A precise bathymetric map of the world's deepest seafloor, Challenger Deep in the Mariana Trench

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Abstract Data from three bathymetric surveys by R/V *Kairei* using a 12-kHz multibeam echosounder and differential GPS were used to create an improved topographic model of the Challenger Deep in the southwestern part of the Mariana Trench, which is known as the deepest seafloor in the world. The strike of most of the elongated structures related to plate bending accompanied by subduction of the Pacific plate is N70°E and is not parallel to the trench axis. The bending-related structures were formed by reactivation of seafloor spreading fabric. Challenger Deep consists of three en echelon depressions along the trench axis, each of which is 6–10 km long, about 2 km wide, and deeper than 10,850 m. The eastern depression is the deepest, with a depth of 10,920 ± 5 m.

Introduction

Challenger Deep in the southwestern section of the Mariana Trench is recognized as the deepest seafloor in the world (Fig. 1). The trench is the boundary where the Pacific plate is subducting under the Philippine Sea plate. The pioneer British exploring ship *Challenger* visited the region during her 1873–1876 world voyage and found a bottom depth of about 8,200 m by sounding line (Thomson and Murray 1895: Table 1). In 1951, another British ship, the Admiralty's HMS *Challenger*, did echosounding and explosives profiling and found a maximum depth of 10,863 ± 35 m (Carruthers and Lawford 1952; Gaskell et al. 1953) In recognition of the work conducted on these two ships, the basin has been called Challenger Deep since 1952. In 1957, the Soviet R/V *Vitiaz* logged a maximum depth of 11,034 ± 50 m at 11°20.9′N, 142°11.5′E (Hanson et al. 1959). However, no cruise since has reported a seafloor depth exceeding 11,000 m in Challenger Deep. Bathymetric measurements using bomb-sounding and a frequency-controlled depth recorder on R/V *Stranger* in August 1959 and R/V *Spencer F. Baird* in 1962 revealed the deepest seafloor in two sedimented axial ponds to be 10,915 ± 10 m (Fisher and Hess 1963). A bathymetric survey by R/V *Stranger* in 1959 found two, possibly three, small elongated depressions deeper than 10,800 m between 142°35′E and 142°05′E (Fisher 2009). In January 1960, the bathyscaph *Trieste* reached seafloor in the western pocket and logged the depth as 10,913 ± 5 m using a manometer to record pressure (Table 2). Using a precision depth recorder with satellite positioning, the R/V *Thomas Washington* mapped one or possibly two axial basins with a depth of 10,915 ± 10 m in 1975 and 1980 (R. L. Fisher personal communication, 1998, 2010). In 1984, S/V *Takuyo*, from the Hydrographic Department of Japan, found three depressions with floors deeper than 10,900 m in Challenger Deep (Hydrographic Department, 1984). The ship employed a multibeam echosounder and reported a maximum depth of 10,924 ± 10 m at 11°22.4′N, 142°35.5′E in the eastern depression. Prior to the *Takuyo* survey, the deepest spot had been thought to be in the western depression. In 1983, the General Bathymetric Chart of the Oceans (GEBCO) Guiding Committee, considering the results of the survey by S/V *Takuyo* together with those by R/V *Thomas Washington*, concluded the maximum depth of Challenger Deep should be accepted as 10,920 ± 10 m (R. L. Fisher personal communication, 1998, 2010). Soon thereafter, several bathymetric

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investigators reported different positions and depths in this area (e.g., Fujimoto et al. 1993; Fujioka et al. 2002; Taira et al. 2005), arguably leaving the exact location and depth of the deepest seafloor unresolved.

Previous seismic and bathymetric studies (Fryer et al. 2003; Gvirtzman and Stern 2004; Miller et al. 2006) show an N–S trending tear in the slab around the southern part of the Mariana Trench. They suggest that the cause of the great depth of the Challenger Deep is partly a result of the subducting lithosphere in the southern part of the Mariana Trench tearing away from the northern part.

The remotely operated vehicle (ROV) *Kaiko* dived in the Challenger Deep for biological studies during three cruises of R/V *Kairei* in 1998, 1999, and 2002 (Hashimoto 1998, 2002; Barry and Hashimoto 2009: Table 2). Bathymetric surveys using a multibeam echosounder on R/V *Kairei* examined the topography of the outer slope of the southern Mariana Trench. In this paper, we describe the topographic expression of the outer slope and identify the deepest seafloor using the bathymetric data obtained during the three cruises.

