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978-1-107-01674-3 - The Hadal Zone: Life in the Deepest Oceans
Alan Jamieson
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Part I

History, geology and technology

Introduction

The history of hadal science is full of the legacies of inquiring scientists who dared to explore the unknown and push the boundaries of the seemingly impossible in order to satisfy human curiosity for the natural world. The story is equally fraught with academic minds who, in their time, publicly deemed impossible many of the fundamental facts about the deep sea that are now taken for granted. For example, deep-sea biologists had to contend with the infamous statement of Edward Forbes who claimed that life did not exist at depths greater than 600 m below sea level (Forbes, 1844). Similarly, over 100 years later, Pettersson (1948) also expressed doubt as to the existence of life deeper than 6500 m, ironically on the eve of the discovery of life at 7900 m (Nybelin, 1951). Challenging the likes of Forbes may indeed have inspired the pursuit of life to deeper than 600 m and may ultimately have led to the discovery of life at nearly 11 000 m, full ocean depth. Around this time, hydrologists navigating the seas discovered areas of ocean that were deeper than ever thought possible. These deep areas, now recognised collectively as the 'hadal zone', are extremely deep trenches, located at tectonic plate boundaries. However, even in the mid-1900s, the theory of plate tectonics and continental drift was still disregarded by many academics. In 1939, on the subject of plate tectonics and continental drift, the well-known geologist Andrew Lawson voiced the then current opinion of many when he said; 'I may be gullible! But I am not gullible enough to swallow this poppycock!' (Hsu, 1992).

The discovery and exploration of the hadal zone has been slow relative to that of other deep-sea habitats. The primary reason for this is that the area of seafloor which encompasses the trenches is small relative to the surrounding abyssal plains. Therefore, trenches were less likely to be encountered during standard sounding surveys. Furthermore, early sounding of extreme depths occurred before there were any theories to estimate how deep the ocean really was, and long before the development of plate tectonic theory. Thus, the trenches as we know them today, their existence and formation, were completely unheard of.

Today, we now not only understand tectonics, but we have also felt the presence of the trenches first hand. From a geological context, the trenches have never before been as conspicuous in the public domain. The 2010 Cauquenes earthquake off Chile (magnitude M_w 8.8) and the 2011 Tōhoku-Oki earthquake off Japan (magnitude M_w 9.0) were both the result of the geological activity of hadal trenches (the Peru–Chile and Japan Trenches, respectively). Furthermore, the latter and the 2004 Indian

Ocean earthquake (magnitude $M_w > 9$; triggered by the Java Trench) are remembered for the devastating tsunamis that followed.

From a biological perspective, progress in sampling the hadal zone has been slow and was initially hampered by the technological challenges associated with its sheer distance from the ocean's surface. Equipment had to be lowered through thousands of metres of water, a challenge once again exacerbated by the fact that full ocean depth was still to be determined. Before the onset of ship-mounted acoustic systems (echo-sounders), determining ocean depth would have been an extraordinarily laborious task. The hadal zone also presented a technical challenge in the form of extremely high hydrostatic pressure. Sampling equipment had to be capable of withstanding over 1 ton of pressure per square centimetre in order to resist implosion.

Despite these challenges, we now know the precise locations of the trenches and have made significant progress in understanding the biology and ecology of life in the deepest places on Earth, whilst having developed some sophisticated and innovative technology along the way. The first part of this book provides a brief synopsis of the people, projects and expeditions that paved the way in the exploration of the final frontier in ocean science (Chapter 1), examines the formation and location of the hadal zone (Chapter 2) and reviews the challenges and innovations of technology for full ocean depth (Chapter 3).

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1 The history of hadal science and exploration

The history of hadal science and exploration is a peculiar story and, largely due the challenges of sampling at such extreme depths, research effort seems to have occurred in waves. Major events in this history are often as disjunct as the trenches themselves. Around the turn of the twentieth century, early pioneers began sampling at greater and greater depths. Following the burst of curiosity concerning the extent to which animal life could be found and the true depths of the oceans, there was a lull in progress. It was in the 1950s when the first major hadal sampling campaigns began with the extensive series of Soviet RV *Vitjaz* expeditions and the round the world Danish RV *Galathea* expeditions. The *Vitjaz* continued to periodically sample the great depths for some time but, in general, research campaigns were few and infrequent. The first manned dive to the deepest place on Earth took place in 1960 amidst a myriad of public interest. However, it was the first and only time that this submersible ventured to the bottom of a trench.

