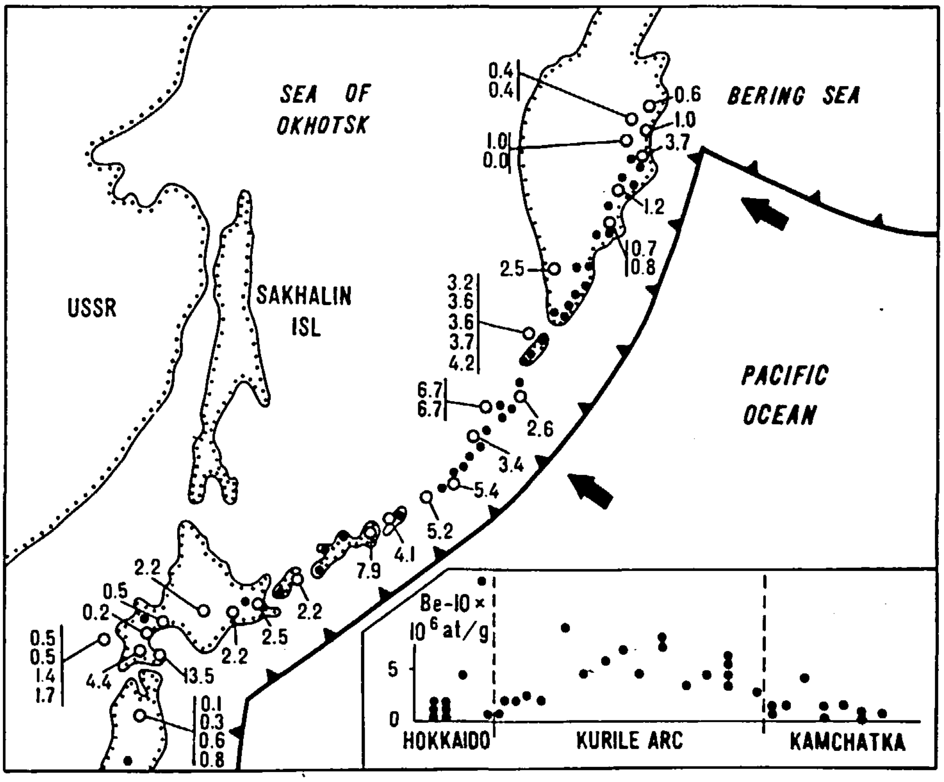


Fig. 1. $^{10}$Be in recent lavas of the Kurile-Kamchatka and some Japanese volcanoes. Concentrations of $^{10}$Be are in $10^6$ at/g. Also shown are lateral variations in $^{10}$Be concentrations along the strike of the Kurile-Kamchatka Arc. Thick lines — position of the Trenches. Circles — volcanoes analyzed for $^{10}$Be, filled circles — other active volcanoes

