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Space geodetic observation of deep basal subduction erosion in northeastern Japan

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Abstract

Observation of tectonic erosion [Von Huene and Scholl, Rev. Geophys. 29 (1991) 279–316] in a subduction zone has been difficult as it leaves little geological and geophysical evidence. Three-dimensional velocity profiles of crustal movement obtained by Global Positioning System across NE and SW Japan agree well with those predicted by the elastic loading of the subducting slabs. However, vertical velocities in the NE Japan forearc show significant negative deviation (relative subsidence). This may indicate loss of material at the plate interface that can be attributed to the erosion of the upper plate by the underthrusting slab (basal subduction erosion). The estimated rate (15 mm/yr down to a slab depth of 90 km) is somewhat faster than the geological average; the erosion speed may be variable being controlled by the surface roughness of subducting slabs.
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1. Introduction

Subduction erosion is the detachment of upper plate rock and sediment and the downward transport of this material along with the subducting lower plate. It is an important geological process controlling the growth of the total continental mass and the supply of water and solid material to the mantle over long timescales. Subduction erosion has two basic mechanisms, i.e. frontal and basal erosion [1,2]. Frontal erosion occurs at a trench; material collapsed from the landward slope is trapped in a horst–graben structure of the subducting plate. Such collapse is accelerated by the underthrusting of high seafloor relief, such as seamounts. Basal erosion occurs as the material at the base of the upper plate is detached and moves toward the mantle with the subducting slab. These two processes carry down upper plate material, make the trench retreat landward, and let forearc subside. Subduction erosion in NE Japan has been investigated by many geologists since ocean drilling (DSDP Legs 56 and 57) at the continental slope of the Japan Trench discovered evidence of large-scale subsidence, i.e. a subaerial unconformity over marine Cretaceous strata several kilometers below sea level [3]. Detailed mechanisms and current rates of the erosion, however, are poorly constrained and understood because

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the erosion process is difficult to observe with geophysical or geodetic measurements.

In SW Japan, there are some indications suggesting on-going subduction erosion near the Nankai Trough, e.g. indentations in the accretionary prism caused by underthrusting seamounts, and large forearc basins [4]. However, unlike NE Japan, large-scale subduction erosion has not been documented in SW Japan. On the contrary, a well-developed accretionary prism exists [5], and active sediment accretion takes place [6] there. In the present study, with modern observations of satellite geodesy, we compare horizontal and vertical velocity profiles of crustal movement across NE and SW Japan, and investigate geodetic signatures of these two typical geological processes in subduction zones, i.e. subduction erosion and sediment accretion.

