Two-dimensional mapping of fine structures in the Kuroshio Current using seismic reflection data

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[1] Multi-channel seismic reflection data acquired in the Pacific Ocean off the Muroto peninsula of Shikoku Island, Japan reveal the two-dimensional distribution of fine structures in the Kuroshio Current. Eighty-one seismic sections, each extending 80 km perpendicular to the current and separated by 100 m, were acquired from 20 June to 15 August 1999 (57 days). The seismic data clearly show that fine structures extend over 40 km perpendicular to the current in almost all of the profiles. A simulation study using acoustic model from CTD data demonstrates that fine structure of temperature and salinity identified in CTD data acquired from the Kuroshio Current off the Ashizuri peninsula yield a synthetic seismic profile with characteristics similar to the Muroto transect profiles.
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1. Introduction

[2] "Kuroshio" is a strong ocean current in the western Pacific Ocean that flows east of Taiwan and extends northeastward along the coast of southern Japan. It has a narrow rapid flow near the surface and in the upper thermocline. Although several studies on fine structures in the Kuroshio Current have been reported [e.g., *Worthington and Kawai*, 1972], the two-dimensional distribution of the fine structures in the Kuroshio Current has not yet been examined. Recently, *Holbrook et al.* [2003] reported that the seismic reflection method can image two-dimensional distributions of fine structures, and several authors have applied this method to investigate fine structures in various oceanographical settings [e.g., *Paramo et al.*, 2003; *Pearse et al.*, 2003]. Furthermore, a joint temperature and seismic reflection study [*Nandi et al.*, 2004] demonstrated that reflection seismology is capable of detecting even weaker fine structure (with temperature contrasts of 0.03°C) in the ocean. Here, we also use multi-channel seismic reflection data acquired in the Kuroshio Current off the Muroto peninsula, southwest Japan, to explore the characteristics of fine structures. Eighty-one seismic profiles acquired over 57 days provide unique information about common fine structures in the Kuroshio Current.

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2. Multi-Channel Seismic Reflection Data

[3] We analyzed multi-channel seismic reflection data acquired by R/V Ewing in 1999 [e.g., *Moore et al.*, 2001] to investigate fine structures within the water column across the axis of the Kuroshio Current (Figure 1). Because the seismic survey was designed for three-dimensional analysis, 81 individual lines with a cross-track spacing of 100 m were surveyed over an 80 km × 8 km area (see Figure 1). All of the lines strike 314°, which is nearly perpendicular to the Kuroshio Current flow direction. Each seismic line is 80 km long and took about 8 hours to shoot. The seismic source consisted of a tuned array of 14 airguns, with a total volume of ~70 liters. The volume of the airguns ranged from 1.3 to 10.5 liters. The receiver array was a 240 channel 6-km-long seismic streamer. Data processing included acoustic velocity analysis, stacking, and migration [*Yilmaz and Doherty*, 1987]. We conducted a post-stack time migration of the seismic traces, but in order to reduce migration artifacts within the section above the seafloor, we limited the migration to the interval from 0 to 2 s in two-way travel time.

3. Fine Structures on Seismic Profiles

[4] We regard the 81 two-dimensional seismic sections as a single transect and attribute differences between the lines as temporal rather than spatial variations. The Kuroshio Current travels the 100 m between adjacent survey lines in less than 2 minutes assuming a current speed of 1 m/s, and across the entire survey (8 km) in just over 2 hours, which is less than the acquisition time of each line. Figure 2 shows eight arbitrarily selected seismic reflection profiles obtained between 27 June and 17 July 1999. Figure 2a shows the seismic profile acquired on 27 June, and includes the interval from 0–6 s to show reflections at the seafloor and geologic structures below the seafloor [*Moore et al.*, 2001]. The reflections from oceanic fine structures, which are of principal concern here, are observed at two-way travel time of 0.4–1.6 s (300–1200 m below the sea surface) (Figure 2). Some fine structures have surprisingly consistent horizontal continuity of over 40 km. The reflections represent contrasts of acoustic impedance, which is the product of acoustic velocity and density. Since acoustic velocity and density are affected by temperature and salinity, rapid changes in temperature and salinity can be imaged as reflections on the seismic profiles. The horizontal straight lines with unusually strong contrast above two-way travel

