

Chapter 2

Characteristics of the Sub-equatorial North-Eastern Pacific Ocean's Abyss, with a Particular Reference to the Clarion-Clipperton Fracture Zone

Abstract The deep seafloor, i.e. seabed areas at depths exceeding 800–1,300 m, cover about 88 % of the world ocean's bottom. The most extensive areas represent the 3,000–6,000 depth range and include abyssal plains (depths > 4,000 m) the largest of which is the abyssal plain of the Pacific Ocean. The water column overlying it consists of a number of layers differing in their major characteristics. The most characteristic layers include that encompassing the oxygen minimum zone (OMZ, 100–1,000 m depth range in the Pacific) and the near-bottom layer, directly impinging on the seafloor. Once considered extremely stable, the near-bottom layer is now known to be prone to hydrodynamic effects such as tides and currents. The latter are generally weak, but periods of intensified current activity are not infrequent. The water column effects influencing the abyssal seafloor include also the transmission of the wind-generated surface physical energy down to the bottom (the “benthic storms”) on the one hand and sedimentation of surface-produced organic matter on the other. Both the benthic storms and organic matter deposition are known to be periodically, or episodically, intensified, thus contributing to natural environmental variability in the abyss. The Pacific abyssal plain sedimentary cover is mostly biogenic in origin. A characteristic part of the Pacific abyss is a huge (about 2 million km²) polymetallic nodule field within the NE sub-equatorial seafloor area experiencing low sedimentation rates and constrained by the Clarion and Clipperton fractures (the Clarion-Clipperton Fracture Zone, CCFZ). CCFZ extends sub-latitudinally along about 4,200 km, its surface inclining slightly westwards with depths in the east-west direction from about 4,000 to about 5,400 m. The seafloor, although generally flat, does show (particularly in the eastern part) distinct topographic features which are volcanic in origin. The relatively thin (50–200 m) sedimentary cover is formed by recent biogenic sediments (siliceous ooze). The major characteristic of the area is the presence of polymetallic nodule deposits. The nodules, occurring at abundances frequently exceeding 10 kg/m², are mostly exposed on the sediment surface, but some are also embedded or buried in the sediment. The nodules, in addition to the occasionally occurring larger hard-rock fragments of cobalt-rich ferromanganese crusts, add to the deep-sea habitat heterogeneity and themselves constitute both a unique

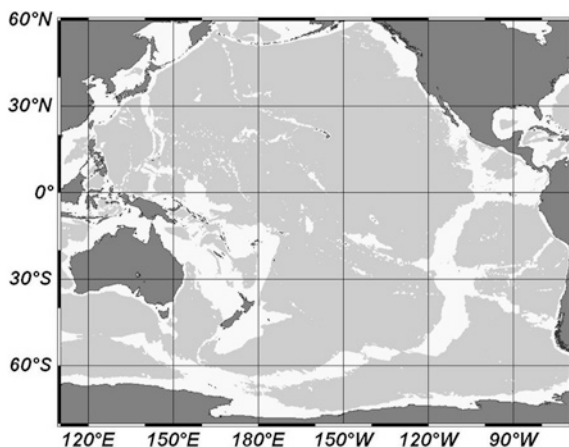
deep-sea habitat, of a great interest to marine ecologists, and an important mineral resource, of a great appeal to the marine mining community the size of which has been recently growing considerably.

Keywords Abyssal depths • Clarion-Clipperton Fracture Zone • Hydrography • Sedimentation • Currents • Bottom topography • Sedimentary cover • Polymetallic nodules

The deep sea is defined as the part of the oceanic water column and seafloor that extends below the permanent oceanic thermocline, i.e. below depth contours of 800–1,300 m (Gage and Tyler 1991; Ramirez-Llodra et al. 2010). That part of the oceanic floor covers about 88 % of the world ocean's floor surface area. The most extensive deep sea bottom is located between the depths of 3,000 and 6,000 m, and generally represents fairly flat surfaces, called the abyssal plains (Angel and Rice 1996, Mantyla and Reid 1983). The largest among them is the abyssal plain of the Pacific Ocean (Fig. 2.1), its part located in the sub-equatorial north-eastern region of the ocean being the major focus of the description below.