The 1990s saw new interest in the trenches when the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) developed the first full ocean depth remotely operated vehicle (ROV) named *Kaikō*. *Kaikō* was used numerous times in the trenches and provided scientists with the tools to access full ocean depth. Aside from JAMSTEC, few other academic institutes were involved in hadal research until the mid-2000s.

We are now in an age where more countries are involved in hadal research than ever before, and the number of projects relating specifically to biology at full ocean depth are too many to mention. Scientists from the USA, UK, Japan, New Zealand and Denmark, among others, are prominently involved in active sampling at hadal depths. Coinciding with this work, scientists have supported high profile ‘firsts’ such as when the *Deepsea Challenger* submersible reached the deepest place on Earth. What actually sparked this recent wave of interest is unclear, but it may be attributed, like most eras in deep-sea research, to the development of new technology. It is also nice to think that this new found interest in the great depths is, in some way, a public response to an ever-changing climate; that people are becoming more aware of the urgency, the means that we possess and responsibility that we now have to investigate the ocean in its entirety; from the air–sea interface to full ocean depth.

1.1 Sounding the trenches

Since the days of Aristotle, the altitude of the land and the depth of the seas have prompted great curiosity. The first deep sounding expeditions began in 1773 with Lord Mulgrave's expedition to the Arctic Ocean, where a depth of 683 fathoms (1249 m) was recorded. In 1817–18, Sir John Ross recorded a depth of 1050 fathoms (1920 m) and collected a sediment sample using a wire deployed 'deep-sea clam' in Baffin Bay, east of Greenland. During the *Erebus* and *Terror* expeditions in 1839–43, Sir James Clark Ross used a 3600 fathoms (6584 m) long wire that was marked every 100 fathoms. The time interval between each mark was noted until the intervals significantly increased, where it was thought that the line had reached the bottom. The same technique was adopted during the British round-the-world expedition on the HMS *Challenger* (1873–76), under the leadership of Charles Wyville-Thomson (Thomson and Murray, 1895). Equipped with 291 km of Italian hemp for sounding wire, the HMS *Challenger* unexpectedly recorded a depth of 4500 fathoms (8230 m) in the northwest Pacific Ocean at latitude 11° 24' N, longitude 143° 16' E, southwest of the Mariana Islands and north of the Caroline Islands in the North Pacific Ocean. This sounding was the first measurement that indicated the existence of extraordinarily deep areas and, in due course, led to the discovery of the Mariana Trench. It was this *Challenger* expedition, the first global marine research campaign, that laid the framework for all future marine research.

At the time of the *Challenger* expeditions, scientists aboard the USS *Tuscarora* employed a similar method for sounding. They used piano wire to record a depth of 4665 fathoms (8531 m) in the Kuril–Kamchatka Trench in the northwest Pacific Ocean, originally coined the *Tuscarora Deep*.

Sir John Murray (1841–1914) documented the first systematic measurements of ocean depth distribution and mean depth of the oceans with which he calculated the first hypsometric curve, thus beginning the process of 'mapping' the oceans in three dimensions (Murray, 1888). Based on the available data of the day, he calculated the volume of the ocean, the volume of the continents above sea level and even the depth of a uniform ocean if the seafloor were level and no continents existed. Following on from the work of Murray (1888), sounding data became more numerous with time. Charts that mapped the oceans, such as those of E. Kossinna in 1921 and T. Stocks in 1938 (cited in Menard and Smith, 1966) were frequently produced and many studies relating to the nature of the seafloor and depth distribution were undertaken (e.g. Murray and Hjort, 1912; Menard, 1958; Menard and Smith, 1966).