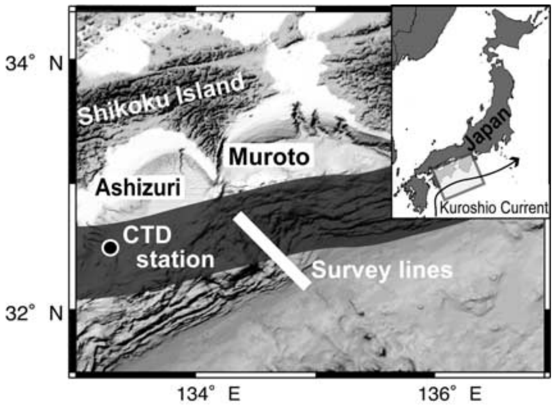

Figure 1. Bathymetric map of the Nankai Trough area, including Shikoku Island and southwestern Japan. The seismic reflection profiles depicted in Figures 2a–2h were obtained within the region, denoted by the thick white line, off the Muroto peninsula. The solid circle off the Ashizuri peninsula shows the location of the CTD measurement in Figure 3. The dark gray belt off the Shikoku Island shows the Kuroshio Current axis (Hydrographic and Oceanographic Department, Japan Coast Guard (JHOD), Quick Bulletin of Ocean Conditions, http://www1.kaiho.mlit.go.jp/KANKYO/KAIYO/qboc/,1999). The map on the upper-right corner shows the large-scale view of the Japan Island and the Kuroshio Current together.

time of 0.4 s (0–300 m below sea surface) are artifacts produced by direct waves from the airguns and reflections from the sea surface. Fine structures that can be resolved as reflections in a seismic profile have a vertical scale greater than a quarter of the acoustic wavelength (Reyleigh's criterion) [*Sheriff*, 2002]. In this survey, the acoustic velocity is 1500 m/s and the dominant frequency is 35 Hz, so that the dominant wavelength is 43 m. We can therefore resolve fine structures whose vertical scale is $>\sim 10$ m.

[5] Successive seismic profiles at 2–3 day intervals (Figures 2b–2h) show different reflection patterns in detail. We are essentially looking at successive cross-sections of the Kuroshio Current at intervals of about 180–450 km assuming a 2–3 day acquisition interval and a current speed of 1 m/s. It is important to note, however, that all panels shown in Figure 2 exhibit fine structures with a horizontal scale of over 40 km; some fine structures continue over 80 km horizontally and cut across the seismic profiles (e.g., Figure 2g). Strong reflections observed in the northwestern part of seismic profiles generally dip to the southeast. The reflection shown with black arrows in Figure 2a has slope of $\sim$1/120. Furthermore, we can observe that reflections merge into a single reflection in many places. We conclude that the fine structure characteristics described above are common features between depths of 350–900 m in the Kuroshio Current.

4. Comparison With CTD Data

[6] No in situ CTD data were obtained during the seismic survey. Since the fine structures observed as seismic reflections seem to be common in the Kuroshio Current, we have examined CTD data acquired in the Kuroshio Current off the Ashizuri peninsula (Figure 1) on 17 September 1994. Vertical profiles of temperature and salinity from the CTD (Figure 3a) show fine structures of temperature and salinity with a vertical scale of about 60 m at depths between 350 and 550 m.

[7] We calculated vertical profiles of density and acoustic velocity (Figure 3b) from the CTD data. The acoustic velocity of seawater is a function of temperature, salinity, and depth. We used an empirically derived formula [*Wilson*, 1960] for this relationship:

$$v_P = 1492.9 + 3(T-10) - 6\cdot10^{-3}(T-10)^2 - 4\cdot10^{-2}(T-18)^2 + 1.2(S-35) - 10^{-2}(T-18)(S-35) + Z/61,$$

where v_P is the acoustic velocity (m/s), T the temperature (°C), S the salinity (‰), and Z the depth (m), respectively. Furthermore, the density of seawater can be calculated by the following equation [*Fofonoff and Millard*, 1983]:

$$\rho = \frac{\rho_0}{1 - p/K},$$

where p is the pressure, ρ_0 the density under the standard atmospheric pressure, and K the bulk modulus of seawater, respectively. ρ_0 and K can be calculated once temperature and salinity are given.

[8] Acoustic velocity generally decreases with depth between the sea surface and 700 m in the survey area, but several fine structures exist between 350 and 550 m (Figure 3b). The change in acoustic velocity across the fine structures is 2–10 m/s. Fine structures are also apparent in the density profile (Figure 3b). Acoustic impedance (Figure 3c) calculated from acoustic velocity and density profiles (Figure 3b) demonstrates that changes in acoustic velocity affect acoustic impedance much more than changes in density. We calculated reflection coefficients from acoustic impedance, convolved them with a 35 Hz Ricker wavelet, and constructed a synthetic wave pattern (Figure 3d). This synthetic wave pattern confirms that fine structures of temperature and salinity observed by the CTD do produce observable reflections. Furthermore, the vertical interval of the synthetic reflections is similar to that observed on the seismic profiles (Figure 2). We therefore conclude that the fine structures imaged in our seismic data off the Muroto peninsula are probably temperature and salinity changes that are similar to those identified on the CTD profile off the Ashizuri peninsula.

