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Deep CTD Casts in the Challenger Deep, Mariana Trench

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On 1 December 1992, CTD (conductivity-temperature-depth profiler) casts were made at three stations in a north-south section of the Challenger Deep to examine temperature and salinity profiles. The station in the Challenger Deep was located at 11°22.78′ N and 142°34.95′ E, and the CTD cast was made down to 11197 db or 10877 m, 7 m above the bottom by reeling out titanium cable of 10980 m length. The southern station was located at 11°14.19′ N and 142°34.79′ E, 16.1 km from the central station, where water depth is 9012 m. CTD was lowered to 7014 db or 6872 m. The northern station was located at 11°31.47′ N and 142°35.30′ E, 15.9 km from the central station, and CTD was lowered to 8536 db or 8336 m, 10 m above the bottom. Below the thermocline, potential temperature decreased monotonously down to 7300–7500 db beyond a sill depth between 5500 m and 6000 m, or between 5597 db and 6112 db, of the trench. Potential temperature increased from 7500 db to the bottom at a constant rate of 0.9 m°C/1000 db. Salinity increased down to 6020–6320 db, and then stayed almost constant down to around 9000 db. From 9500 db to the bottom, salinity increased up to 34.703 psu at 11197 db. Potential density referred to 8000 db increased monotonously down to about 6200 db, and it was almost constant from 6500 db to 9500 db. Potential density increased from 9500 db in accordance with the salinity increase. Geostrophic flows were calculated from the CTD data at three stations. Below an adopted reference level of 3000 db, the flow was westward in the north of Challenger Deep and eastward in the south, which suggests a cyclonic circulation over the Challenger Deep. Sound speed in Challenger Deep was estimated from the CTD data, and a relation among readout depth of the sonic depth recorder, true depth, and pressure was examined.

Keywords:
· CTD casts in Challenger Deep,
· temperature and salinity in Mariana Trench,
· geostrophic shear in the deep trench,
· sound speed in Challenger Deep,
· titanium alloy cable and the CTD winch system.

1. Introduction

Many oceanographers have accepted the challenge of measuring water properties in the deep trenches in the world, especially in the Challenger Deep of 11034 m depth in Mariana Trench. Ordinary steel wire cannot be safely reeled out more than about 7 km because a safety factor, the ratio of breaking strength to the load, is not more than 2 due to the weight of the wire itself. The safety factor 2 is a minimum for safe operation of oceanographic winch wire to avoid breakage. Mantyla and Reid (1978) measured temperature, salinity and dissolved oxygen down to 11215 db at the bottom of the Challenger Deep with reversing thermometers and sampling bottles carried by a free fall vehicle. Roemmich *et al*. (1991) observed temperature and salinity with a conductivity-temperature-depth profiler (CTD) down to 6404 db in the Mariana Trench. The CTD sensors have limited depth capability of 6000 db or 6500 db, and a super deep CTD is under development to examine continuous profiles of temperature and salinity in deep trenches. CTD operation needs an electric cable for power supply and data transmission, and lightweight cable also has to be developed.

In 1989, R/V Hakuho Maru of Ocean Research Institute, the University of Tokyo, was built to replace the old vessel. The physical oceanography group made efforts to acquire a capability for direct measurement of temperature, salinity, and current velocity down to the deep places in the world, because the deepest trenches exist in the western Pacific Ocean. Current measurements were achieved in 1987 by developing a super deep cur-

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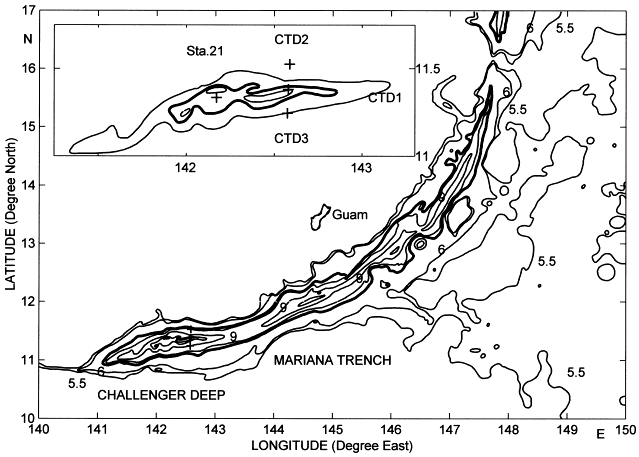

Fig. 1. Bottom topography of the southern portion of the Mariana Trench with isobaths of 5500 m, 6000 m, 7500 m (thick line), 9000 m, 10000 m and 10500 m. The inset panel shows the Challenger Deep described by isobaths of 9000 m, 10000 m (thick line) and 10500 m. Three CTD stations and Sta. 21 of INDOPAC-II are marked.

