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Rock rigidity distribution in a subduction zone, Japan

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Abstract. This paper discusses results obtained by observing rock rigidity changes over time and space in seismoactive crustal and mantle regions in the subduction zone of the Pacific plate beneath Eurasia. Data on P-wave first arrivals from earthquakes listed in bulletins of the seismic station network worldwide are used. By discriminating between brittle vs. ductile failures in earthquake foci, we assess the rigidity parameter of rock mass in which earthquake focus occurs. Our method affords scanning rigidity both through time and to depth. Discussed are scanograms of rigidity vs. time for a layer of fixed thickness and width along the spreading zone and scanograms in time-depth coordinates for two subduction zone-transverse crust-mantle sections along arc segments. It is concluded that (i) the rock rigidity control method using the character of P-wave first arrivals from local earthquakes has proved its workability in the complex tectonic setup of the subduction zone of the Pacific plate, (ii) crustal and mantle rock rigidity changes over time with a period of ca. 6 years, which coincides with the period of the Chandler wobble of the earth's axis, (iii) the apparent rock rigidity is lower in the crust than in the mantle, due likely to a greater healing rate of source ruptures in the mantle, (iv) crustal rigidity of the Pacific plate is lower than that of the Eurasian plate, and (v) the contact zone between the plates exhibits a transverse (nearly horizontal) layering of the rigidity distribution. We believe that the pioneering results from applying our method will prove useful to experts in tectonics, geodynamics, and seismicity in the study region.

High seismicity and a dense seismic station network are prerequisite to successfully apply the rock mass rigidity observation method. By discriminating between brittle and ductile failures in earthquake foci, not only is it possible to visualize the spatial distribution of the rigidity parameter in seismoactive media, but also to watch how it changes over time. This work addresses the results obtained using this method from the tectonically complex subduction zone of the Pacific plate. For the Japanese Isles, where the above applicability conditions for the method are met, two types of scanograms have been computed, (i) for a 50 km thick sequence in L–T coordinates, where L is the length along the zone in great circle degrees and T is time in years, and (ii) for areally delimited localities in H–T coordinates, where H is depth in kilometers. From certain localities 2° in width, subduction zone-transverse sections displaying the rigidity parameter distribution over a fixed time interval were constructed. In this paper, we focus on our own new data, assuming that their interpretation is to be handled by those specialists interested in the tectonic setup of the subduction zone.

The Pacific subduction zone is known to be distinguished by high seismicity along its entire length. A characteristic feature of the spatial distribution of earthquake foci is the so-called Benioff zone, plunging beneath the Eurasian shield. This tenet is the cornerstone of the plate tectonic model, according to which the Pacific plate is underthrusting the Eurasian plate. For this reason, obtaining evidence on physical properties and the stress-deformation state of rocks at the contact of the continental and oceanic plates is of huge interest.

The method to assess rigidity of seismoactive rock masses is based on identifying the dominance of brittle versus ductile failures in earthquake foci, and it is presented in [*Lykov and Mostryukov,* 1996; *Lykov et al.,* 2001]. Note that the entire

