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Flow separation of intermediate water in the lees of sills off Taiwan from seismic observations

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Abstract

Flow separation can occur when a stratified flow passes over an obstacle. Previous studies concerning flow separation are mostly observed in the shallow water regions, e.g., fjord, driven by tidal flows. In this study, a novel view of flow separations of the intermediate water over the Hengchun Ridge and Ryukyu Arc off Taiwan is firstly reported using seismic oceanography by reprocessing the seismic data from two cruises 97306 and EW9509 in 2001 and 1995, respectively. Both seismic images show that water masses are separated by internal interfaces detached from sill crests. Over the Hengchun Ridge, it was previously considered that the intermediate water flowed out of the South China Sea into the Hengchun Trough. Flow separation occurred at the lee-side of the ridge forming a continuous interface > 15 km between the intermediate and deep water at 900 m depth. This interface suggests that (1) mean flow of the intermediate water always flowed eastward and (2) no lee wave was generated or radiated even during a spring ebb tide. Near the East Taiwan Channel, the only major passage of the Kuroshio into the Okinawa Trough, flow separation occurred when the Kuroshio intermediate water flowed over the Ryukyu Arc at 500 m depth. The separation interface is nearly horizontal and extends > 25 km from the sill break to the trough. Parameter estimations and morphologic comparisons show that both separation cases are neither boundary-layer separation nor post-wave separation. Model data from OFES (Ocean General Circulation Model For the Earth Simulator) reveal dense pools existing downstream of the sill crests. We propose that a density-forced flow separation mechanism could be responsible for the observed flow separations and absence of lee waves in this study.

1 Introduction

Flow separation is a nonlinear fluid phenomenon which has been widely observed in the lee of steep topography both in the atmosphere and ocean. It occurs when both the surface mean flow velocity and its gradient are zero at a critical point (separation/attachment/detachment point), where the flow streamlines no longer remain attached to the topographic surface (Garrett, 1995; Belcher and Hunt, 1998). Laboratory experiments show that two flow separation regimes, i.e., boundary-layer separation (Fig. 1a) and post-wave separation (Fig. 1b), exist dependent on the non-dimensional parameters Nh/U (stratification) and h/L (aspect ratio), where N is the buoyancy frequency, h is the height of the hill, U is the upstream velocity, and L is the half-width of the hill (Baines, 1995). In general, for low Nh/U, boundary-layer separation will occur when h/L exceeds a critical value. For low h/L, post-wave separation will occur when Nh/U exceeds a critical value. Field observation of the unequal stratification across the Knight Inlet Sill revealed another possible regime termed "density-forced separation" (Fig. 1c) which was further supported by numerical simulations (Klymak and Gregg, 2000, 2003).

Among both field observations and numerical simulations, most of the studies have focused on the fjord of Knight Inlet for studying the flow separation over a sill during the ebb tide (Klymak and Gregg, 2000, 2003; Lamb, 2004; Cummins and Armi, 2010); while some of the studies have been interested in the flow separation occurring at coastal headlands (Farmer et al., 2002; Edwards et al., 2004). However, flow separation in water deeper than several hundred metres has never been reported as far as we know. The primary reason might be no available observation technique to capture such finescale features easily. Recently, a new method "seismic oceanography" based on conventional seismic reflection profiling allows us to relate water column acoustic reflections to oceanic finescale structures (Holbrook et al., 2003). It has the capability of showing mesoscale to finescale features with a typical spatial resolution of 10 m. Within the past decade, seismic oceanography has been used to image various oceanographic features, such as subsurface eddies (Biescas et al., 2008; Papenberg et al., 2010; Menesguen et al., 2012), surface eddies (Mirshak et al., 2010; Tang et al., 2014a), currents (Tang et al., 2013), and internal waves (Holbrook and Fer, 2005; Tang et al., 2014b), and thermohaline staircases (Biescas et al., 2010; Fer et al., 2010).

OSD
11, 1871–1893, 2014

In the present paper, we report two examples of flow separation for the first time, in the intermediate water off Taiwan observed using the seismic reflection profiling technique. We focus on two deep/steep water mass barriers beneath two great water passages, Luzon Strait and the East Taiwan Channel, where the seismic images show near-horizontal continuous interfacial reflections, which were interpreted as flow separations in the lee of the sills. An encouraging report by Eakin et al. (2011) has shown a case study of lee-wave generation, which is a companion process of flow separation causing form drag as well (Edwards et al., 2004).