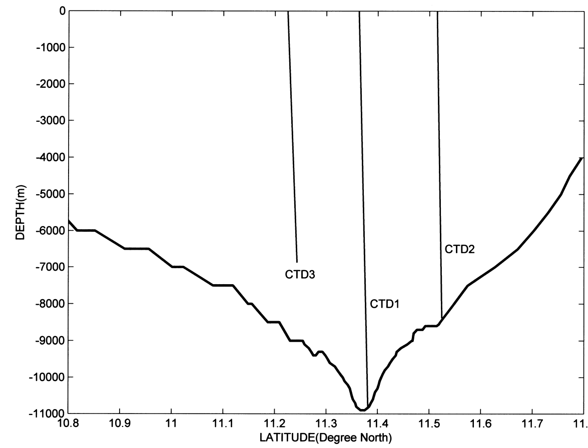

Fig. 2. A cross section of the Mariana Trench along 142°35′ E drawn by the data of Anonymous (1992), and the present observation. Positions of start and the deepest of the CTD casts are shown.

rent meter and an acoustic release contained in titanium alloy tubes (Taira *et al.*, 2004). In 1989, a super-deep CTD, model SBE-9, was developed by the Sea-Bird Inc. using a pressure housing of titanium alloy tube at our request.

The load of CTD cable is mainly the weight of the cable in water, and a light-weight cable is required. Although fiber rope is light, it is difficult to use for a winch due to frictional damage. Titanium alloy is as strong as steel, and the weight is 57% of steel. The titanium alloy cable was designed by Nippon Steel Corporation in 1989 at our request. However, it costs more than eight times as much as the steel cable. Funding was available to reel the cable in the winch drum in April 1992. The cable was composed of seven copper conductors, 1.35 mm in diameter, contained in a polyethylene inner tube, and a double armor of titanium strands, 1.04 mm diameter, i.e., 14 strands for the inner armor and 20 strands for the outer. The overall diameter was 8.15 mm, and the breaking strength was 3200 kg. The safety factor was 2 for 11 km layout in the water, i.e., 1342 kg, and a payload of 258 kg. A traction winch was used to avoid damage to the cable. The cable may be scratched by iron pulleys, and nylon plates were stuck on the contact faces of the traction winch, and those of the pulleys. A swell-compensator was used to reduce hydro-mechanical resistance caused by the up-and-down motion of the cable in the water.

Ship time of about 15 hours for the CTD casts in the Mariana Trench was available in the cruise for Tropical Oceans and Global Atmosphere programme (KH-92-5 Cruise). Three CTD casts were made, one in the Challenger Deep, one 15.9 km to the north and one 16.1 km to the south. The observed results are described in this paper. The readers can find the profiles in the Catalog of Ocean Research Institute for 1993–1997, and in other publications.

2. Operation of CTD

The CTD casts were made at three stations in the Mariana Trench as shown in Fig. 1. The ship cruised from the south, and CTD casts were made in order from south to north, CTD3, CTD1 and CTD2. Rosette samplers were removed from the frame because the depth capability of the controller was less than 7000 m. An acoustic pinger was used to detect the distance from the bottom.

The operation of CTD3, the southern station, was started at 06:43 (GMT) on 1 December 1992 at 11°13.47′ N and 142°35.42′ E, where readout depth was 8433 m. The depth was corrected to 8624 m as described in section 5. We limited the maximum depth to less than 7000 db for the first operation of the winch system beyond 6500 db. The cable was reeled out 6946 m at 08:49. The pressure was increased to 7014 db after a stop, corresponding to a depth of 6872 m (see Section 5). The position of the maximum pressure at the position of the station adopted was 11°14.19′ N and 142°34.79′ E, and corrected water depth was 9012 m.