2. Velocity profiles across NE and SW Japan

The Japanese nationwide dense Global Positioning System (GPS) array, GEONET (GPS
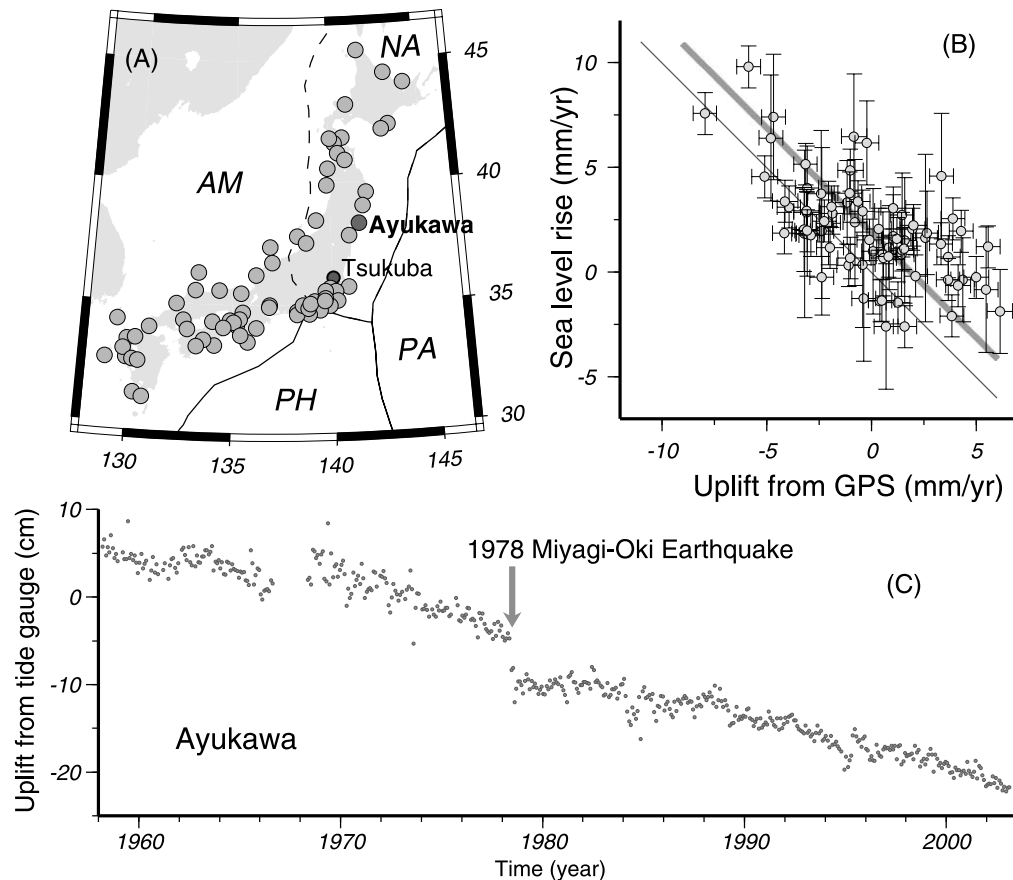

Fig. 1. Comparison of vertical velocities from GPS and tide gauges. In SW Japan converge the Amurian (AM) and the Philippine Sea (PH) plates, while in NE Japan the Pacific (PA) and the North American (NA) plates converge (A). Sea level rise rates at tide gauges (gray dots) and vertical velocities at nearby GPS sites are negatively correlated with a small excess sea level rise indicated as the offset between the thick gray line (best-fit line) and a thin solid line on which the two quantities coincide with each other (B). Errors for GPS velocities are 1σ (error of Tsukuba [small black dot] velocity in ITRF2000 [11] is considered), and those for tide gauges are ±1, ±2, ±3, ±4 mm/yr for sites observed >40, >30, >20, and <20 years. The data from the Ayukawa tide gauge (large grey dot) show a sudden coseismic subsidence in the 1978 earthquake and secular subsidence, violating the classical concept that coseismic uplift cancels cumulative interseismic subsidence (C).

Earth Observation Network), has detected fast [7,8] and slow [8] fault slips, and helped us explore geophysical implications of periodic [9] and secular [10] crustal movements. Most of the observations are for horizontal movements because of poor accuracy and lower signal-to-noise ratio of the vertical in GPS positioning, but longer observation periods are making it possible to discuss secular uplift or subsidence rates. Here we use three-dimensional velocity fields obtained from the official solution of GEONET by Geographical Survey Institute 1996.2–2000.5. Relative vertical velocities of GPS points were converted to those with respect to the geocenter (the center of gravity of the Earth) by fixing the Tsukuba (92110) velocity to the value given in the International Terrestrial Reference Frame (ITRF) 2000 [11]. Fig. 1 compares long term sea level change rates at 76 tide gauges [12] obtained after removing oceanographic signals using Kato's [13] method, and vertical velocities of nearby GPS points. They are negatively correlated and the vertical GPS velocity is lower than tide gauge data by ∼1.9 mm/yr, which reflects eustatic sea level rise in the western

Pacific area due to the melting of the Antarctic and Greenland ice sheets [14].

