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Drilling the Seismogenic Zone: Some Paradoxes

Tetsuzo Seno*

Earthquake Research Institute, University of Tokyo

Abstract

I point out two possible paradoxical difficulties in the important target of the IODP in subduction zones, i.e., drilling the seismogenic zone. First, an area close to the trench axis, with an apparent slip derived from tsunami data, might not be seismogenic in the conventional sense. It could be an area that has slipped with almost no friction along with a seismic slip at depth. This is inferred from tsunami earthquakes that ruptured the shallowest portion of the plate boundary, which has a stable sliding frictional character. This portion might have entered a no-friction state before tsunami earthquakes, due to the pore fluid pressure rising almost to the lithostatic. The area under the lower trench slope, which is believed to be able to be drilled by the riser ship, therefore might not be seismogenic in the conventional sense. Second, even when drilling is done in the so-called seismogenic zone, it might be difficult to penetrate an asperity, if asperities have a fractal distribution. Careful investigation would, therefore, be necessary to interpret the results of drilling and monitoring at deep borehole observatories in the seismogenic zone. Even if a borehole penetrates a barrier portion, however, monitoring the transience of the frictional properties, including pore fluid pressure, would be useful for understanding earthquake occurrence in subduction zones.

Key words: IODP, seismogenic zone, asperity, barrier, tsunami earthquake, pore pressure

1. Introduction

Drilling the seismogenic zone of an active subduction boundary is the main target of the IODP (Integrated Ocean Drilling Program) in the coming decades using the riser ship "Chikyu". The Nankai Trough, which has been studied extensively and has a shallow water depth, would be one of the most feasible subduction boundaries for this purpose. Due to the limitation of the water and sub-bottom depths of a drill hole, the area that can be drilled is very narrow along the landward trench slope of the Nankai Trough (Fig. 1, Kimura *et al.,* 2001). Even if it is narrow, it has been generally believed that the uppermost part of the coseismic zone of the 1946 Nankai and 1944 Tonankai earthquakes is included in this area (Fig. 1). In this short article, I point out the possibility that this general belief could not be true, when a transient nature of frictional properties along the shallowest subduction pate interface is taken into account. I further point out that, even in the so-called seismogenic zone, it might be difficult to drill an asperity, which has an unstable sliding frictional property, if asperities have a fractal distribution.

2. Updip limit of the seismogenic zone

Generally, the subduction plate boundary within ca. 50 km from the trench axis is aseismic, reflecting the stable sliding frictional property of unconsolidated sediments (Byrne *et al.,* 1988; Scholz, 1990; Hyndman *et al.,* 1997; Moore and Saffer, 2001). The updip limit of the seismogenic zone corresponds to 100-150℃ at the plate interface (Hyndman *et al.,* 1997). Metamorphism, including phase transition of clay minerals, and various diagenesis, along with reduction of pore fluid pressure, start to occur at around this temperature, and are attributed to the transition to the unstable sliding character of the seismogenic zone (e.g., Moore and Saffer, 2001).

For example, in the northern Honshu subduction

* e-mail: seno@eri.u-tokyo.ac.jp (1-1-1, Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan)