Environmental conditions in the abyss have been described in detail in a number of studies important for a biologist interested in environmental effects of anthropogenic interventions on deep-sea communities. The most pertinent of those publications include the papers by Menzies (1965), Gage and Tyler (1991), Tyler (1995), and Hannides and Smith (2003). As well as providing important overviews of the deep-sea environment, the publications mentioned, the earliest and the most recent of which span a period of almost 40 years, supply evidence on how the human perception of the deep-sea environment changed as research methods and techniques were improving and more and more large-scale study programmes were being implemented.

Fig. 2.1 The spatial extent of the Pacific abyssal plain; the shaded area shown indicates seafloor at depths exceeding 3,500 m; drawing made using the ODV software (Schlitzer 2004)



It is now recognised that the abyssal seafloor is influenced by phenomena and processes occurring in the surface waters which are themselves affected by atmospheric forcing agents—atmospheric circulation, wind stress, precipitation, evaporation, and energy fluxes (Amador et al. 2006). Phenomena such as eddies and mesoscale processes, El Niño Southern Oscillation (ENSO), and interdecadal variability and climate change (Willett et al. 2006; Wang and Fiedler 2006; Mestas-Nunez and Miller 2006) produce effects which, transmitted down the water column and modified along the way, influence the deep seafloor.

The water column overlying the abyssal seafloor shows a number of characteristic layers, differing in their physical, chemical, and biological variables. The most notable of those layers include the so-called oxygen minimum zone (OMZ) and the bottom (near-bottom) water, both of potential (OMZ) and actual (near-bottom water) importance for the benthic communities. The oxygen minimum zone in the eastern tropical Pacific is very pronounced; it occurs generally within 100–1,000 m (Hannides and Smith 2003; Wishner et al. 1995) and does not extend to the abyssal depths.

Another important water layer is the near-bottom one. The origins of the Pacific near-bottom water can be traced to the surface layer of the Antarctic region. As a result of complex interactions that involve mixing, sinking, and advection, that surface water sinks towards the bottom to form the Antarctic Bottom Water (AABW) in the Weddell Sea (Tsuchiya and Talley 1996). Its branches move northwards and penetrate into the Atlantic, Indian, and Pacific Oceans, the penetration routes being restricted and modified by topographic structures on the bottom, such as the East Pacific Rise. According to the pattern described in detail by Tsuchiya and Talley (1996), AABW moves along a major pathway towards the NE basin of the Pacific which is a route that carries the cold Antarctic water from the Equator to the north-east and eastwards via the Horizon Passage (~19°N; 169°W) at the northern tip of the Line Islands Ridge and via the Clarion Passage (~12°N; 165°W) in the western part of the Clarion Fracture. A portion of that stream flows eastwards through the northern part of the Clipperton Fracture. Bottom water (at depths exceeding 4,000 m) in the Pacific is formed by the Lower Circumpolar Water (LCPW), a mixture of AABW and the North Atlantic Deep Water (NADW) formed in the northern North Atlantic (Fiedler and Talley 2006). As described by Fiedler and Talley (2006), LCPW flows into the eastern tropical Pacific from the Northeast Pacific Basin along the western flank of the East Pacific Rise (105–110°W), at the end of a circuitous path in a northward deep western boundary current through the Central Pacific Basin and then as an eastward branch between the Hawaiian and Line Islands (Johnson and Toole 1993).

In many areas of the Pacific, including its eastern flanks, the hydrodynamic energy of currents is enhanced by hydrothermal venting (Tivey et al. 2002). Both the currents and the venting are recognised sources of a considerable variability in the oceanographic regime in the deep sea. Irrespective of that variability, however, the major trait of deep-sea bottom water masses is a fairly narrow range of changes of their major hydrographic characteristics in individual regions: over vast areas of the seafloor, the temperature varies from about 4 °C to about –1 °C,

while the mean salinity is 34.8 ± 0.3 psu (dropping to the minimum mean value of 34.69 psu in the NE and eastern part of the Pacific). The bottom water masses overlying the sub-equatorial NE Pacific seafloor are old (in terms of the amount of time since their contact with the surface water layers), but their dissolved oxygen content is close to saturation. Although, as AABW moves away from the centre of its formation, the dissolved oxygen pool becomes gradually depleted due to metabolic processes (Mantyla and Reid 1983; Tsuchiya and Talley 1996), it does not drop below the level of 2 ml l^{-1} , a threshold critical for the survival of benthic communities (Rabalais et al. 2010).