The operation of CTD1, the central station, was started at 11:07 at 11°22.78′ N and 142°35.34′ E, where corrected water depth was 10888 m. At 13:39, the distance from the bottom was 7 m as measured by the pinger, at 11°22.78′ N and 142°34.95′ E. The maximum pressure was 11197 db, which corresponded to 10877 m. Depth of the station is estimated to be 10884 m by adding the dis-

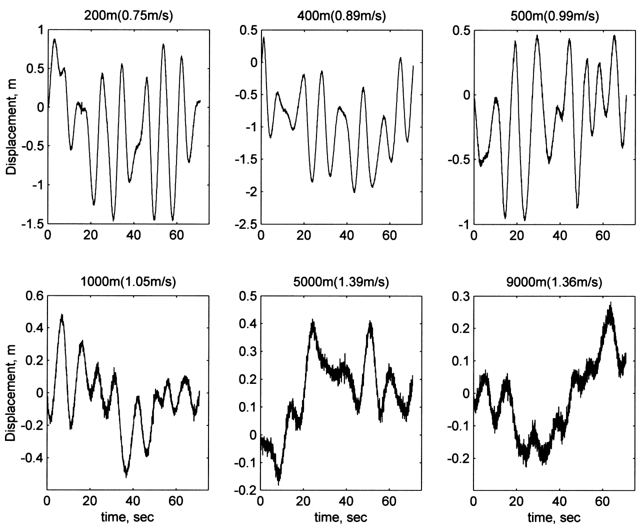

Fig. 3. Vertical displacements of the CTD sensor estimated from recorded pressure at six depths from 200 m to 9000 m. Mean descent speeds, shown in parentheses, are subtracted.

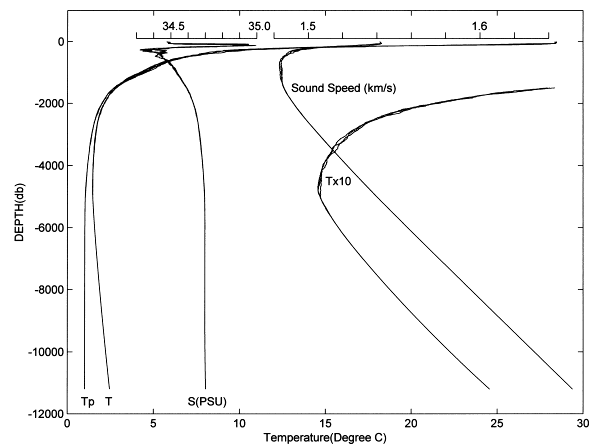

Fig. 4. In situ temperature T, multiplied by 10 times T × 10, potential temperature Tp, salinity S, and sound speeds observed at three stations.

tance measured by the pinger. However, the depth recorder gave a corrected depth of 10899 m, which may show bottom undulation. The reel out was 10980 m, and the remaining cable was in the last layer of the stock drum. The load on the cable was 1.37 ton, and the safety factor was 2.3.

The operation of CTD2, the northern station, was started at 17:01 at 11°30.89′ N and 142°35.47′ E, where the corrected depth was 8436 m. Rough sea prevented depth measurement after a reel out of 7000 m. At 19:18, the distance from the bottom was 10 m at 11°31.47′ N and 142°35.30′ E. The length of wire out was 8352 m. The maximum pressure was 8536 db, which corresponded to 8336 m, and the depth of the station was estimated to be 8346 m by adding the distance measured by the pinger.

The ship was maneuvered to keep the CTD cable ascending vertically into the water from the gallows. Figure 2 shows that the ship moved northward by 2.0 km for CTD1, 1.1 km for CTD2, and 1.3 km for CTD3. The ship also moved westward by 0.7 km for CTD1, 0.30 km for CTD2, and 1.1 km for CTD3. Ratios of the maximum depth of CTD sensor to cable reel out were 99.1% for CTD1, 99.8% for CTD2, and 98.9% for CTD3. This shows that CTD was lowered almost plumb vertically.

An active swell compensator, manufactured by Mitsubishi Heavy Industries, Ltd., was controlled by an integrated signal of the accelerometer mounted on a vertical gyroscope under the gallows. The double integration was done numerically (e.g., Taira *et al.*, 1971) by a process computer. The pneumatic piston stretches when the ship is descending, and contracts when ascending. The cable length is adjusted within ±2 m when the swell compensator is in operation. The swell compensator is used for a cable load exceeding 50 kg, or for a cable reel out of more than 300 m.