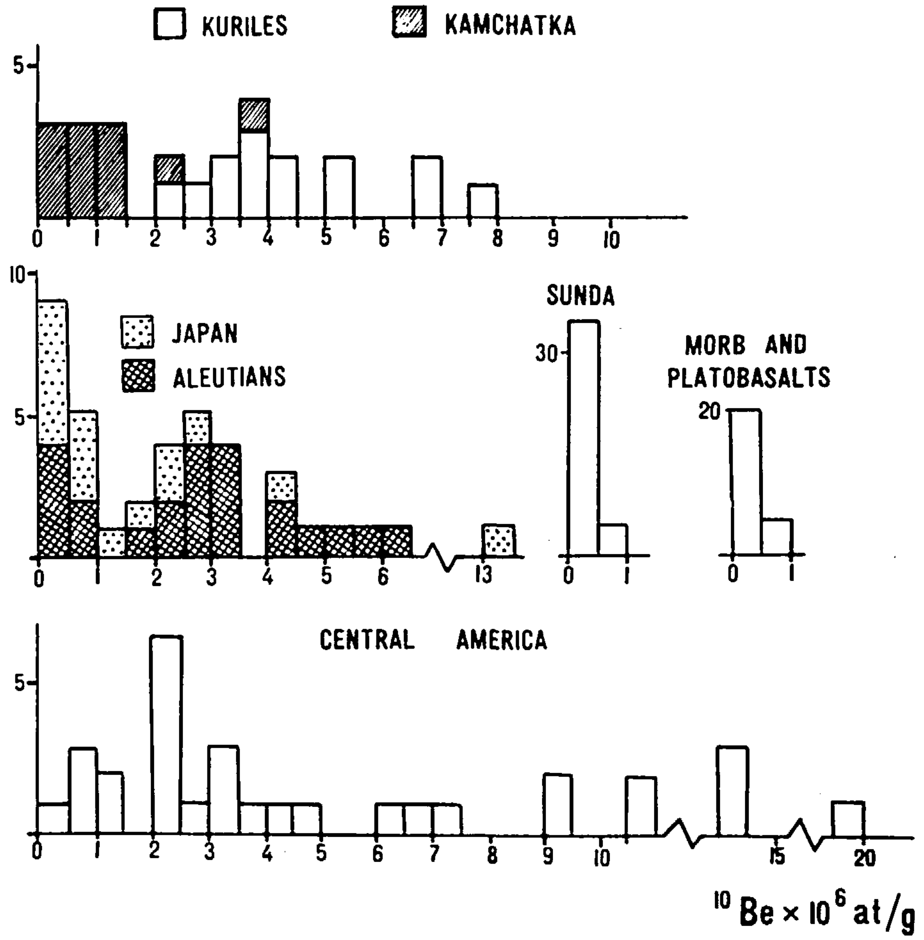


Fig. 2. Histograms of $^{10}$Be distribution in lavas of the Kurile-Kamchatka arc volcanoes in comparison with other arcs. Data for all arcs but the Kurile-Kamchatka are from *Tera* et al. [4]

Because of its short life, $^{10}$Be in oceanic sediments decays during subduction from the trench to the zone of magma generation. Subduction times in the Kuriles and Kamchatka are 2.1 and 2.4 Ma respectively; a difference that would reduce $^{10}$Be in the Kamchatka lavas by 15% relative to the Kuriles. Clearly other factors, sedimentological of geophysical or geochemical, contribute to the observed disparity. Possible explanations are: 1) The $^{10}$Be budget of the sedimentary pile is controlled by the amount of young, $^{10}$Be rich, pelagic sediments. The lower $^{10}$Be values for Kamchatka could be due to dilution of the pelagic sediment with relatively $^{10}$Be poor continental sediment, as seen in DSDP core 192, 2) Reflecting its short half-life, most of the $^{10}$Be is found in the uppermost 10 – 100 m of the sediment column. Sediment accretion off Kamchatka and sediment subduction beneath the Kuriles would explain the pattern, 3) Lavas from Kamchatka may assimilate more old (> 10 Ma) $^{10}$Be poor continental crust, 4) More sediment is incorporated in the Kuriles than in Kamchatka. There is data [8] that differentiation of magmatic melt later erupted through Krasheninnikov volcano took place dicectly within its volcano-structure; that is why rather high values of $^{10}$Be reported in its lavas ($3.7 \cdot 10^6$ at/g) can be possibly caused by assimilation by magma of young caldera filling sediments.

We tried to calculate approximate level of sediment contribution to magmatic sources of the Kurile-Kamchatka lavas using the formula of *Tera* et al. [4].

$$n = \frac{f n_0 s}{\lambda h} \exp(-\lambda l/v)$$

where: $n$ – $^{10}$Be, at/g, in arc lava; $n_0$ – $5 \cdot 10^9$ at/g, average concentration of $^{10}$Be in the Pacific pelagic sediments; $s$ – sedimentation rate, cm/yr, on the surface of the Pacific plate near the Trench; $\lambda$ – $4.62 \cdot 10^{-7}$ year$^{-1}$, $^{10}$Be decay constant; $h$ – sediment thickness, cm; l – down-dip distance to roots of volcanoes, cm; $f$ – fraction sediment in lava. For the Kurile-Kamchatka arc system the following parameters have been used [5, 9]: $s$ = 20 m/Ma for Kuriles and 22 m/Ma for Kamchatka – these values are in between those for the Japanese and the Aleutian arcs [4]; $h$ = 300 m for Kuriles and 400 m for Kamchatka; $v$ = 9.5 cm/yr; l = 230 km for Kuriles and 345 km for Kamchatka.

The obtained results show (Fig. 3) that the maximum upper limit of sediment incorporation for the Kuriles is 4%, for Kamchatka less than 2% (only for Krasheninnikov volcano ~3.5%). These data confirm our previously drawn conclusion [2, 10] on the base of evaluation Sr and Nd isotopic ratios and patters of REE distribution that the amount of sediments participating in melting reactions in the Kuriles is not great but the process of sediment incorporation itself is quite feasible and real. Reported data is the first direct evidence of plate subsidence in that particular sector of the Pacific Ocean – Asian Continent transition zone and should be taken into consideration when making any geodynamic reconstructions for that region.

On the $^{10}$Be/$^9$Be – Be diagram Kurile and Kamchatka lavas make a broad negative array (Fig. 4). According to *J. Morris* and *F. Tera* [6] such pattern can be caused by two processes – direct melting or mixing. In the first case a parcel of the mantle which includes a larger proportion of sediments (or sediment derived melts or fluids) must melt to larger degrees, yielding lavas with relatively high $^{10}$Be and low $^9$Be concentrations.