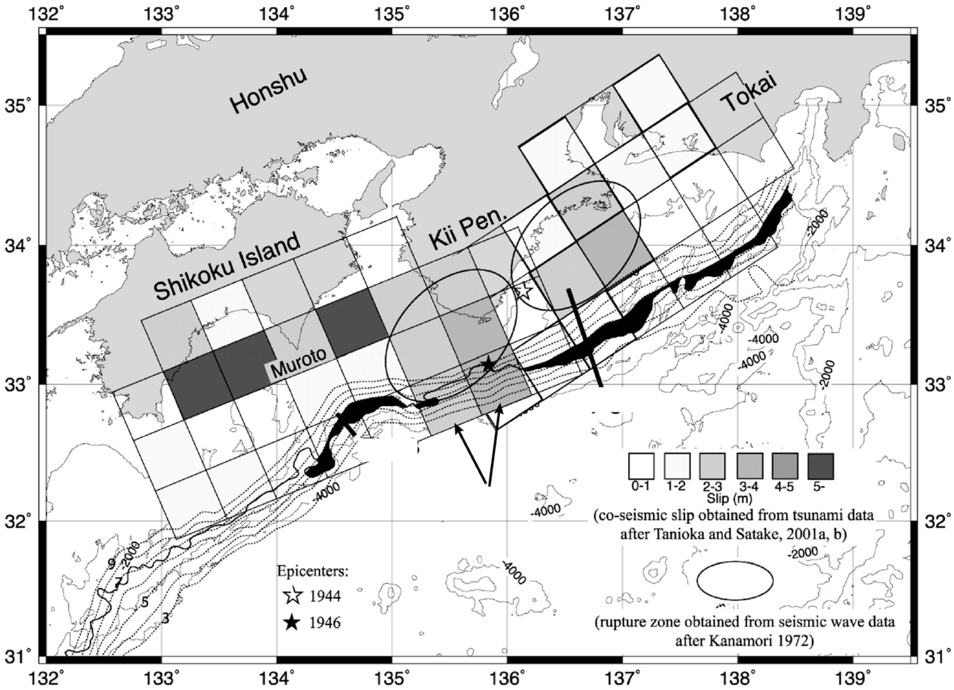

Fig. 1. Location map of the Nankai margin, illustrating the coseismic slip areas of the 1944 and 1946 earthquakes (after Kimura *et al.,* 2001). Areas marked in black are locations with <2.5 km water depth and <6 km sub-bottom depth to the plate interface. The boxes with different shading represent different amounts of coseismic slip revealed by tsunami data (Tanioka and Satake, 2001 a, b). The ellipses are rupture zones obtained from seismic wave data (Kanamori, 1972). Two boxes with significant slips near the trough axis are indicated by arrows.

zone along the Japan Trench, this characterization of the frictional property at the shallow plate interface seems to hold. Hirata *et al.* (1983), using ocean bottom seismometer observations, showed that within 50 km or so landward from the trench axis, seismicity is very low. Although aftershock zones of three recent large interplate earthquakes, the 1989 (M_s 7.4), 1992 (M_s 7.1), and 1994 (M_s 7.5) Sanriku earthquakes, are distributed close to the trench axis, their fault slips, revealed from strong motion records, occurred more than 50 km landward from the trench axis (Yamanaka *et al.,* 2001; see Fig. 1 of Seno, 2002).

However, there are serious exceptions to this characterization: tsunami earthquakes. Recent studies of tsunami waveforms generated by tsunami earthquakes (e.g., Satake and Tanioka, 1999) showed that seismic faulting of these earthquakes occurred very close to the trench axis. In the northern Honshu arc, the 1896 Sanriku tsunami earthquake ruptured a ~50 km wide boundary landward of the trench axis (Tanioka and Satake, 1996; Tanioka and Seno, 2001 a). The 1946 Aleutian, 1992 Nicaragua, and 1996 Peru tsunami earthquakes, also possess similar features; that is, they ruptured the subduction boundary just inside of the trench axis (Tanioka and Seno, 2001 b; Satake, 1994; Satake and Tanioka, 1999). The slow slip nature of tsunami earthquakes (e.g., Kanamori and Kikuchi, 1993) is probably related to the rupture of the shallowest boundary. However, a peculiar feature is that they ruptured the plate interface with a stable sliding frictional property, which would act as barriers when loaded by a sudden slip (Fig. 2 b, Tse and Rice, 1986; Kato and Hirasawa, 1999; Boatwright and Cocco, 1996).

Seno (2002) interpreted these phenomena as a transient feature of the frictional property along the plate interface. When the pore fluid pressure p at the decollement rises close to the lithostatic pressure, the friction $\sigma^*\mu$ becomes very small, even if σ^* (a−b) is still positive, where $\sigma^*=\sigma-$p is the effective normal stress, μ is the coefficient of friction, and a and b represent frictional dependence on rate and state, respectively (Dieterich, 1979; Ruina, 1983). Although a−b might transfer to be negative in some fault gouges at a very small σ^* (Saffer *et al.,* 2001), I neglect this because it belongs to a conditionally stable re-