The CTD signal was recorded every 0.0417 seconds, or 24 samples per second. Figure 3 shows displacement for 70 s at several depths. The displacement was derived from pressure divided by in-situ density. Mean descending speed, shown in parentheses, was subtracted. Vertical amplitudes were about 2 m for 200 m depth with a period of about 10 s, which was caused by the rolling motion of the ship. At 300 m of wire out, the swell compensator started to work. The amplitude was about 1.5 m for 400 m depth, and 1.2 m for 500 m depth. The displacement for 1000 m depth had a periodicity of about 8 s, which was caused by the pitching motion of the ship. The amplitude was 0.4 m for 5000 m depth, and 0.2 m for 9000 m depth. The cable was reeled out by 8–14 m in 8 s of pitching motion or 10 s of rolling motion. The cable and the CTD frame had no ascending motion relative to the surrounding water, and the hydro-mechanical resistance was remarkably reduced. The swell compensator was considered to be effective in allowing the CTD sensor to descend plumb vertically.

3. Deep Structures of Temperature, Salinity, and Density

The CTD was first lowered down to about 5 m depth before a pump was run, then it was raised up within 0.5 m from the surface. We used this value as the sea surface data. Conductivity, temperature, and pressure, were averaged for each 1 db. Salinity and potential temperature were calculated by Unesco (1983).

Mantyla and Reid (1978) measured temperature and

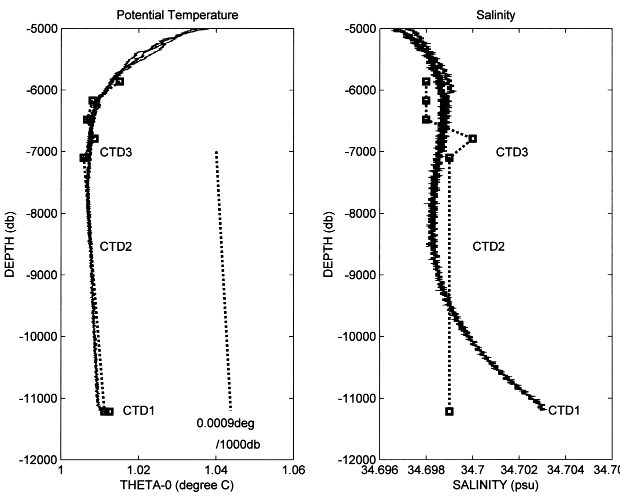

Fig. 5. Potential temperature (left panel), and salinity (right panel) below 5000 db. Squares show the data of INDOPAC-II Sta. 21. A dotted line shows temperature increase rate of 0.9 m°C/1000 db.

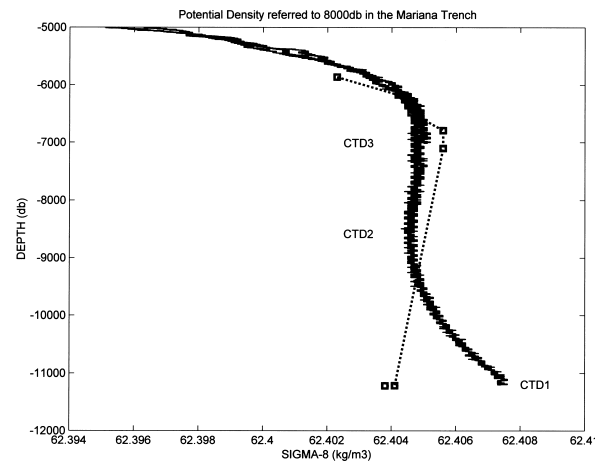

Fig. 6. Potential density referred to 8000 db below 5000 db. Squares show those calculated from the data of INDOPAC-II Sta. 21.

salinity by reversing thermometers and bottles at two stations in the Mariana Trench. One of their stations, INDOPAC-II Sta. 21, was at 11°20′ N, 142°10.3′ E in the Challenger Deep, as shown in Fig. 1. They used a free vehicle for the measurements at 11212 db and 11215 db. Our measurements did not include water sampling and calibration of the CTD sensors was done in 1989. We found that temperature of our measurement was higher by 0.004°C and that salinity was higher by 0.011 psu. The difference may be caused by drift of CTD sensors, and we simply subtracted 0.004°C for temperature and 0.011 psu for salinity.

Figure 4 shows temperature, salinity, potential temperature, and sound speed measured at three stations. A curve of temperature magnified 10X also shown in the figure. The sea surface temperature was 28.402°C (in ITS-90), and it decreased to a minimum of 1.455°C at 4700 db. Temperature increased in the deep layers due to adiabatic compression, and it was 2.455°C at 11197 db. Temperature change is clearly shown by the magnified curve. At the temperature minimum layer around 4700 db, temperature was slightly different, i.e., 1.455°C for CTD1, 1.470°C for CTD2, and 1.456°C for CTD3. Below the temperature minimum layer, the difference among three stations was small.

