Does Kamchatka belong to North America? An extruding Okhotsk block suggested by coastal neotectonics of the Ozernoi Peninsula, Kamchatka, Russia

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ABSTRACT

This paper addresses one part of an outstanding tectonic problem regarding the nature of the plate boundary between Eurasia and North America in northeastern Russia. In this region, the northwestern corner of the Pacific plate interacts either simply with the North American plate, or more complexly with one or more blocks independent of North America. North of this corner, evidence of uplift, tilting, and convergence contradicts the prevailing, simpler model. On the Ozernoi Peninsula, ~150 km north of the subducting Pacific plate, marine terraces indicate uplift rates of 0.1 to 0.3 mm/yr, with faster rates to the east. Historic and paleoseismic records provide evidence for recurring tsunamigenic, thrust earthquakes offshore of the Ozernoi Peninsula, the most recent a Mw 7.7 earthquake in 1969. A multiplate model where an eastward-moving Okhotsk block, including most of Kamchatka, is converging with a clockwise-rotating Bering block better explains these observations than does the unbroken North American plate model.

Keywords: Kamchatka, Quaternary marine terraces, neotectonics, plate tectonics, Okhotsk, Bering Sea.

INTRODUCTION AND SETTING

Does Kamchatka belong to North America or not? Where and how does the North American plate terminate after the Atlantic-Arctic spreading ridge passes through its Euler pole in northeastern Russia (Fig. 1)? This region remains ''the last frontier of plate tectonics'' (Cook et al., 1986). On the Pacific plate side, the northwestern corner of the Pacific plate is well defined by subduction along the Kuril-Kamchatka trench and transcurrent motion along the Komandorskii[1]-Aleutian trench (Fig. 1). Just north of the Komandorskii-Aleutian trench, the Komandorskii Island block (McElfresh et al., 2002) has been established by global positioning system (GPS) measurements (Gordeev et al., 2001) to be moving toward Kamchatka, as predicted by geologic evidence of accretion on the Kamchatskii Peninsula (Geist and Scholl, 1994) (Fig. 1). North of the Komandorskii Island block, recent geophysical models and petrologic evidence favor a ''torn-slab'' scenario, where the Pacific plate has broken off and fallen away (Park et al., 2002; Portnyagin et al., 2005).

Beyond the trenches and the Komandorskii Island block, major puzzles remain. There are many models and scant data to constrain questions such as, does the North American plate (1) encompass the entire region (the prevailing or conservative view), or (2) is it broken locally into smaller blocks (in addition to the Komandorskii Island block) such as the Bering and Okhotsk blocks (Fig. 1A)? If the latter, where are the boundaries of these blocks in this region, and how are the blocks moving? In a single North American plate model, the Pacific plate converges with southern Kamchatka (North American plate) at a rate of about 8 cm/yr (DeMets et al., 1994), but no tectonic activity is predicted north of the Kamchatskii Peninsula. However, convergence in this northern region could be explained if an Okhotsk block (or plate) is moving eastward, extruded by the convergent rotation of the Eurasian plate and the North American plate south of the Euler pole (Cook et al., 1986) (Fig. 1A). Convergence would be enhanced if the Bering block is rotating clockwise (Mackey et al., 1997).

Several approaches can help address such plate-boundary and plate-motion questions, including seismicity patterns (Mackey et al., 2004) and GPS measurements (Takahashi et al., 1999; Steblov et al., 2003). However, the region is only sparsely instrumented, and instrumental and historic records may be too short to resolve long-term trends. In order to garner longer-term histories, our approach to answering these questions is to examine the neotectonics of the Ozernoi Peninsula, and for comparison, the better-understood Kamchatskii Peninsula (sometimes incorrectly called Cape Kamchatka or Kamchatka Mys Peninsula [as in Gaedicke et al., 2000]) just to the south (Fig. 1B). The Kamchatskii and Ozernoi Peninsulas are major promontories in the southwestern Bering Sea (Fig. 1B), underlain by the Komandorskii Basin (Fig. 1B), which is not now seismically active. The western edge of the basin comprises both an extinct subduction zone (Seliverstov, 1998) and the eastern boundary of the Olyutorskii terrane (Garver et al., 2000); this boundary is seismically active (Cook et al., 1986; Mackey et al., 2004).