2 Water passages

There are two great water passages in the study region (Fig. 2). One is Luzon Strait off south Taiwan and the other is the Yonaguni Depression off east Taiwan (or the East Taiwan Channel). Luzon Strait is the entrance of the South China Sea throughflow and the only passage for exchange of the intermediate and deep water between the South China Sea and the Pacific Ocean (Qu et al., 2009). The most representative view about the water exchange across Luzon Strait is a “sandwich-like” vertical flow pattern, i.e., with an eastward flow in the intermediate layer but with westward flows in the upper and deep layers (Qu, 2002; Tian et al., 2006; Sheu et al., 2009). In this study, the intermediate water above the Hengchun Ridge (Fig. 2; western ridge of Luzon Strait) is the most concerned layer which has been considered as an eastward flow essentially (Chen and Huang, 1996). At the northern part of the strait, its background flow velocity at 1000 m depth reaches 10 $cm\,s^{-1}$ (Tian et al., 2006).

The East Taiwan Channel is located between Taiwan and western end of Ryukyu Islands (Iriomote-jima Island) with width of ~ 150 km and depth shallower than 1000 m. It is the primary passage of the Kuroshio water flowing into the Okinawa Trough from surface to intermediate depth (Chen, 2005; Matsuno et al., 2009; Nakamura et al., 2013). Previous investigations have shown the mean Kuroshio transport across the

OSD
11, 1871–1893, 2014

East Taiwan Channel is ∼ 20 Sv and the northward current velocity at 400 m depth is ∼ 20 cm s^{-1} (Zhang et al., 2001).

The lee-sides of the Hengchun Ridge and Ryukyu Arc are both steep as seen in Fig. 2. From the seismically imaged geometries of the obstacles shown in Sect. 4, the estimated lee-side aspect ratios of the Hengchun Ridge and Ryukyu Arc are 0.27 and 0.23, respectively. Such aspect ratios tend to generate both boundary-layer separation and post-wave separation according to the phase diagram by Baines (1995). Previous numerical simulations, however, always found standing lee-waves at Luzon Strait (Cai et al., 2002; Buijsman et al., 2012) and no flow separation was reported.

3 Data and methods

Two seismic cruises 97306 and EW9509 were carried out by R/V *Tanbao* and *Maurice Ewing* off Taiwan in 2001 and 1995, respectively (Liu et al., 1997; Tang and Zheng, 2011). A subsection of the seismic data was extracted from each of the cruises, named as S01 and S95 hereafter (Fig. 2). During the acquisitions, the section S01 goes across the Hengchun Ridge from west to east, and the section S95 runs over the Ryukyu Arc from north to south. Their specific timespans of data acquisitions are from 09:00 to 15:00 on 5 August 2001 and 22:30 on 24 August 1995 to 17:30 the next day. Finally, a pre-stack depth migration method was applied to image the water column structure from the seismic data. During the migration, we used the two-layer velocity models with smoothed boundaries at 600 m depth simplified from the Argo profiles (data from www.argo.org.cn) (Tang et al., 2013). Further detailed acquisition and processing parameters concerning these two cruises and their subsections are listed in Table 1.

Considering no in situ hydrographic data were acquired during the seismic experiments, we used three types of available data to support the seismic observations. The first type of data is the model outputs of the OFES (Ocean General Circulation Model For the Earth Simulator; http://apdrc.soest.hawaii.edu). The OFES is an eddy-resolving, high resolution (0.1°), 3 day snapshot, near-global ocean model (Qu et al.,

OSD
11, 1871–1893, 2014

2012). The snapshots on 4 August 2001 and 24 August 1995, which are closest to the seismic acquisition dates for S01 and S95, respectively, were used in the study. The second kind of information is the barotropic tidal predictions derived from the TPXO7.2 tidal model (Egbert and Erofeeva, 2002). The third group of contributions is the satellite altimetry data of sea level anomaly (SLA), which were used to constrain the structures from the sea surface appearances (Tang and Zheng, 2011).

4 Results

Finescale water column structures across the Hengchun Ridge (S01) and Ryukyu Arc (S95) are presented in Figs. 3 and 4, respectively. In the present study, the phenomena of most concern are the near horizontal reflections extending from the right sides of the sill crests for tens of kilometres.