Horizontal and vertical velocity data of SW (Fig. 2) and NE Japan (Fig. 3) were taken from rectangles ∼80×∼500 km that cross SW and NE Japan. These rectangles include promontories and islands to enable wide trench-normal distance range, and are free from recent events with non-secular signals. The observed velocities are compared with the curves predicted by the backslip (slip deficit) model in an elastic half space [15]. In NE and SW Japan, plate coupling is assumed full for depths from 5 to 50 km and 5 to 25 km, respectively, and gradually decreases to zero at 65 and 35 km, respectively [16]. Euler vectors derived by space geodesy were used to calculate convergence vectors at NE [11] and SW Japan [10], assuming the North American–Pacific and the Amurian–Philippine Sea plate pairs, respectively. Along the eastern margin of the Japan Sea, the Amurian Plate subducts eastward beneath NE Japan, where relative velocity vector was taken from Heki et al. [17]. Slab geometry is not clear there, so we assumed a fault plane analogous to past
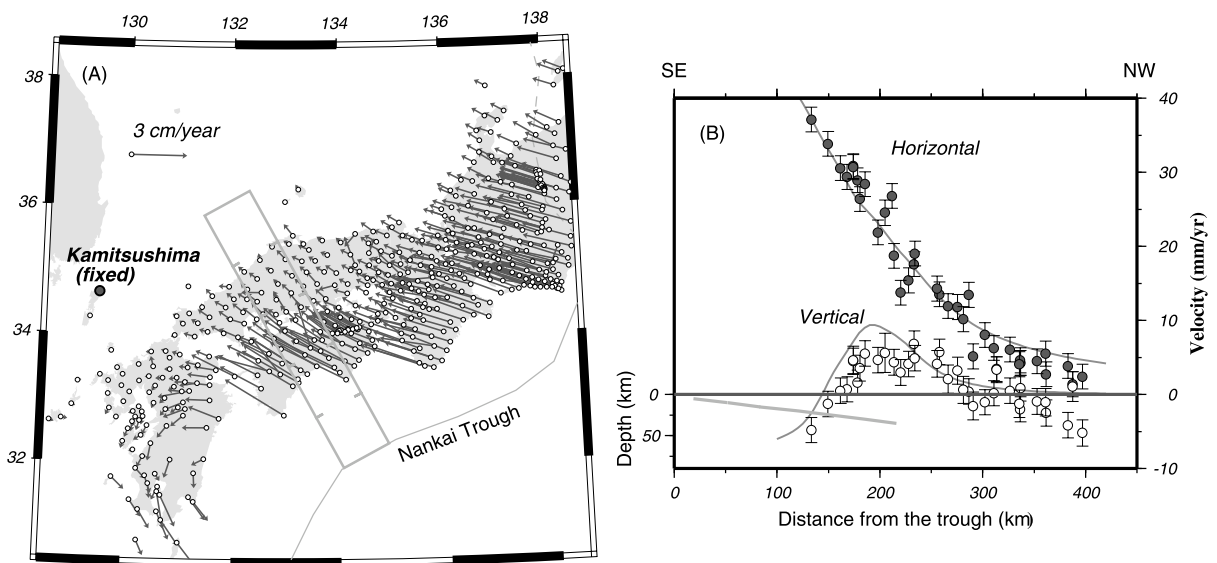