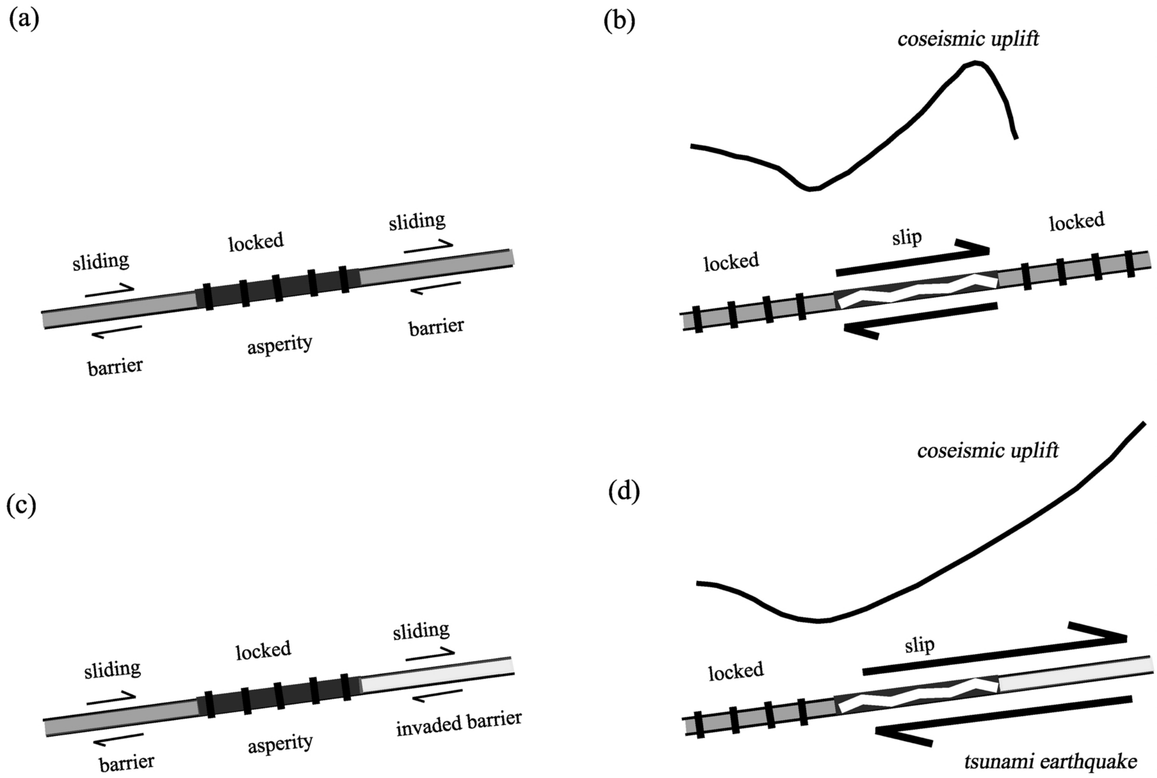

Fig. 2. Schematic cross-sections of a subduction zone thrust near the trench axis. (a) The seismogenic asperity is surrounded by zones with stable sliding frictional properties (barriers). The barrier near the trench is composed of unconsolidated sediments. (b) When the asperity breaks, coseismic uplift appears above the asperity. In contrast, the stable sliding zones act as barriers, and gradually release the stress as afterslip. (c) The barrier near the trench axis has been invaded by elevated pore fluid pressure and has very low friction. (d) When the asperity breaks with the invaded barrier, the coseismic slip occurs over the asperity plus the invaded barrier, and the coseismic uplift appears near the trench axis, which generates abnormal tsunamis.

gime, due to the smallness of σ^* (a−b) (e.g., Scholz, 1990), and it would not affect the consideration below. The very smallness of the friction would make it possible for the slip to rupture in the updip direction to the trench axis when any asperity located deeper breaks (Fig. 2 d). The details of the nature of the fault slip will depend on how pore fluid pressure is decreased or increased during the slip, in association with dilatancy or thermal pressurization. However, the extent of decrease of the pore pressure associated with dilatancy would be at most 10% (Segall and Rice, 1995), and would not affect the overall frictional behavior provided the pore pressure has risen close to the lithostatic. Seno (2003) called this transience of the frictional property invasion of barriers.