Data and Methods

A regional bathymetric survey of the Challenger Deep was conducted in 1998 by R/V *Kairei*, Japan Agency for Marine-Earth Science and Technology, using a SeaBeam 2112 multibeam echosounder. The SeaBeam 2112 operates at 12 kHz with a 2° by 2° beam width and can produce up to 149 beams across a 150° wide swath. The *Kairei*'s sonar appears to achieve about an 80° swath at depths below 10,000 m (Nakanishi 2011a). Based on the results of the regional bathymetric survey in 1998, R/V *Kairei* carried out a more focused bathymetric survey in 1999. Ship tracks were designed to cross the deepest points determined by the 1998 survey in each depression (Fig. 2a). In 2002, R/V *Kairei* conducted a detailed bathymetric grid survey with an interval of 6 arc seconds (about 180 m) around the candidate site for the deepest seafloor. The ship speed during the survey in 1998 was 10–15 knots; however, in 1999 and 2002, a slower speed of about 5 knots was used to reduce the spacing of bathymetric data.

To process the bathymetric data and to make maps, MB-System (Caress and Chayes 1996), Generic Mapping Tools (Wessel and Smith 1998), and Marine Geophysics Basic Tools (MAGBAT; Tamaki et al. 1992) were used. Bathymetric data were passed through a despiking algorithm that filtered the unflagged data automatically using MB-System's filtering tool, *mbclean*. All beams were then manually edited using *mbedit,* MB-System's visually interactive ping-editing tool, to remove bad beams missed during the filtering step and to revive good beams flagged incorrectly.

To increase the reliability of bathymetric data, we constructed sound-velocity profiles of each cruise from the continuous measurements of vertical conductivity, temperature, and depth (CTD). CTD measurements down to about 10,780 m were simultaneously carried out by the instrument in ROV Kaiko during its dives in the 1998 and 1999 cruises. Because of the lack of CTD measurements in depths shallower than 20 m, sound-velocity profiles in depths shallower than 20 m were made using expendable bathythermographs during each cruise. The sound velocity at sea surface was automatically measured during the surveys by the sound velocity-meter unit of the *Kairei*'s SeaBeam 2112. We used Del Grosso's (1974) equation to calculate sound velocities. For the bathymetric data obtained in the 2002 cruise, we adopted the sound-velocity profiles made from the CTD measurements in the 1999 cruise because the CTD instrument was malfunctioning during the 2002 cruise. The absolute accuracy of sound speeds by CTD measurements is something better than 0.5 m/s (Sea-Bird Electronics, Inc. 2004). The relative sound velocity uncertainty due to the error of CTD measurements is less than 0.05 m/s, which does not have efficient effect to estimate depth (Hammerstad 2001).

Positioning was achieved using the Skyfix differential global positioning system, a GPS positioning system that is based on clock and orbit corrections supplied by NASA's Jet Propulsion Laboratory, with a mean accuracy of < 3-5 m (Johnston 1994). This navigation system made it possible to determine the location of the deepest place more accurately than in previous surveys. The dynamic and follow up accuracies of the gyrocompass on R/V *Kairei*, Yokogawa CMZ500, are within ± 0.75° × secant(latitude) and within 0.1° or less, respectively. The vertical reference unit in the *Kairei*'s SeaBeam2112 is Datawell HIPPY 120C Mark II, which is commonly used in SeaBeam systems. Asada and Yabuki (2001) reported that the HIPPY-120C on S/V *Kaiyo* of Hydrographic and Oceanographic Department, Japan Coast Guard, provided an accuracy of a few cm for the heave measurement and accuracy of 0.05° for the rolling and pitching.

The SeaBeam 2112 system is capable of a depth accuracy (per-beam repeatability) of 0.5% of

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water depth on at least 90% of the beams. The depth accuracy of the *Kairei*'s Seabeam 2112 is better than 0.5% of water depth in deeper than 9,000 m of water depth and that of center beam is better than 0.1% of water depth (Nakanishi 2011a). The scatter in the raw bathymetric data makes it difficult to determine a maximum depth with more accuracy than has been reported in previous works. Consequently, we gridded the bathymetric data to reduce the scatter using a Gaussian weighted average (Caress and Chayes 1996) for each survey. We determined that a 250-m grid spacing should be used because the beam interval across the track is about 190 m and that along the track is 100–200 m. We used all beam data from the 1998 and 1999 surveys, but we used only center beam data for the 2002 survey to increase precision in depth and position measurements.