Fig. 2. Comparison of observed velocities and those calculated using the backslip model [15] in SW Japan. Trench-normal horizontal (gray) and vertical (white) velocities of GPS points within the rectangle as large as ∼80 km×∼500 km (ticks on the longer sides of the rectangle show 100 km distances normal to the arc) in SW Japan (A) are plotted as functions of distance from the Nankai Trough (B). The black dot in A indicates the fixed point (Kamitsushima). Thin gray curves in B are the velocity profiles predicted by the slip deficits at the plate interface. Error bars show 3σ. A thick gray curve in the lower part of B denotes the cross-section of the upper surface of the subducting slab where slip deficits are assumed.
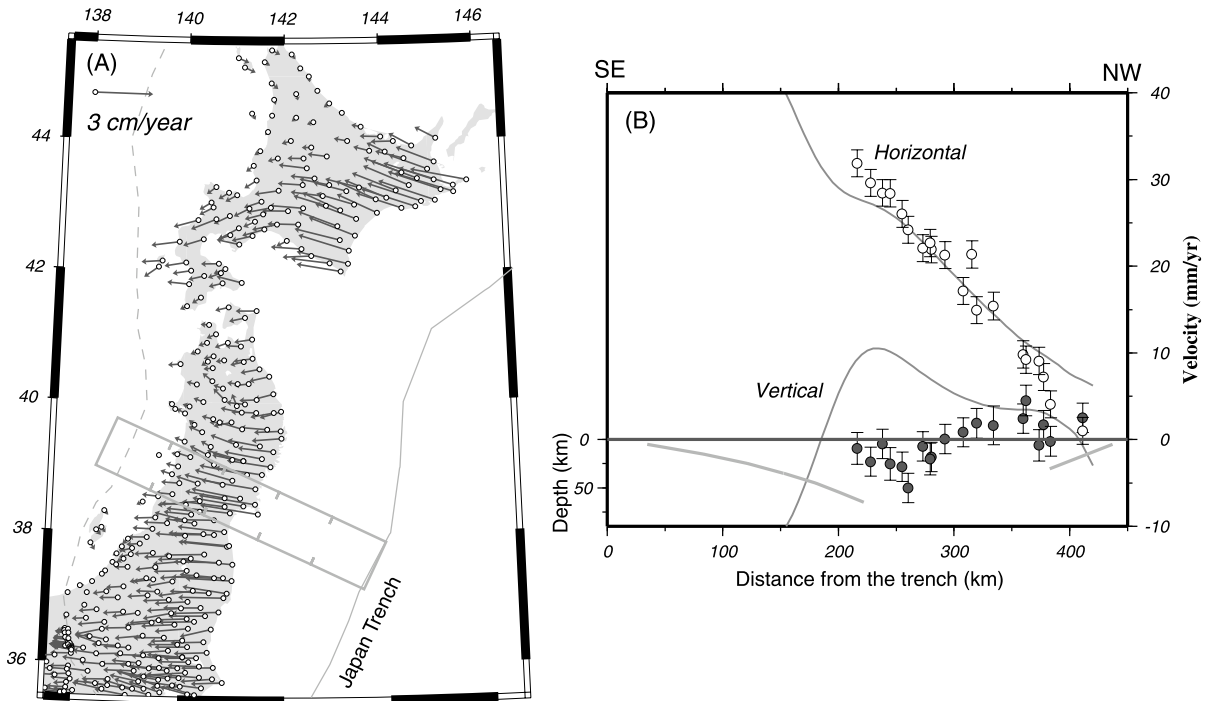
Fig. 3. Comparison of observed and calculated velocities in NE Japan. Negative deviation of the observed vertical velocities (i.e. relative subsidence) from the curve would be due to the on-going basal subduction erosion at the Pacific–NE Japan convergent margin. Thick gray curves in the lower part of B denote the cross-sections of the upper surface of the two slabs subducting along the Japan Trench (left-hand side) and the eastern margin of the Japan Sea (right). See the caption of Fig. 2 for more detail.

earthquakes along this zone, e.g. the 1983 Central Sea of Japan [18] and the 1964 Niigata [18] earthquakes. This additional convergence is only ∼1/5 of the rate at the Japan Trench, and does not greatly influence NE Japan forearc movements.

The vertical velocity reference is reasonably defined by the geocenter, but selecting horizontal references is not straightforward. For SW Japan, I fixed Kamitsushima (Fig. 2), which is >500 km distant from the Nankai Trough. In NE Japan, because subduction occurs at both sides of Japan, a stable reference cannot be found within the arc. There an artificial translation is given to the horizontal velocity profile so that they match the predicted curve.

3. Forearc subsidence in NE Japan

In both NE and SW Japan, horizontal crustal movements are consistent with the backslip model

[15] predictions. Vertical velocities agree well with the model in SW Japan (Fig. 2). However, they deviate negatively (show relative subsidence) from the model in NE Japan (Fig. 3), which may indicate: (1) viscous flow effect, (2) wrong coupling strength and/or convergence rates, (3) a tectonic factor causing the NE Japan forearc to subside but keeping SW Japan stationary. Crustal velocities may vary during an earthquake cycle due to viscous relaxation in the asthenosphere. Cohen [19] calculated such cyclic components under various conditions, and showed a viscous effect does modulate interseismic displacement 'rates'. The results also showed that it hardly changes 'directions', so the uplift/subsidence pattern remains similar throughout the cycle. In the NE Japan rectangle (Fig. 3), interplate thrust earthquakes have been occurring quasi-periodically with intervals of 30–40 years for the past few centuries [18]. Tide gauge data in Ayukawa (Fig. 1), spanning >40 years, record the last event, the 1978 Miyagi-