Irrespective of the narrow ranges of oceanographic variables mentioned above, certain attributes of the deep sea show oceanographic gradients and manifestations of physical variability that strongly impinge upon biological communities of both the water column and the deep seafloor. Particularly notable in this respect are changes in hydrostatic pressure in the water column. Depth-dependent changes in hydrostatic pressure represent the longest continuous environmental gradient on Earth, the hydrostatic pressure increasing by 10^5 Pa with each 10 m depth increase (Gage and Tyler 1991). The importance of the gradient for physiology and ecology of deep-sea organisms is evident from a number of studies. The most important earlier publications include a collection of papers edited by Hochachka (1976). To cite a more recent work, Young and Tyler (1993) referred to hydrostatic pressure as a factor controlling the vertical distribution of various echinoid species. The hydrostatic pressure gradient has also been invoked to explain depth-related changes in diversity and density of benthic organisms: for example, Tyler (1995) contended that the hydrostatic pressure of about 6×10^7 Pa (equal to that prevalent at the depth of about 6,000 m) is a clear bathymetric boundary for the fauna. A number of higher taxa such as decapods, sea anemones, and echinoids are absent at depths exceeding 6,000 m, while other taxa, particularly holothurians and polychaetes, occur there at relatively high densities. Barophilic adaptations are known also among microorganisms (Fang et al. 2000; Tholosan et al. 1999).

In addition, the hydrostatic pressure affects calcium carbonate solubility and thus can indirectly influence the deep-sea fauna. The carbonate compensation depth (CCD), i.e. the depth at which calcium carbonate is no longer solid and becomes dissolved, lies at different depths in various oceans and averages globally about 4,500 m (Coxall et al. 2005). In the eastern Pacific, it is shallower than in other oceans, being found at about 3,500 m (Nienstedt and Arnold 1988; Seibold and Berger 1993; Tyler 1995) to drop to depths larger than 5,000 m in the western part of the CCFZ (Kotlinski, pers. comm.). The hydrostatic pressure-mediated calcium carbonate solubility is important for carbonate enrichment of the deep seafloor and participates in controlling the chemical composition of sediments at those depths (Brown et al. 1989). It is also important for the composition of abyssal benthic communities by greatly restricting the distribution of calcareous shell-bearing organisms, e.g. calcareous foraminiferans (Gooday 1994).

The abyssal seabed topography results from interaction between continental plate spreading characteristics and sedimentation of organic and inorganic particles from shallower depths (Kotliński 1999; Whitmarsh et al. 1996). Although

abyssal plains are relatively flat compared to the continental margins and slopes flanking them, modern techniques of abyssal topography exploration (e.g. multi-beam surveys) show that the abyssal relief can be rendered complex by the presence of guyots, seamounts, and underwater volcanoes that often occur in chains and as seamount ridges, as well as by a multitude of smaller-scale topographic features (Kotliński, pers. comm.). Moreover, since the abyssal plains are intersected by mid-oceanic ridges, their surfaces are fractured in numerous places. The areas away from fractures and ridges show very gentle slope angles (on the order of 1:1,000) (Gage and Tyler 1991).

