Features of internal solitary waves revealed by seismic oceanography data

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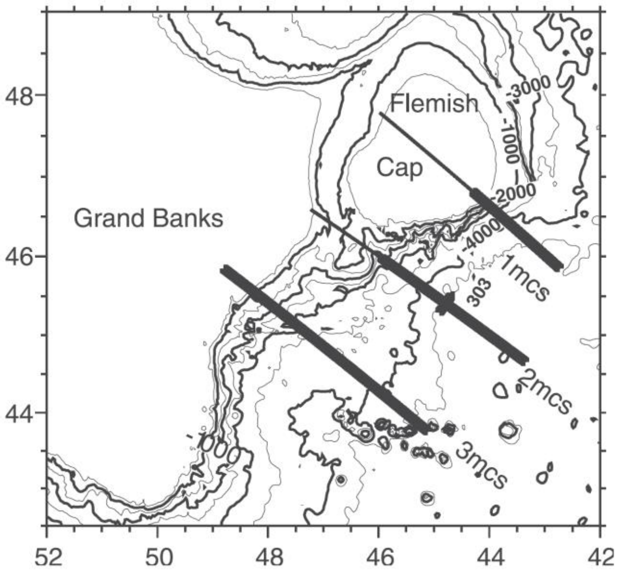
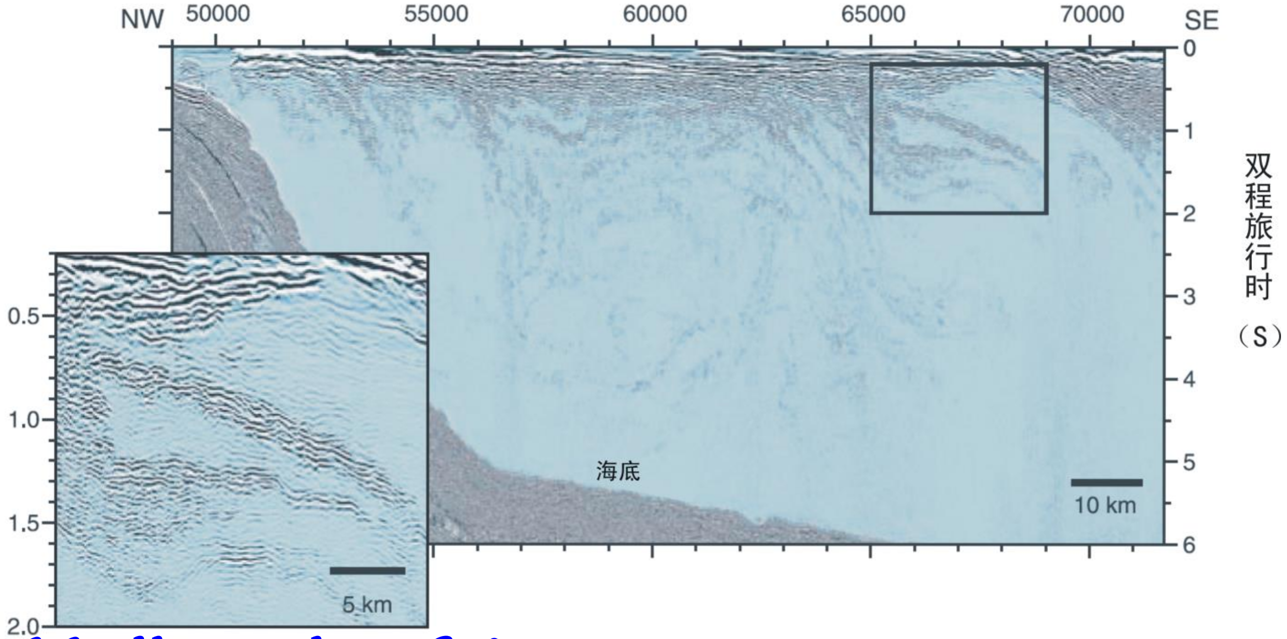
Contents

- Introduction to Seismic Oceanography(SO) and Internal Solitary Waves （ISWs） studies
- ISWs near the Strait of Gibraltar in the Mediterranean Sea by SO
- ISWs in the South China Sea by SO
- ISWs Pacific offshore Central America by SO
- New techniques for visualization of fine structure dynamic changes
- Summary

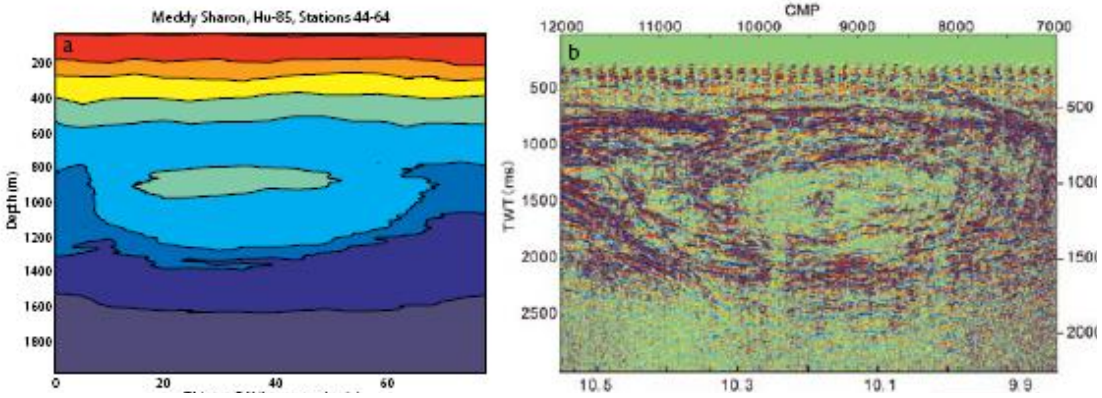
Seismic Oceanography

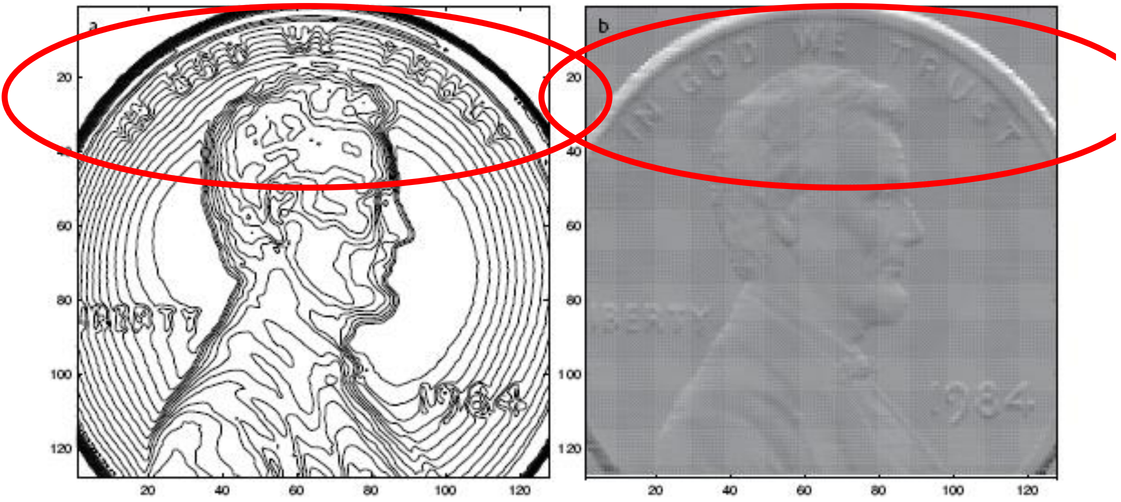




•2003，Holbrook，Science

European Union(EU) launched a large research project "Geophysical Oceanography" in February, 2006.





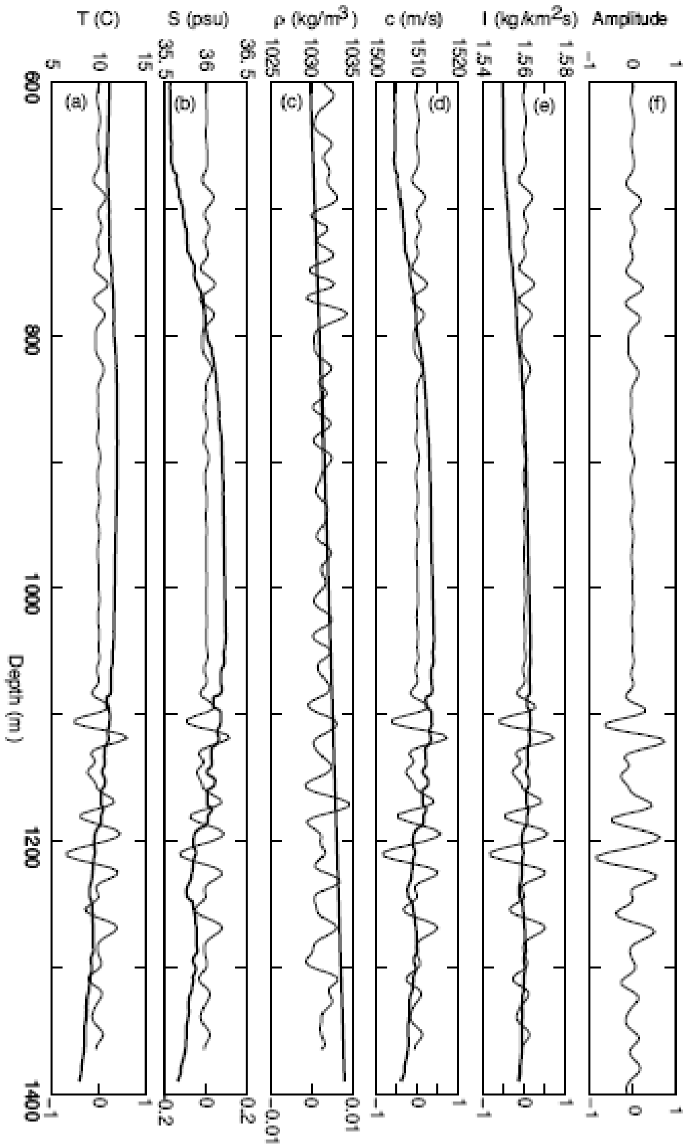
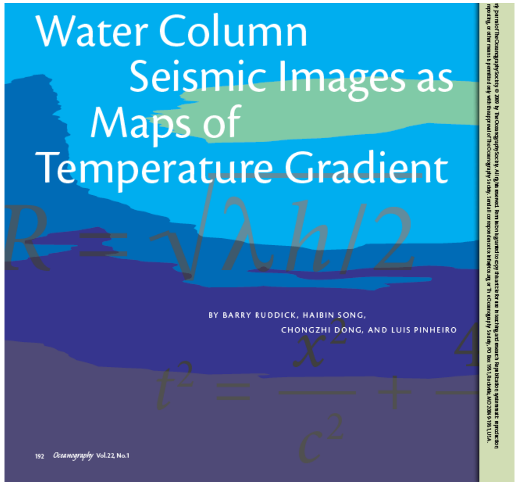
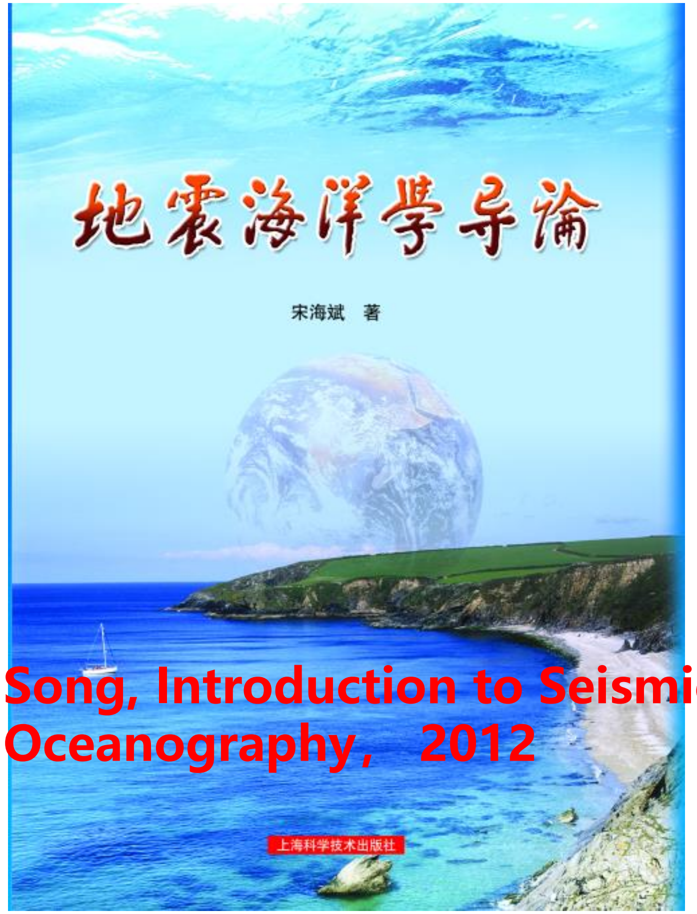


Figure 5. Oceanographic profiles versus depth (y-axis) of (thick line, upper axis scales): (a) temperature T, (b) salinity S, (c) density ρ, (d) sound velocity c, and (e) acoustic impedance I, calculated from CTD profile observations. Lower-axis scales: contribution to the synthetic seismogram (thin line, lower-axis scales) calculated by convolution of w with: (a) dT/dz, (b) dS/dz, (c) dρ/dz, (d) dc/dz, (e) dI/dz, and (f) R. Derivative quantities have been scaled as described in the text. The main point is that the synthetic seismo- ... smoothed over the scale of the source wavelet.