Oki (*M* 7.3) earthquake. Although some difference exists between the rates immediately before and after the event, the site subsided persistently throughout the cycle. Hence possibility 1, viscous flow, is ruled out although this effect has a certain influence over the estimated erosion rate. Possibility 2 is also not plausible. We could make the forearc subside by extending the coupled zone to a depth of 100–120 km [20]. However, this would be inconsistent with our knowledge of seismogenic depth in NE Japan where interplate thrust earthquakes occur at depths shallower than 50–60 km [21]. Here we adopt possibility 3, and hypothesize that a tectonic factor of basal subduction erosion gives rise to the observed forearc subsidence.

The formulation of Okada [22] is often used to relate surface deformation to dislocation of a fault at depth. It assumes a homogeneous elastic half space instead of the realistic layered viscoelastic spherical Earth, but has been successfully applied for most local crustal deformation cases. We applied this to the present study to estimate the basal erosion rate at depth using relative subsidence data. Instead of shear dislocation (earthquakes) and crack opening (dike intrusions), we assumed compressional dislocation (fault-normal shortening) on a certain part of the plate boundary to model the material loss associated with the basal erosion. Because the coverage of GPS points is limited, we assume a uniform rate of basal erosion and infer the best combination of three quantities, amount of erosion rate, its downdip, and updip extent. Fig. 4 shows a prediction for the nominal case where 15 mm/yr shortening occurs above a depth range to the subducting slab of 5–90 km. Three sets of predictions are also shown for different amounts of shortening (red curves) and its downdip (green curves) and updip (blue curves) extent. The blue curves suggest that the land GPS data are insensitive to the updip extent. This is understood by comparing the weighted
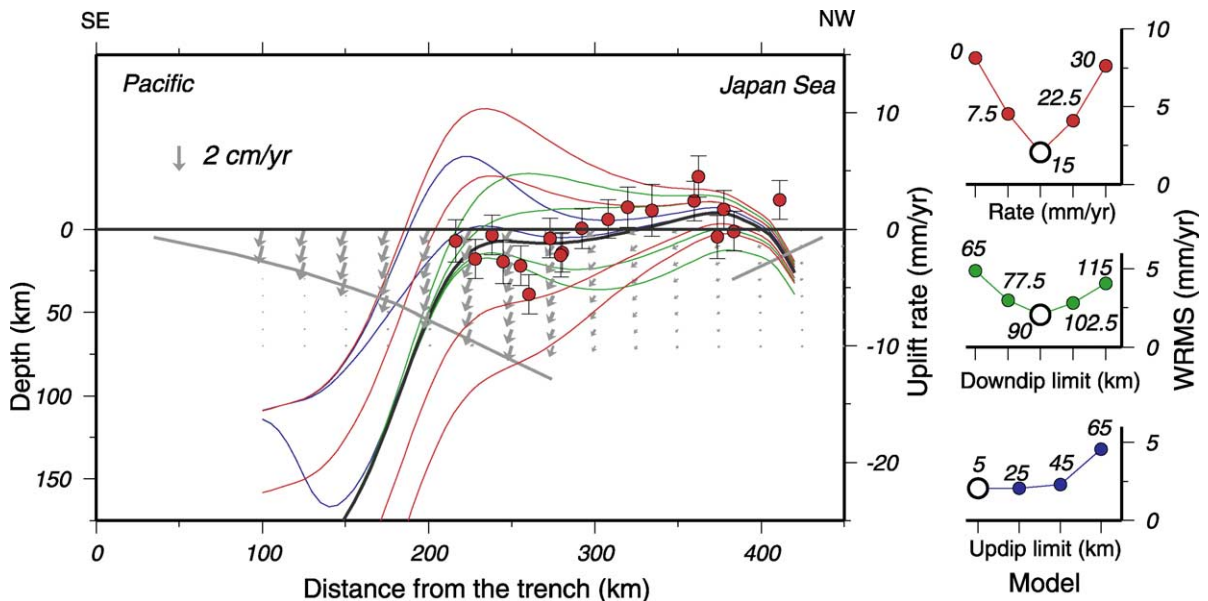