Alternatively the negative trends could result from mixing processes. If so, the trends indicate that magmas derived from sediment contaminated mantle subsequently interact with low $^{10}$Be, high $^9$Be material. The high $^{10}$Be end-member could be old sediments, small volume partial melts of uncontaminated mantle, remelts of subducted oceanic crust (without young sediments), remelts of older arc crust or assimilated continental crust. Unfortunately the data do not yet exist to evaluate these possibilities in any further detail. However, it should be said that similar trends besides the Kurile-Kamchatka arc system are found also for other island arcs, e.g. New Britain and Central American.

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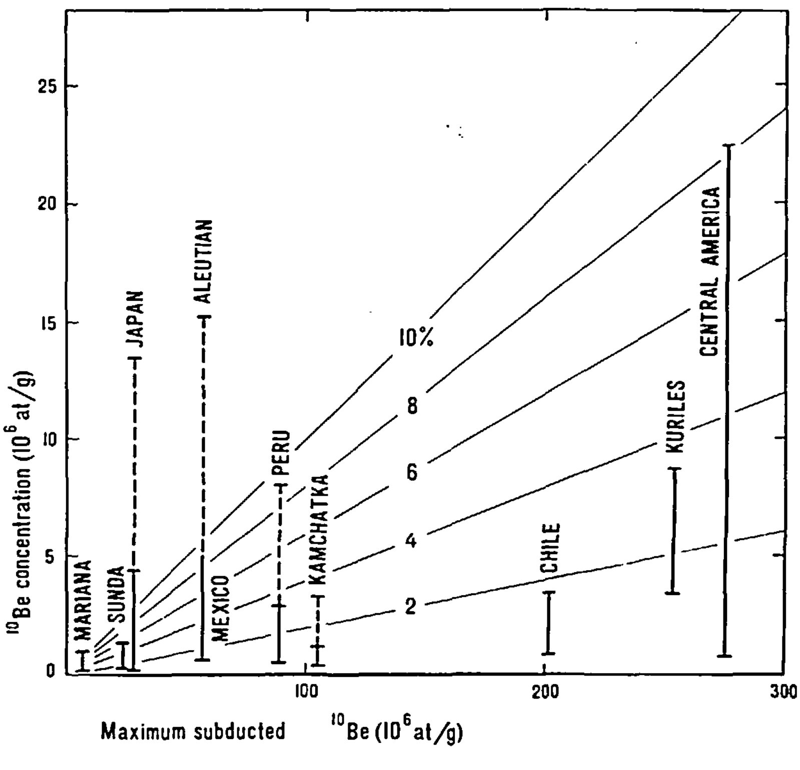


Fig. 3. Diagram for determination of sediment fraction in arc lavas. Calculations were made assuming 100% incorporation of a sediment into a melt. According to *Tera* et al. [4] with the new data for Kuriles and Kamchatka

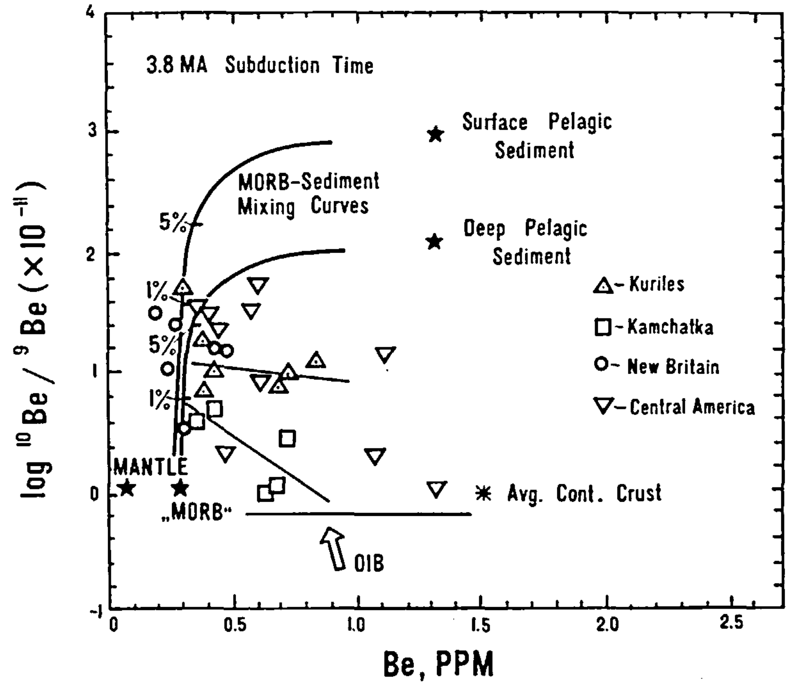


Fig. 4. $^{10}$Be/$^{9}$Be – Be diagram for recent lavas of Kurile, Kamchatka, New Britain and Central American arcs [6]. Mixing curves were calculated for mixing between magma with MORB-like Be content and sediments where $^{10}$Be/$^{9}$Be ratio of the sediments was corrected for $^{10}$Be decay during a 3.8 Ma subduction time. Tie marks indicate % sediment in the mixture

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