The section S01 (Fig. 3) has been presented by Tang and Zheng (2011). The horizontal reflections in the lee of the sill were interpreted as the lower boundary of the intruded intermediate water from the South China Sea. In more detail, this set of reflections at ~ 900 m depth is detached from the rightest peak of the rugged topography and extends ~ 15 km downstream. Vertical fluctuations and lateral wavelengths of the reflections are less than 50 m and 2 km, respectively. In this study, we interpret that it is a water mass boundary caused by flow separation. Above the boundary and below 500 m depth, the moderate reflections are re-stratified from the well-mixed water above the Hengchun Ridge (Tang and Zheng, 2011). Below the main boundary, the water is characterized as acoustic blanking near the sill slope and weak reflectivity with eastward dipping reflectors beyond, forming a wedge with a tip close to the sill crest.

The subsection S95 shows a more typical feature of flow separation in the lee of the Ryukyu Arc on the Okinawa Trough side (Fig. 4). There is a strong near-horizontal boundary formed at ~ 500 m depth separating the intruded Kuroshio water above and homogeneous deep water below. The spatial extension of the boundary is ~ 25 km from the separation point to the center of the Okinawa Trough. Scrupulous checking of

OSD
11, 1871–1893, 2014

the weak reflections below the main boundary shows that when the water leaves the separation point, the obliquely downward flow forms and extends to ~ 800 m depth at the center of the Okinawa Trough. Such an appearance is similar to the phenomenon observed in the Luzon Trough on the subsection S01.

On the seismic image of S95, however, a prominent structure is a wedge with south-dipping reflections dominating the whole upper-left corner. This feature may be representative of two possible processes: one is the upwelling of the Kuroshio water (Chen, 2005), and the other is the geostrophic current field. The latter assumption is consistent with the SLA (Fig. 5) that the subsection S95 cuts across the edge of a giant anticyclonic eddy during the seismic cruise. Therefore, we believe that the eddy current drives or sheds the northward component of the flow around the northern eddy base. When the eddy-induced current flows over the topography into the Okinawa Trough, the flow separation occurs at the sill crest.

5 Discussions

In order to interpret the flow separations occurring on the downstream sides, the background currents across the sills need to be known. Such preconditions were satisfied as follows. (1) Previous essentials of the current fields across the sills. Many observations have shown that the intermediate water comes out of the South China Sea predominately at the northern part of Luzon Strait (Chen and Huang, 1996; Qu, 2002; Tian et al., 2006). Likewise, the strong northward Kuroshio through the East Taiwan Channel is permanent (Johns et al., 2001). (2) The imaged structures are consistent with imprints left by the assumed current directions, but not if the currents are reversed. In Luzon Strait, the possible process of the intermediate water flowing out of the South China Sea has been analyzed carefully by Tang and Zheng (2011). In the East Taiwan Channel, the anticyclonic eddy can induce current flow into the Okinawa Trough easily. (3) The near horizontal boundaries extending from the sill crests could be important indications for the current directions. A water boundary on the right at the depth of the

OSD
11, 1871–1893, 2014

sill crest would be inevitable when the water flows as we expected, but would be an occasional event when the water flow is reversed.

The separation point at the sill crest of Hengchun Ridge is much more ambiguous than it is at the Ryukyu Arc. This might be controlled by the roughness of the topography including the three-dimensional topographic effects. If the topography is rugged with strong lateral effects, it will form a volume of stirred turbulent water that weakens the characteristic contrast with the neighboring water, and thus the exact detaching point is obscured. Conversely, the flow over a smoother topography acts as a typical two-dimensional hydraulic model with a clear separation point. Typical examples have been shown by Klymak and Gregg (2001) and Dewey et al. (2005).

Features common to Hengchun Tough and Okinawa Trough are the weak obliquely downward reflections downstream with ~ 300 m vertical extent below the main water boundaries (Figs. 3 and 4). These may relate to weakly stratified water pools of the stagnating downstream currents. Such a spatial overlay between the downstream flow and stagnant water is opposite to numerical results (Farmer and Armi, 1999; Lamb, 2004) and field observations (Armi and Farmer, 2002; Cummins and Armi, 2010), in which stagnant water pools overlie the downslope jets.