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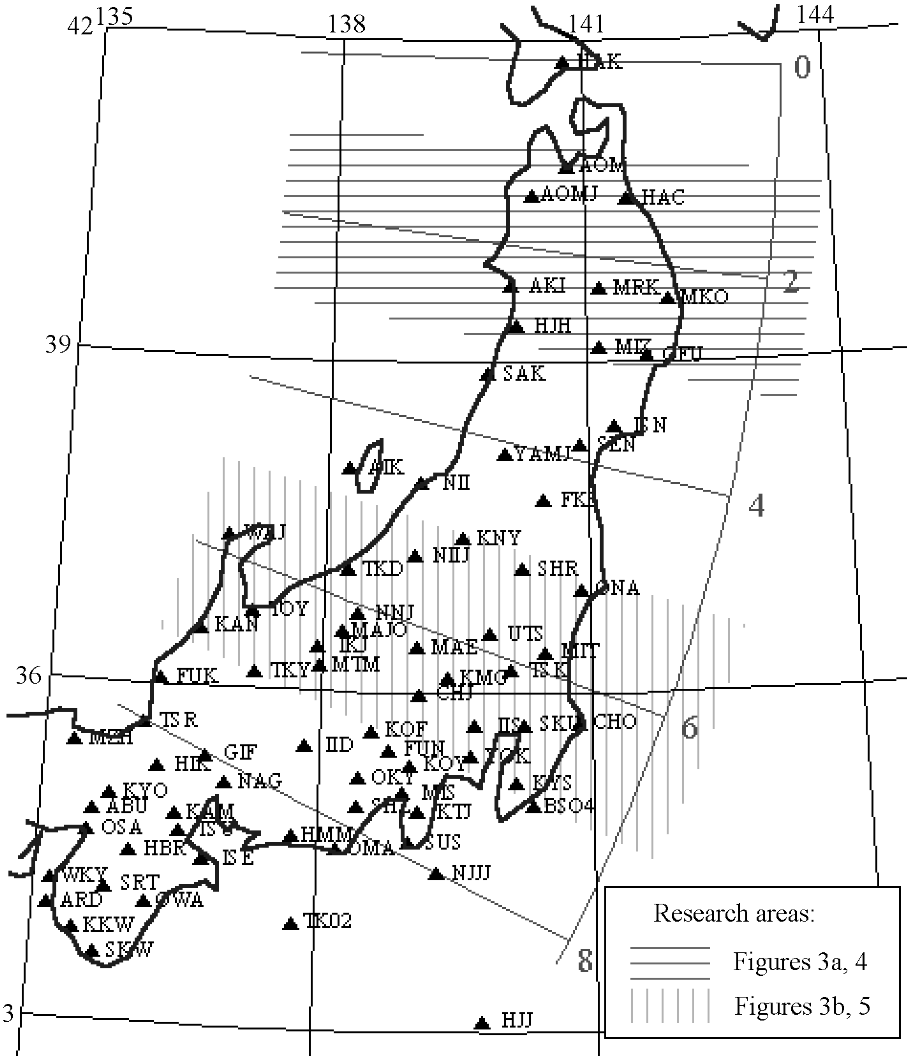

Figure 1. Location of study zones in the northern and central parts of Honshu Island, Japan.

information at our disposal relates only to those crustal and mantle regions where earthquakes occur.

First, let us define a strip 1° wide, which runs along the deep-sea trench and where seismicity is highest at depths up to 50 km. Because our analysis involved data from the bulletins of the seismic station network worldwide, the minimum earthquake magnitudes suitable to quantify the rigidity parameter (RG) were limited to M=3 or 4. Minimum dimensions of both time- and space-averaging windows depend on the number of earthquakes put to processing and, consequently, on their minimum magnitude. In this connection, we address regional peculiarities of the rigidity distribution and not the processes that occur in specific earthquake foci.

Figure 1 displays the geographic location of our constructions that follow. The reference seismic stations supplying information to the International Seismic Center (ISC) are tagged with ISC codes; the network was thinned arbitrarily to avoid overcrowding the figure.

A scanogram along the subduction zone is depicted in Figure 2, with time (in years) plotted on the abscissa versus the great circle distance from zero point (in degrees), on the ordinate. The figure brings out two localities with rigidities elevated consistently over time within the subduction zone. These localities turned out to correspond to local positive Bouguer anomalies Δg [*Pavlov et al.,* 1972]. The main distinctive feature of the scanogram is the rigidity parameter being time modulated. Duration of the principal period, readily discernible visually, is ca. 6 years. Judging from the data in [*Avsyuk,* 1996], this is the period of the Chandler wobble of the earth's axis. Quite conceivably, the giant dimensions of the subduction zone and its relative structural uniformity, as well as the hugeness of the coupling plates'