Sea surface salinity was 34.48 psu, and there was a maximum around 110–130 db: 34.99 psu for CTD1, 34.94 psu for CTD2, and 34.98 psu for CTD3. There was a salinity minimum around 260–310 db: 34.348 psu for CTD1, 34.336 psu for CTD2, and 34.393 psu for CTD3. Below the minimum layer, salinity increased to 34.699 psu at 6000 db.

Sound speed at the surface was 1542 m s^{-1}, and there was a minimum at 730–760 db: 1484 m s^{-1} for CTD1, 1483 m s^{-1} for CTD2, and 1484 m s^{-1} for CTD3. Below the layer, sound speed increased in the deeper layers, and it was 1653 m s^{-1} at 11197 db of CTD1.

The Challenger Deep is located in the southern portion of Mariana Trench separated by a sill 5500 m deep from the northern portion. Isobaths of 5.5 km, 6 km, 9 km, 10 km, and 10.5 km are shown in Fig. 1. The isobath of 5500 m (i.e., 5.5 km) extends to the outside of the trench, and the isobath of 6000 m encloses the trench. The sill depth of the trench is between 5500 m and 6000 m, or between 5597 db and 6112 db. Figure 5 shows potential temperature and salinity below 5000 db. Potential temperature had a random error of 3–5 db vertical wavelengths with amplitudes of 0.0002°C, and an average over 20 db was used for comparisons as described below. Potential temperature decreased gradually and the rate became smaller around 7000 db. There is a potential temperature minimum of 1.0067°C at 7300–7500 db. Below the minimum layer, potential temperature increased at a rate of 0.9 m°C/1000 db to the bottom. For example, potential temperature of CTD1 was 1.0071°C at 8000 db, and 1.0100°C at 11170 db. Squares in the left panel of Fig. 5 show the potential temperature observed by Mantyla and Reid (1978), who also show a temperature increase at a nearly equal rate.

The right panel of Fig. 5 shows the profile of salinity. Salinity also had a random error of 3–5 db vertical wavelengths with amplitudes of 0.0002 psu, and an average over 20 db was used below. At three stations salinity was 34.697 psu at 5000 db, and 34.699 psu at 6000 db. There was a salinity maximum: 34.6987 psu at 6320 db of CTD1, 34.6989 psu at 6250 db of CTD2, and 34.6991

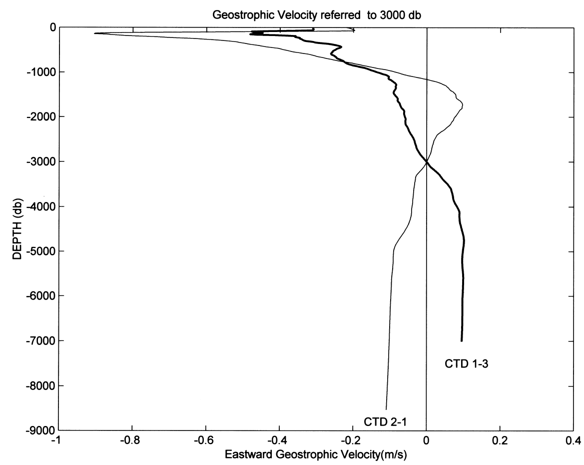

Fig. 7. Eastward geostrophic velocity referred to 3000 db, the thin curve for the north of Challenger Deep and the thick for the south.

psu at 6020 db of CTD3. Below the maximum layer there was a salinity minimum: 34.6982 psu at 8040 db of CTD1, and 34.6982 psu at 8180 db of CTD2. Below 10000 db salinity of CTD1 increased toward the bottom: 34.6999 psu at 10000 db, and 34.7030 psu at 11197 db. Squares in the panel show salinity measured by Mantyla and Reid (1978). Salinity was 34.700‰ at 6793 db, and 34.699‰ at 7103 db, 11212 db, and 11215 db, and the salinity does not increase at the bottom according to their measurement.

Figure 6 shows potential density referred to 8000 db. The potential density increased rapidly from 5000 d to about 6200 db, and it was homogeneous at 6500–9500 db. The random error in the potential density was with 3–5 db wavelengths and 0.0003 kg m^{-3} amplitudes. There was a maximum of 62.4048 kg m^{-3} at 6510 db, and a minimum of 62.4045 kg m^{-3} at 8490 db. The difference was as large as the random error, and we considered that density inversion did not occur. From 9500 db to the bottom, potential density increased in accordance with the salinity increase, and it was 62.4075 kg m^{-3} at 11197 db. The increase was ten times as large as the random error. The potential density estimated from salinity and temperature by Mantyla and Reid (1978) gave an inversion of potential density from 62.4056 kg m^{-3} at 7103 db to 62.4038 kg m^{-3} at 11215 db.