Ruddick, Song*, et al., Oceanography, 2009



Song, Introduction to Seismic Oceanography, 2012

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Estimating depth of polarity conversion of shoaling internal solitary waves in the northeastern South China Sea

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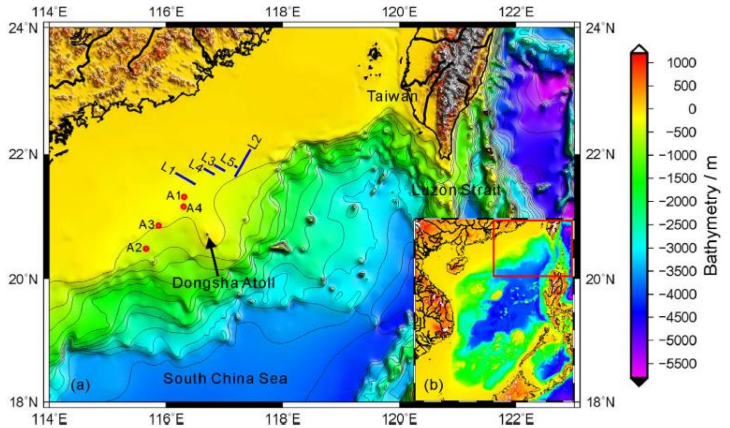


ig. 1. Bathymetry of the northeastern South China Sea. The red rectangle in context map (b) denotes the area of (a). The blue lines labeled L1 to L5 de
ɜismic sections employed in this paper. The red circles labeled A1 to A4 denote positions of the four Argo profiles shown in Fig. 8. All the seismic and Argo (
009. The dates of collecting L1 to L5 are 10, 28, 24, 15, 11, separately, and the dates of collecting A1 to A4 are 12, 28, 24, 16, separately. The correspondence of seismic and Argo data:
1/L5~A1, L2~A2, L3~A3, L4~A4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

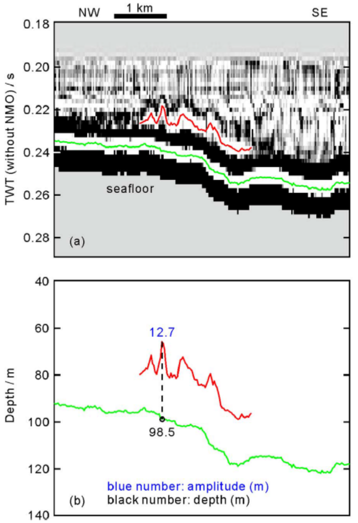


Fig. 6. Same as Fig. 2 but for L5. This section shows an elevation ISW packet and the middle one has the largest amplitude.

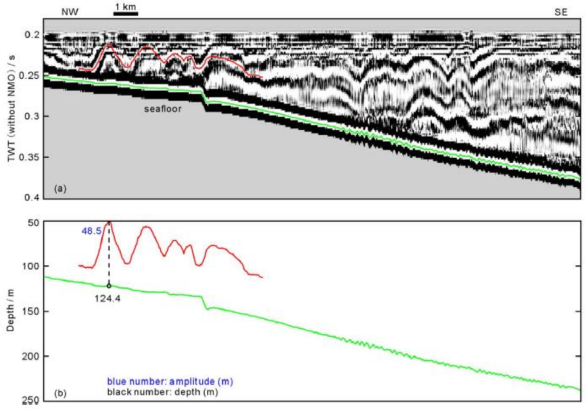


Fig. 4. Same as Fig. 2 but for L3. This section shows an elevation ISW packet.

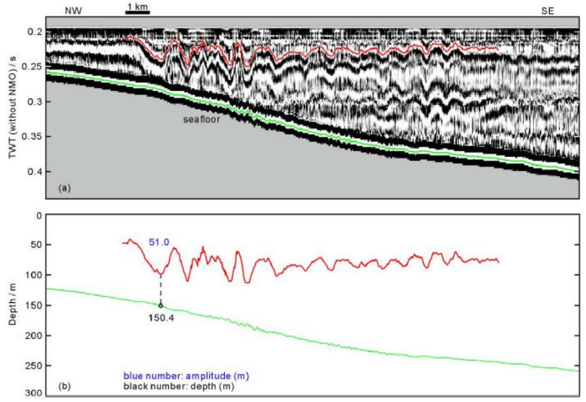


Fig. 5. Same as Fig. 2 but for L4. This section shows an ISW packet with a transition wave as its leading wave.

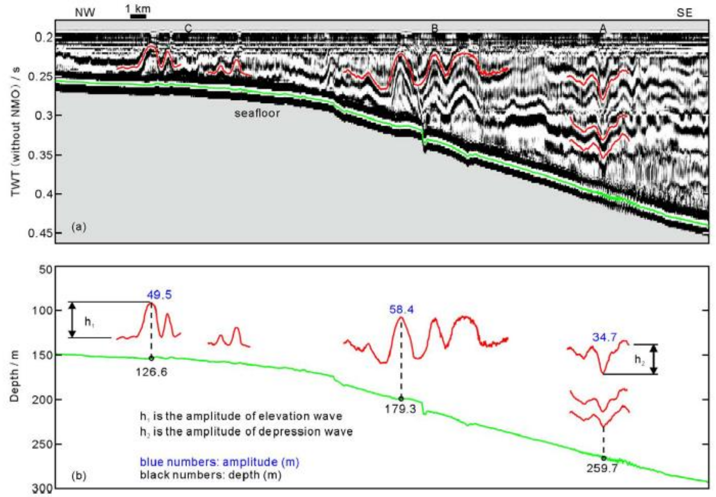
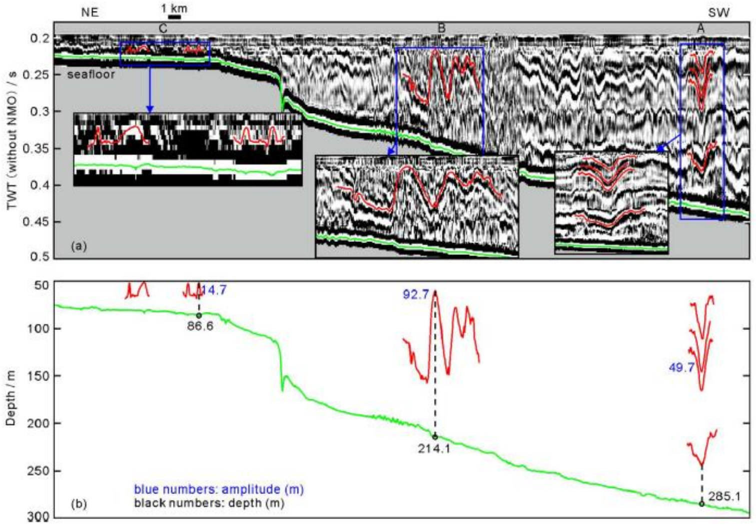
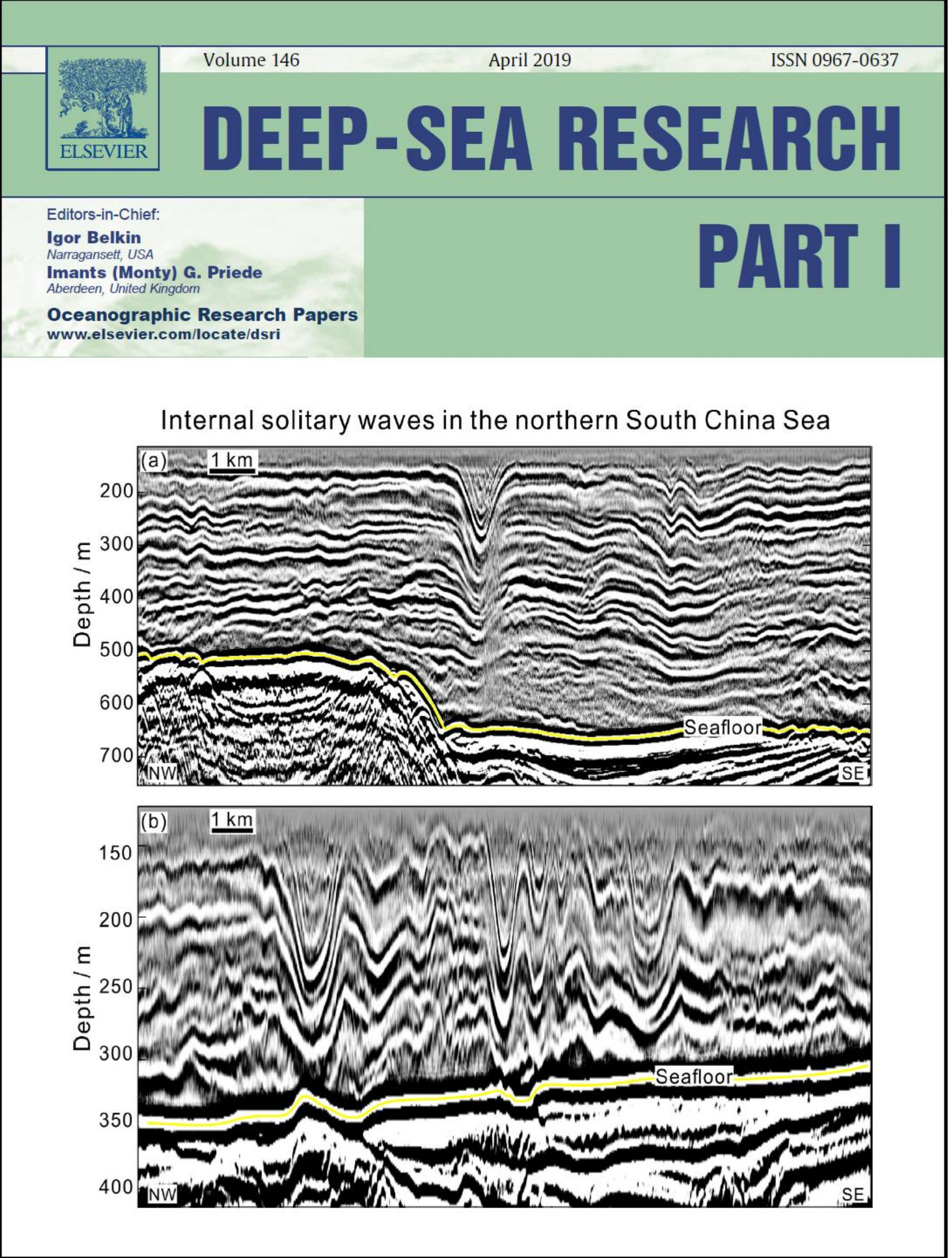