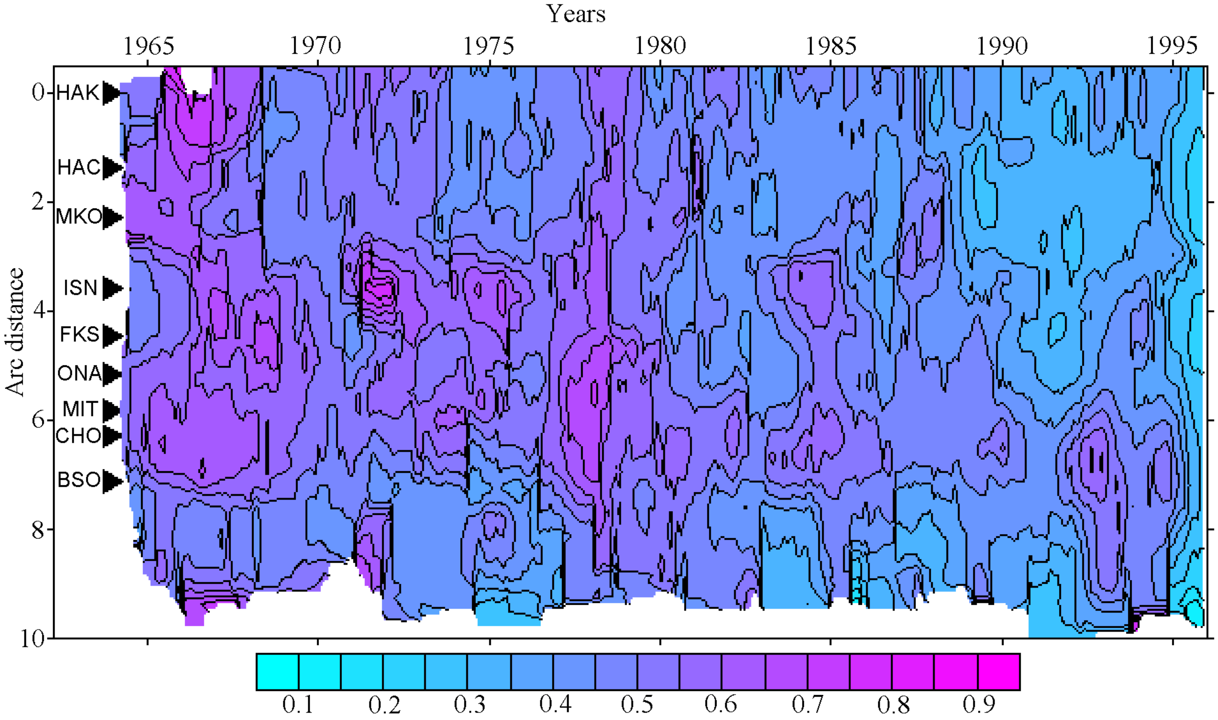

Figure 2. Scanogram of rigidity in time vs. arc distance along the trench coordinates.

masses, account for rock properties in the subduction zone being sensitive to extraterrestrial factors.

In order to study the depth dependence of this effect, two scanograms in depth-time coordinates for two separate localities were computed (Figure 3). This sort of scanning is akin to deep seismic sounding. The high representativity of the raw data on earthquakes affords obtaining reliable information to depths of up to 250 km. The figure shows how the rock rigidity increases with depth. This increase is especially impressive across the crust–upper mantle transition. A time modulation of rock rigidity similar to that in the previous scanogram, and which is better pronounced in the upper part of the mantle, is discernible. The totality of evidence implies a global scale process, while the synchroneity in covariations of rock rigidity and absolute gravity values on the one hand [*Sakuma,* 1973] and the earth's axis wobbles on the other [*Avsyuk,* 1996] is suggestive of a common underlying cause for these phenomena. In our opinion, one should note the increase in seismicity due to large earthquake occurrence during the half-periods of increased rock rigidity and increased volcanism during the half-periods of reduced rock rigidity. Interpretation of these facts calls for a special study.