4. Geostrophic Flows

We made CTD casts at three stations in the Mariana Trench, one in the Challenger Deep, and the others 15.0 km north and 17.2 km south from the central station. Geostrophic flows were estimated from the observed temperature and salinity (e.g., Unesco, 1991). Figure 7 shows the geostrophic flows referred to 3000 db, CTD2-1 in the north of Challenger Deep, and CTD1-3 in the south. A westward flow prevailed in the upper layer, which may be the North Equatorial Current (e.g., Uehara and Taira, 1990). Surface velocities were –0.22 m s^{-1} in the north and –0.31 m s^{-1} in the south. The maximum speed of the westward flow was 0.48 m s^{-1} at 90 db in the south, and the flow exceeded 0.4 m s^{-1} at 80–170 db. In the north, the maximum speed of the westward flow was 0.91 m s^{-1} at 90 db and the flow exceeded 0.7 m s^{-1} at 110–210 db. The flow was eastward at 1160–3000 db with a maximum of 0.10 m s^{-1} at 1720 db in the north of Challenger Deep. In April 1992, Shinoda *et al.* (1995) observed the westward North Equatorial Current by ADCP in the southwest of Guam, around 11°N and 143°E, with surface velocity of 0.4–0.5 m s^{-1}. They did not observe a subsurface maximum of current speeds.

The surface velocities were smaller than those of subsurface maxima by 0.7 m s^{-1} for the north, and 0.2 m s^{-1} for the south. It seems that the winds from the west reduced the surface currents to the west. However, reduction of surface current by 0.7 m s^{-1} could be achieved by a steady wind with a speed of more than 20 m s^{-1}, which is too strong in the sea area. Salinity profiles in Fig. 4 show maxima centered around 120 db. The thickness of the high salinity water decreased from south to north: 105 db for CTD3, 88 db for CTD1, and 68 db for CTD2. Intrusion of the high salinity water from the south is suggested. Below the surface mixed layer of 60 db thickness, density varied among three stations down to about 140 db. Density at 80 db increased from south to north: σ_t = 25.83 kg m^{-3} for CTD3, σ_t = 26.40 kg m^{-3} for CTD1, and σ_t = 27.88 kg m^{-3} for CTD2. Geostrophic shears of 0.2 m s^{-1} and 0.7 m s^{-1} reflected the density distribution.

Below the reference level, the flow was opposite: eastward in the south of Challenger Deep, and westward in the north. The flows in the deep layers were 0.097 m s^{-1} for the former and –0.103 m s^{-1} for the latter. The opposite flows suggest a cyclonic circulation in the trench. We did current measurements in the Mariana Trench across the Challenger Deep from July 1995 to October 1996 (Taira *et al.*, 2004). The mooring stations were located 24.9 km north and 40.9 km south of the center of Challenger Deep. The array was designed to detect the cyclonic circulation along an isobath of about 7000 m in the southern portion of Mariana Trench. However, the observed currents were weak and the cyclonic circulation was not significant. The flows shown in Fig. 7 may be derived from an inadequate reference level or they may be confined in the center of the Deep, within 16 km north and south of the center as the separation of the CTD stations.

Table 1. Uncorrected depth calculated by a constant sound speed of 1500 m s^{-1} (RD), corrected depth (TD) and pressure (PR).