Both peninsulas exhibit high relief in the east, where marine terraces are prominent (Fig. 2), and lowlands to the west. On the Ozernoi Peninsula, over a proposed Okhotsk-Bering plate boundary (Fig. 1), Holocene and Pleistocene marine terraces exhibit uplift rates comparable to more tectonically active zones on Earth (Lajoie, 1986; Johnson and Libbey, 1997). Moreover, the 1969 Ozernoi Mw 7.7 earthquake and following tsunami are consistent with active convergence. We think that the uplift of both peninsulas is tectonic in origin. Variability in uplift rate is inconsistent with epeirogenic land-level change, and the good fit of data with relatively constant uplift over hundreds of thousands of years is not consistent with glacio-isostatic processes.

METHODS

We measured the altitude of uplifted late Quaternary marine terraces to calculate uplift rates (as in Lajoie, 1986). The altitude of the *shoreline angle,* or base of a paleo–sea cliff, is considered most representative of maximum sea level during interglacial times, correlated to odd-numbered marine isotope stage (MIS). Calculation of uplift rates using marine terraces requires correlation of a particular terrace to a particular stage. In our field area, although Pleistocene terraces are clear in the landscape (Fig. 2), they have been affected by fluvial and glacial processes so that marine deposits are either lacking or buried, and direct numerical

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[1] Russian place names are transliterated to English using Library of Congress standards; the ending ''ii'' is commonly spelled ''iy'' or simply ''i'' in other publications.

Geology; May 2006; v. 34; no. 5; p. 353–356; doi: 10.1130/G22062.1; 3 figures; 1 table.