Towards the turn of the twentieth century, new sounding devices were developed by the British Royal Navy, notably the *Hydra Rod* (so-called following its design by the blacksmith onboard the HMS *Hydra*) and the *Baillie rod* (named after the navigating lieutenant on HMS *Challenger* who designed it) (Thomson and Murray, 1895). The first depth sounding of greater than 5000 fathoms was recorded during a British expedition on the HMS *Penguin* in 1895 using a Baillie rod lowered with piano wire. They recorded a depth of 5155 fathoms (9144 m) in the Kermadec Trench in the southwest

Pacific Ocean off the north coast of New Zealand. Shortly afterwards, the German vessel *Planet* measured a greater depth in the Philippine Trench, where later, the Dutch would record an even deeper 5539 fathoms (10 319 m) using the first audio-frequency sounding methods onboard the *Willebord Snellius*. Using this primitive but pioneering audio-frequency technique of recording sound echo, the Scripps Institution of Oceanography's USS *Ramapo* measured a depth of 5250 fathoms (9600 m) in the Japan Trench (now known to be the Izu-Bonin Trench, south of the Japan Trench in the northwest Pacific Ocean). Another Scripps vessel, *Horizon*, also recorded 5814 fathoms (10 633 m) in the Tonga Trench (southeast Pacific Ocean) and named the site *Horizon Deep* (Fisher, 1954). Following these new findings, the German vessel *Emden* recorded a measurement of 5686 fathoms (10 400 m), once again in the Philippine Trench. The record for the greatest depth found was broken once more by the USS *Cape Johnson* during World War II, with a reading of 5740 fathoms (10 500 m) in the Philippine Trench off Mindanao, which was for years thought to be the deepest place on Earth (Hess and Buell, 1950). The method of projecting sound and recording the echo to measure the depths, coined 'echo sounding', was developed and quickly superseded wire-deployed methods.

The new echo-sounder method often relied on 'bomb sounding', whereby someone threw a half-pound demolition block of TNT off the ship to create the sound source from which the echo was received onboard the ship via a transducer amplifier (Fisher, 2009). This method, albeit primitive relative to today's technology, was accurate enough to distinguish between the trench floor at the axis and the trench slopes. It was used to sound the maximum depths of the Middle America, Tonga, Peru–Chile and Japan Trenches (Fisher, 2009). It ultimately led to the discovery of the deepest point on Earth: the *Challenger Deep* in the Mariana Trench (nearly 11 000 m; Carruthers and Lawford, 1952; Gaskell *et al*., 1953).

The ability to accurately sound the depths of the oceans using ship-mounted acoustic systems provided sounding data with relative ease, and with much greater replication and resolution than wire-deployed systems. Such accuracy led to several in-depth reports on the internal topography, morphology and sedimentation of some deep trenches, for example, Fisher (1954), Kiilerich (1955) and Zeigler *et al*. (1957). However, there was still the question of how the trenches were formed. Figure 1.1 shows how these early soundings were interpreted into three-dimensional topography and Figure 1.2 shows the equivalent data using modern sounding methods but based on the same principles.

1.2 Development of plate tectonic theory

The discovery of the deep trenches occurred long before the development of any theories relating to how they came to be. The discovery of continental drift, which, in turn, prompted the discovery of plate tectonics and convergence zones (where trenches occur), was nearly 360 years in the making. Abraham Ortelius (1596) first noted how