RD	TD	PR	RD	TD	PR	RD	TD	PR
10527	10902	11224	10528	10903	11225	10529	10905	11227
10530	10906	11228	10531	10907	11229	10532	10908	11230
10533	10909	11231	10534	10910	11232	10535	10912	11234
10536	10913	11235	10537	10914	11236	10538	10914	11237
10539	10915	11238	10540	10916	11239	10541	10917	11240
10542	10919	11242	10543	10920	11243	10544	10921	11244
10545	10922	11245	10546	10923	11246	10547	10924	11247
10548	10926	11249	10549	10927	11250	10550	10928	11251
10551	10929	11252	10552	10930	11253	10553	10931	11254
10554	10933	11256	10555	10933	11257	10556	10934	11258
10557	10935	11259	10558	10936	11260	10559	10937	11261
10560	10939	11263	10561	10940	11264	10562	10941	11265
10563	10942	11266	10564	10943	11267	10565	10944	11268
10566	10946	11270	10567	10947	11271	10568	10948	11272
10569	10949	11273	10570	10950	11274	10571	10951	11275
10572	10952	11276	10573	10953	11278	10574	10954	11279
10575	10955	11280	10576	10956	11281	10577	10957	11282
10578	10958	11283	10579	10960	11285	10580	10961	11286
10581	10962	11287	10582	10963	11288	10583	10964	11289
10584	10965	11290	10585	10967	11292	10586	10968	11293
10587	10969	11294	10588	10970	11295	10589	10971	11296
10590	10971	11297	10591	10973	11299	10592	10974	11300
10593	10975	11301	10594	10976	11302	10595	10977	11303
10596	10978	11304	10597	10980	11306	10598	10981	11307
10599	10982	11308	10600	10983	11309	10601	10984	11310
10602	10985	11311	10603	10987	11313	10604	10988	11314
10605	10989	11315	10606	10990	11316	10607	10990	11317
10608	10991	11318	10609	10992	11319	10610	10994	11321
10611	10995	11322	10612	10996	11323	10613	10997	11324
10614	10998	11325	10615	10999	11326	10616	11001	11328

5. Does the Maximum Depth of Challenger Deep Exceed 11000 m?

The thickness of the water column for one decibar was estimated from pressure divided by in-situ density, and by gravitational acceleration which is a function of latitude and pressure (Unesco, 1983). A sum of thickness from the surface to a certain pressure gives the true depth to the pressure. The depth of 10877 m was obtained for 11197 db, the maximum pressure at CTD1. The depth of 8336 m was for 8536 db at CTD2, and the depth of 6872 m was for 7014 db at CTD3. The estimates differed by less than 2 cm by using the CTD1 data for the remaining two stations

The travel time of sound waves was estimated by dividing the thickness of the water column for one decibar by the sound speed in the layer. Uncorrected depth, or readout depth, is obtained by multiplying a constant sound speed of 1500 m s^{-1} by the sum of the travel time. Table 1 shows readout depth (RD) and true depth (TD) for a pressure (PR) range from 11224 db to 11328 db. The sound speed and the in-situ density beyond 11197 db were calculated for a constant salinity at 11197 db and in-situ temperature estimated from that at 11197 db by calculating the adiabatic compression. Carter's (1980) Table gives the same true depth for readout depth down to 4000 m, and a greater depth by 2 m for 5000–8000 m, by 4 m for 9000–10500 m, and by 5 m for a readout depth exceeding 10600 m.

We used the multi-narrow beam profiler, SEA-BEAM 500, setup as a single beam depth recorder to obtain the readout depth. While conducting the operation at CTD1, we obtained readout depths of 10605 m and 10561 m at 11°22.6′ N and 142°35.0′ E, and 10549 m at 11°22.9′ N and 142°34.0′ E. The true depths were 10989 m, 10940 m and 10927 m, respectively.

In 1951, the Research Vessel Challenger VIII discovered the 10863 m Deep at 11°19′ N and 142°15′ E. In 1957, the Russian Research Vessel Vitiaz measured the maximum depth of 11034 m at 11°20.9′ N and 142°11.5′ E in the Challenger Deep (Hanson *et al.*, 1959; Fisher and Hess, 1963). In 1984, the Japanese Hydrographic Survey Ship Takuyo conducted a multi-narrow beam survey and found that the depth exceeded 10500 m at three places in Challenger Deep (see the inset panel of Fig. 1) and that 10924 m in the eastern place at 11°22.4′ N and 142°35.5′ E was the deepest (Anonymous, 1992). The depth, 10924 ± 10 m, was approved by International Hydrographic Organization in 1993 as the maximum depth of the Challenger Deep. Present CTD data were referred for the depth correction. The readout depth of Vitiaz is 10600 m, of which the true depth is 10983 m in Table 1. The readout depth of Takuyo is 10548 m, and the true depth in Table 1 is 10926 m. Fujimoto *et al.* (1993) resurveyed the Challenger Deep by the Sea Beam and obtained a readout depth of 10550 m, of which the true depth is 10928 m.

A half power point of beam width of the Sea Beam is 2.7 by 2.7 degrees, which covers an area of about 500 m by 500 m square at a depth of 11000 m. Taira and Takeda (1969) showed that recorded wave forms were distorted by measurements with a sonic wave gauge of a finite beam width mounted on the ship bow. Distance to a crest can be measured successfully, but the distance to the trough cannot be detected due to the reflection from the crests for waves shorter than the beam width. The wave gauge records a flat surface as high as the crest. When the wavelength is longer than the beam width, the gauge records a shallower trough due to reflection from the highest points within the beam width.