As the scanograms demonstrate how the rigidity distribution changes over time, it makes sense to consider how the architecture of the subduction zone is portrayed in the rigidity pattern. Figures 4 and 5 show subduction zone–transverse sections. Figure 4 presents the rigidity parameter distribution in the strip under the northern part of Honshu Island, and Figure 5, in the strip beneath its central part. The horizontal axis is graduated in great circle degrees with a zero point over the trench. Because the rigidity distribution changes over time, the sections were constructed for two time intervals. One interval, from 1974 to 1982, includes a half-period of increased rigidity with a maximum in 1978, and the other, from 1988 to 1996, spans the period of a systematically observable decrease in the rigidity parameter (Figures 2, 3). It is worth noting here that the decline in rigidity might be an artifact of the increasing sensitivity of the seismic network, leading to smaller earthquakes being recorded, while ocean-based stations, which should ensure the identification of the polarity of P-wave arrivals, are clearly deficient.

Figures 4 and 5 show that the Pacific plate to 40–60 km depths is characterized by a perceptibly reduced rigidity. This effect is pronounced in both the first and second time intervals and on both sections. *Balesta* [1981] gives a generalization of data and views of many researchers (Aki, Kanamori, Fedotova, Tarakanov, etc.), who detected reduced seismic velocities, especially as regards S-and surface waves, in the crust and mantle of the Pacific plate, as compared to the continent. Another remarkable feature of the sections is rigidity variations transverse to the plunge of the Benioff zone. Note that rigidity highs and lows did not