If tsunami earthquakes represent ruptures of considerable spatial extents of invaded barriers, as proposed by Seno (2002), ordinary earthquakes might partially share this feature; that is, they may involve a rupture of a limited area of invaded barriers near the trench axis. Along the Nankai Trough, during the 1605 Keicho tsunami earthquake, a vast area close to the trench axis was ruptured and produced disastrous tsunamis along the coast of southwest Japan (Ishibashi, 1983; see Fig. 3 of Seno, 2002). Looking at the source areas of the tsunamis accompanying the 1944 Tonankai and 1946 Nankai earthquakes (Fig. 1, shaded areas; Tanioka and Satake, 2001 a, b), the two boxes, south of Kii Peninsula and located very close to the trench axis, had significant slip (Fig. 1; boxes indicated by the arrows). I infer that these two boxes might represent rupturing of the shallowest plate interface that had been invaded. Although a tsunami source area corresponds to coseismic ocean bottom deformation, the area does not necessarily coincide with the portion of seismic wave radiation. In Fig. 2 d, the block, above an invaded fault gouge next to the trench axis, moves along with the seismic slip of the landward block (asperity), producing an uplift of the ocean bottom, i.e., tsunamis, but it would not radiate any significant seismic waves.

The gouge at the plate interface in the two boxes in Fig. 1 might then not be an asperity, but have different physical and chemical properties than those in the ordinary seismogenic zone at depth. They might be composed of unconsolidated sediments with a stable sliding frictional property. It is noted that the area beneath which decollement can be drilled by the riser ship (Fig. 1; the filled area) does not cover any other boxes located further landward of these two.

3. What is the seismogenic zone?

Concern over whether a drill hole really penetrates the seismogenic zone, however, is not only restricted to the boundary close to the trench axis. I point out here, even in the so-called seismogenic zone, a drill might fail to penetrate a fault gouge that has a frictional property of unstable sliding (i.e., with negative $a-b$). Let us call a fault patch with negative $a-b$ an asperity, and that with positive $a-b$ a barrier. (The conditionally stable area, with negative $a-b$ but small $\sigma^*(a-b)$, is included in the barrier portion for simplicity). It is not likely that a large area of the seismogenic zone is covered by a single asperity. Dieterich and Kilgore (1996) showed that contact areas between two rock specimens have a fractal distribution with fractal dimensions between 1.0 and 2.7. It is known that the seafloor topography is fractal (Mareschal, 1989), and that the frequency-size distribution of seamounts has a power law (G. Kimura, personal comm., 2001). It is then natural to expect that subduction zone thrusts have fractal contact areas, provided that bumps in topography such as seamounts become asperities (Cloos, 1992).

Seno (2003), taking into account these factors, proposed a simple fractal model of asperities, which resembles Cantor dust. An order n circular-shaped asperity contains a number of N_a order $n+1$ asperities, whose radius is $1/\lambda$ of the larger one. Barriers surround these order $n+1$ asperities (Fig. 3). In this model, when one of the order $n+1$ asperities breaks seismically, the rupture does not propagate to other asperities, as barriers surround it. The order n asperity does not fail seismically as a whole in this case. If some barrier area of the order n asperity is invaded, breakage of an asperity inside the invaded area can propagate to other asperities as an earthquake (Fig. 3). This situation is similar to the occurrence of tsunami earthquakes.

In this fractal asperity model, as a fault area, i.e., an asperity size, increases, a fractional area occupied by barriers increases, and then the stress drop decreases. Seno (2003) derived scaling relations between the fault area and the seismic moment from the model, and estimated D (fractal dimension)$=1.4$, $\lambda=4.8$, and $N_a=9$, comparing the scaling relations with the observed seismological data.