Results

Topographic features around the Challenger Deep

The bathymetric map (Fig. 2b) shows the change in strike of the trench axis around 142°20′E, being N85°E to the east and N80°E to the west of that longitude. Three en echelon depressions are located along the trench axis, and each depression is elongated in an about N75°E direction, which is not parallel with the trench axis (Fig. 3). The depressions bounded at the 10,850 m contour in Fig. 3 are 6–10 km long and about 2 km wide. ROV *Kaiko* dives showed that the seafloor of the western depression is soft and very smooth (Hashimoto 1998, 2002; Barry and Hashimoto 2009).

The other remarkable topographic feature in the study area is a set of many elongated ridges and escarpments, which are accompanied by plate bending on the outer slope (Fig. 2c). Our map reveals two distinct strikes for these structures, although previous works (e.g., Fryer et al. 2003) reported that their strikes are uniformly parallel to the trench axis. One strike is N85°E, the same as that of the trench axis around Challenger Deep. The other is N70°E and oblique to that of the trench. The structures parallel to the trench axis are located only near the trench axis. The strike of a trench and the inherited seafloor spreading fabric in the subducting plate are commonly considered to be factors controlling the strike of elongated topographic structures on the oceanward slope (e.g., Masson 1991; Kobayashi et al. 1998; Nakanishi 2011b). The control of the inherited seafloor spreading fabric operates when it is oblique to the trench axis by less than 25–30°. In all other cases, the elongated topographic structures are parallel or subparallel to the trench axis (Masson 1991; Kobayashi et al. 1998; Nakanishi 2011b). The discrepancy between the elongated structures striking N70°E and the trench axis implies that the structures result from reactivation of the seafloor spreading fabric.

The seafloor spreading fabric in the study area is obscured by the absence of magnetic anomaly lineations. The Japanese Lineation set, which is a Mesozoic magnetic anomaly lineation, exists in the East Mariana Basin, east of the Mariana Trench (Nakanishi et al. 1992a), leading Nakanishi et al. (1992b) to propose that the subducting plate along the southern part of the Mariana Trench is a part of the Pacific plate formed in the Mesozoic. The Japanese Lineation set has two strikes. Lineations older than chron M21 (about 148 Ma) strike N45°E, and those younger than chron M20 (about 147 Ma) strike N70°E. The strike of the elongated structures south of the trench is the same as that of lineations younger than chron M20. If the elongated structures are caused by reactivation of the seafloor spreading fabric, the age of the subducting plate in the study area is younger than chron M20 and not the same as that of the East Mariana Basin. This indicates that the age of the subducting plate is not the cause of the great depth of the Challenger Deep.

The topographic expression of the elongated structures is a half graben with ridge and escarpment rather than full graben. The spacing of ridges is 3–5 km, and their heights are 200–400 m. Full-graben structure generally develops parallel to the trench axis (Masson 1991; Ranero et al. 2005; Nakanishi 2011b). Studies of other trenches (e.g., Ranero et al. 2005; Nakanishi 2011b) have also shown that the dominant topographic expression is a half graben in places where the seafloor spreading fabric has been reactivated. The studies support that the elongated structures in the study area are the result of a reactivation of the seafloor spreading fabric.

The deepest place in Challenger Deep

The regional bathymetric map made from the data obtained in 1998 shows that the greatest depths in the eastern, central, and western depressions are 10,922 ± 74 m, 10,898 ± 62 m, and 10,908 ± 36

m, respectively, making the eastern depression the deepest of the three (Fig. 3, Table 3). The western depression in the 1998 survey had a much larger number of data points because the dive sites of ROV *Kaiko* were located there and bathymetric data were collected between the dives. The uncertainty of the depths is calculated as two times the standard deviation of the data within a 380-m-diameter circle centered on the deepest places, because a multibeam echosounder beam represents an average depth over the beam footprint, which at depths of about 10,900 m has a 380-m diameter (radius = $10,900 \times \tan(1°)$). The standard deviations of the eastern, central, and western depressions are 37.2, 31.1, and 18.2 m, respectively (Table 3). The larger standard deviations of the eastern and central depressions are the result of the smaller number of data points and the configuration of ship tracks (Fig. 2).

To confirm the accuracy of the bathymetric grid file, we compared the depths at the dive sites of ROV *Kaiko* in the 1998 cruise extracted from the bathymetric grid file with the depth data obtained by a manometer installed on the vehicle of ROV *Kaiko* (Fig. 3). The positioning accuracy for the vehicle of ROV *Kaiko* using the Long Base Line acoustic navigation system is within 25 m in any depth (Kyo et al. 1995).