5. Reflection Coefficient From the Reflection Amplitudes

[9] We have calculated reflection coefficients (the fractional change in acoustic impedance) from the fine structure reflections, seafloor reflections, and from the first seafloor multiple reflections [*Warner*, 1990]. *Nandi et al.* [2004] applied this method to estimate reflection coefficients at acoustic boundaries and found that reflection coefficients correlate positively with temperature contrasts determined from expendable bathythermograph (XBT) and expendable conductivity-temperature depth profiler (XCTD) data. They

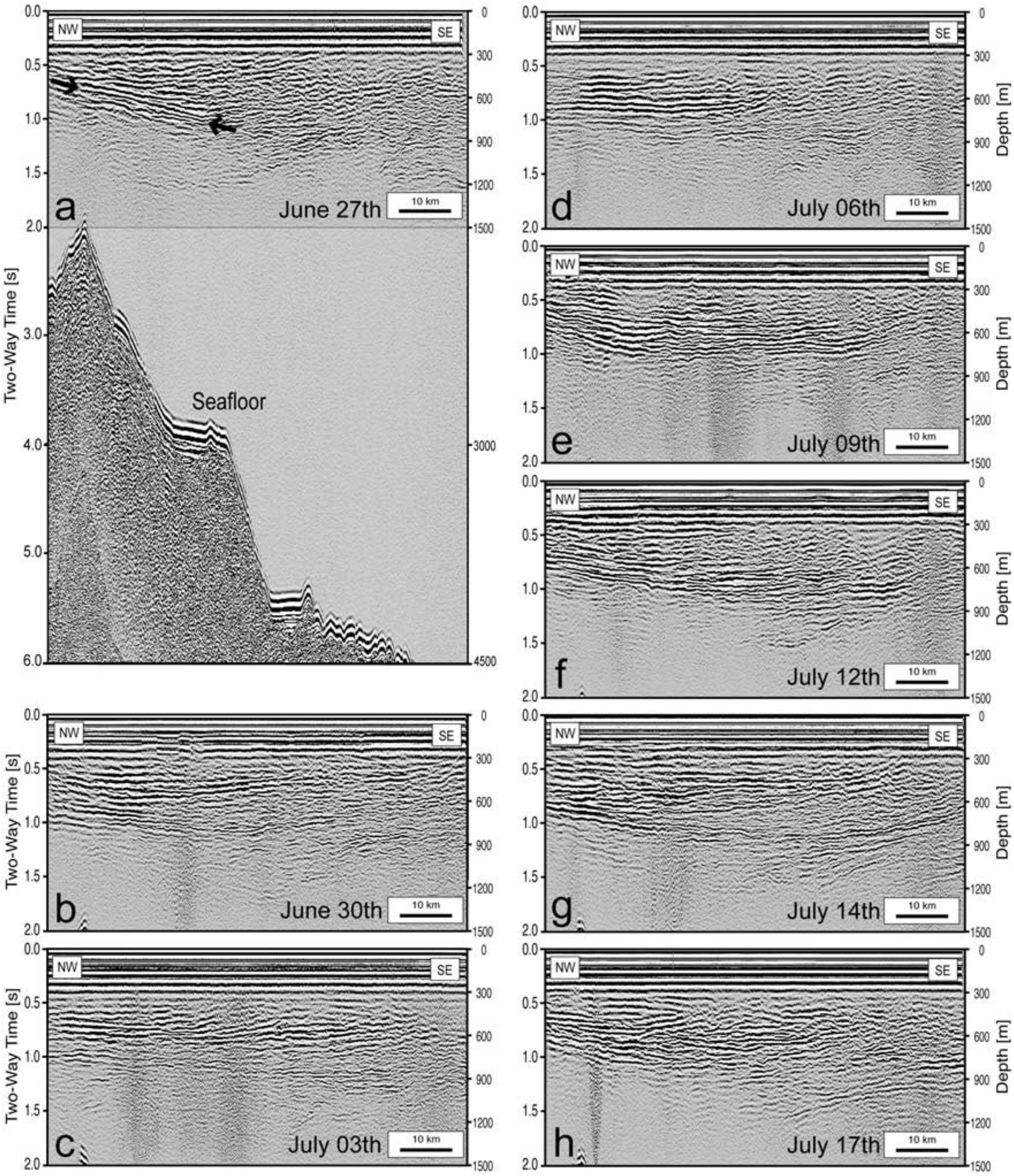

Figure 2. Stacked seismic profiles: (a) 27 June, (b) 30 June, (c) 3 July, (d) 6 July, (e) 9 July, (f) 12 July, (g) 14 July, and (h) 17 July 1999. These seismic profiles are arbitrarily selected from 81 profiles. The vertical axis to the left shows two-way travel time in seconds, while that in the right side shows the depth calculated from two-way travel times assuming an acoustic velocity of 1500 m/s. (a) displays the seismic profile for two-way travel time of 0–6 s, and (b)–(h) for that of 0–2 s. The black arrows on Figure 2a represent the location of the reflection used for calculation of reflection coefficient. The left (right) of Figure 2 corresponds to northwest (southeast).

concluded that reflection amplitudes are robust indicators of relative temperature contrasts in the ocean.