Flow separations have not been significantly affected by tidal currents during the seismic acquisitions. This because only continuous currents could form the 15 km (1.7 day for 0.1 $\mathrm{m\,s^{-1}}$) and 25 km (1.4 day for 0.2 $\mathrm{m\,s^{-1}}$) separation boundaries in the Luzon Trough and Okinawa Trough, respectively, without considering the decay at the end of the boundaries. Although the barotropic and baroclinic tides were strongly time dependent and varied intensely (Fig. 6; Jan et al., 2008), the tidal currents might have not changed the mean flow directions during those times. And thus the continuity of the boundaries had not been destroyed. Therefore, it seems that the flow separations occurred under a broad range of current velocities which affect the non-dimensional parameter Nh/U essentially, where the buoyancy frequency N is nearly uniform at the sill crests.

OSD
11, 1871–1893, 2014

For the hydraulic aspect of the stratified flow over topography, several other hydraulic processes could occur including upstream processes and downstream responses (Armi and Farmer, 2002; Cummins et al., 2006). Above the Hengchun Ridge, the upstream disturbance was extremely strong. Both disturbances from the multi-front zone above and the rugged topography beneath should be responsible for the acoustic blanking, which is suggestive of well-mixed water (Tang and Zheng, 2011). The upstream disturbances above the Ryukyu Arc were mainly from the warm eddy by shedding or driving processes. Surprisingly, except for the flow separations, no other phenomena have been captured upstream or downstream from the sill crests (phenomena such as hydraulic jumps, flow bifurcations, overlying stagnant pools, downslope currents, or lee waves).

However, existence of the lee waves on the lee side of the Hengchun Ridge has been widely modeled by previous studies, in which the lee waves propagate upslope over the ridge and evolve into a number of internal solitary waves, i.e., the so-called "lee-wave mechanism" (Cai et al., 2002; Buijsman et al., 2010, 2012). But in this study, why were no lee waves generated or radiated even during the period of spring tide (Fig. 6)? This question is raised because the internal solitary waves in the northern South China Sea are tidally modulated and pervasive around the period of spring tide (Ramp et al., 2004). Our observation might argue against the "lee-wave mechanism" since the duration of the flow separation lasts at least 1.7 days. Further, although lee waves are also expected to form on the lee-side of the Ryukyu Arc because of the long enough current duration and supercritical slope (Buijsman et al., 2012), our observation shows no lee waves either.

Simple parameter estimations (Table 2) of h/L and Nh/U in Luzon Strait are 0.27 and 9.0, respectively. In the Ryukyu Arc, the parameters are 0.23 and 8.8, respectively. Obviously, parameters from both locations fall into the post-wave separation regime rather than the boundary-layer separation as predicted by Baines (1995). However, the post-wave separation regime contradicts our observations in which the separation points are at the sill crests rather than farther down the sill faces. A similar situation

OSD
11, 1871–1893, 2014

has been reported in Knight Inlet (Klymak and Gregg, 2000, 2003). They proposed that the density contrast across the sill might be responsible for the observed flow separation. A downstream dense pool can suppress growth of lee-waves and facilitate flow separation along the lower density boundary of the intruded water above.

It is possible that the density contrast across the sills is different because of the different water masses in the different basins. For examples, Qu et al. (2006) have shown that the deep water is denser on the Pacific side than on the South China Sea side across Luzon Strait; Chen (2005) has traced upwelling of the Kuroshio intermediate water from the Pacific into Okinawa Trough and then onto the East China Sea shelf, as indicated by isopycnal lifting. In order to verify whether there are positive density contrasts across two sills, the potential density fields are derived from the OFES model during the periods of seismic cruises. The results clearly show the dense pools downstream of the sills (Fig. 7), although the density contrasts are quite small ($< 0.1\,\mathrm{kg\,m^{-3}}$). Thus we believe that the flow separations occurring in the two study cases might be density-forced. Nevertheless, whether such a small density contrast can induce flow separation and suppress lee wave growth needs to be proved by both numerical modeling and field observation. An example in support of our supposed mechanism is that lee waves are easily generated in the Caribbean Sea, where waters across the sharp topography are from the same basin with even stratification (Eakin et al., 2011).