The precision of the manometer is 0.025% of its full scale, that is, less than 3 m at a depth of 10,000 m. The discrepancy between the bathymetric data of the bathymetric grid and the depth data of the manometer is about ± 2 m, indicating that our bathymetric grid file is in good agreement with the manometer data. The sediment in the Challenger Deep is very soft (Barrry and Hashimoto 2009). In soft sediment, acoustic beams from SeaBeam2112 may penetrate the seafloor and result in a deeper depth than the true depth. The consistency of our bathymetric data with the depth data of the manometer indicates that the effect of penetration of acoustic beams in soft sediment is negligible. The agreement also validates our estimation of depth using the sound speed profiles.

On 31 May 2009, the hybrid remotely operated vehicle (HROV) *Nereus* reached a depth of 10,903 m at 11°22.1′N, 142°35.4′E in the eastern depression of the Challenger Deep (Bowen et al. 2009; Fletcher et al. 2009; Table 2). The depth of the landing site, 10,903 m, is 14 m shallower than that of our result. The discrepancy seems to be the result of the precision of navigation of the dive because it was positioned without long-baseline navigation (Whitcomb et al. 2010).

The cross track survey in the 1999 R/V *Kairei* cruise shows that the greatest depths in the eastern, central, and western depressions are 10,920 ± 10 m, 10,894 ± 14 m, and 10,907 ± 13 m, respectively, which supports the results of the 1998 survey (Fig. 3, Table 3). The discrepancy between the 1998 and 1999 surveys in the position of the deepest places in each depression is less than 360 m (Table 3), which is smaller than the diameter of the footprint around the center beam. We concluded that the deepest places in each depression determined by the 1998 and 1999 surveys are in the same positions. The detailed grid survey in 2002 showed that the deepest site is located around 11°22.260'N, 142°35.589'E, with a depth of 10,919.7 m (Fig. 4), about 290 m southeast of the deepest site determined by S/V *Takuyo* in 1984 and about 240 m east of the deepest place determined by the 1998 survey. The distances are again smaller than the footprint of the center beam. We conclude that our result is compatible with that determined by S/V *Takuyo*.

There are 19 sounding points in a circle 380 m in diameter at the center of the deepest point, and the depth ranges from 10,915 m to 10,926 m within that circle (the red broken circle in Fig. 4). The mean, median, and mode of the data are all 10,920 m, and the standard deviation is 2.5 m. We consequently recognize the deepest location in the Challenger Deep to be 10,920 ± 5 m, which is the same as that determined by GEBCO but with a lower uncertainty. Our result also indicates that the 95% of depth differences repeatability of the center beam is better than 0.05% of depth at a depth of about 10,900 m.

Conclusions

Three bathymetric surveys by R/V *Kairei* construct a precise bathymetric map of the Challenger Deep and reveal the following:

1. The Challenger Deep has three depressions with depths greater than 10,850 m.
2. Elongated topographic structures accompanied by plate bending exist in the oceanward slope of the Challenger Deep.
3. The elongated structures have two strikes. One is N85°E and the same as the trench axis. The other is N70°E.
4. Most bending-related structures, except those near the trench axis, were formed by reactivation of seafloor spreading fabric.
5. The deepest seafloor in the world is located in the eastern part of the eastern depression at a

depth of 10,920 ± 5 m.