[10] On the basis of this method, we estimated the temperature contrasts implied by the seismic reflection amplitude. We applied spherical divergence correction for the seismic traces prior to measuring reflection amplitude. From the amplitudes we derived reflection coefficients of ~0.0014 for clear reflections imaged on the nearest-trace seismic profiles (black arrows in Figure 2a). From the reflection coefficients, we calculated the change of acoustic velocity to be ~4.2 m/s, assuming a constant density. The estimated acoustic velocity contrast is almost the same as that observed in the CTD data off the Ashizuri peninsula (Figure 3b). Furthermore, a comparison between the temperature and acoustic velocity profiles of the CTD data (Figures 3a and 3b) suggests that the temperature contrast

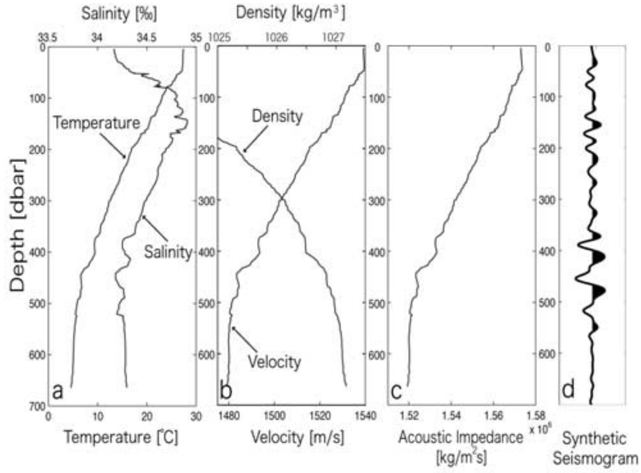

Figure 3. Vertical profiles of (a) temperature and salinity obtained from CTD data off the Ashizuri peninsula on 17 September 1994, (b) acoustic velocity and density calculated from temperature and salinity, (c) acoustic impedance calculated from acoustic velocity and density, and (d) synthetic seismogram calculated from acoustic impedance.

associated with the fine structures imaged as clear reflections on the seismic profile (Figure 2) is ~1°C.

6. Summary and Discussions

[11] Seismic reflection data off the Muroto peninsula, southwest Japan, have revealed the existence of fine structures, with a horizontal scale of ~40 km, in the Kuroshio Current. Furthermore, 81 seismic profiles acquired during two months have shown that these fine structures are not transient features of the Kuroshio Current, at least at this time scale. A simulation study demonstrates that fine structures of temperature and salinity observed in CTD data from the Kuroshio Current off the Ashizuri peninsula can produce reflection patterns that are similar to the fine structures on seismic profiles acquired off the Muroto peninsula.

[12] The fine structures, the vertical scale of which is about several tens of meters, have been often found in CTD profiles from various regions of the world. The possible causes for such structures include (a) intrusions between two different water masses [*Ruddick and Richards*, 2004], (b) mechanical mixing in the vertical direction [*Browand et al.*, 1987], (c) symmetric instability [*Emanuel*, 1994], (d) double-diffusive convection due to heat and salt [*Ruddick and Gargett*, 2004], and (e) double-diffusive instability due to momentum and density [*McIntyre*, 1970]. Regardless of the causes, the horizontal continuity of the fine structures over a distance of 40 km across a western boundary current has not been reported to the best of our knowledge.

[13] The fine structures are found at a depth of 300–600 m near the axis of the Kuroshio Current, where both the horizontal gradient of temperature and salinity and the vertical shear are large. The former may cause horizontal intrusions, while the latter symmetric instabilities or Kelvin-Helmholtz instabilities. Vertical profiles of temperature and salinity (Figure 3a) suggest that stratification in this region is unstable for salt-finger double-diffusive convection. We cannot rule out any of the possible causes (a)–(e), either operating solely or in conjunction, in this region.

[14] Since vertical fine structures play an important role in vertical and horizontal mixing of heat, salinity, momentum, etc., and may even affect large-scale phenomena such as thermohaline circulation, it is important to clarify how the fine structures, which appear to be common in the Kuroshio Current, form. In the near future we plan to acquire in situ measurements of temperature and salinity simultaneously with new seismic reflection data to further understand the fine structures across the Kuroshio Current.

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