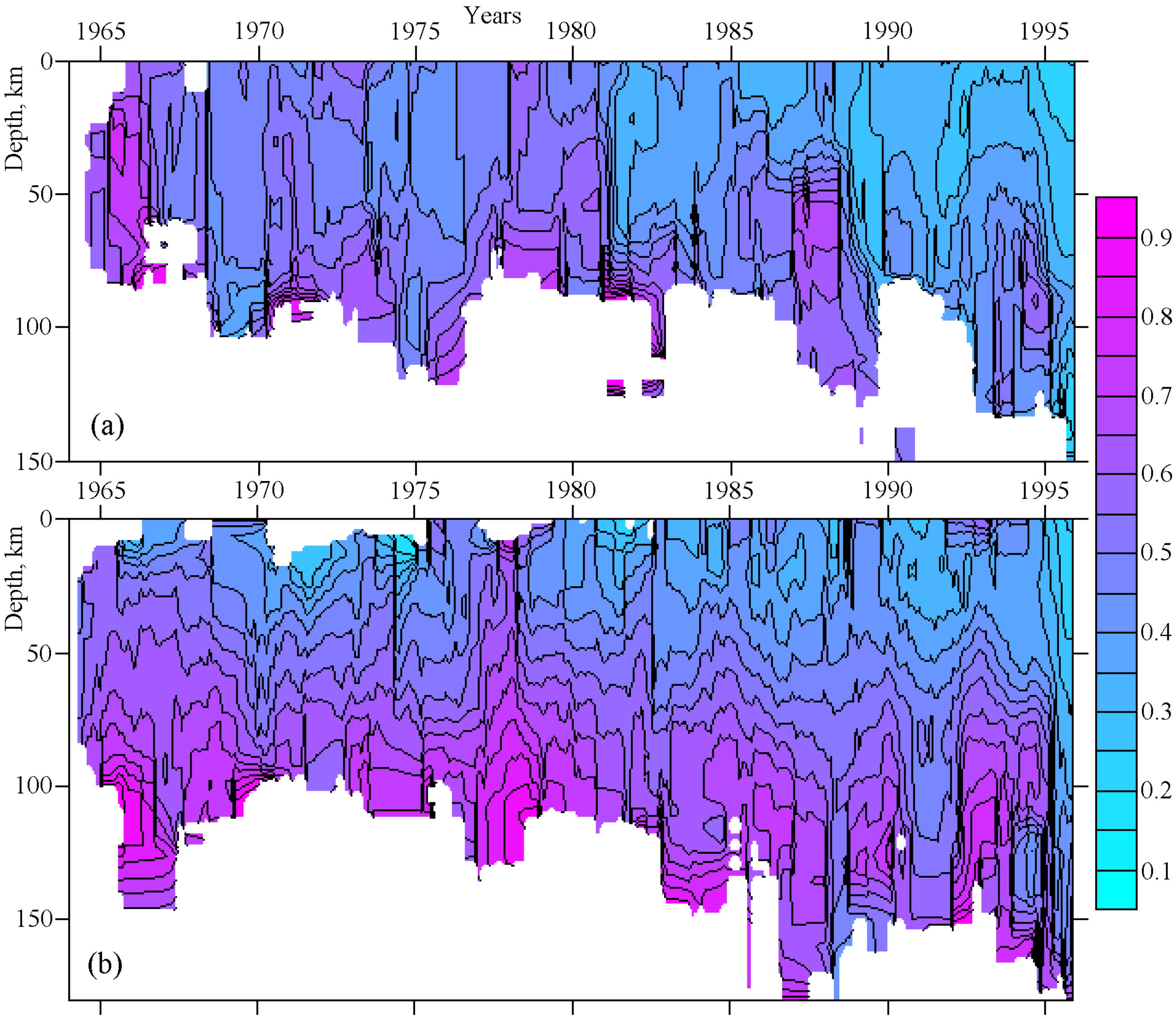

Figure 3. Scanograms of rigidity in time vs. depth coordinates from the northern (a) and central (b) parts of Honshu Island.

change their spatial position between 1974 and 1996. It is worth recalling at this point R. Z. Tarakanov's 1967 work [*Tarakanov and Levyi,* 1969], which first expressed the idea that the upper mantle in the vicinity of the Japan–Kurile arc can be imaged as alternating layers of increased and reduced strength with increased and reduced velocities, respectively. This suggestion was further supported by [*Matveeva and Slavina,* 1973].

A conservative conclusion can be made that the subduction mechanism remained unchanged over 22 years, even large earthquakes failing to alter the situation. Consequently, the plate underthrusting process is steady-state and energy- and mass-consuming, while events such as earthquakes do not affect its dynamics or the stress–deformation state along the contact of the plates. It might be for this reason that most part of predictive observations from Japan suggest that measurement systems respond to earthquakes but fail to record the source preparation of large earthquakes or their development [*Report...,* 2000]. In this context, the rock rigidity control method might prove more informative as a predictive tool. Indeed, Figure 3 in [*Lykov and Mostryukov,* 1996] shows clearly that large earthquakes from that period of time could have been predicted from the rigidity parameter. The effectiveness of the rigidity control method in solving predictive problems may be enhanced considerably by employing expeditious data from local networks of high sensitivity stations. Expertise like that is being amassed for California, the United States, where the speedy processing of numerical records of $M > 0.5$ earthquakes affords a real-time rigidity monitoring [*Lykov et al.,* 2001].