The abyssal plain sedimentary cover is mainly biogenic in origin: it forms as a result of sedimentation of remnants of pelagic fauna and flora which, once on the seafloor, are subjected to diagenetic processes of various intensity, depending on temperature and pressure (Brown et al. 1989; Menzies 1965, Seibold and Berger 1993; Tyler 1995; Whitmarsh et al. 1996). Rates of sedimentation and sediment accumulation vary between and within the oceans, depending largely on productivity of the surface waters: for example, the sediment accumulation rate in the northern Atlantic is estimated at 3.0–5.0 mm/year against the estimated 1.6 mm/year in NE Pacific (Kotliński and Rühle 1998). The deposited particles give rise to the so-called pelagic sediments, very finely grained, forming a highly hydrated surface layer which overlays the hard basalts of the oceanic fundament (Brown et al. 1989; Kotliński 1999; Seibold and Berger 1993). The thickness of those sediments depends on the crust age and sedimentation rate; the sedimentary cover in areas away from spreading centres can be several hundred metres thick. Such sediments cover vast expanses of abyssal plains, imparting on them a characteristically monotonous landscape shown in underwater images of the abyssal zone (Fig. 2.2). The soft sediment is thus the basic substratum type in the abyssal. Hard substrata, particularly in the form of basaltic rock outcrops, are much less common, but exist nonetheless. Hard substrata are mainly restricted to regions of

Fig. 2.2 A view of the Pacific abyssal plain in the eastern part of the Clarion-Clipperton Fracture Zone (CCFZ) (*Photo* courtesy of IOM)

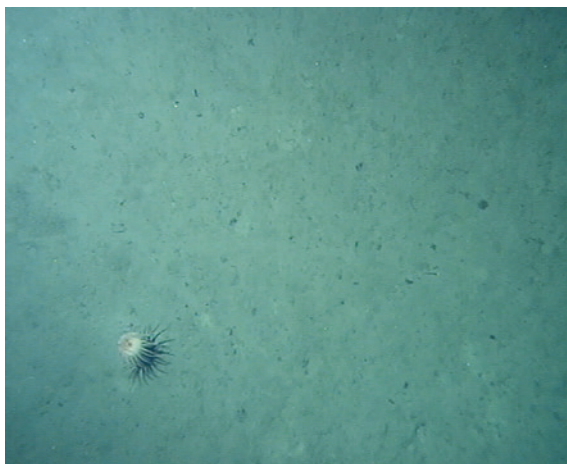




Fig. 2.3 A nodule-covered seafloor with crust fragments in the CCFZ (*Photo* courtesy of IOM)

recent volcanic activity and areas of weak and very weak sedimentation (Hannides and Smith 2003). In the latter, the hard substratum is provided primarily by polymetallic (ferromanganese) nodule deposits and associated polymetallic (cobalt-rich ferromanganese) crust fragments, present in certain areas (Brown et al. 1989; Hein and Petersen 2013; Kotliński 1999; Seibold and Berger 1993) (Fig. 2.3).

The seafloor topography and the surficial sediment layer are involved in complex interactions between major factors governing the conditions of life of benthic communities (Snelgrove and Butman 1994), and are affected by hydrodynamic energy of the near-bottom water layer. Vectors of that energy are the near-bottom currents, one of the least known physical forces in the deep sea (Gage and Tyler 1991). Information on the near-bottom current pattern in the abyssopelagic regions is very scant due to the absence, in most part of the world's oceans, of data from direct current meter measurements. It is assumed that the currents active in that region are controlled by forces resulting from thermohaline and tidal phenomena. The thermohaline circulation is a result of the formation of dense water masses around the Antarctic and their sinking to deeper layers, coupled with movement towards the Equator and north of it, along corridors formed by bottom topography (Tsuchiya and Talley 1996). The water flow resulting from thermohaline variability is modified by a tidal component; its strongest manifestation is a semi-diurnal shift in current direction. There is evidence showing that the pattern of those internal deep-sea tides may also reflect spring-neap oscillations. In addition, the resultant near-bottom current has been observed to change its direction periodically, or even to reverse it, as a result of kinetic energy being transferred from the surface to the bottom of the water column in eddies forming on the surface (Willett et al. 2006) and spanning the entire water column down to the near-bottom layers (Kontar and Sokov 1994; Sokov and Demidova 1992). It is also assumed that this transfer of kinetic energy contributes significantly to the motion of the deep sea water masses. Mesoscale (50–200 km) eddies carry an amount of energy up to 100 times that of the background level. Such eddies are formed as a result of wind action upon the ocean's surface; their energy is transferred to the abyssopelagial

where it may periodically change current direction and increase current velocity. The process, termed a “benthic storm” (Aller 1997; Brown et al. 1989; Kontar and Sokov 1994), can destabilise the sediment surface and erode it, thereby directly influencing the structure of benthic communities (Aller 1997; Thistle 1998; Thistle and Levin 1998; Thistle et al. 1999).