Figure 4 shows a cross-section of fractal asperities along the plate interface. The 2-D fractal geometry of $\lambda=4.8$ and $N_a=9$ is projected to a 1-D Cantor set. Suppose a drilling hole penetrates an asperity of order 0, the chance that it also penetrates an order 1 asperity is $N_a/\lambda^2 \sim 0.4$. The probability that the hole penetrates an order n asperity is $(N_a/\lambda^2)^n$. This probability becomes as small as $5.4x \times 10^{-4}$ when $n \sim 8$, which is the order of the smallest unit asperity with an intact rock strength (Seno, 2003). This means that, even if we drill the so-called seismogenic zone, it most likely penetrates a barrier portion that has a stable sliding frictional property (Fig. 4). To interpret physical and chemical properties of drilled cores

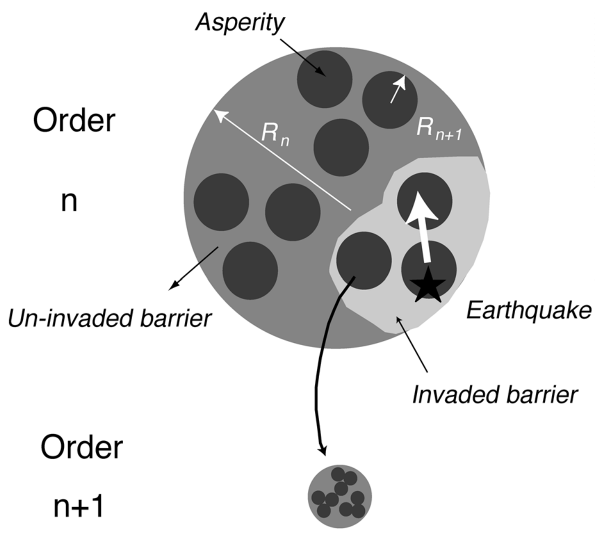

Fig. 3. Fractal geometry of asperities (Seno, 2003). An order n asperity contains a number of N_a order $n+1$ asperities. The ratio of R_n/R_{n+1} is λ. When part of an order n asperity is invaded (lightly shaded), this can rupture as an earthquake when an order $n+1$ asperity inside breaks.

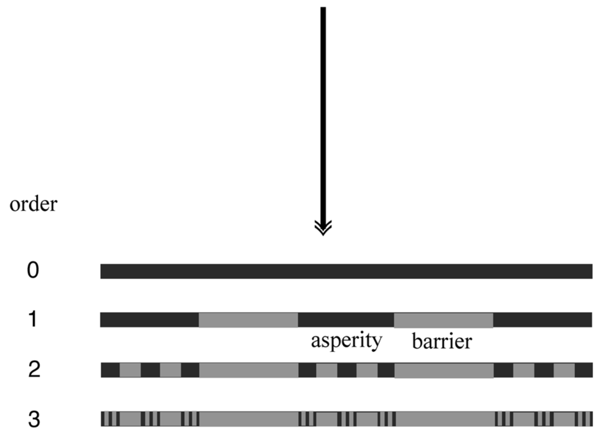

Fig. 4. A drilling pipe penetrating fractal asperities, in the cross-section of a subduction zone plate interface. N_a and λ are set to be 9 and 5, respectively, and asperities are projected to the 1-D section as a Cantor set. The fractal dimension in this section is 0.68.

and results of monitoring deep borehole observatories, in terms of seismogenic, careful investigations would be necessary, because we do not have enough information yet to judge whether the plate interface is an asperity or a barrier only from drilled cores. Even if a borehole penetrates a barrier portion, however, monitoring the transience of the frictional properties, including pore fluid pressure, would be useful for understanding earthquake occurrence in subduction zones. If invasion of barriers is necessary for ordinary interplate earthquakes, not only for tsunami earthquakes, to occur, as proposed by Seno (2003), the pore fluid pressure is expected to rise close to the lithostatic prior to the coming Tonankai and Nankai earthquakes.

4. Conclusions

I point out two possible paradoxical difficulties about the important target of the IODP in subduction zones, i.e., drilling and monitoring the seismogenic thrust. First, an area with an apparent slip derived from tsunami studies might not be a seismogenic fault. If it is an area of invaded barriers and slipped with almost no friction along with a seismic slip at depth, it might imply that it is still difficult to reach the seismogenic zone within the ability of the riser ship. Second, even if drilling is done in the so-called seismogenic zone, it might be difficult to penetrate an asperity, if asperities have a fractal distribution. Careful investigation would be necessary to interpret the results of drilling and monitoring in the seismogenic zone.

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