Fig. 4. Vertical velocities of GPS points in the NE Japan velocity profile (same data as in Fig. 3). Solid black curve is the nominal model predicted by the backslip and basal erosion of 15 mm/yr on the slab surface at depths 5–90 km. Arrows denote displacement at grid points due to the erosion calculated following Okada [22]. A thick gray curve shows the upper surface of the subducting slab. The red curves show predictions when the erosion rate is changed to 0.0, 7.5, 22.5 and 30 mm/yr (from top to bottom), and green (blue) curves show sensitivities to the downdip (updip) extent of the eroded slab (5–65, 5–77.5, 5–102.5, 5–115 km for green, and 65–90, 45–90 and 25–90 km for blue, both from top to bottom). Three diagrams to the right show behaviors of the weighted root-mean-squares (WRMS) of the differences between the 19 vertical velocity data and curves predicted with different parameters. Large open circles in the three diagrams show the nominal model (15 mm/yr, 5–90 km).

root-mean-squares shown to the right; erosions over the depths 45–90 km, 25–90 km and 5–90 km satisfy the data almost equally. Horizontal deformation also occurs by the erosion but is negligible in comparison with large compressional strain due to interseismic backslip.

4. Discussion

For NE Japan, several kinds of erosion rates have been estimated by von Huene and Lallemand [23], with which we compare the geodetic rate derived here. The rate of crustal material loss of 40–55 km³/Myr/km has been derived by reconstructing the ancient geometry of the submerged margin of NE Japan. This is not applicable to our study because we discuss the loss of upper plate materials including both mantle and crust. Another value is the average subsidence rate, 320 m/Myr since 22 Ma, at an outer forearc drill point, inferred from the age and current depth of the subaerial unconformity. This is not applicable, either; because isostatic adjustment might cancel the initial subsidence leaving only the permanent subsidence due to the loss of light crustal material (isostasy may not work well in a 'dynamic' place like subduction zones, though).

The quantity pertinent to the current study might be the landward retreat rate of the trench v_t (Fig. 5), which is suggested to be > 3 km/Myr [23] from the final inundation age of the unconformity, paleo-trench depth of > 7 km, and continental slope of 5°. Here we revise this value by assuming the subduction zone geometry similar to present: if the current land–trench distance of ~ 200 km has been constant, the fact that the drill point, which was subaerial at 16 Ma, is only 30 km apart from the trench now [23] suggests that the trench has retreated 170 km in 16 Myr, with an average rate of ~ 10 km/Myr (10 mm/yr). Uneven erosion rates would let the slab dip angle θ evolve in time, but here we assume uniform erosion and that the geometry has been kept similar (Fig. 5). Let θ and v_t be 30° and 10 mm/yr, respectively, then the deep basal erosion rate $v_t \sin \theta$ would be 5 mm/yr. The current rate of 15 mm/yr from space geodesy is three times as large. Erosion at this segment of NE Japan might be temporarily accelerated by the subducting seamount. The asperity that has been causing earthquakes every 30–40 years there [18] could originate from this seamount. Although the forearc subsidence is a general feature in NE Japan, there is some along-trench variation in the rate of subsidence [24]. Subduction erosion seems to be, un-
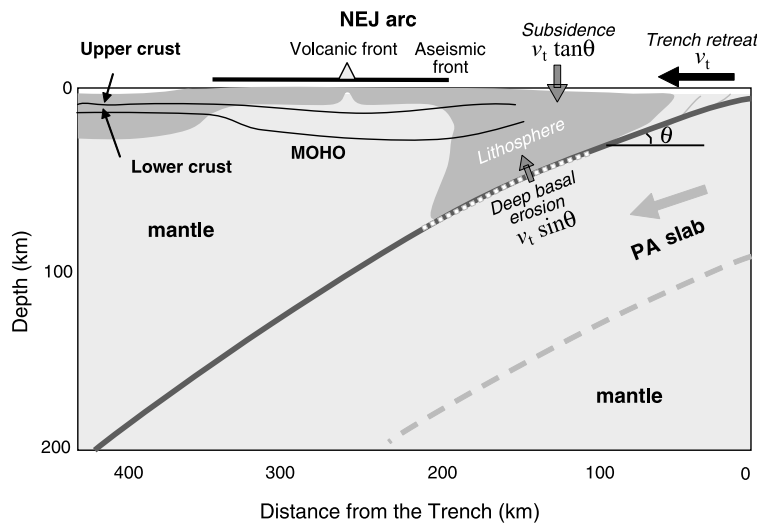