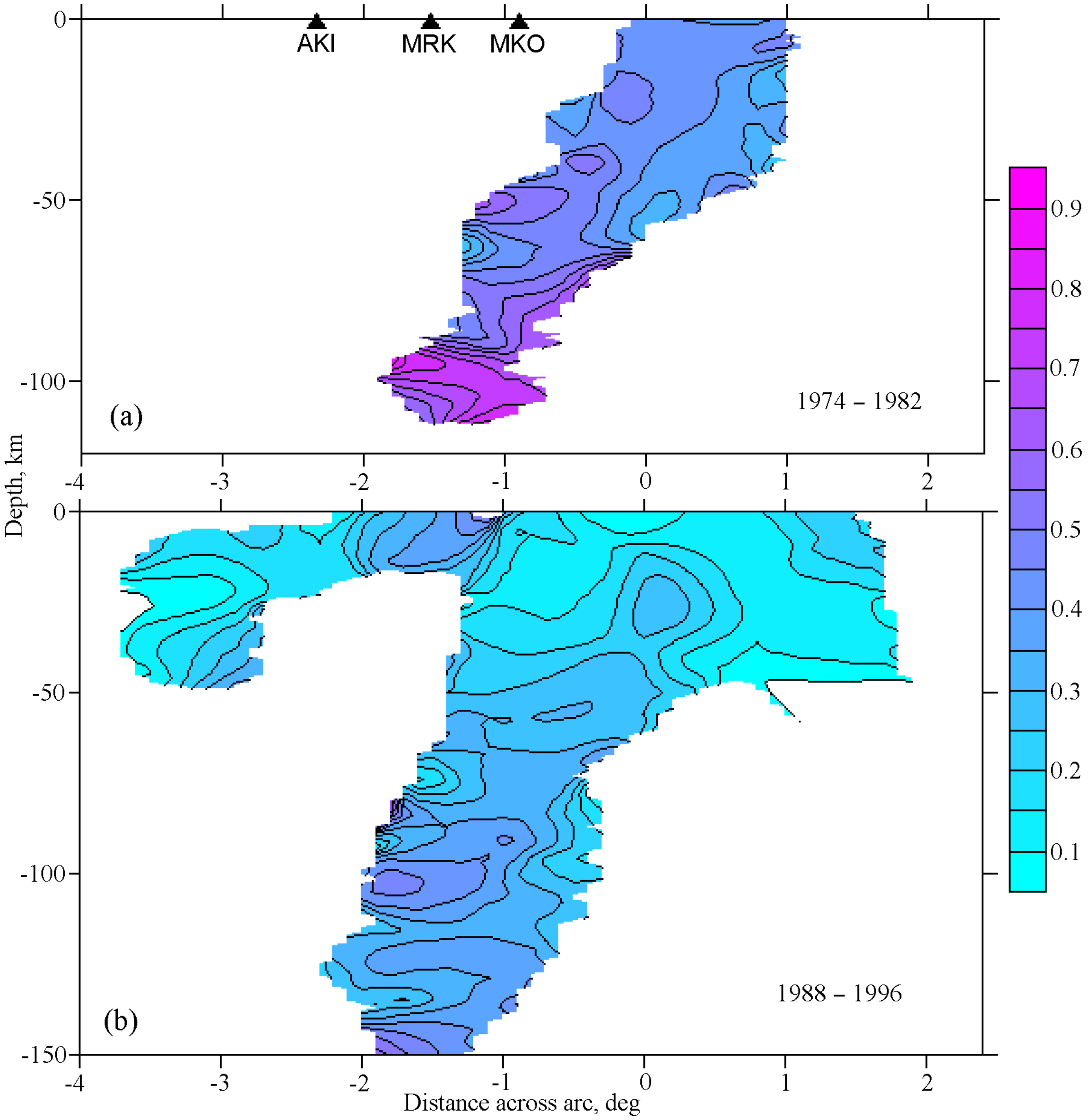

Figure 4. Scanograms of rigidity in distance from trench vs. depth coordinates for two time intervals, (a) 1974–1982 and (b) 1988–1996, northern part of Honshu Island.

Conclusions

1. The rock rigidity control method using the character of P-wave first arrivals from local earthquakes has proved its workability in the complex tectonic setup of the subduction zone of the Pacific plate.

2. The crustal and mantle rock rigidity has been shown to change over time with a period of ca. 6 years, which coincides with the period of the Chandler wobble of the earth's axis.

3. The apparent rock rigidity is lower in the crust than in the mantle, due likely to a greater healing rate of source ruptures in the mantle. Crustal rigidity of the Pacific plate is lower than that of the Eurasian plate.