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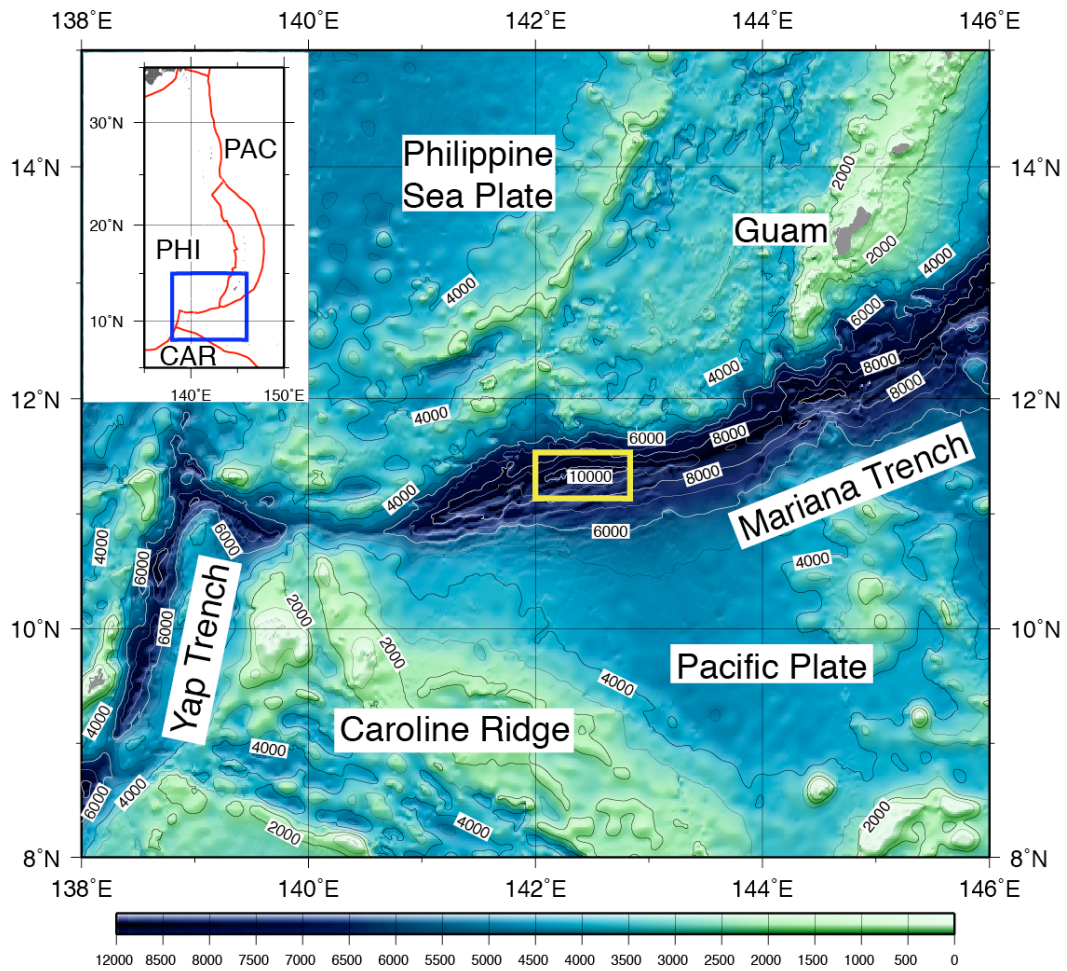
Fig. 1 Bathymetric chart around the southern Mariana Trench (contour interval = 1000 m). Seafloor topography is from Smith and Sandwell (1997). White contour lines indicate depths of deeper than 6,000 m. The yellow rectangle encompasses the study area (Fig. 2). The index map shows the location of this map relative to other northwest Pacific features. The red lines represent the present plate boundaries from Bird (2003). PAC, PHI, and CAR denote Pacific, Philippine Sea, and Caroline plates, respectively
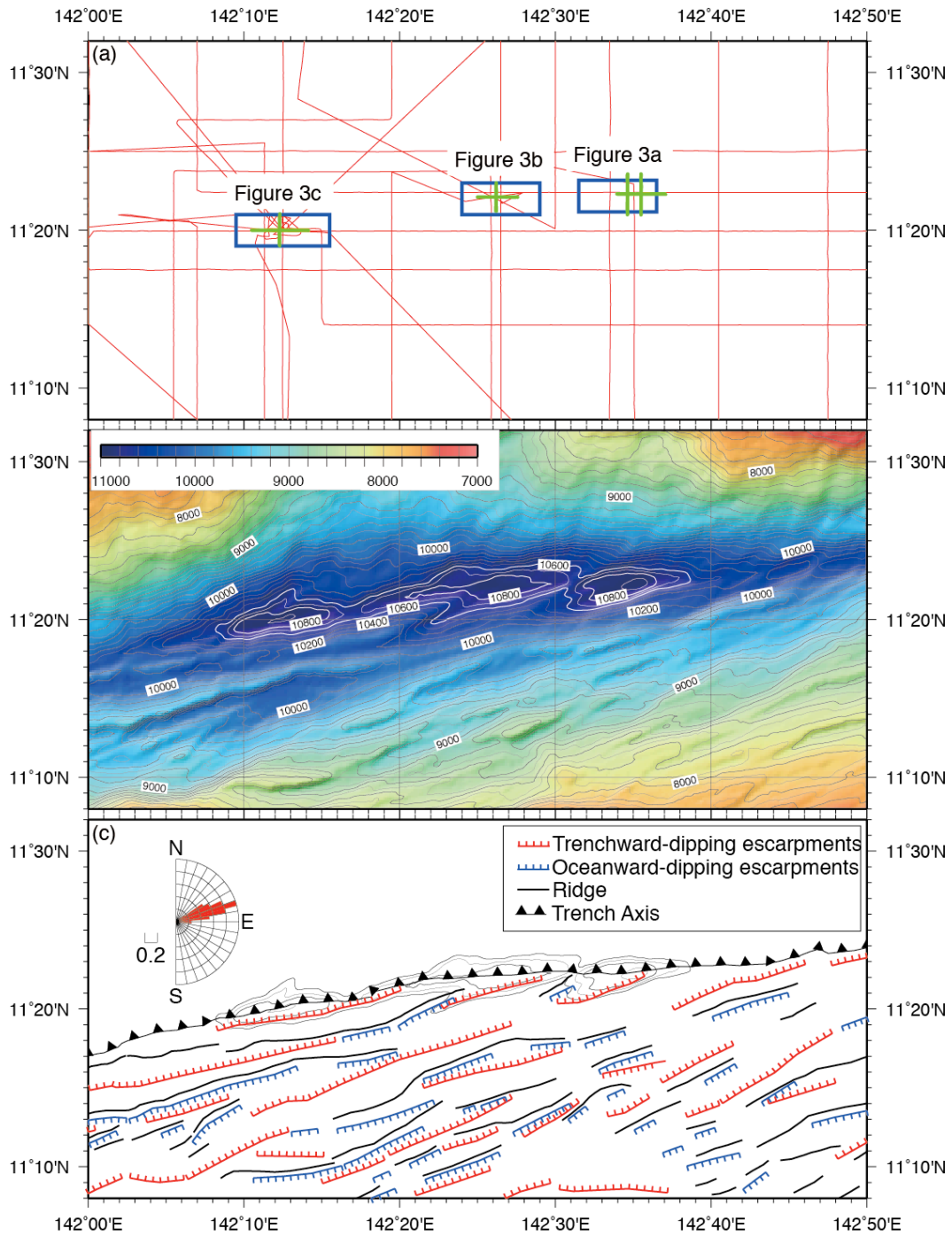
Fig. 2 (a) Track chart of the 1998 and 1999 R/V *Kairei* cruises used in this study. The blue rectangles represent the areas shown in