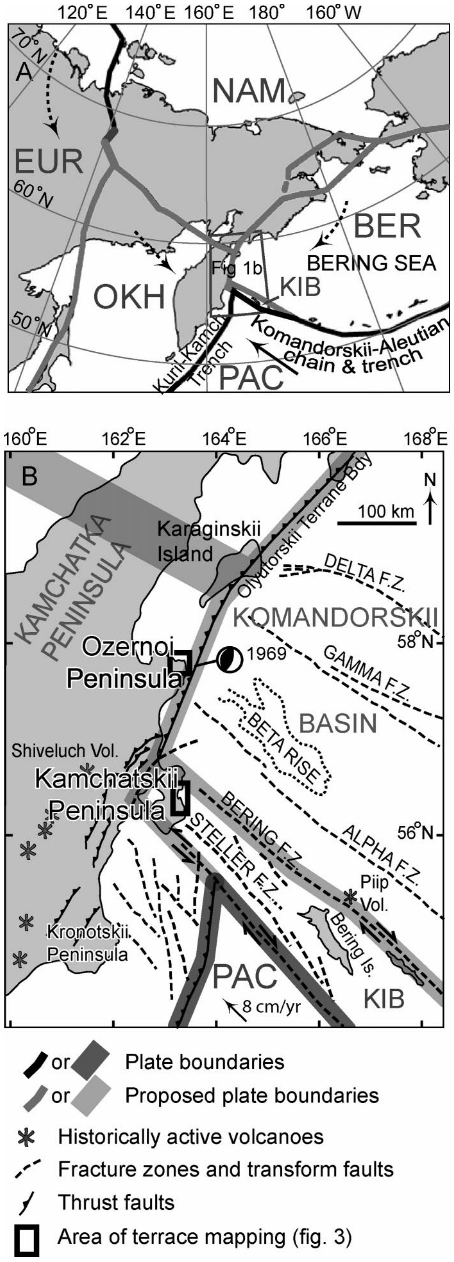

Figure 1. A: Proposed plate and tectonic blocks in northeastern Russia. In the unbroken North American plate model, the Bering and Okhotsk blocks would remain part of the North American plate. NAM—(small) North American plate; EUR—Eurasian plate; PAC—Pacific plate; BER—Bering block (as in Mackey et al., 1997); OKH—Okhotsk block (as in Gordeev et al., 2001); KIB—Komandorskii Island block (as in McElfresh et al., 2002). Arrows show suggested motion of plates relative to a fixed (small) NAM. B: Tectonic setting of the northwestern corner of the Pacific plate and western Komandorskii Basin. Compiled and revised from Baranov et al. (1991), Geist and Scholl (1994), Garver et al. (2000), and Gaedicke et al. (2001). The Olyutorskii terrane is also known as the Vetlovka terrane. Also shown: location and fault-plane solution for the 1969 Ozernoi earthquake (Cormier, 1975). The position of the northern boundary of the Okhotsk block is not well defined (shown by broad gray band); some models place it as far south as the Kamchatskii Peninsula.

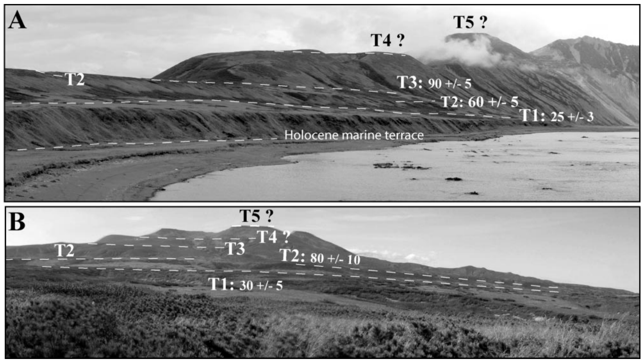

Figure 2. Landscapes showing marine terrace sequences. A: Transect B, north side of Cape Nose, Kamchatskii Peninsula (see Fig. 3). B: Transect X, Ozernoi Peninsula (see Fig. 3), from front edge of T1 (lowest Pleistocene terrace).

dating of these terraces has not been accomplished. No Pleistocene tephras are well preserved. Thus, we use the standard method of terrace correlation with sea-level highstands (Lajoie, 1986, and many others).

The best-represented terrace worldwide is the one correlated to the Last Interglacial Maximum (MIS 5e) (Hearty and Kindler, 1995; Johnson and Libbey, 1997). The age of MIS 5e is arbitrarily fixed to range from 130 to 116 ka (Kukla et al., 2002) but is demonstrated to range from 134 to 113 ka in Hawaii and Barbados (Muhs et al., 2002) with a peak from 128 to 116 ka on tectonically stable coastlines (Muhs, 2002). Older marine terraces well represented in worldwide sequences are those related to MIS 9 (ca. 303–339 ka) and 11 (ca. 362–423 ka) (Imbrie et al., 1984). Compilations show that sea level was 3 ± 3 m higher than present during MIS 5e, MIS 9, and MIS 11, and −1 ± 1 m relative to present sea level during MIS 7 (Hearty and Kindler, 1995; Zazo, 1999). Consequently, MIS 7 (ca. 180–240 ka; Imbrie et al., 1984) marine terraces are less pronounced and sometimes absent (Zazo, 1999).

Fieldwork carried out in 2003 included topographic surveys of Holocene beach and terrace profiles and altimeter transects of Pleistocene marine terraces. Along Holocene profiles, we made excavations and used the oldest preserved marker tephra (Braitseva et al., 1997) in soil above marine sand, to establish a minimum terrace age. For Pleistocene marine terraces, we measured altitudes of shoreline angles with digital altimeters calibrated to the most recent high tidemark. Tide tables were used to relate high tide to a mean sea-level datum; all terrace altitudes are given in meters above mean sea level. With the same altimeter, we estimated barometric drift and calibrated on the high tidemark before and after measuring terrace altitudes. As we worked near sea level, the equation relating pressure and altitude does not have to be corrected. The altitude error range in tables and figures comes primarily from a field estimate of paleoshoreline preservation, as barometric drift was relatively small.