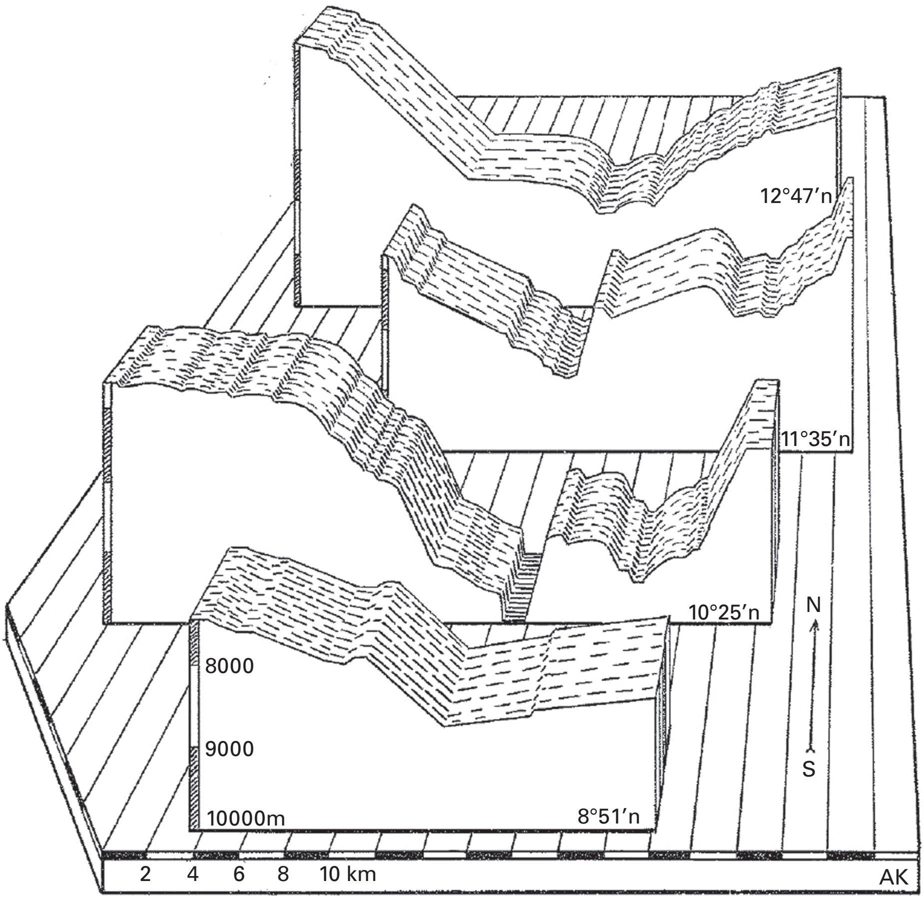

Figure 1.1 Trench bathymetry obtained using early sounding techniques: sections of the bottom of the Philippine Trench. From Kiilerich (1955); reproduced with the permission of *Galathea Reports*).

the continents, in particular South America and Africa, ‘seemed to fit together’ as if they had once formed a single land mass; an observation reiterated by others in the 1700s and 1800s (Romm, 1994). Around the turn of the twentieth century, Roberto Mantovani suggested the previous existence of a super continent (what is now known as Pangaea). However, credit for the development of continental drift theory, beyond simple observations of a ‘jigsaw-puzzle fit’, came from the German meteorologist Alfred Wegener (Wegener, 1912; Demhardt, 2005). Wegener hypothesised that the continents had once formed a single land mass prior to splitting apart and drifting to their current locations. The splitting apart of Pangaea was thought to have occurred by volcanic activity and this led Mantovani to suggest that the Earth was expanding (Mantovani, 1909). This was, of course, not the case and over the coming years various theories from Wegener and others were put forth ranging from lunar gravity driven drift, centrifugal pseudo-force and astronomical precession. None of them, however, proposed a sufficiently