Fig. 3. Red and green lines are tracks of the cruises in 1998 and 1999, respectively. (b) Bathymetric map (contour interval = 100 m). White contour lines indicate depths of deeper than 10,600 m. (c) Distribution of topographic structures related to plate bending. Rose diagram shows the strikes of bending-related topographic structures
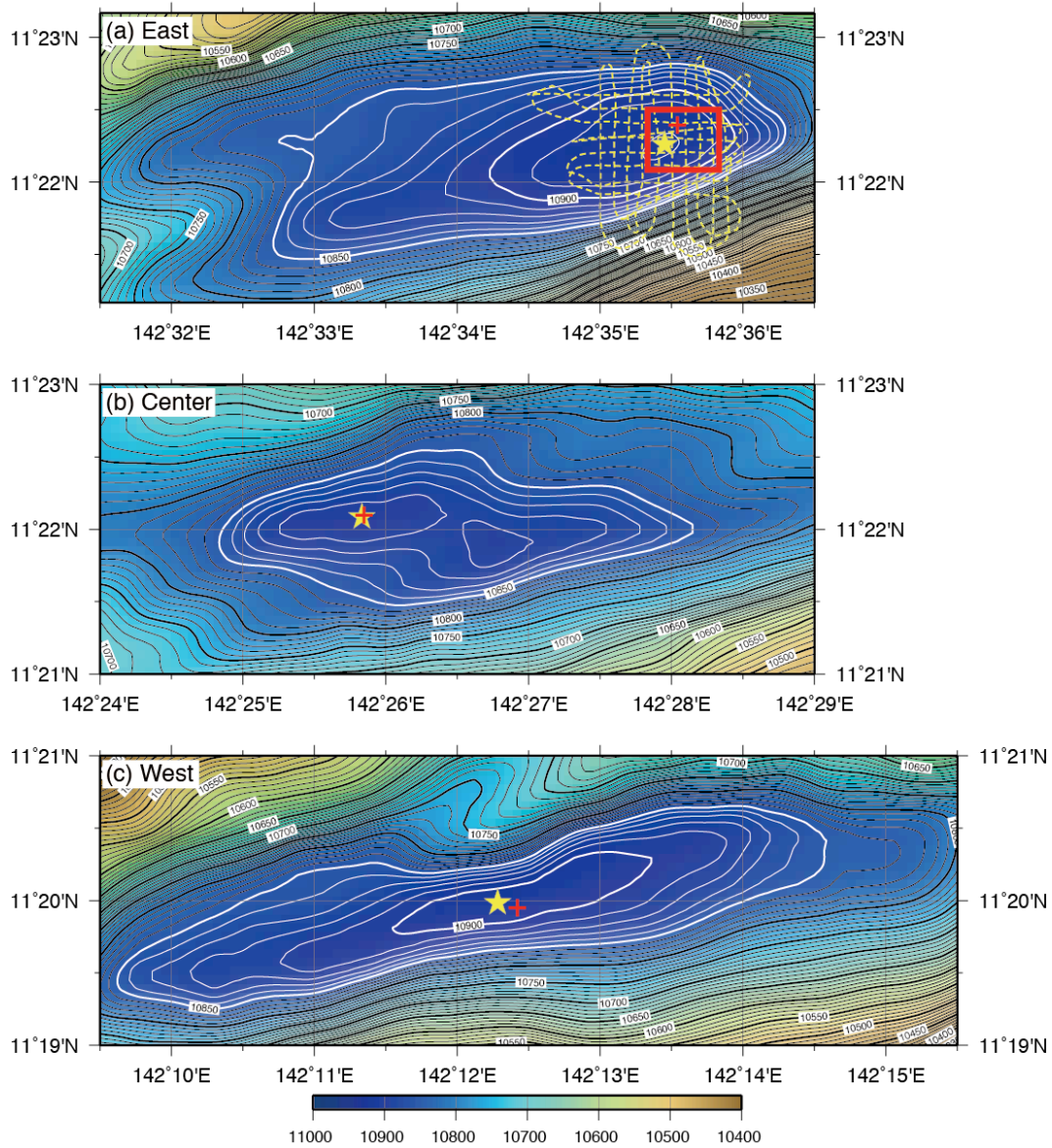
Fig. 3 Bathymetric maps of three depressions made using the bathymetric data of the 1998 R/V *Kairei* survey (contour interval = 10 m). White contour lines indicate depths of 10,850 and 10,900 m. Yellow stars represent the deepest points in each depression determined by the 1998 R/V *Kairei* survey, and red crosses are the selected dive sites of ROV *Kaiko* from 1995 to 1999 (Tables 2 and 3). The