4. The contact zone between the plates exhibits a transverse (nearly horizontal) layering of the rigidity distribution.

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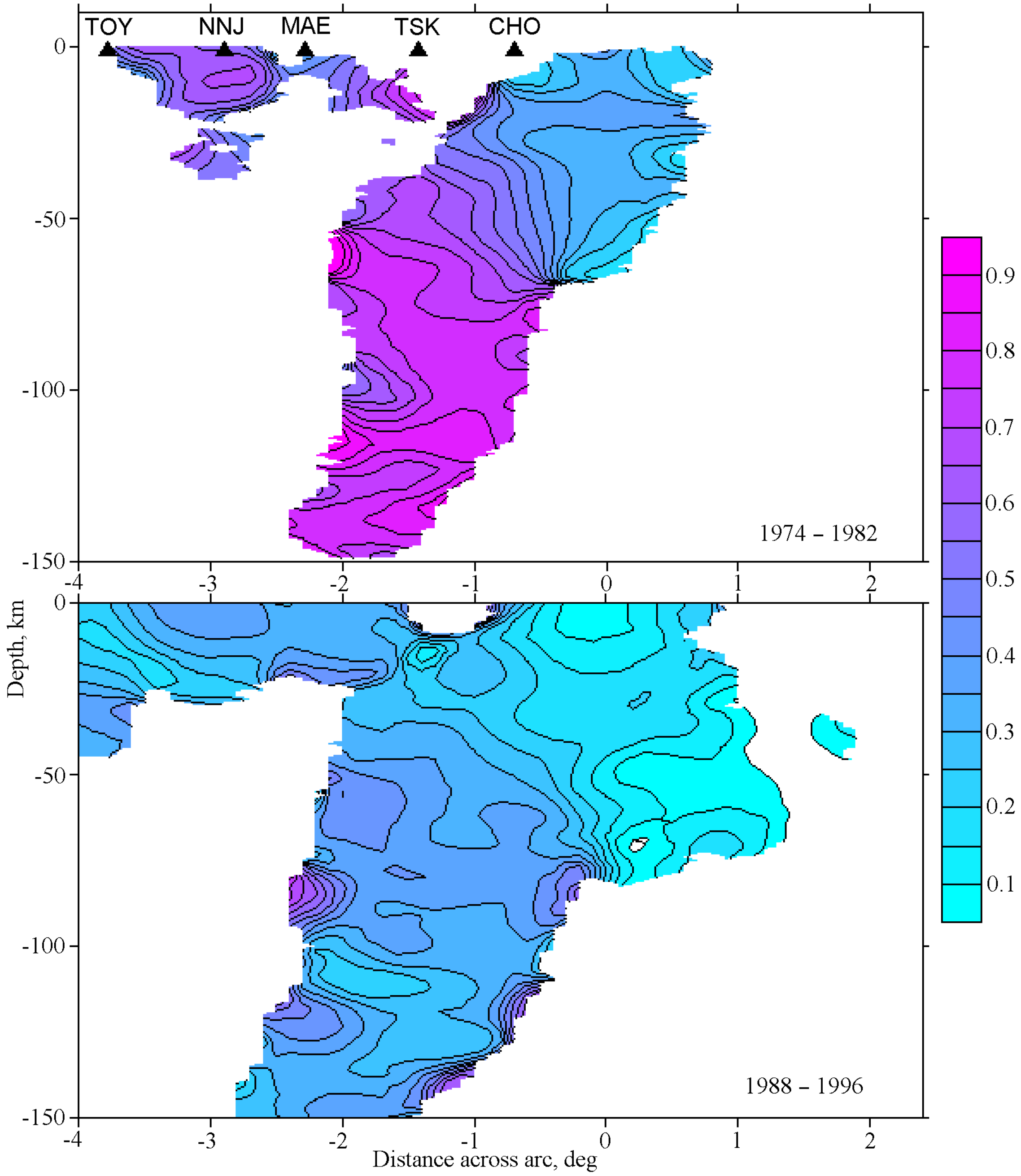

Figure 5. Scanograms of rigidity in distance from the trench vs. depth coordinates for two time intervals, (a) 1974–1982 and (b) 1988–1996, central part of Honshu Island.

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