Fig. 2. (a) Common offset gather of L1. A, B and C denote three ISWs (packets). A is a depression ISW; B is an ISW packet with a transition wave as its leading wave; C is an elevation ISW packet. Red lines denote the picked horizons for waves. Green line denotes the picked horizon for seafloor. (b) NMO correction for the horizons picked in (a). These horizons show correct structures of waves and seafloor in depth domain. Blue numbers denote the amplitudes of the corresponding waves, and black numbers denote the corresponding seafloor depths. h1 and h2 are the diagrams to show the amplitudes of elevation wave and depression wave separately. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



ig. 3. Same as Fig. 2 but for L2. (a) zoom in the three ISWs (packets) marked by blue rectangles to show them clearly. A is a depression ISW; B is an ISW packet with a transition wave
s its leading wave; C is an elevation ISW packet. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



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Analyzing amplitudes of internal solitary waves in the northern South China Sea by use of seismic oceanography data

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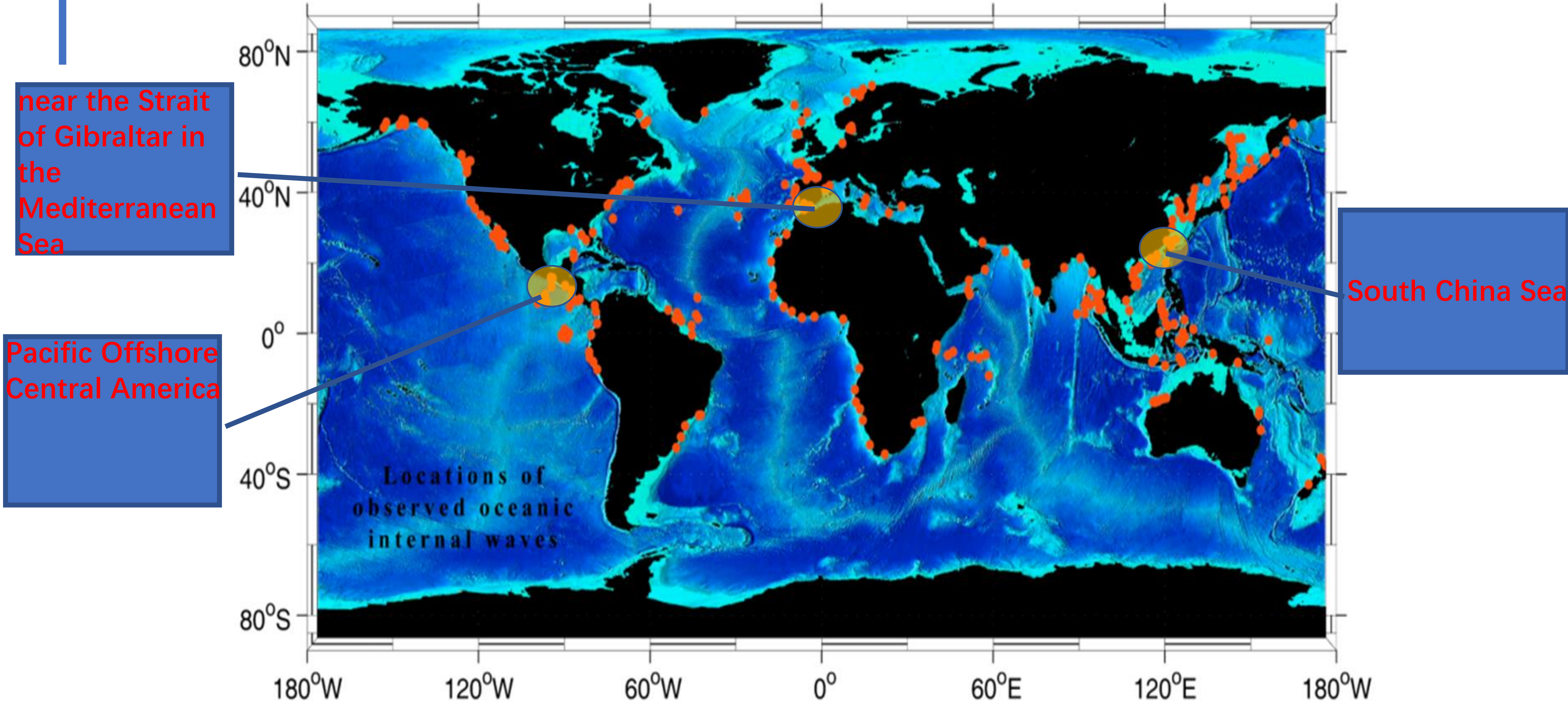
ABSTRACT

In the northern South China Sea, numerous multichannel seismic reflection sections are used to identify internal solitary wave (ISW) packets and extract wave amplitudes and corresponding water depths. The analyzed data show that these depression ISWs occur on the upper continental slope at water depths between 263 m and 740 m, with maximum amplitudes ranging from 35 m to 128 m. Our results, in conjunction with previous studies, suggest that the maximum amplitudes of the ISWs on the northern South China Sea continental slope are highly correlated with seafloor depths and that they have a logarithmic function relationship. The maximum amplitudes decrease with decreasing water depths. Interactions between the ISWs and the seafloor play a crucial role in decreasing ISW maximum amplitudes, especially in shallow areas. In addition, we compare the observed vertical amplitude distribution with theoretical results and find that they are concordant. The "bottom depth" (H) in the boundary conditions of eigenfunctions represents the extension depth of the ISW rather than the actual seafloor depth. Here, the ISW extension depth is where the ISW amplitude becomes zero and the seafloor depth is just under the ISW. If the ISW interacts intensely with the seafloor, its observed vertical amplitude distribution may exhibit prominent differences from the theoretical result.

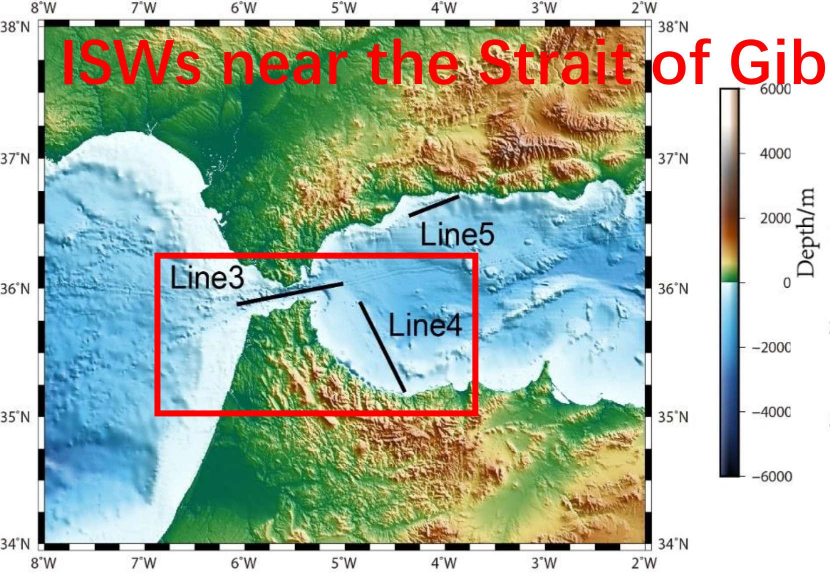
Front cover page article

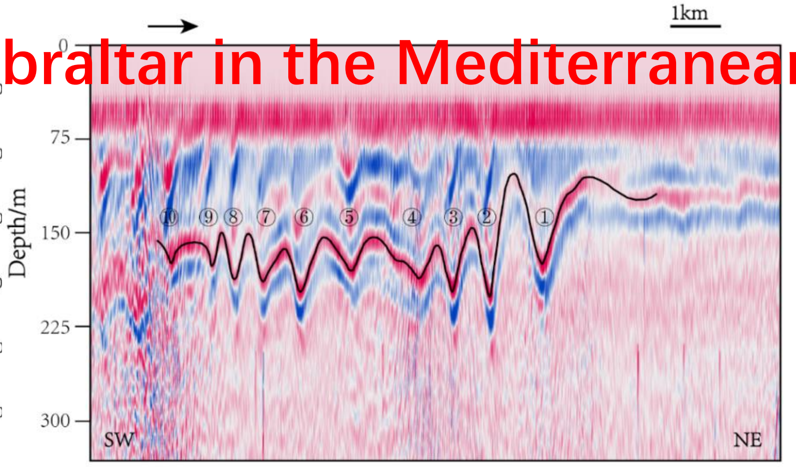
Global ISWs distribution

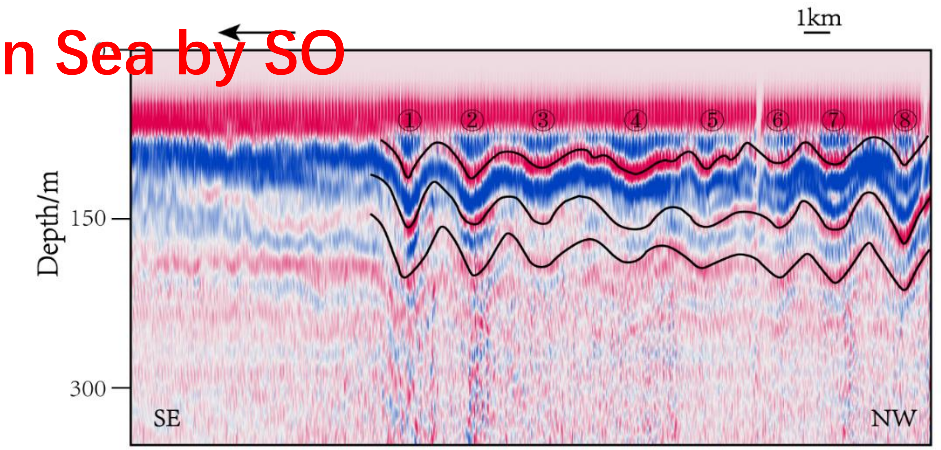


Global ISWs distribution（Global Ocean Associates，2002）

ISWs near the Strait of Gibraltar in the Mediterranean Sea by SO







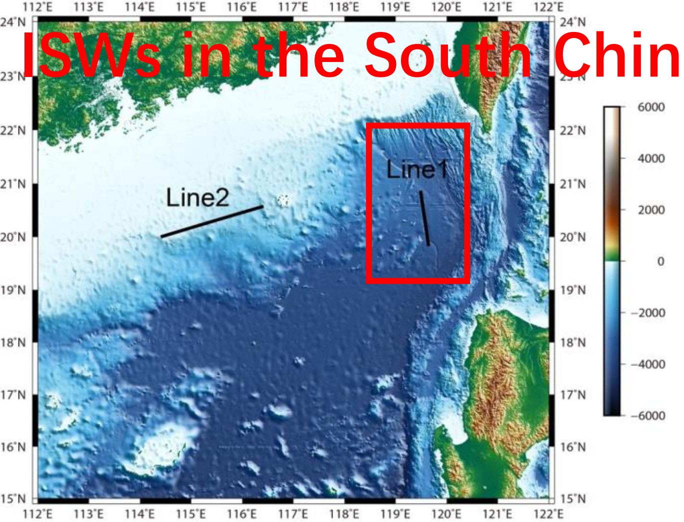
ISWs Characteristics in Line3

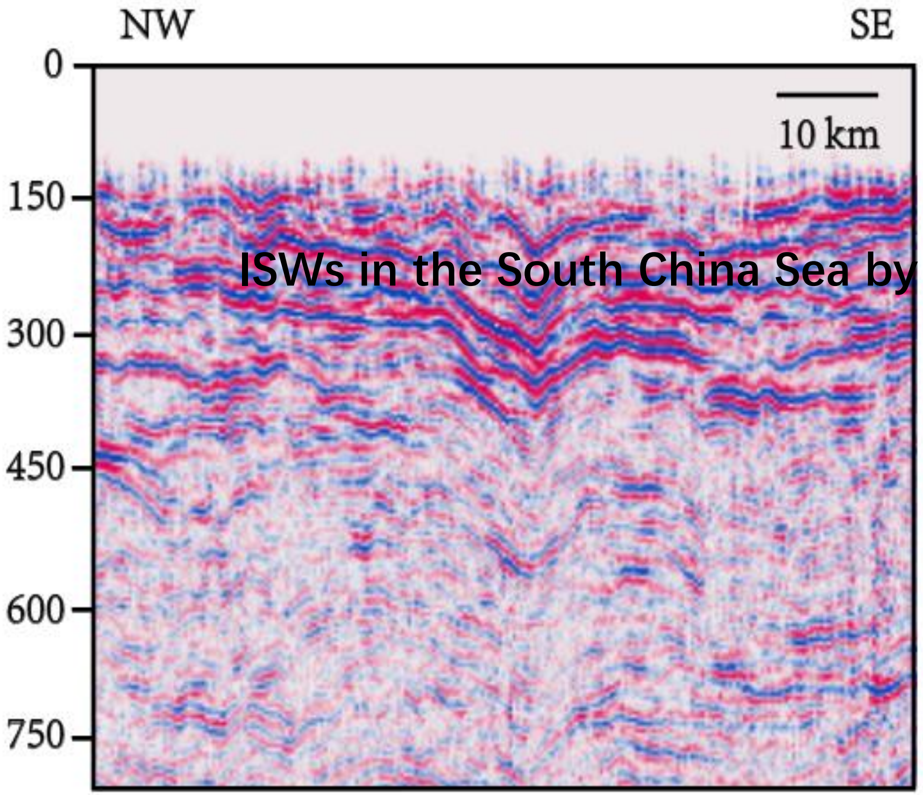
ISW#	Amplitude/ m	Half-height width after correction/m	Phase speed m/s	Vert. Vel. cm/s
1	74.5	1065.0	1.63	11.2
2	61.3	506.3	1.56	18.6
3	51.4	560.1	1.51	13.7
4	38.8	932.8	1.45	6.0
5	34.9	613.7	1.43	8.1
6	44.7	600.4	1.48	10.9
7	37.9	514.5	1.44	10.5
8	42.5	356.0	1.47	17.3
9	34.4	306.3	1.43	15.9
10	25.8	493.5	1.38	7.2