red box in (a) encompasses the area shown in Fig. 4, and the yellow dashed lines show the track lines of the 2002 R/V *Kairei* survey
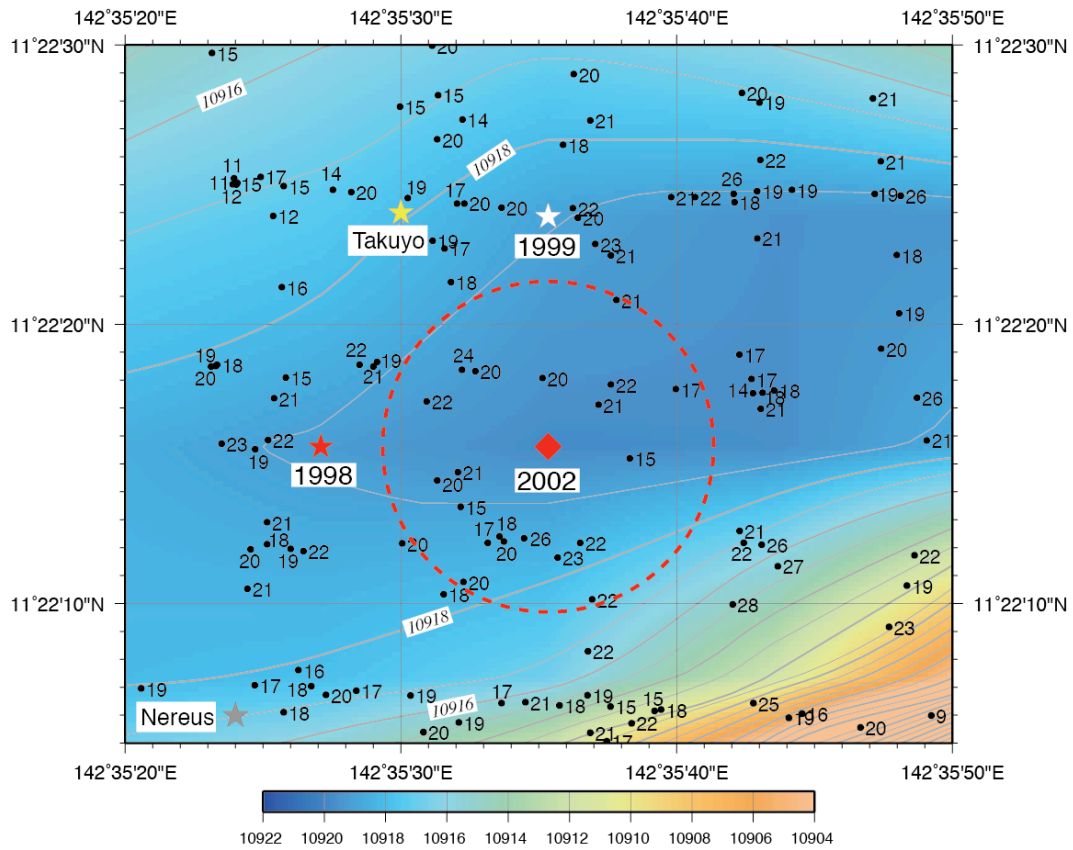
Fig. 4 Data plot of the center beams obtained during the 2002 R/V *Kairei* survey with 1-m contour lines superimposed for reference. Numbers show depths after subtracting 10,900. The red diamond is the deepest place determined in the 2002 R/V *Kairei* survey. Red, white, and yellow stars represent the deepest seafloors determined by the data from the 1998 R/V *Kairei* survey, the 1999 R/V *Kairei* survey, and the 1984 S/V *Takuyo* survey, respectively. The gray star shows the dive site of HROV *Nereus* in 2009 (Table 2). The Red dashed circle is the beam width of the center beam at 10,900 m