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OSD
11, 1871–1893, 2014

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OSD
11, 1871–1893, 2014

Table 1. Primary acquisition and processing parameters of two seismic cruises and their subsections used in this study.

cruise	97306	EW9509
research vessel	*Tanbao*	*Maurice Ewing*
month/year	Aug 2001	Aug–Sep 1995
source volume	49 L	138 L
source depth	8 m	8 m
trigger-mode	50 m	20 s
trace number	240	160
channel space	12.5 m	25 m
streamer depth	10 m	8 m
record length	12 s	16 s
sampling rate	2 ms	2 ms
sampled section	S01	S02
ship heading	eastward	southward
ship mean speed	5.0 kn	3.5 kn
section length	65 km	110 km
sampled traces	120 near-source	60 near-source
velocity model	1510/1480 $m\,s^{-1}$	1500/1480 $m\,s^{-1}$
date	5	24–25
time span	9:00–15:00	22:30–17:30 (+1 d)

OSD
11, 1871–1893, 2014

Table 2. Parameters estimated for the two study regions. See descriptions of the parameters in the text.

	h (m)	L (m)	N (s^{-1})	U ($m\,s^{-1}$)	h/L	Nh/U
Luzon Strait	300	1100	0.0030	0.10	0.27	9
Ryukyu Arc	320	1400	0.0055	0.20	0.23	8.8

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11, 1871–1893, 2014

Flow separation of intermediate water

Q. S. Tang et al.

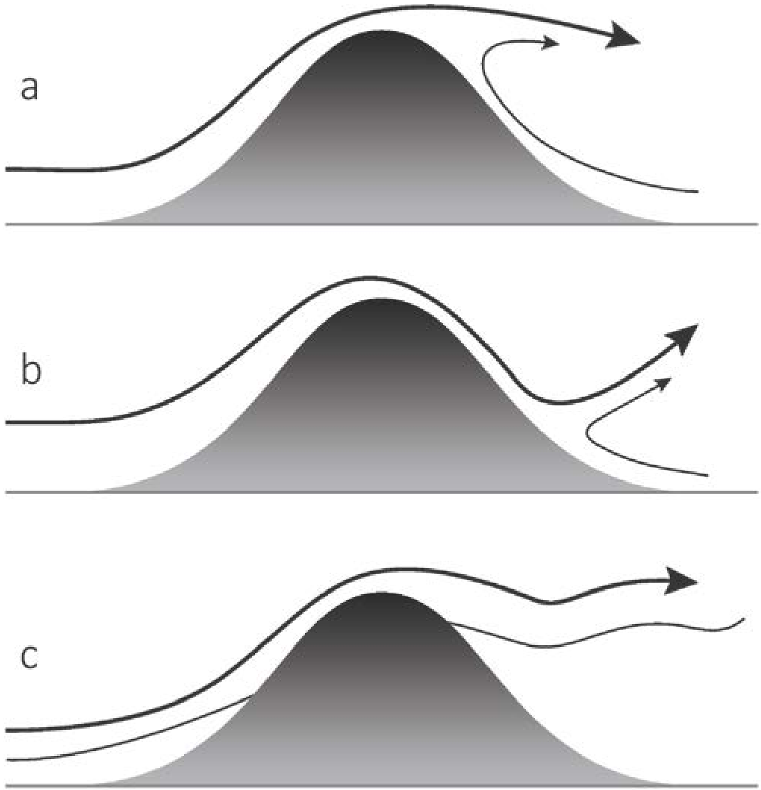


Figure 1. Schematic diagrams of the three conceptual models of flow separation regimes modified from Baines (1995) and Klymak and Gregg (2000). **(a)** Boundary-layer separation: flow separates from the topographic crest over a turbulent well-mixed region. **(b)** Post-wave separation: flow separates further downstream beneath the first lee-wave crest. **(c)** Density-forced separation: flow separates due to a density pool downstream.