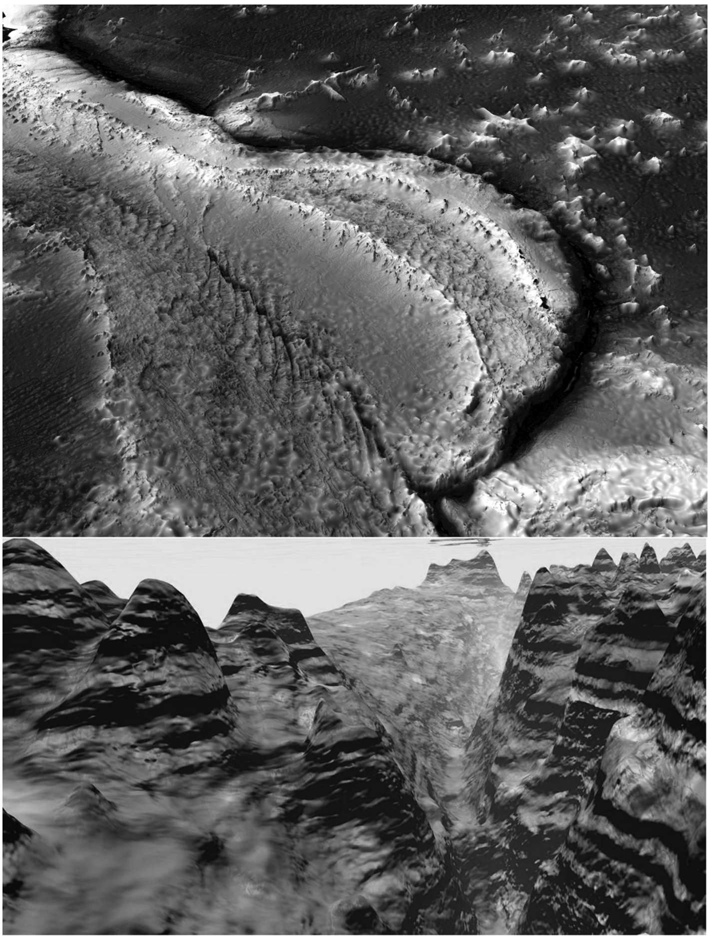

Figure 1.2 Examples of modern digital swathe bathymetry showing the three-dimensional bathymetry of the Mariana Trench. Above and below is a frame grab from a computer generated 'fly-through' movie, note the 100-fold vertical exaggeration. Images courtesy of Peter Sloss, NOAA/NGDC (retired).

strong force to explain the drift. In the absence of a driving force for continental drift, the theory was not accepted generally for many years and it sparked lively debates between 'drifters' (supporters of the theory) and 'fixists' (opponents of the theory) (Scheidegger, 1953).

An Australian geologist, Samuel Carey, advocated the continental drift theory of Wegener. Carey provided a mechanism to explain such processes whereby super continents divide and drift and cause the generation of new crustal zones in deep oceanic ridges. His theory, however, still backed the idea of an expanding Earth. Despite the eventual acceptance of plate expansion, the expanding Earth theory was erroneous.

Further support for continental drift came during the late 1950s and early 1960s as bathymetry of the deep ocean provided evidence of seafloor spreading along the mid-oceanic ridges (e.g. Heezen, 1960; Dietz, 1961; Vine and Matthews, 1963). The advances in early seismic imaging techniques along the deep trenches adjacent to many continental margins showed how the oceanic crust could 'disappear' into the mantle, providing evidence, for the first time, that was contrary to the expanding Earth theory. The disappearance of one crust beneath another was termed 'subduction' (Amstutz, 1951).

It was the onset of magnetic instruments (magnetometers) which provided unequivocal evidence of multiple lithospheric plates. Magnetometers, adapted from World War II airborne and submarine detection systems, identified unexpected magnetic anomalies and variations across the ocean floor. They detected volcanic rock (iron-rich basalt) which contained a strongly magnetic mineral (magnetite) that gave the basalt measurable magnetic properties. Furthermore, the Earth's magnetic field was recorded at the time when the newly formed rock was cooled. The magnetic variations turned out to be recognisable patterns and not random. A 'zebra-like' striped pattern emerged when a wide area of seafloor was scanned. These striped patterns were areas of normal polarity alternating with areas of reversed polarity.

The discovery of magnetic striping prompted theories that mid-ocean ridges were structurally weak zones, where the seafloor was being torn apart lengthwise along the ridge crest, pushed apart by magma rising up from the Earth's mantle through these weak zones to create new oceanic crust, a process we now know as 'seafloor spreading' (SFS). The SFS hypothesis represented major progress in the development of the plate tectonic theory.