Table 1 Selected sounding results in the Challenger Deep

Year	Vessel	Depth (m)	Position Latitude	Position Longitude	Reference
1875	*HMS Challenger*	8,184	11°24′N	143°16′E	Thomson and Murray (1895)
1951	*Challenger VIII*	10,863±35	11°19′N	142°15′E	Carruthers and Lawford (1952)
1957	*Vitiaz*	11,034±50	11°20.9′N	142°11.5′E	Hanson et al. (1959)
1959	*Stranger*	10,850±20	11°20.0′N	142°11.8′E	Fisher and Hess (1963)
1962	*Spencer F. Baird*	10,915±20	11°20.0′N	142°11.8′E	Fisher and Hess (1963)
1975	*Thomas Washington*	10,915±10	11°20.0′N	142°11.8′E	R. L. Fisher (personal communication, 1998, 2010)
1980	*Thomas Washington*	10,915±10	11°20.0′N	142°11.8′E	R. L. Fisher (personal communication, 1998, 2010)
1984	*Takuyo*	10,924±10	11°22.4′N	142°35.5′E	Hydrographic Department, Japan Marine Safety Agency (1984)
1992	*Hakuho-maru*	10,933	11°22.4′N	142°35.5′E	Fujimoto et al. (1993)
1992	*Hakuho-maru*	10,989	11°22.6′N	142°35.0′E	Taira et al. (2005)
1998	*Kairei*	10,938±10	11°20.34′N	142°13.2′E	Fujioka et al. (2002)

Table 2 Selected dive sites in the Challenger Deep. The dive sites of ROV *Kaiko* and HROV *Nereus* are shown in Figs 2 and 3, respectively.

Year	Vehicle (Dive number)	Depth (m)	Latitude	Longitude	Reference
1960	Bathyscaph *Trieste*	10,913±5	11°19′N	142°15′E	Piccard and Dietz (1961)
1995	ROV *Kaiko* (Test dive)	10,911	11°22.39′N	142°35.54′E	Takagawa et al. (1997)
1996	ROV *Kaiko* (Dive 21)	10,898	11°22.10′N	142°25.85′E	Takagawa et al. (1997)
1998	ROV *Kaiko* (Dive 71)	10,907	11°19.95′N	142°12.42′E	Hashimoto (1998)
2009	HROV *Nereus* (Dive 11)	10,903	11°22.1′N	142°35.4′E	Bowen et al. (2009)

Table 3 Depths and positions of the deepest place in each depression determined by the 1998 and 1999 R/V *Kairei* surveys

Depression	Survey year	Position		Depth (m)	Standard deviation (m)	Final depth (m)	Number of data points*1
		Latitude	Longitude				
East	1998	11°22.260'N	142°35.452'E	10,922.0	37.2	10,922±74	18
	1999	11°22.398'N	142°35.589'E	10,919.5	5.2	10,920±10	21
Center	1998	11°22.085'N	142°25.833'E	10,897.7	31.1	10,898±62	29
	1999	11°21.986'N	142°25.696'E	10,894.7	7.1	10,894±14	43
West	1998	11°19.985'N	142°12.283'E	10,907.6	18.2	10,908±36	424
	1999	11°19.924'N	142°12.367'E	10,906.6	6.5	10,907±13	47

*1: Number of data points within a 380-m-diameter circle centered on the deepest place.