OSD
11, 1871–1893, 2014

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄ | ►
◄ | ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

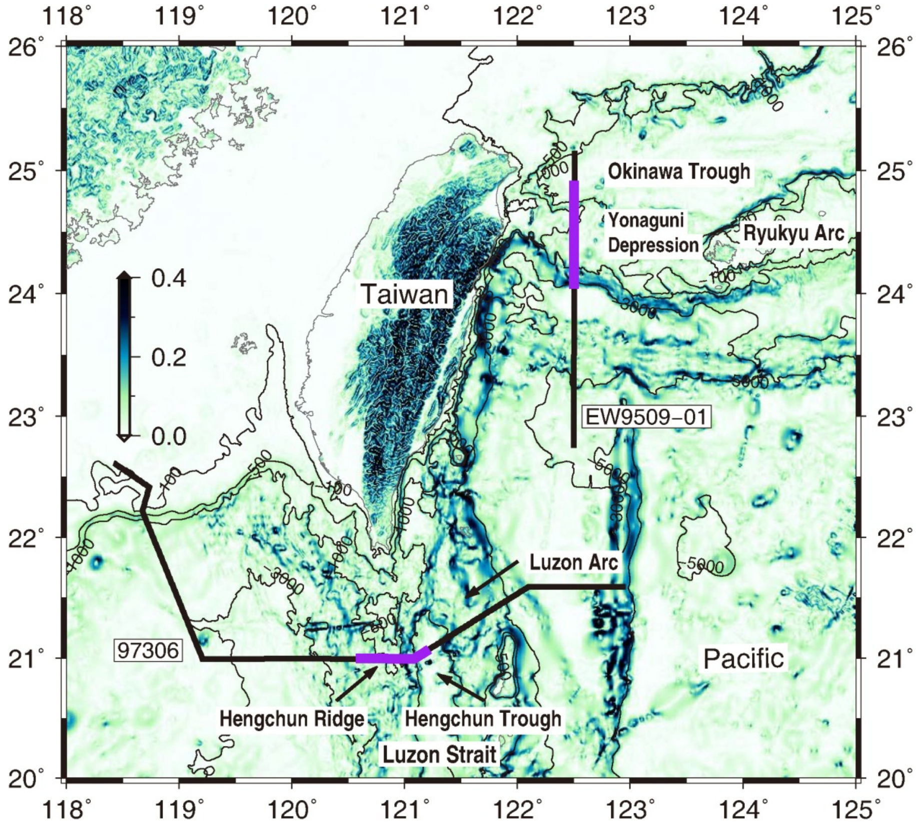


Figure 2. Topographic slope (aspect ratio) map with superimposed bathymetric contours around Taiwan (topographic data from http://topex.ucsd.edu). The black lines are two seismic sections 97306 and EW9509-1. Their corresponding subsections (S01 and S95, bold purple lines) across Luzon Strait and Ryukyu Arc are used in the present study.

OSD
11, 1871–1893, 2014

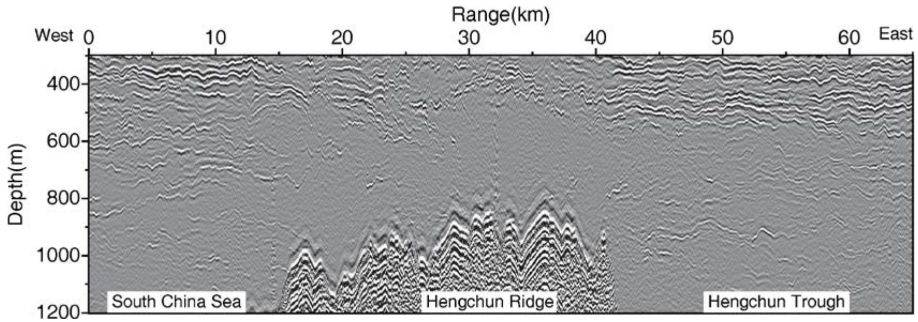


Figure 3. Seismic image of the water column for the subsection S01 across Luzon Strait from west to east acquired from 09:00 to 15:00 on 5 August 2001.

OSD
11, 1871–1893, 2014

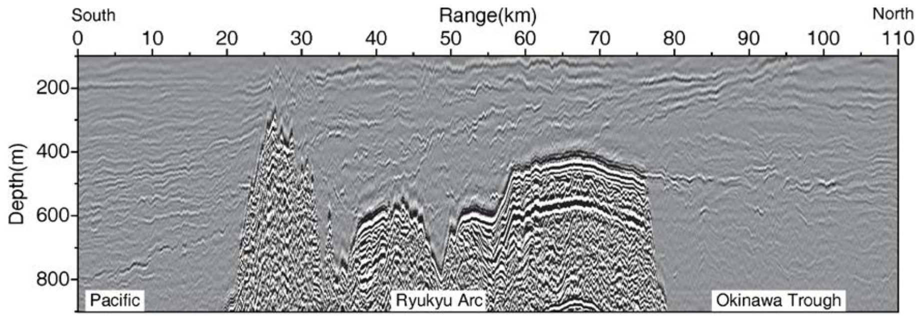


Figure 4. Seismic image of water column for the subsection S95 across the Ryukyu Arc from north to south acquired from 22:30 (right) on 24 August 1995 to 17:30 the next day (left).