ISWs Characteristics in Line4

#ISW	Amplitude/m	Half-height width after correction/m	Phase speed m/s	Vert. Vel. cm/s
1	53.1	1117.8	1.59	7.8
2	42.1	1282.5	1.53	5.0
3	24.9	1518.9	1.44	2.3
4	27.0	1721.8	1.45	2.2
5	23.7	1172.7	1.44	2.8
6	22.2	1192.9	1.43	2.6
7	32.0	1270.9	1.48	3.6
8	38.5	1113.6	1.51	5.2

ISWs in the South China Sea by SO



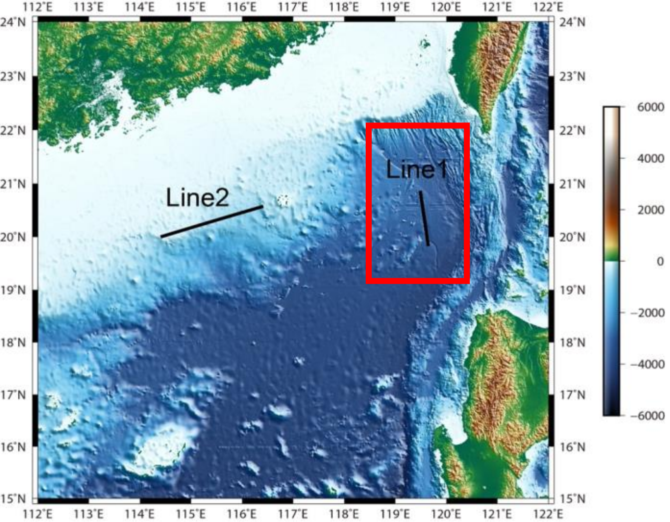


ISWs in the South China Sea by SO

Line1

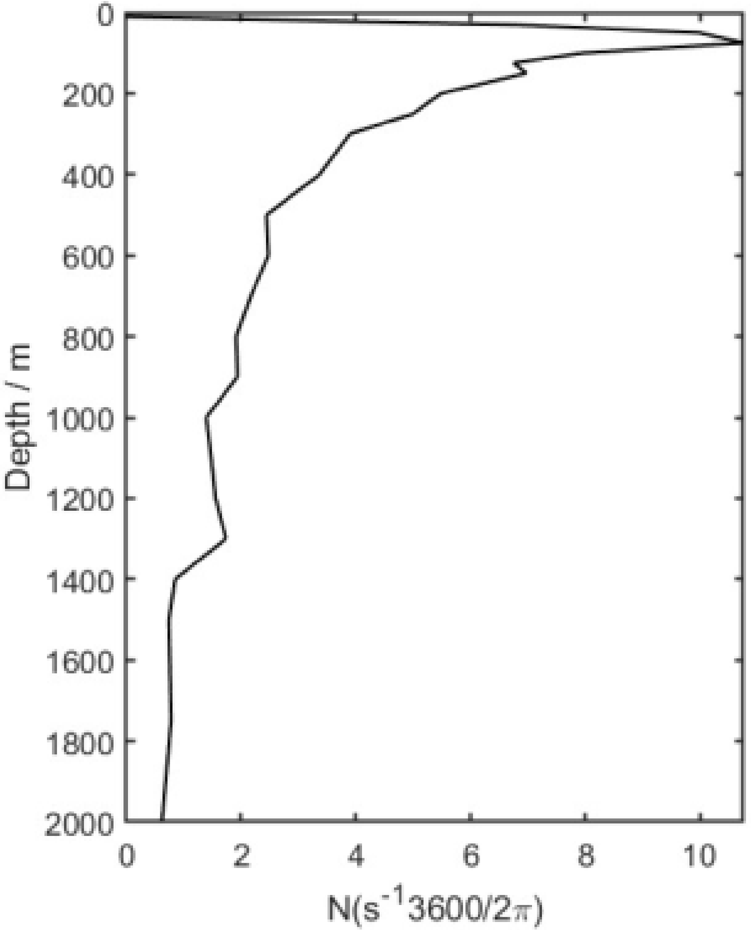
Amplitudes of one ISW in Line1

Water depth/m	Amplitude/m
151.8	**75.2**
164.3	77.2
194.3	69.3
221	57.6
269.7	27.5
243.8	73.9
277.7	66.6
319.5	75.6
345.2	67.7
370.7	71.0
409.1	**50.8**
423.2	76.6
482.8	64.2
488	73.0

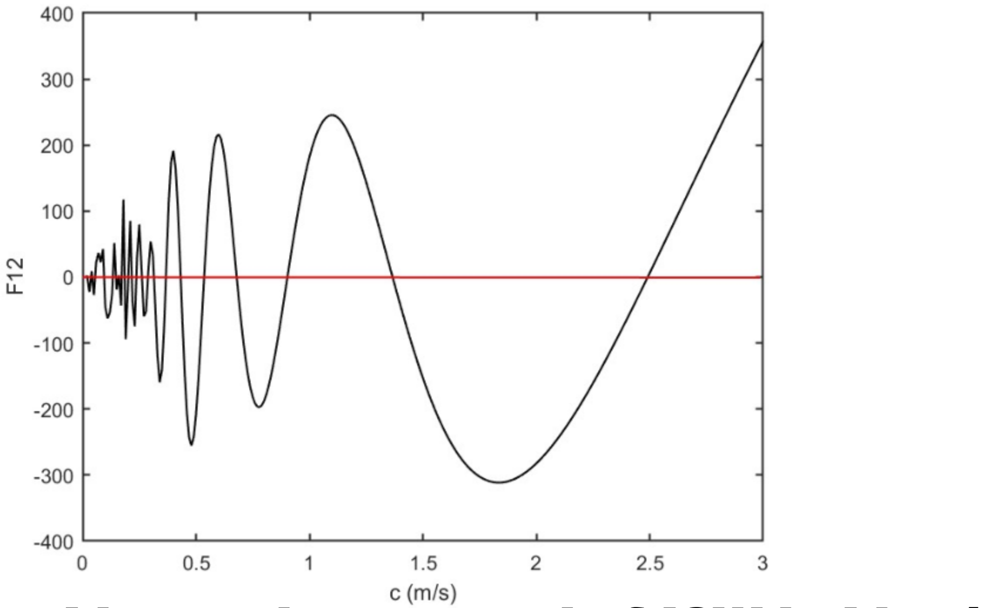


Pycnocline depth: 75m
Pycnocline ranges: 25-206m

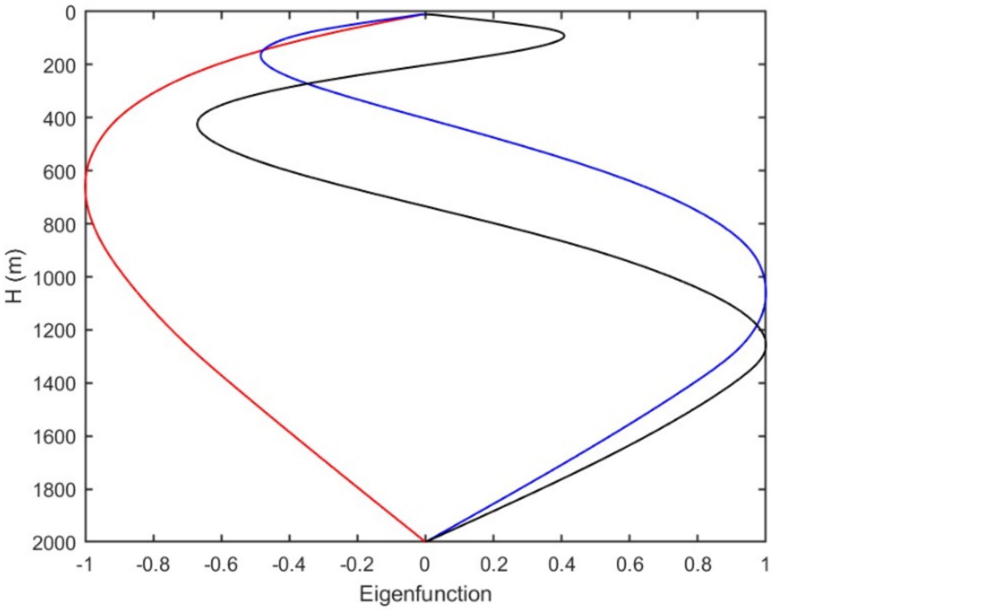
Nonlinear parameter α=-0.00868
Phase speed： 2.72m/s
Apparent half-height width： 4.6km
Vertical velocity： 4.7cm/s