Fig. 5. Schematic diagram showing the deep basal subduction erosion in NE Japan. The erosion is considered to take place at a part of the plate interface shown by the broken curve, as the thinning of the mantle lithosphere due to the transport of the materials above the subducting slab down to depth. The shaded area shows the NE Japan island arc lithosphere.

like plate motions, fairly non-uniform in space and time controlled by the slab surface roughness [25]. The causal link between forearc subsidence, subduction erosion and occurrence of great interplate earthquakes through asperities [4] would be an important future subject of subduction zone dynamics.

Water released during subduction is considered to play important roles in basal subduction erosion [1]. Fluids migrate upward and weaken the base of the upper plate allowing fragmentation by hydrofracturing to produce slurry of tectonic clasts that are carried down to depth with subducted sediment. A significant amount of water is suggested to be released at various depths [26]. At a shallow depth, oceanic sediment releases water as the subducted column consolidates. At greater depth ($\sim$50 km in NE Japan [27]), high temperature and pressure cause hydrous and clay minerals in the underlying oceanic crust to release water, which is assimilated by the upper plate in the conversion of olivine to serpentine and chlorite. The serpentinized mantle lithosphere is hypothesized to be detached from the upper plate and dragged down by the slab (the process corresponding to the deep basal erosion, i.e. thinning of the mantle lithosphere), and eventually releases water beneath the volcanic front ($\sim$150 km in NE Japan [27]) encouraging magma genesis for arc volcanism. Our study may give a quantitative constraint to clarify these deep processes. For Japan, basal erosion is presumed to occur continuously along the stable-sliding part of the plate interface ($<$5 km or $>$45 km). At seismogenic depths, however, erosion might occur episodically together with interplate thrust events, attaining a similar long-term average rate to the non-seismogenic parts. Land geodetic data are insensitive to basal erosion shallower than 45 km (Fig. 4), and it remains ambiguous whether basal erosion is continuous or episodic there.

Subduction erosion and sediment accretion are not always exclusionary, that is, they may occur at different depths of one subduction zone. For example, in SW Japan, frontal sediment accretion and subduction erosion thinning of the backstop seem to have been occurring simultaneously since $\sim$20 Ma. However, as suggested by von Huene and Scholl [1], many subduction zones are dominated either by sediment accretion (e.g. SW Japan) or by subduction erosion (e.g. NE Japan). In SW Japan, measured vertical velocities are consistent with the model prediction and do not show excessive uplift or subsidence (Fig. 2). There accretion and/or erosion might be occurring slowly or only along the shallow part of the plate interface for which land geodetic data are insensitive. Geodetic measurements show that the Cascadia subduction zone forearc is undergoing long-term coastal uplift of 1.0–1.5 mm/yr in addition to interseismic uplift of a few mm/yr [28]. This is consistent with its being an accretion-dominated zone bordered by a large accretionary prism. Interseismic uplift consistent with the prediction is also found in Alaska [29], which is also an accretion-dominated zone. GEONET covers the southernmost part of the Kurile Arc (eastern Hokkaido), which is an erosion-dominated subduction zone. Fairly rapid subsidence and trench-normal shortening similar to NE Japan are seen here [24], for which the same interpretation as in NE Japan would apply. GEONET also covers the Ryukyu and the Izu-Bonin arcs (both are erosion-dominated), but GPS points do not have enough trench-normal range to let us draw their velocity profiles.

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