DATA AND ANALYSIS

Holocene Terraces and Sea Level

For a number of sites, we measured the elevation of the back of the Holocene marine terrace and estimated the elevation of the shoreline angle (Table 1) by assuming that mid-Holocene eustatic sea level in the North Pacific was ~2 m higher than today (Douglas et al., 2001), and that ~5 m of sediment overlies the wave-cut platform (based on the elevation of modern beach profiles above that platform). At field sites on both peninsulas, the Holocene shoreline began prograding ~5000 years ago (based on the oldest preserved tephra). There are large uncertainties in the Holocene data, relative to measured elevations, but we consider significant the trend of rising elevation of this shoreline angle toward the outer part of each peninsula, consistent with trends in Pleistocene terrace elevations. Uplift rates for the late Holocene are an order of magnitude faster than Pleistocene rates presented below.

Pleistocene Marine Terraces

On the outer Kamchatskii Peninsula, we mapped five Late Pleistocene marine terraces along more than 20 km of rocky coast (Figs. 2A and 3). On the northeastern part of the Ozernoi Peninsula, we mapped two marine terraces; in some places, remnants of older terraces were detectable (Figs. 2B and 3), and it was possible to define at least three to five paleoshorelines above the Holocene. Because the elevations of these terraces are an order of magnitude higher than the uncertainties in sediment-cover thickness and paleoeustatic sea level mentioned for the Holocene, these uncertainties have no effect on overall interpretation.

On both peninsulas, following standard practice (Johnson and Libbey, 1997), we correlate the prominent T1 marine terrace with MIS 5, and in order to get the *minimum* uplift rate we correlate the shoreline of this terrace with the peak or maximum of this interglacial (MIS 5e) (Fig. 3). This correlation gives long-term uplift rates ranging from 0.10 ± 0.07 mm/yr (0.1 m/k.y.) to 1.12 ± 0.20 mm/yr (1 m/k.y.) (Table 1). These rates are comparable

TABLE 1. TERRACE ELEVATIONS AND CALCULATED UPLIFT RATES

Profile	Terrace elevation (m)				Uplift Rate (mm/a or m/ka)				
	H	T1	T2	T3	T1 = MIS 5e	T2 = MIS 7	T2 = MIS 9	T3 = MIS 9	T3 = MIS 11
A	n.d.	22–28	55–65*	85–95	0.11–0.25	0.22–0.37	0.15–0.23	0.24–0.33	0.19–0.28
B	0	20–30	55–65*	~	0.1–0.27	0.22–0.37	0.15–0.23		
C	1–2	17–23	47–63*	70–90	0.08–0.21	0.19–0.36	0.12–0.22	0.19–0.31	0.15–0.26
D	2–3	42–48	70–80#	~	0.26–0.43	0.28–0.45	0.19–0.28		
E	>3	63–73	~	~	0.42–0.65				
F	n.d.	70–80	~	~	0.47–0.71				
G	n.d.	130–150	~	~	0.92–1.33				
Z	0	10–20	32–42	~	0.02–0.18	0.12–0.24	0.08–0.15		
Y	0–1	25–35	~	~	0.14–0.31				
X	1–2	25–35	70–90	~	0.14–0.31	0.28–0.51	0.19–0.31		
W	2	40–50	~	~	0.25–0.45				

Note: Profile locations and plots of data are shown in Fig. 3; H—Holocene; n.d.—no data near that terrace profile. Error as represented by range of terrace elevations is discussed in the text. Age ranges assigned to calculate uplift rates: MIS 5e 113–134 ka (see text); MIS 7 180–240 ka; MIS 9 303–339 ka; MIS 11 362–423 ka (Imbrie et al., 1984).

*Terrace 2a; #Terrace 2b; ~ not measured with altimeter.

to uplift rates determined through the same method in other parts of the Pacific rim (Ota and Yamaguchi, 2004).