the buoyancy frequency N for Line1

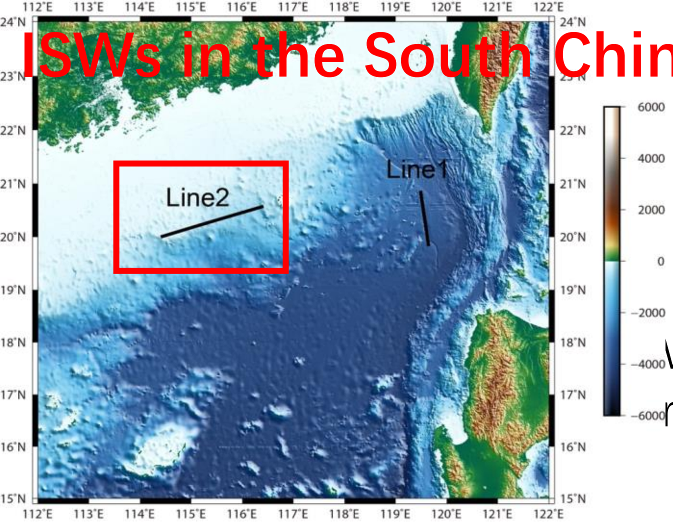


Linear phase speed of ISW in Line1



Eigenfuctions, mode-1 in red,mode-2 in blue and mode-3 in black

ISWs in the South China Sea by SO



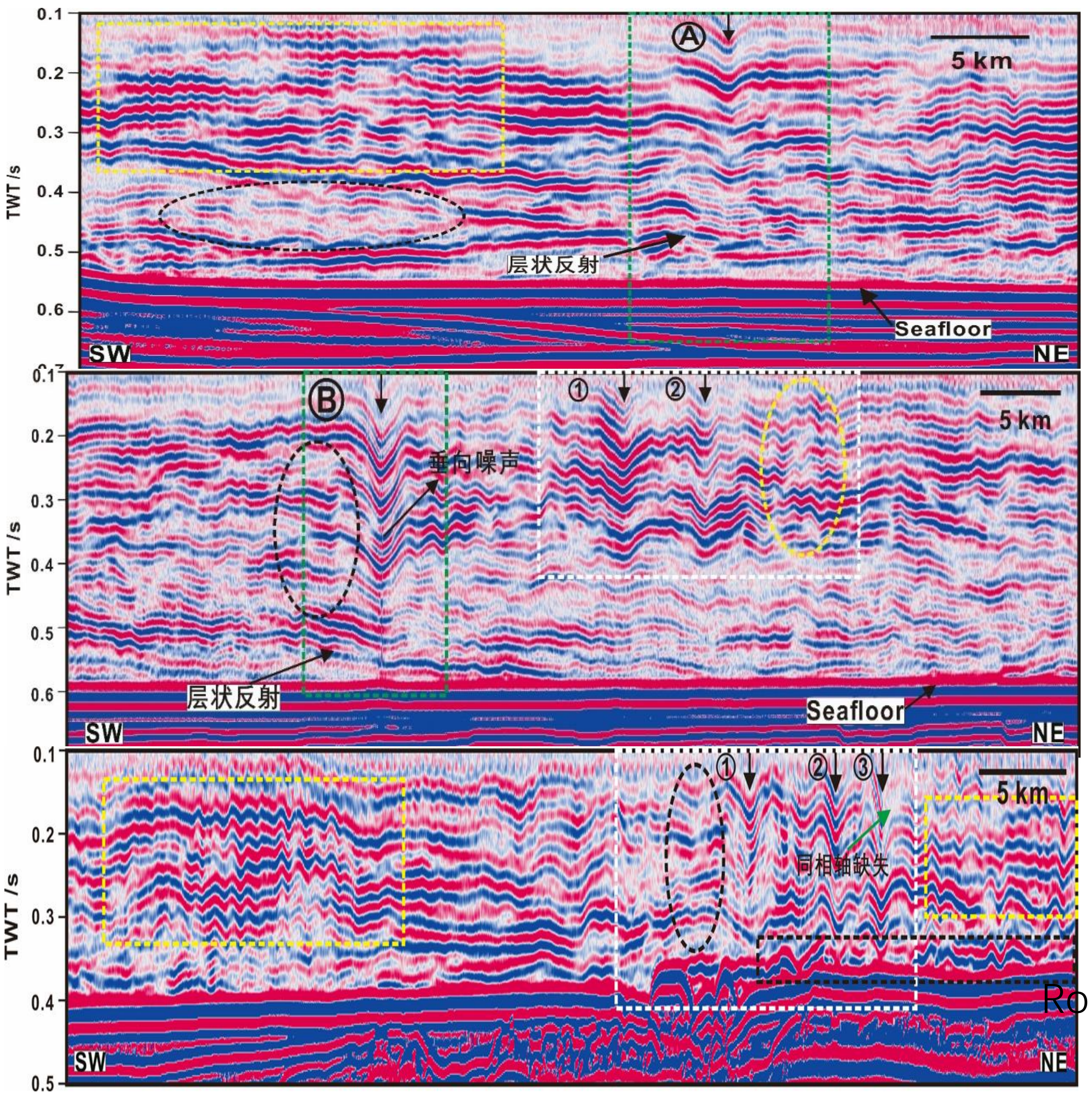
HFIWs

Weak amplitude refection zone

ISW

Vertical noise

High-frequency internal waves(HFIWs)



ISW

ISW packet

HFIWs

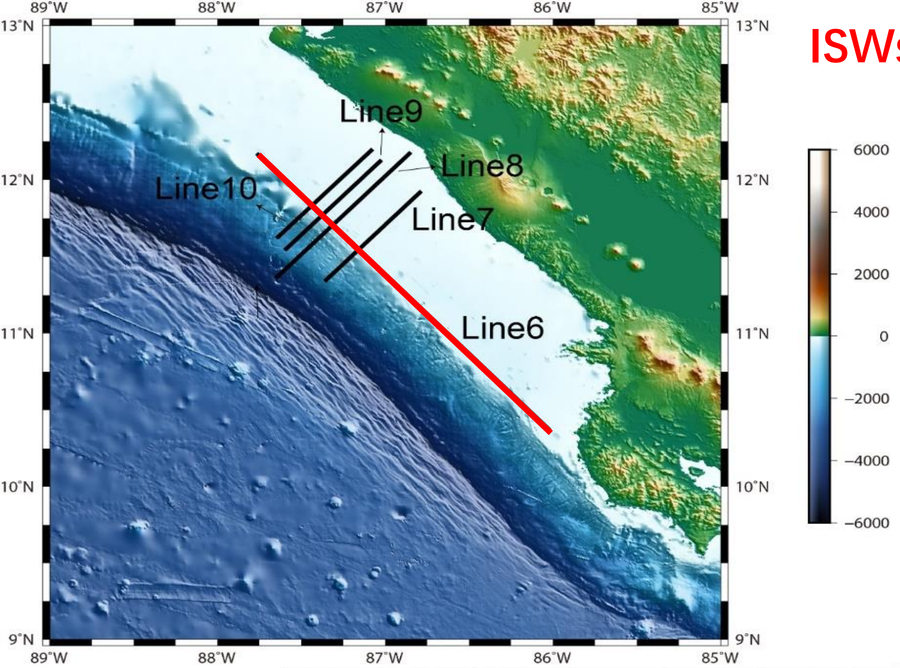
HFIWs

ISW

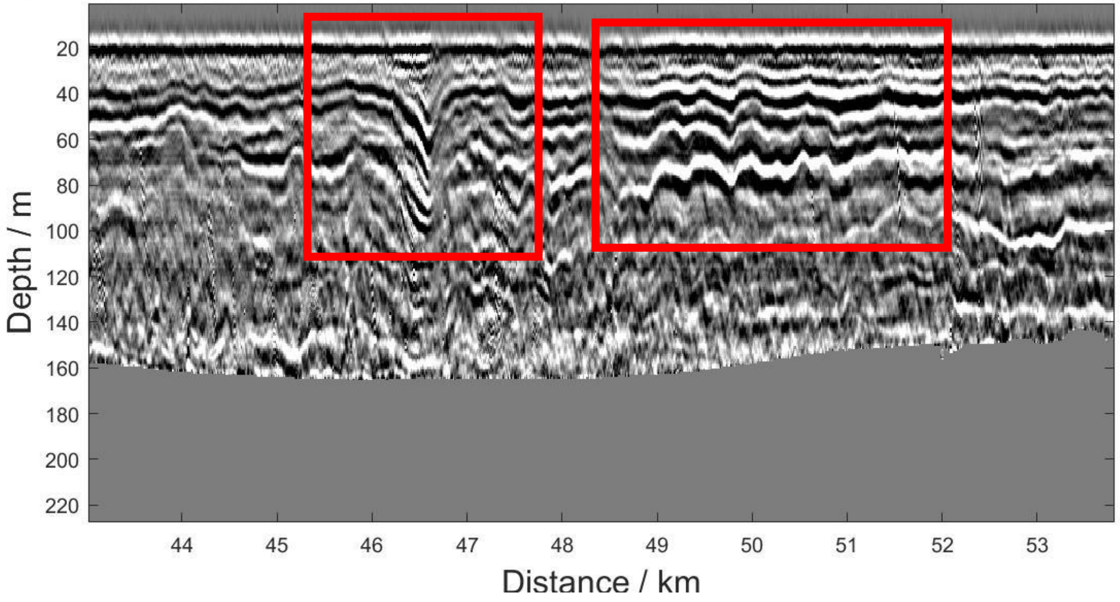
Rough seafloor

ISWs in Line 2

ISWs offshore Central America by SO



Mode-1 depression ISW



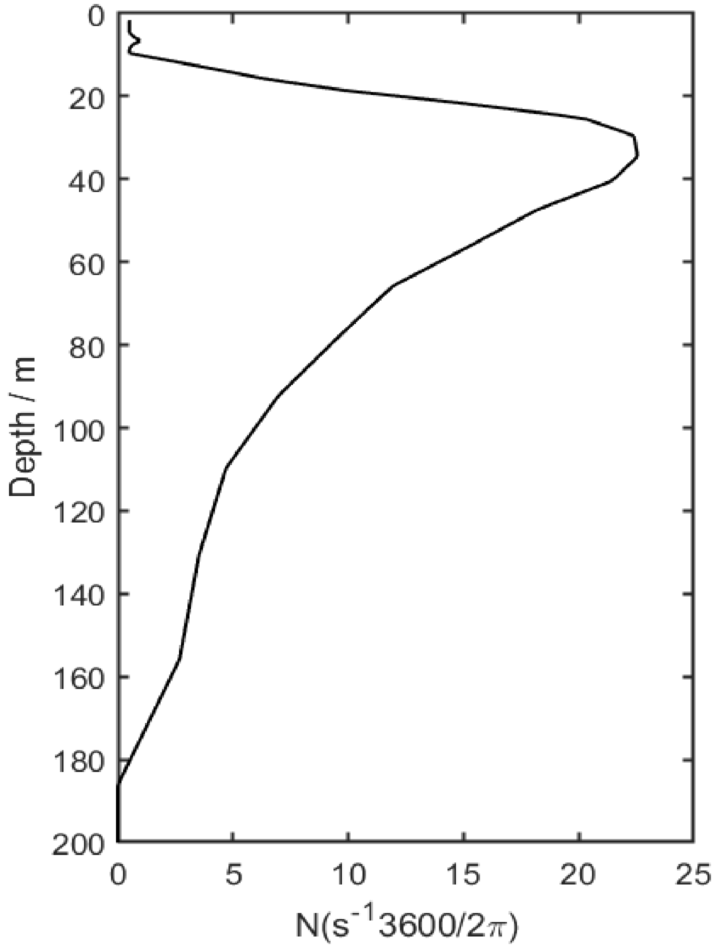
One section of Line 6

Amplitude with depth change of ISW in Line6

Water depth/m	Amplitude/m
26.24	18.21
32.63	26.3
40.86	30.29
48.93	32.2
57.45	32.43
73	29.63