The official acceptance of plate tectonics (originally termed 'New Global Tectonics') by the scientific community occurred at a symposium at the Royal Society of London in 1965. In addition to the discovery of seafloor spreading at divergent zones and subduction at convergent zones, adding the new concept of transform faults to the general tectonic model provided the final piece of the puzzle completing the explanation for tectonic plate mobility (Wilson, 1965). Two years later, at a meeting of the American Geophysical Union, it was proposed that the Earth's surface was made up of 12 rigid plates that move relative to each other (Morgan, 1968) and this was quickly followed by a complete model based on six major plates and their relative motions (Le Pichon, 1968).

In the 1960s and early 1970s frustration grew as identification of the structures that were diagnostic to the working of subduction processes was greatly inhibited by the technical challenges of extreme water depths and the steep slopes of the trenches (von Huene and Shor, 1969; Scholl *et al*., 1970). The extreme depths made conventional rock and sediment sampling by dredging difficult, while the steep trench slopes caused a reduction in the resolution of subsurface structures captured by the acoustic imaging techniques. Such techniques were, by then, available to most researchers (von Huene and Sholl, 1991). By the mid-1970s, offshore seismic reflection studies had resolved some of the important issues such as sediment subduction and accretion (Karig and Sharman, 1975; discussed in detail in Chapter 2).

Since the 1980s, advances in offshore geological and geophysical techniques and technologies have permitted the remote exploration of the deep subsurface structures of convergent margins (e.g. the Mariana Trench; Fryer *et al*., 2002). Swath-bathymetry now readily provides accurate areal images of the morphology of even the most complex topography, such as trenches, and it is able to do so with incredible detail and clarity (see Fig. 1.2).

1.3 Establishing full ocean depth

During the *Challenger II* expeditions in 1951, the vessel returned to the Mariana Trench in the northwest Pacific Ocean, this time equipped with an echo sounder. A depth of 5940 fathoms (10 860 m) was recorded at 11° 19' N, 142° 15' E (Carruthers and Lawford, 1952; Gaskell *et al*., 1953). In conjunction with the echo soundings, a Baillie rod was deployed, and on the third attempt a sample of 'red clay' was retrieved from the deepest point on Earth, newly named Challenger Deep. Challenger Deep is still regarded as the deepest point on Earth although the exact depth often varies. For example, in 1957, the Soviet vessel *Vitjaz* recorded 11 034 m (and dubbed the area the 'Mariana Hollow'; Hanson *et al*., 1959), whereas the American MV *Spenser F. Baird* recorded 10 915 m in 1962 and the Scripps INDOPAC expedition recorded 10 599 m in 1977 (Yayanos, 2009). A review by Angel (1982) states the maximum depth as 11 022 m but does not cite the source. JAMSTEC have visited Challenger Deep more times than any other country due to the construction of the full ocean depth rated ROV *Kaikō*, deployed from its mother ship RV *Kairei* (Mikagawa and Aoki, 2001). The Japanese literature states the depth of Challenger Deep as 10 890 m (Taira *et al*., 2004), 10 897 m (Takami *et al*., 1997), 10 898 m (Kato *et al*., 1997, 1998), 10 933 m (Fujimoto *et al*., 1993) and 10 924 m (Akimoto *et al*., 2001; Fujioka *et al*., 2002). On 24 March 1995, the ROV *Kaikō* descended to 10 911 m and placed a plaque bearing the name and date of the dive to officially mark the deepest point on Earth (Fig. 1.3).