The basic source of energy for abyssal benthic communities is the biological production in the water column, particularly in its surface layers. A significant portion of that production is the organic matter formed by primary producers, the phytoplankton. Under certain conditions, the phytal material produced in the top water layers may sediment all the way down to the abyssal depths and reach the seafloor there as the relatively undegraded phytodetritus (e.g. Billett et al. 1983; Pfannkuche et al. 1999; Scharek et al. 1999; Thiel et al. 1988/1989). Usually, however, while sinking, the organic material undergoes various transformations: it may be subject to degradation, decomposition, and partial dissolution. It is invariably colonised by microorganisms and may be enveloped by extracellular polymers they produce, which enhances scavenging of other particulate material in the water column and the formation of macroaggregates known as the “marine snow” (Allredge and Silver 1988). Thus, some of the transformations may increase the particle sinking rate (Angel 1984; Brown et al. 1989; Fowler and Knauer 1986). Data provided by analyses of sediment trap contents show that as much as 1–7 % of the surface production may reach the abyssal bottom (Pfannkuche et al. 1999; Tyler 1995). Another form of organic matter flux to deep-sea sediments occurs as rather ephemeral, but important for local organic enrichment, events of sinking of large organic remains (dead macrophytes, fish, cephalopods or whales) onto the deep seafloor [cf. research on whale falls reviewed by Smith and Baco (2003) and Smith et al. (1998)].

Geochemical conditions in the sediment were reported to covary with the surface primary production rates and the particulate organic carbon (POC) fluxes (Hannides and Smith 2003). The geochemical conditions are reflected by profiles of dissolved oxygen in the sediment, oxygen penetration generally increasing with increasing distance from the Equator (Hammond et al. 1996) as a result of decreasing oxygen metabolic consumption within the sediment.

The picture of abiotic components of abyssal ecosystems was initially painted by studies leading to the milestone paper by Menzies (1965) who described a relative homogeneity of salinity, temperature, and dissolved oxygen content of the water masses overlying vast expanses of the abyssal seafloor. This gave rise to a widely held notion, a paradigm of sorts, that abyssal ecosystems are extremely stable, the only manifestations of instability involving the hydrostatic pressure and the occasional near-bottom turbidity currents. That deeply rooted conviction was challenged within the past two decades or so, as data collected during large-scale oceanographic research programmes such as the World Ocean Circulation Experiment (WOCE) (Tsuchiya and Talley 1996) or the Joint Global Ocean Flux Study (JGOFS) (Stoecker et al. 1996) began to accumulate and reveal a different picture. More and more frequently, evidence of variability—along different spatial and temporal scales—in a number of factors shaping the abyssal environment has

been provided. The variability is manifested as, e.g. diel changes in near-bottom current patterns brought about by deep-sea tides, or by important disturbances in the hydrodynamics due to the downward transport of the surface wind gyre energy (Kontar and Sokov 1994, Sokov and Demidova 1992). Biotic parameters, too, are subject to variability which is largely seasonal, as demonstrated by studies on vertical POC fluxes from the near-surface water layers. Based on POC fluxes reported in the literature, Hannides and Smith (2003) divided the NE Pacific abyssal plain into three zones: the eutrophic abyss (from the Equator up to 5°N), with the POC flux of about 1–2 g C/m² year; the mesotrophic abyss (from 5°N to 15°N), with the POC flux of about 0.5–1.6 g C/m² year; and the oligotrophic abyss (underlying the central North Pacific gyre), with POC fluxes typically lower than 0.5 g C/m² year. Variation in the quality and rate of the POC flux was reported to affect the sediment bio- and geochemistry (Hammond et al. 1996) as well as the functioning and structure of benthic communities (Kalogeropoulou et al. 2010; Tyler 1988).