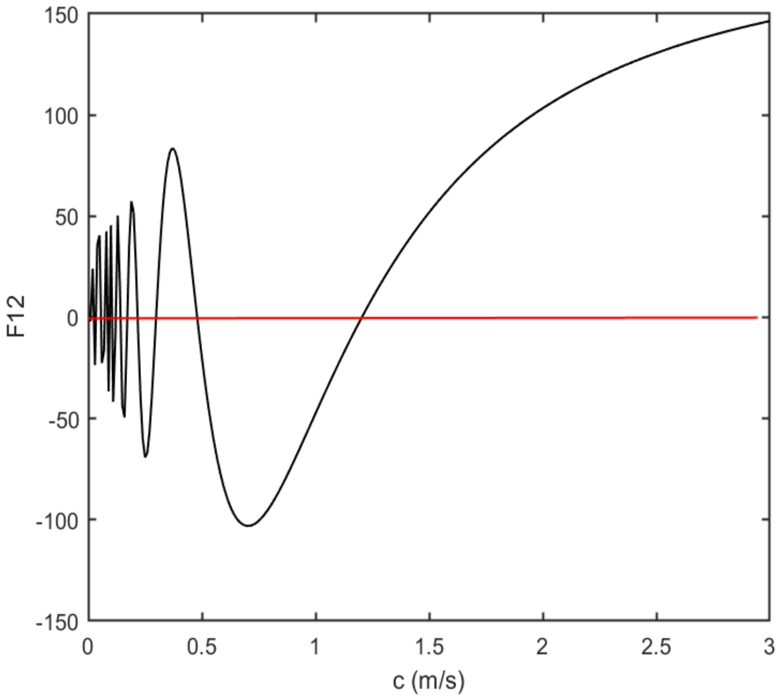
Pycnocline depth:34m

Pycnocline range:19-70m



the buoyancy frequency N at station(86.75°W, 11.83°) on Dec.19, 2004

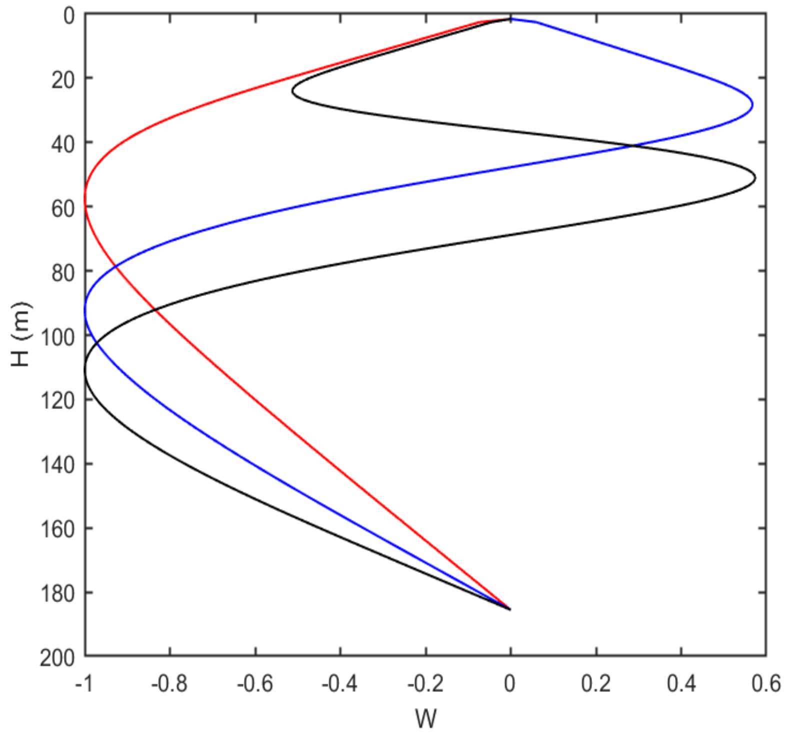
Linear phase speed 1.2039m/s



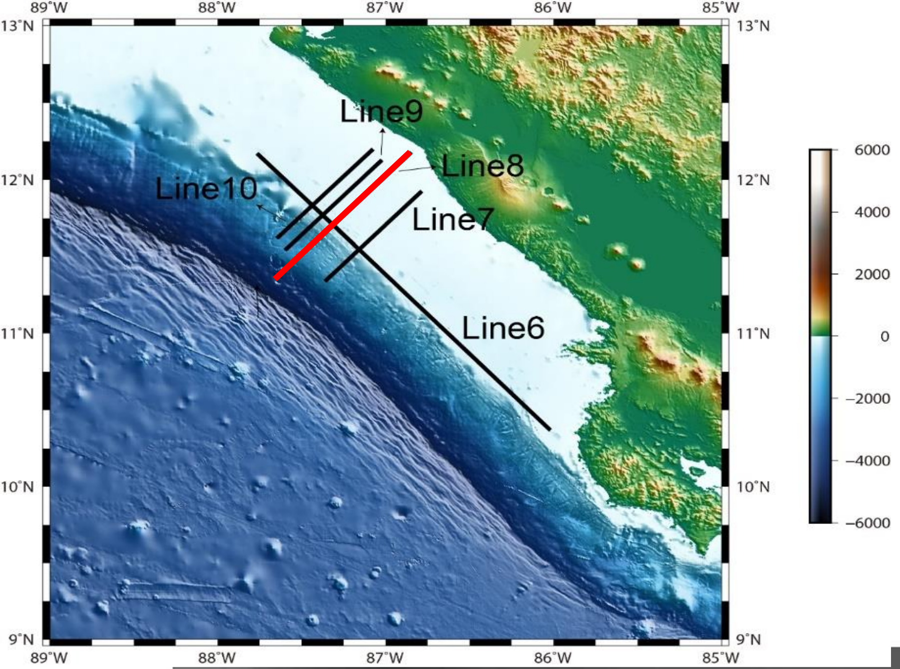
Linear phase speed

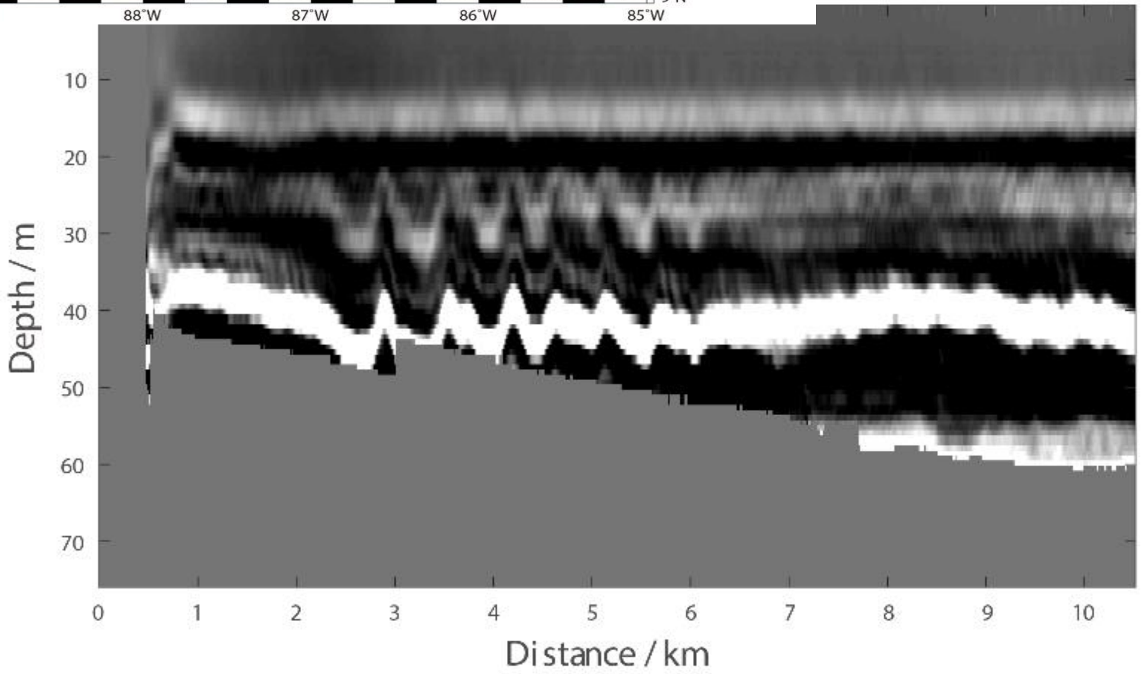
Phase speed: 1.62m/s

Vertical velocity 24.79cm/s



Eigenfuctions, mode-1 in red,mode-2 in blue and mode-3 in black





One section of Line 8

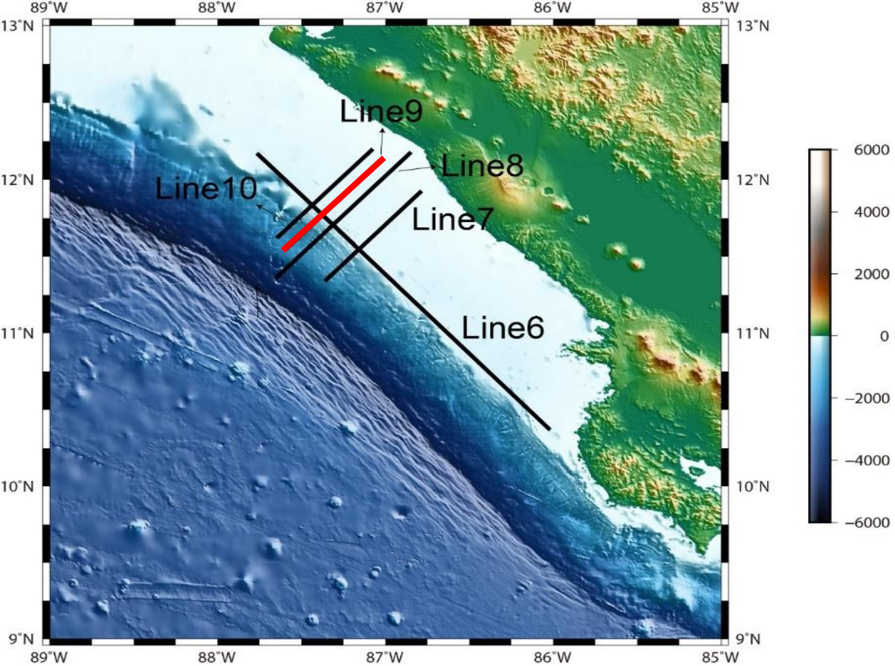
6 mode-1 elevation ISWs

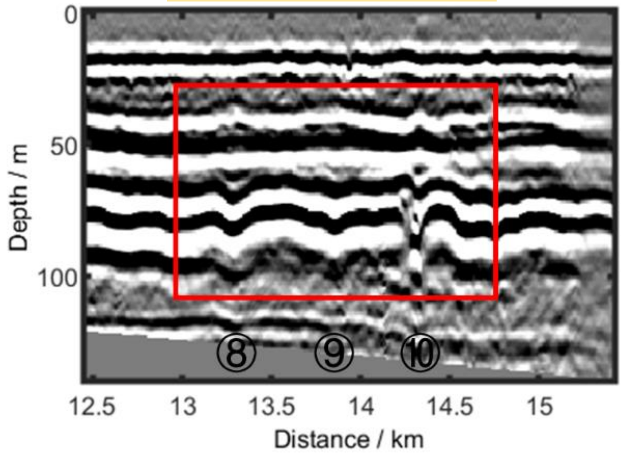
Amplitudes of ISWs in Line8

ISW#	Amplitude/m
1	8.22
2	8.13
3	6.5
4	4.97
5	4.06
6	3.24

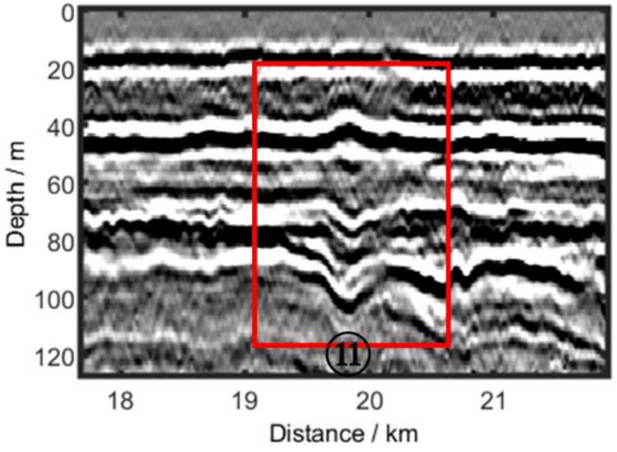
elevation:
2-5m
depression:
4-14m

11 mode-2 ISWs

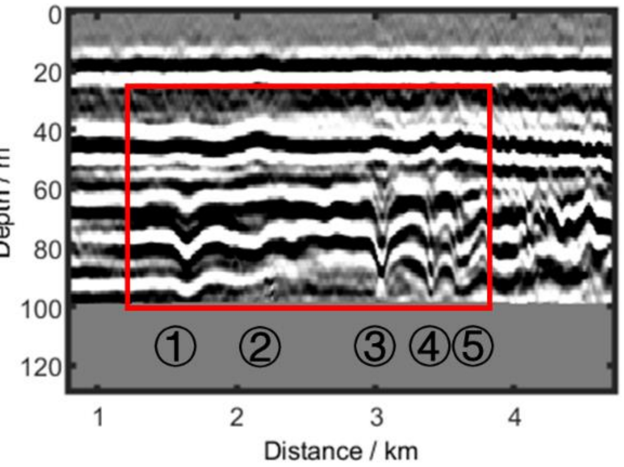




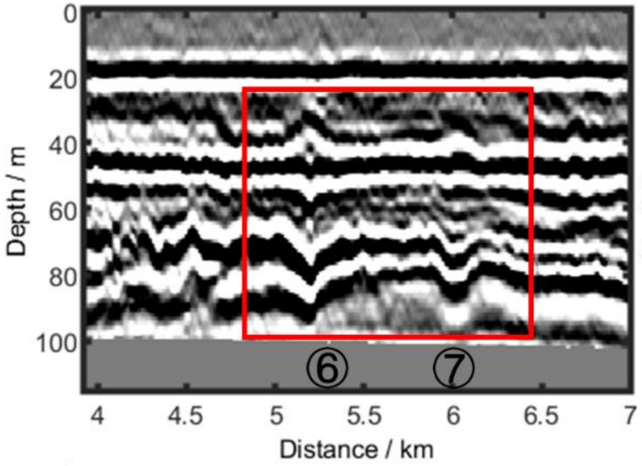
(d)