OSD
11, 1871–1893, 2014

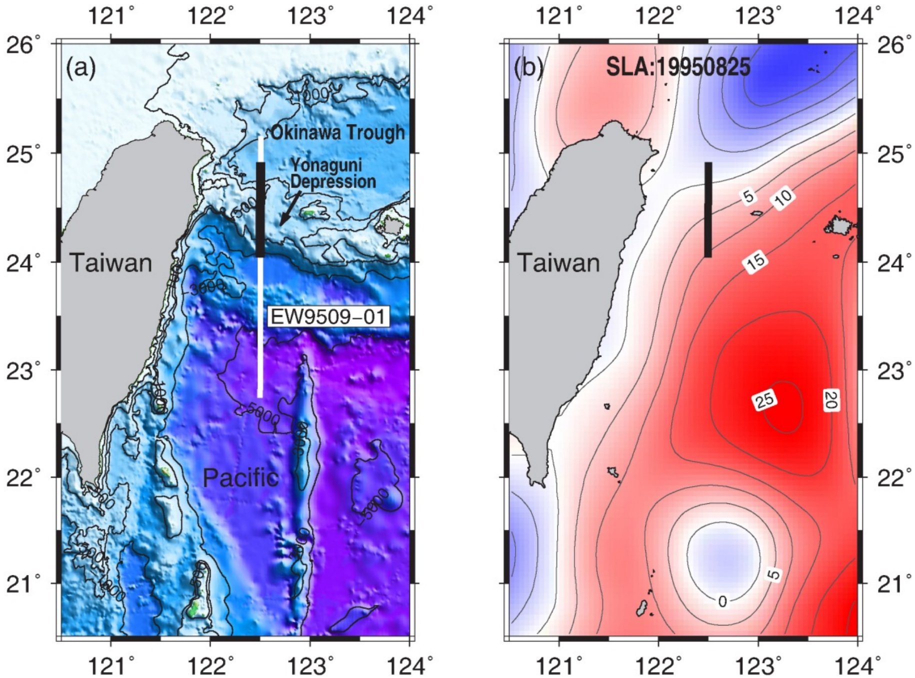
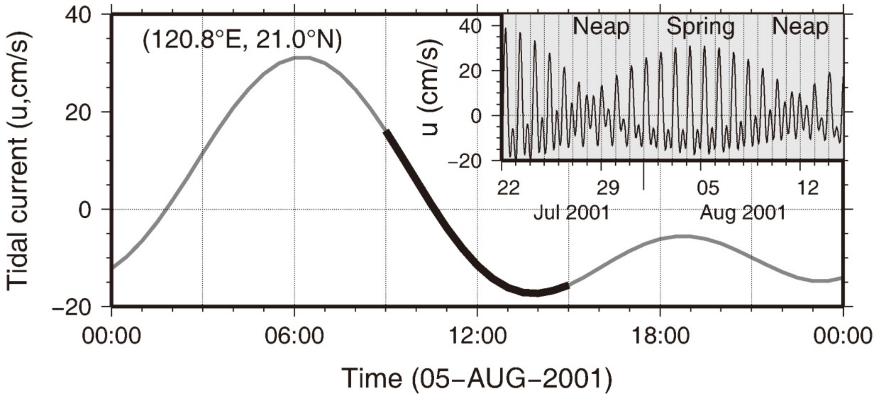


Figure 5. (a) Bathymetry off east Taiwan superimposed with seismic section EW9509-1 (white) and its subsection S95 (black). **(b)** The SLA and its contours on 25 August 1995. Black line is the subsection S95.