Our depth measurements were made while drifting at a ship speed of 0.9 km per hour at the station of CTD1. We considered that a trough deeper than Vitiaz's record by 5 m was detected by the slow drift. There is a possibility that a depth exceeding 11000 m with a horizontal scale less than the beam width of measurements exists in the Challenger Deep.

6. Discussion

Salinity increased in the bottom layer of Challenger Deep, up to 34.703 psu at 11197 db, as shown in the right panel of Fig. 5. High salinity water exceeding 34.70 psu has not been observed in the deep layer around Mariana Trench (e.g., Owens and Warren, 2001). Kawabe *et al.* (2003) observed high salinity water of 34.704 psu in Melanesian Basin around 9°N and 165°E at 5300 db. However, they show that salinity in the bottom layer in the western area is less than 34.700 psu. Mantyla and Reid (1978) observed a salinity of 34.699‰ at the bottom of Challenger Deep. Their station, INDOPAC-II Sta. 21 at 11°20′ N, 142°10.3′ E, is located in the central deep, one of three deep places in the Challenger Deep confirmed by the S/S Takuyo. Our station CTD1 was located in the eastern deep. We must wonder whether the high salinity water is supplied via an unknown path from the South Pacific Ocean to the eastern deep.

The salinity rise below 9500 db made the potential density increase to achieve a stable stratification. The potential density referred to 8000 db had a maximum of 62.4048 kg m^{-3} at 6510 db, where in-situ temperature was 1.6454°C and salinity 34.6988 psu. If we assume that the potential density at 11197 db is equal to that at 6500 db, the salinity of 34.6994 psu gives potential density of 62.4048 kg m^{-3} for the in-situ temperature of 2.4555°C. The salinity may be the same as that observed by Mantyla and Reid (1978) at the bottom of Challenger Deep. There remains a possibility that performance of our CTD system was not adequate enough for this subtle problem.

Direct current measurements may give an absolute reference for the geostrophic flow. Three current meters were moored at 9687 m, 10489 m and 10890 m in the center of the Challenger Deep for 442 days from 1 August 1995 to 16 October 1996 (Taira *et al.*, 2004). The depth of current meters was too great to be used for reference of the geostrophic flows shown in Fig. 7. The cyclonic circulation depicted by the geostrophic flows was not significant in the direct current measurement at 24.9 km north and 40.9 km south from the center of the Challenger Deep. The circulation may be confined within the CTD stations, i.e., ±16 km longitudinally. Johnson (1998) showed that the cyclonic circulation is formed by upwelling over a trench caused by intrusion of high density water into the bottom layer. The circulation was suggested to be caused by the bottom water intrusion into the Challenger Deep, not into the whole Mariana Trench.

7. Summary

We made CTD casts at three stations across the Challenger Deep. The deepest cast down to 11197 db was made in the Challenger Deep at 11°22.78′ N and 142°34.95′ E. Our observational results may be summarized as follows:

1) CTD operation by reeling out 10980 m of titanium cable was successfully accomplished by the winch system. Vertical motion of the CTD sensor at 9000 m depth was diminished to 10% of that at 200 m by the active swell compensator.

2) Below the thermocline, potential temperature decreased monotonously down to about 7300–7500 db beyond a sill depth between 5500–6000 m or 5597–6112 db. Potential temperature increased from 7500 db to the bottom at a rate of 0.9 m°C/1000 db. Salinity below the minima at about 300 db increased down to 6020–6320 db. From 9500 db to the bottom, salinity increased in the Deep.

3) Potential density referred to 8000 db increased monotonously down to about 6200 db at three stations, and it was almost constant from 6500 db to 9500 db. Potential density increased from 9500 db to the bottom in accordance with the salinity increase.

4) Geostrophic flows were calculated from the CTD data at three stations. High salinity water centered at 120 db was thicker in the southern station, and an eastward flow diminished the westward North Equatorial Current in the surface layer. Below the reference level at 3000 db, the flow was westward in the north of Challenger Deep and eastward in the south. A cyclonic circulation is suggested to form over the Challenger Deep.

5) Sound speeds in the Challenger Deep were estimated from the CTD data. For the uncorrected depth of 10605 m measured during the CTD operation, true depth was estimated to be 10989 m.

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