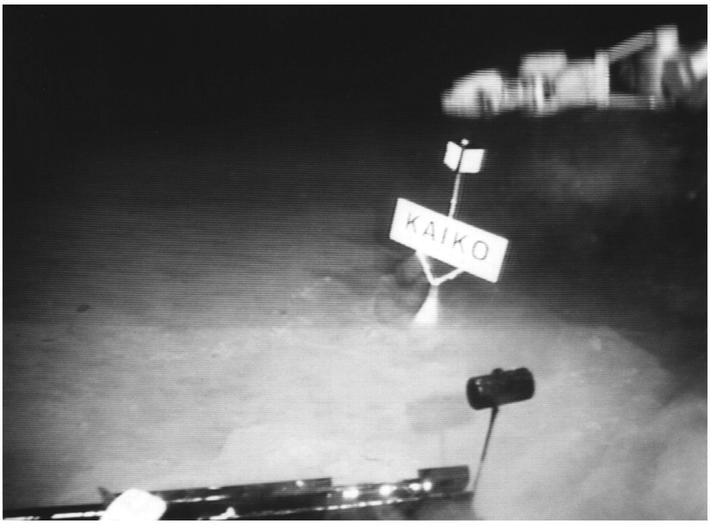

Figure 1.3 Video frame grab of the Japanese full ocean depth rated ROV *Kaikō* placing a flag to mark the deepest place on Earth; Challenger Deep, 10 911 m in the Mariana Trench. Image © JAMSTEC, Japan.

Table 1.1 Summary of both sounding and direct measurement of the deepest place on Earth; Challenger Deep in the Mariana Trench. Modified from Nakanishi and Hashimoto (2011).

Sounding

Year	Vessel	Depth (m)	Reference
1875	HMS *Challenger*	8184	Thomas and Murray (1895)
1951	*Challenger VIII*	10 863 ± 35	Carruthers and Lawford (1952)
1957	*Vitjaz*	11 034 ± 50	Hanson *et al.* (1959)
1959	*Stranger*	10 850 ± 20	Fisher and Hess (1963)
1962	*Spencer F. Baird*	10 915 ± 20	Fisher and Hess (1963)
1975	*Thomas Washington*	10 915 ± 10	R.L. Fisher (pers. comm. in Nakanishi and Hashimoto, 2011)
1980	*Thomas Washington*	10 915 ± 10	R.L. Fisher (pers. comm. in Nakanishi and Hashimoto, 2011)
1984	*Takuyo*	10 924 ± 10	Hydrographic Dept. Japan Marine Safety Agency (1984)
1992	*Hakuho-Maru*	10 933	Fujimoto *et al.* (1993)
1992	*Hakuho-Maru*	10 989	Taira *et al.* (2005)
1998	*Kairei*	10 938 ± 10	Fujioka *et al.* (2002)
1998/99	*Kairei*	10 920 ± 5	Nakanishi and Hashimoto (2011)

Selected dives

Year	Vehicle	Depth (m)	Reference
1960	Bathyscaphe *Trieste*	10 913 ± 5	Piccard and Dietz (1961)
1995	ROV Kaikō (test)	10 911	Takagawa *et al.* (1997)
1996	ROV Kaikō (Dive 21)	10 898	Takagawa *et al.* (1997)
1998	ROV Kaikō (Dive 71)	10 907	Hashimoto (1998)
2009	HROV *Nereus*	10 903	Bowen *et al.* (2009b)

In 2009, using a modern, deep-water multi-beam sonar bathymetry system, the American RV *Kilo Moana* sounded 10 971 m at Challenger Deep. The equipment is thought to have accuracy better than 0.2% of the depth, suggesting accuracy to within ±11 m (10 960–10 982 m). The area of Challenger Deep is, of course, unlikely to be flat and this accounts for the variation in exact depth measurements taken (the mean of the above depths is 10 908 m ± 114 S.D.). As technology improves in accuracy and precision, it is reasonable to assume the most up-to-date *in situ* value, in this case the 2009 RV *Kilo Moana* value of 10 971 m. However, a more recent study focused entirely on what the exact depth of the Challenger Deep is and concluded that it consists of three en-echelon depressions along the trench axis, each of which is 6–10 km long (~2 km wide), and each deeper than 10 850 m where the eastern depression is the deepest at 10 920 ± 5 m (Nakanishi and Hashimoto, 2011). Table 1.1 summarises the depth estimates and measurement by both sounding and *in situ* measurements.

Different instruments with varying accuracies and interpretations will undoubtedly produce more depth records in the vicinity of 10 900 m, but the important point is that the trench is ‘nearly 11 000 m’ deep and furthermore there are four other trenches that are also ‘nearly 11 000 m’ deep; the Philippine (10 540 m), the Kuril–Kamchatka (10 542 m), the Kermadec (10 177 m) and the Tonga Trenches (10 800 m).