For carving of the T2 terrace, there are two hypotheses for the MIS responsible (Fig. 3; Table 1). The first hypothesis correlates T2 with MIS 7 (penultimate interglacial, ca. 220 ka, “weaker” than MIS 5e). The second hypothesis correlates T2 with MIS 9 (“strong” interglacial, ca. 330 ka). For most transects where T2 was measured (T2a on X, Z, A, B, C in Table 1), the latter hypothesis (T2 = MIS 9) produces more uniform uplift rates per transect (Fig. 3). However, for transect D, which has the highest uplift rate for a transect where T2 was measured, T2b = MIS 7 produces the more uniform rate. These results are as expected, because MIS 7 was weaker than MIS 5 or 9, and its terraces are typically only preserved where uplift rates are more rapid (Zazo, 1999).

On both peninsulas, either hypothesis can fit with the existence and morphology of T3, a wider terrace than T2; that is, T3 can be related to MIS 9 or MIS 11. Without direct dating of marine terrace deposits, it is a challenge to address this problem. However, with the exception of transect D and others with faster uplift rates (where T2 and T3 were not measured), we favor the second hypothesis (T2a = MIS 9 and T3 = MIS 11) because it generates nearly constant uplift rates at each profile.

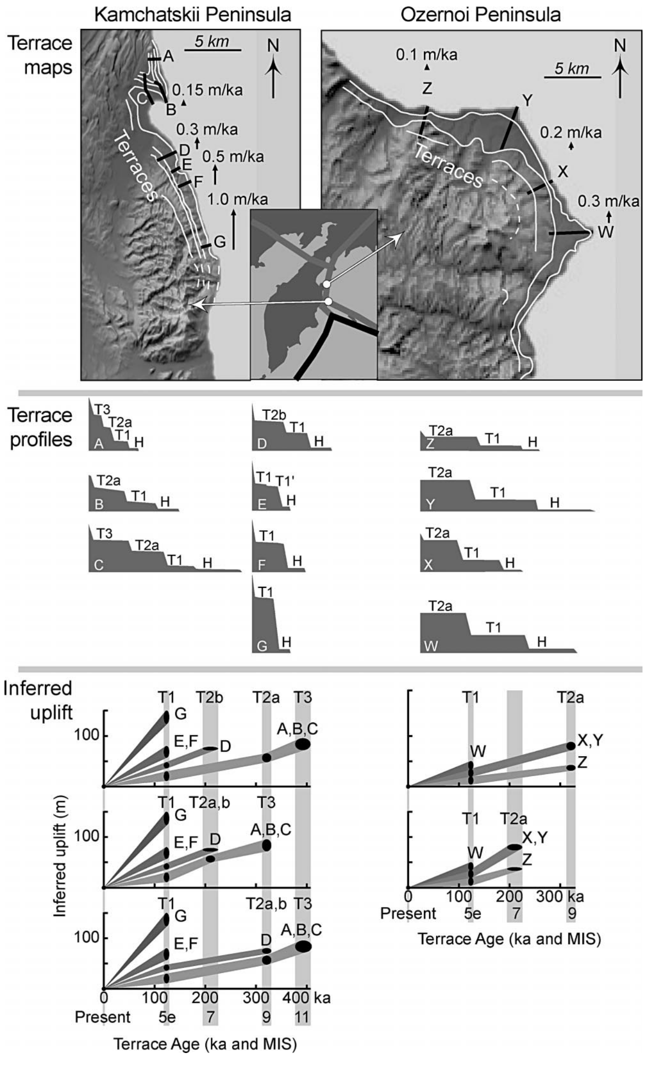

Figure 3. Marine terrace transects on the Kamchatskii and Ozernoi Peninsulas (see Fig. 1B for locations). Plots of displacement of Quaternary shoreline angles against accepted ages of marine terraces corresponding to marine isotope stage (MIS), giving uplift rates (as in Table 1). Width of lines represents estimated error in terrace elevation and MIS age (see Table 1). For all cases, the lowest Quaternary terrace (T1) is correlated to MIS 5e. Two alternative interpretations of T2 are presented for each peninsula: T2 = MIS 7, or T2 = MIS 9 (see text and Table 1).