In this context, sedimentation of the phytodetritus, mentioned above, seems to be extremely important. Effects of that sedimentation on geo- and bio-chemical processes in the abyssal sediment as well as its significance in controlling variation in food resources, the structure and functioning of benthic communities, and physiological processes of abyssal organisms have been vigorously pursued over the recent several years (Fileman et al. 1998; Kalogeropoulou et al. 2010; Khripunoff et al. 1998; Pfannkuche et al. 1999; Smith et al. 1996, 1997). Biological effects of phytodetritus input to the abyssal seafloor will be discussed in Chap. 3.

The abyssal biology may also reflect variability effected on longer temporal and wider spatial scales, e.g. changes in surface biological production brought about by global climatic phenomena such as the El Niño Southern Oscillation (ENSO) (Gage and Tyler 1985; Neira et al. 2001; Pennington et al. 2006; Tyler 1995). For example, Pennington et al. (2006) cite studies which reported the warm phases of ENSO, the El Niños, to have several-fold reduced nutrient supply, with a concomitant decrease in primary production and water chlorophyll *a* content in the eastern tropical Pacific, while the cool phase of ENSO called La Niña produced an opposite effect in the form of a massive bloom with predictably dramatic biological consequences.

As already said, of a particular importance for this book is the Clarion-Clipperton Fracture Zone (CCFZ), a part of the sub-equatorial NE Pacific's abyssal plain (Fig. 2.4), and particularly its eastern part housing the claim area of Interoceanmetal Joint Organization (IOM) (cf. Fig. 3; Kotliński 1998b). As CCFZ is a site of extensive and abundant polymetallic nodule deposits, its geological set-up and the characteristics important from the standpoint of future development of the deposits have already been, and are, vigorously explored and amply documented (e.g. Andreev and Gramberg 1998; Barash et al. 2000; IOM 1993; Kotliński 1998a, b, 1999; Tkatchenko and Stoyanova 1998; Tkatchenko et al. 1997). CCFZ covers about 2 million km² of the abyssal plain seafloor in the sub-equatorial north-eastern part of the Pacific, flanked to the north by the Clarion Fracture and by the Clipperton Fracture to the south (Fig. 2.4). The area extends sub-latitudinally along about 4,200 km and is about 300–900 km wide. The area's

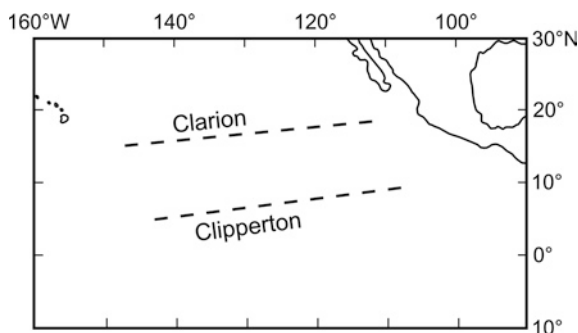


Fig. 2.4 A schematic of locations of the Clarion and Clipperton Fractures in the sub-equatorial NE Pacific