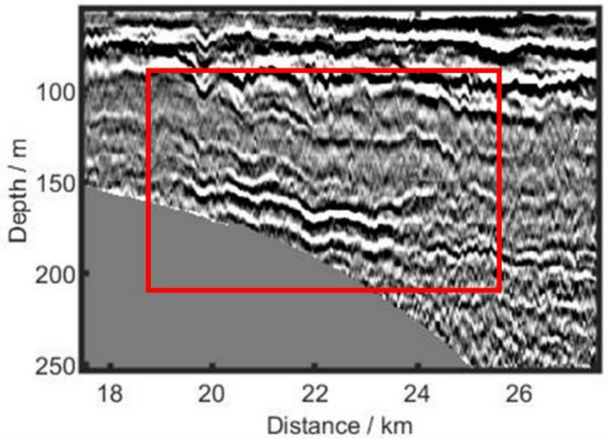
(e)



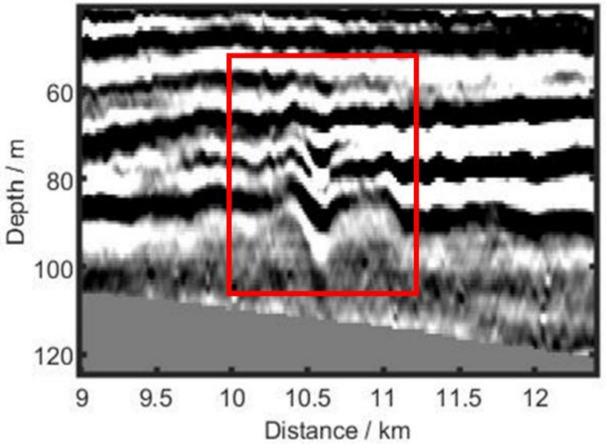
(b)



(c)

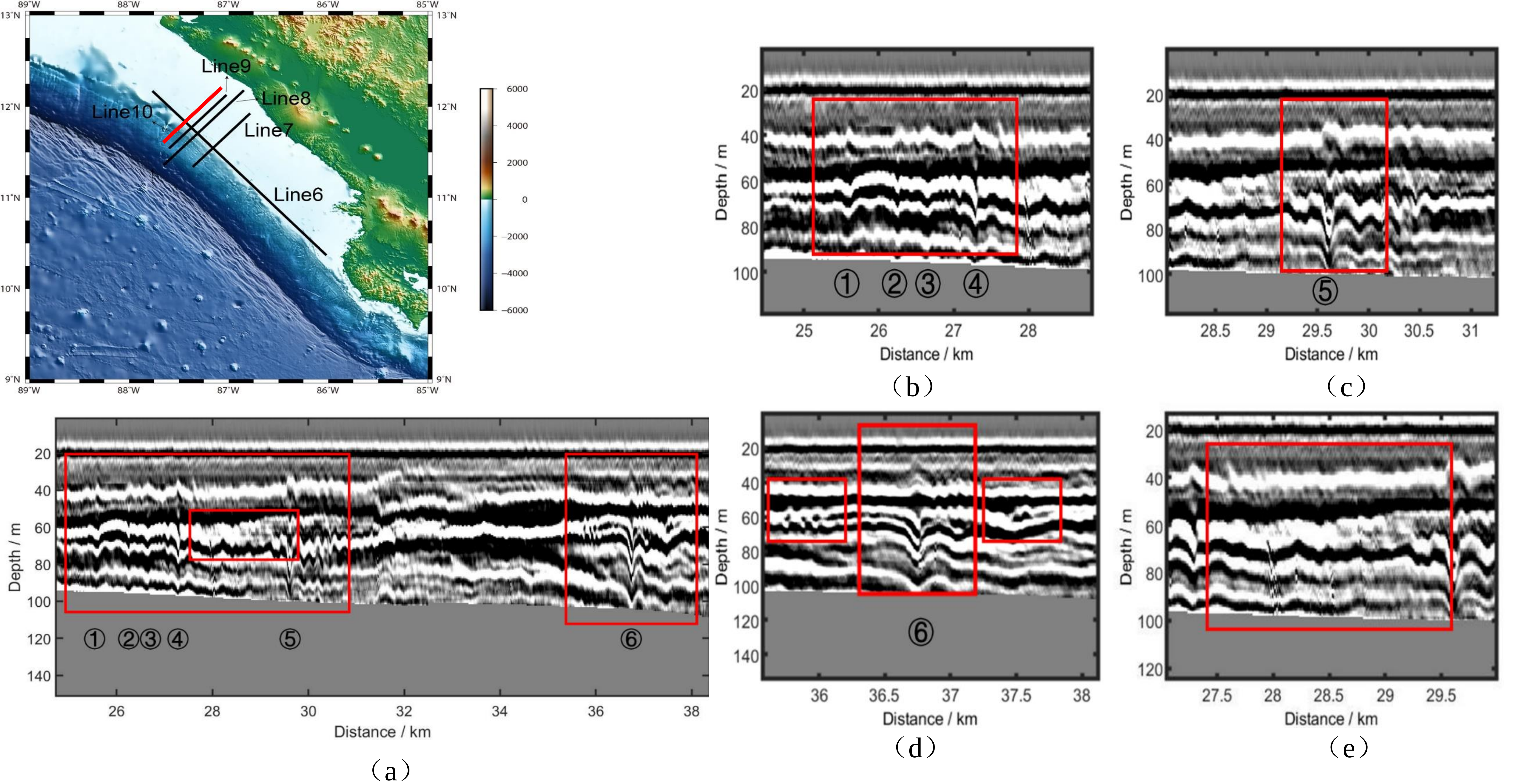


(f)

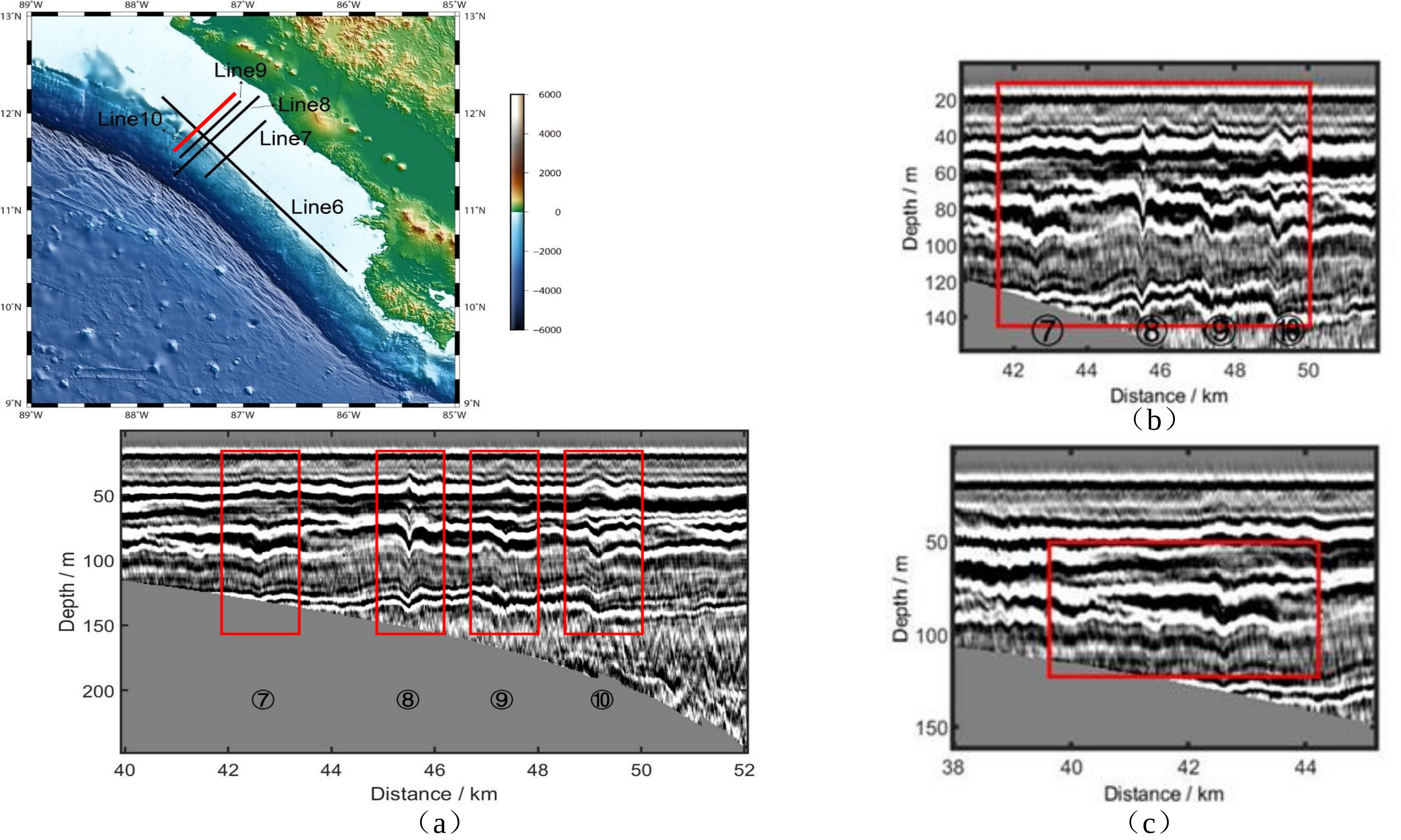


(g)

Sections of Line 9



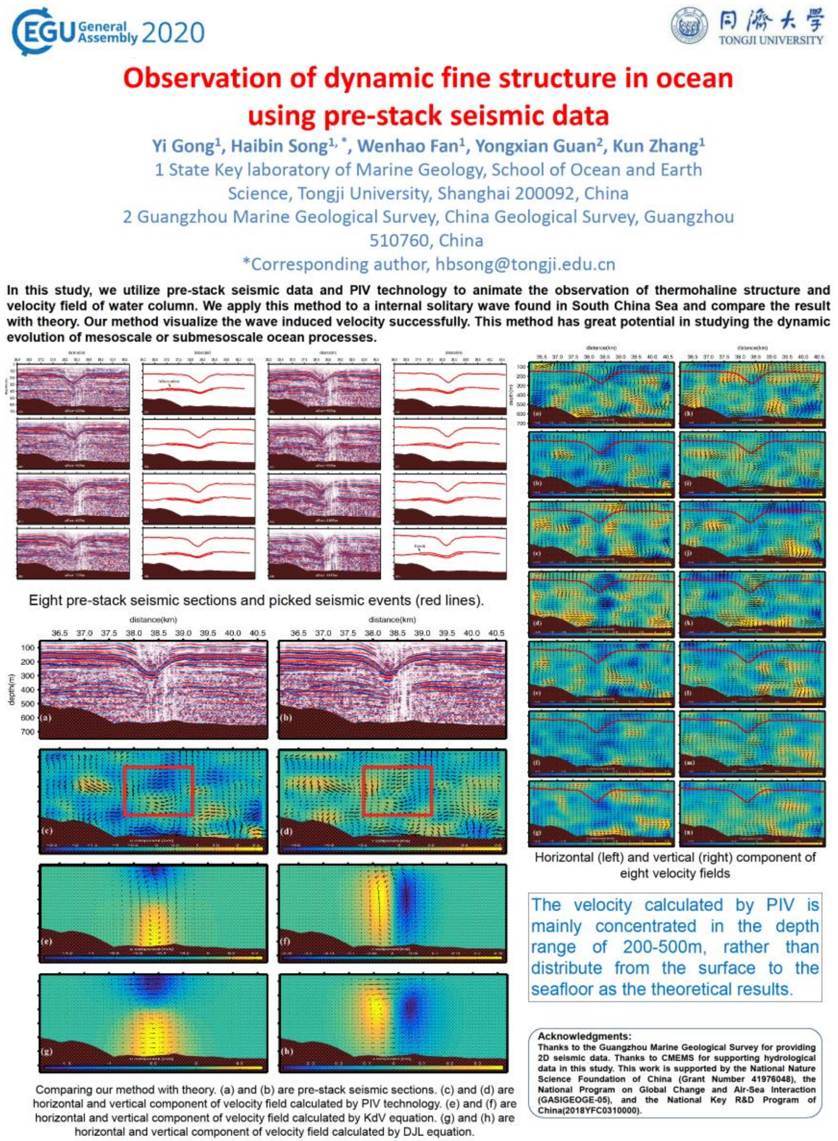
Sections of Line 10-part 1



Sections of Line 10-part 2

New techniques for visualization of fine structure dynamic changes

Prestack migration+PIV method



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Observation of dynamic fine structure in ocean using pre-stack seismic data

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In this study, we utilize pre-stack seismic data and PIV technology to animate the observation of thermohaline structure and velocity field of water column. We apply this method to a internal solitary wave found in South China Sea and compare the result with theory. Our method visualize the wave induced velocity successfully. This method has great potential in studying the dynamic evolution of mesoscale or submesoscale ocean processes.