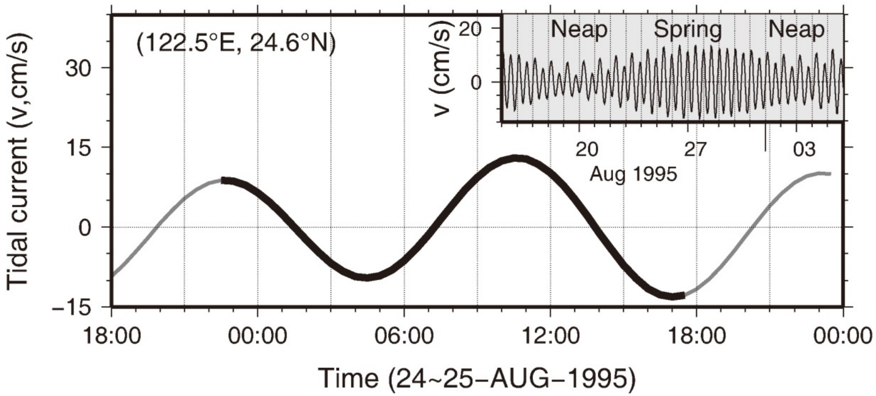


Figure 6. Predicted eastward (+u) and northward (+v) barotropic tidal currents across the Hengchun Ridge (upper) and Ryukyu Arc (lower), respectively. Thick black lines are the current velocities during the periods corresponding to the seismic acquisitions. Grey lines are the current velocities before and after the seismic acquisition of the subsections. Insets are the spring-neap tidal cycles over adjacent days.

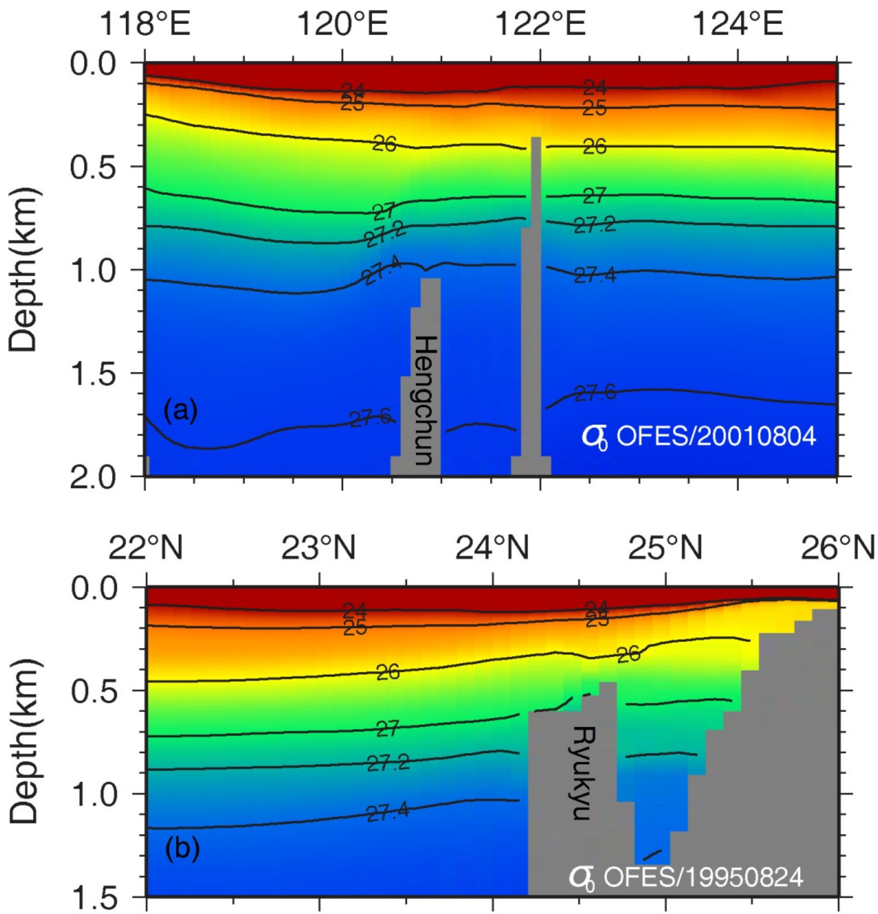


Figure 7. Potential density sections derived from the OFES model (http://apdrc.soest.hawaii.edu) during the times of the seismic cruises. **(a)** Across Luzon Strait along latitude 21°. **(b)** Across the Ryukyu Arc along longitude 122.5°.

OSD
11, 1871–1893, 2014