1969 Ozernoi Earthquake and Tsunami

On 22 November 1969, 23:09:35 GMT (locally midday, 23 November), an earthquake jolted the Ozernoi region. Many different magnitudes for this earthquake have been published; it is currently catalogued with a 7.7 moment magnitude. The epicenter was located at 57.8°N, 163.6°E, just off the Ozernoi Peninsula (Fig. 1B). Cormier (1975) interpreted this event as a thrust, and using body waveform analysis, Daughton (1990) found a thrust fault-plane solution, striking N50°–80°E and dipping 5°–10°NW. The 1969 Ozernoi earthquake was followed by a tsunami with local runup of 5–7 m from Karaginskii Bay south, with a local maximum of about 10 m on the Ozernoi Peninsula (Zayakin, 1981).

Around the Ozernoi and Kamchatskii Peninsulas, we have mapped the 1969 tsunami deposit (above the 1964 Shiveluch tephra or the 1956 Bezymianniy tephra) and expanded the runup catalogue for this tsunami to all our field sites in the southwestern Bering Sea. Moreover, we have found facies evidence of post-1956 subsidence (peat containing 1956 Bezymianniy tephra overlain by lagoonal mud) at the northern and southern extremes of the Ozernoi Peninsula, which we interpret to be coseismic with 1969. Using these data, a tide gauge record, and Daughton's fault-plane solution, Vasily Titov (Bourgeois et al., 2004) modeled this tsunami with 4 m of fault offset, corresponding to 3.5 m horizontal shortening.

Extrapolating this analysis to the paleoseismic record, we roughly estimate a rate of horizontal shortening for this region. Based on the record of prehistoric tsunami deposits, the average recurrence interval for Ozernoi-like events is 100–200 years (Bourgeois et al., 2006). Taking the maximum of 200 years, and using a 3 m shortening for 1969, we calculate the long-term convergence of the Ozernoi Peninsula (Okhotsk block) with the Komandorskii Basin (Bering block) to be roughly 20 ± 10 mm/yr.

DISCUSSION AND CONCLUSIONS

Our findings throw light on local plate boundaries in this poorly studied region. Uplift rates of the Ozernoi Peninsula are comparable to rates on tectonically active margins (Lajoie, 1986; Ota and Yamaguchi, 2004), if less than rates on the Kamchatskii Peninsula, a small collisional orogen.

Whereas the source of shortening on the Kamchatskii Peninsula is well established, on Ozernoi it is not. The Ozernoi Peninsula exhibits uplift rates of 0.1–0.3 mm/yr and evidence of compression and shortening via earthquakes such as that in 1969 and those inferred from prehistoric tsunamigenic earthquakes. Convergence rates on the order of 20 mm/yr are consistent with these observations and analyses. Possible sources of this convergence include (1) shear distributed from the Pacific plate, north of the Komandorskii Island block (Fig. 1B), (2) existence of a clockwise-rotating Bering block (Mackey et al., 1997), and (3) existence and eastward extrusion of the Okhotsk block (Cook et al., 1986). In examining these possibilities, and using our new data, we reject shear distribution from the Pacific plate because of lack of seismicity in the Komandorskii Basin, distance (150 km) of the Ozernoi Peninsula from the active subduction zone, and the torn-slab model (Park et al., 2002) (no Pacific plate under this region).

Uplift and tilting of the Ozernoi Peninsula along with apparent reactivation of a thrust fault such as the boundary of the Olyutorskii terrane (Fig. 1B) shows that convergence is ongoing in this region. A slowly clockwise-rotating Bering block (as in Mackey et al., 1997), in combination with eastward movement of an Okhotsk block, relative to the Komandorskii Basin (Fig. 1), may produce enough convergence to explain these observations. Moreover, the northern boundary of the Okhotsk block, which has been shown in different positions (e.g., McElfresh et al., 2002), must lie north of the Ozernoi Peninsula. In any case, neotectonic activity (Quaternary uplift, deformation, and seismicity) on the Ozernoi Peninsula is not consistent with an unbroken North American plate model, because in this model, the source of deformation north of the northwestern corner of the Pacific plate is not explained.

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