Eight pre-stack seismic sections and picked seismic events (red lines).

Horizontal (left) and vertical (right) component of eight velocity fields

The velocity calculated by PIV is mainly concentrated in the depth range of 200-500m, rather than distribute from the surface to the seafloor as the theoretical results.

Comparing our method with theory. (a) and (b) are pre-stack seismic sections. (c) and (d) are horizontal and vertical component of velocity field calculated by PIV technology. (e) and (f) are horizontal and vertical component of velocity field calculated by KdV equation. (g) and (h) are horizontal and vertical component of velocity field calculated by DJL equation.

Acknowledgments:
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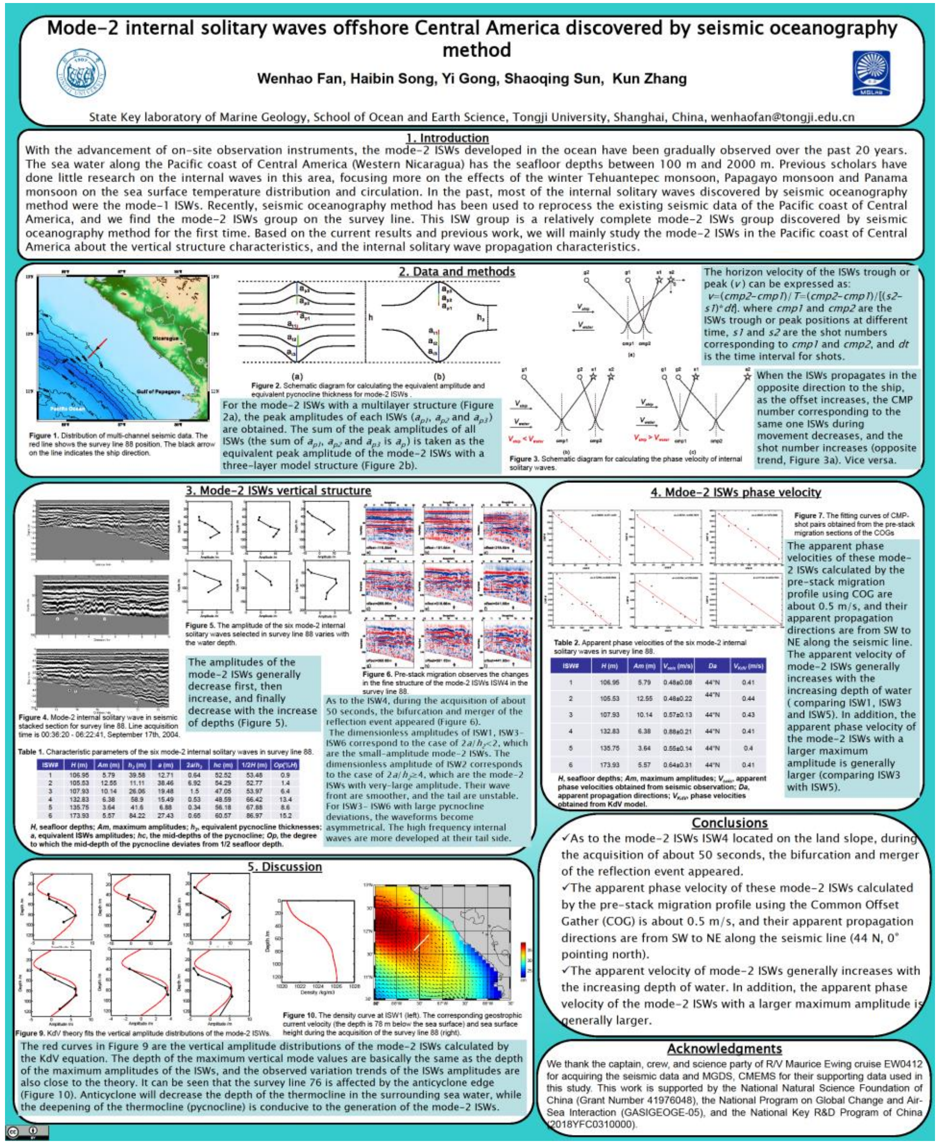

Mode-2 internal solitary waves offshore Central America discovered by seismic oceanography method

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1. Introduction

With the advancement of on-site observation instruments, the mode-2 ISWs developed in the ocean have been gradually observed over the past 20 years. The sea water along the Pacific coast of Central America (Western Nicaragua) has the seafloor depths between 100 m and 2000 m. Previous scholars have done little research on the internal waves in this area, focusing more on the effects of the winter Tehuantepec monsoon, Papagayo monsoon and Panama monsoon on the sea surface temperature distribution and circulation. In the past, most of the internal solitary waves discovered by seismic oceanography method were the mode-1 ISWs. Recently, seismic oceanography method has been used to reprocess the existing seismic data of the Pacific coast of Central America, and we find the mode-2 ISWs group on the survey line. This ISW group is a relatively complete mode-2 ISWs group discovered by seismic oceanography method for the first time. Based on the current results and previous work, we will mainly study the mode-2 ISWs in the Pacific coast of Central America about the vertical structure characteristics, and the internal solitary wave propagation characteristics.

2. Data and methods

Figure 1. Distribution of multi-channel seismic data. The red line shows the survey line 88 position. The black arrow on the line indicates the ship direction.

Figure 2. Schematic diagram for calculating the equivalent amplitude and equivalent pycnocline thickness for mode-2 ISWs.

For the mode-2 ISWs with a multilayer structure (Figure 2a), the peak amplitudes of each ISWs (a_{p1}, a_{p2} and a_{p3}) are obtained. The sum of the peak amplitudes of all ISWs (the sum of a_{p1}, a_{p2} and a_{p3} is a_p) is taken as the equivalent peak amplitude of the mode-2 ISWs with a three-layer model structure (Figure 2b).

The horizon velocity of the ISWs trough or peak (v) can be expressed as: $v=(cmp2-cmp1)/T=(cmp2-cmp1)/[(s2-s1)*dt]$. where $cmp1$ and $cmp2$ are the ISWs trough or peak positions at different time, $s1$ and $s2$ are the shot numbers corresponding to $cmp1$ and $cmp2$, and dt is the time interval for shots.

When the ISWs propagates in the opposite direction to the ship, as the offset increases, the CMP number corresponding to the same one ISWs during movement decreases, and the shot number increases (opposite trend, Figure 3a). Vice versa.

Figure 3. Schematic diagram for calculating the phase velocity of internal solitary waves.

3. Mode-2 ISWs vertical structure

Figure 4. Mode-2 internal solitary wave in seismic stacked section for survey line 88. Line acquisition time is 00:36:20 - 06:22:41, September 17th, 2004.

Figure 5. The amplitude of the six mode-2 internal solitary waves selected in survey line 88 varies with the water depth.

The amplitudes of the mode-2 ISWs generally decrease first, then increase, and finally decrease with the increase of depths (Figure 5).

Figure 6. Pre-stack migration observes the changes in the fine structure of the mode-2 ISWs ISW4 in the survey line 88.

As to the ISW4, during the acquisition of about 50 seconds, the bifurcation and merger of the reflection event appeared (Figure 6).

The dimensionless amplitudes of ISW1, ISW3-ISW6 correspond to the case of $2a/h_2<2$, which are the small-amplitude mode-2 ISWs. The dimensionless amplitude of ISW2 corresponds to the case of $2a/h_2\geq4$, which are the mode-2 ISWs with very-large amplitude. Their wave front are smoother, and the tail are unstable. For ISW3- ISW6 with large pycnocline deviations, the waveforms become asymmetrical. The high frequency internal waves are more developed at their tail side.

Table 1. Characteristic parameters of the six mode-2 internal solitary waves in survey line 88.

ISW#	H (m)	Am (m)	h_2 (m)	a (m)	$2a/h_2$	hc (m)	1/2H (m)	Op(%H)
1	106.95	5.79	39.58	12.71	0.64	52.52	53.48	0.9
2	105.53	12.55	11.11	38.46	6.92	54.29	52.77	1.4
3	107.93	10.14	26.06	19.48	1.5	47.05	53.97	6.4
4	132.83	6.38	58.9	15.49	0.53	48.59	66.42	13.4
5	135.75	3.64	41.6	6.88	0.34	56.18	67.88	8.6
6	173.93	5.57	84.22	27.43	0.65	60.57	86.97	15.2

H, seafloor depths; Am, maximum amplitudes; h_2, equivalent pycnocline thicknesses; a, equivalent ISWs amplitudes; hc, the mid-depths of the pycnocline; Op, the degree to which the mid-depth of the pycnocline deviates from 1/2 seafloor depth.

4. Mdoe-2 ISWs phase velocity

Figure 7. The fitting curves of CMP-shot pairs obtained from the pre-stack migration sections of the COGs

The apparent phase velocities of these mode-2 ISWs calculated by the pre-stack migration profile using COG are about 0.5 m/s, and their apparent propagation directions are from SW to NE along the seismic line. The apparent velocity of mode-2 ISWs generally increases with the increasing depth of water (comparing ISW1, ISW3 and ISW5). In addition, the apparent phase velocity of the mode-2 ISWs with a larger maximum amplitude is generally larger (comparing ISW3 with ISW5).

Table 2. Apparent phase velocities of the six mode-2 internal solitary waves in survey line 88.

ISW#	H (m)	Am (m)	V_{seis} (m/s)	Da	V_{KdV} (m/s)
1	106.95	5.79	0.48±0.08	44°N	0.41
2	105.53	12.55	0.48±0.22	44°N	0.44
3	107.93	10.14	0.57±0.13	44°N	0.43
4	132.83	6.38	0.88±0.21	44°N	0.41
5	135.75	3.64	0.55±0.14	44°N	0.4
6	173.93	5.57	0.64±0.31	44°N	0.41

H, seafloor depths; Am, maximum amplitudes; V_{seis}, apparent phase velocities obtained from seismic observation; Da, apparent propagation directions; V_{KdV}, phase velocities obtained from KdV model.

5. Discussion

Figure 9. KdV theory fits the vertical amplitude distributions of the mode-2 ISWs.

Figure 10. The density curve at ISW1 (left). The corresponding geostrophic current velocity (the depth is 78 m below the sea surface) and sea surface height during the acquisition of the survey line 88 (right).

The red curves in Figure 9 are the vertical amplitude distributions of the mode-2 ISWs calculated by the KdV equation. The depth of the maximum vertical mode values are basically the same as the depth of the maximum amplitudes of the ISWs, and the observed variation trends of the ISWs amplitudes are also close to the theory. It can be seen that the survey line 76 is affected by the anticyclone edge (Figure 10). Anticyclone will decrease the depth of the thermocline in the surrounding sea water, while the deepening of the thermocline (pycnocline) is conducive to the generation of the mode-2 ISWs.

Conclusions

✓As to the mode-2 ISWs ISW4 located on the land slope, during the acquisition of about 50 seconds, the bifurcation and merger of the reflection event appeared.

✓The apparent phase velocity of these mode-2 ISWs calculated by the pre-stack migration profile using the Common Offset Gather (COG) is about 0.5 m/s, and their apparent propagation directions are from SW to NE along the seismic line (44 N, 0° pointing north).

✓The apparent velocity of mode-2 ISWs generally increases with the increasing depth of water. In addition, the apparent phase velocity of the mode-2 ISWs with a larger maximum amplitude is generally larger.

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Summary

- We used the seismic oceanography method to study the structural characteristics of internal solitary waves (ISWs) near the Strait of Gibraltar in the Mediterranean Sea, in the South China Sea and Pacific offshore Central America.
- In the pacific region offshore Central America, there are lots of mode-2 ISWs revealed from seismic oceanography data.
- Lots of legacy seismic data can be used to characterize ISWs in different continental margins
- New method (Prestack migration +PIV) can visualize ISWs evolution and sub-mesoscale processes

Thanks！

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