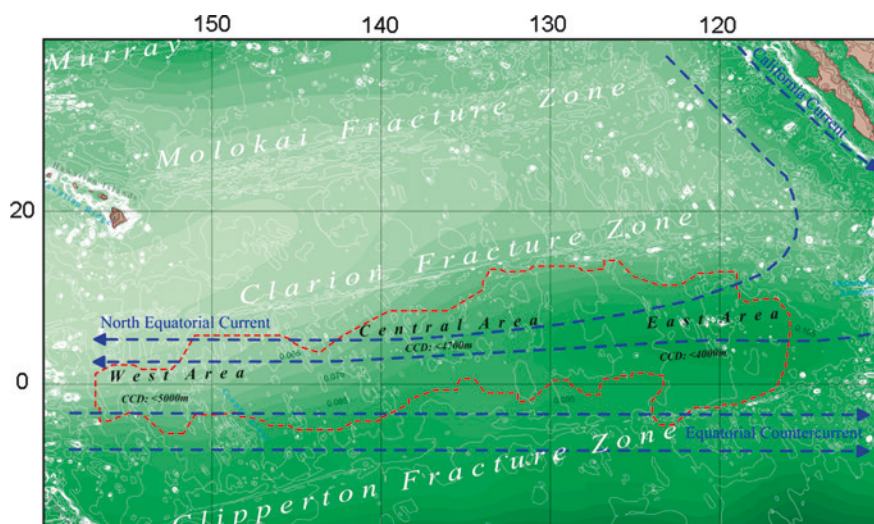


Fig. 2.5 Oceanographic features of the sub-equatorial NE Pacific; CCFZ contoured by *dashed line in red* (Drawing courtesy of R. Kotliński)

hydrography is shaped by a system consisting of the westward-flowing Northern Equatorial Current and by the eastern-flowing Northern Equatorial Countercurrent (Fig. 2.5). The currents form a divergence system, very complicated due to its seasonal variability and local and regional wind eddies (Fiedler and Talley 2006; Sokov and Demidova 1992; Willett et al. 2006). In spring and summer, the northern boundary of the Equatorial Countercurrent reaches to 12–13°N, to shift southwards to 10°N in autumn and winter (Ozturgut et al. 1978; Tkatchenko and Stoyanova 1998).

The CCFZ water column structure reveals the presence of 5 water layers differing in their temperature and salinity (IOM 1993; Johnson and Toole 1993;

Tkatchenko and Stoyanova 1998; Tkatchenko et al. 1997; Wijffels et al. 1996). The upper mixing zone extends to about 50–150 m (Demidova 1999), while the oxygen minimum zone (OMZ) encompasses the depth range of 300–500 m (Ozturgut et al. 1978); in the eastern part of the CCFZ, the OMZ was recorded to span the depth range of 120–2,500 m (Kotliński et al. 1996), with dissolved oxygen contents dropping to well below 1 ml O₂ /l. The near-bottom layer shows temperature and salinity ranges of 1.3–1.6 °C and 34.4–34.88 psu, respectively, the dissolved oxygen content averaging 3.6–3.8 ml O₂ /l (Kotliński et al. 1996).

The recent literature reviewing satellite observations-based (SeaWiFS; <http://seawifs.gsfc.nasa.gov>) data on chlorophyll *a* distribution (Morgan 2000; Pennington et al. 2006) shows the chlorophyll *a* values in the CCFZ to be generally rather low (on the order of 0.1–0.25 mg/m³), but higher than in the areas north of CCFZ (cf. Fig. 2.5). In addition, SeaWiFS chlorophyll estimates seem to indicate a seasonal cycle, with higher values in the boreal winter (Pennington et al. 2006). The rather scant data on primary production estimates in the top part of the CCFZ water column show the average daily production to vary widely from 20.4 (Kolosov 1988) to 133 mg C/m² in the water layer extending down to the depth at which the light intensity is 1 % of that on the surface (Ozturgut et al. 1978). The major (even up to 100 %) part of the newly formed organic matter is attributed to the nanoplankton activity (Hyun et al. 1998; Ozturgut et al. 1978; Semina et al. 1997). There is evidence (Smith 2013) of substantial east-west and south-north gradients in the overlying primary production in CCFZ. As pointed out by Pennington et al. (2006), many important aspects of the biological productivity of the area remain unclear, although it is noteworthy that the region is a major site of yellowfin tuna occurrence (Ballance et al. 2006).

In terms of POC fluxes, CCFZ belongs to the broadly defined mesotrophic abyss of Hannides and Smith (2003). As noted by Smith (2013), the east-west and south-north gradients in surface primary productivity are reflected in the flux of organic matter to the abyss. The flux rate were reported to vary temporally, the downward transport being particularly intensive in spring (Yamazaki and Kajitani 1999). That sedimentation may result in deposition of the phytodetritus on the sediment surface, particularly in depressions of the surficial layer (Smith et al. 1996, Radziejewska 2002, Thiel et al. 1988/1989, Radziejewska, pers. observ.) Smith et al. (1996) measured the plant pigment contents [chloroplastic pigment equivalent (CPE) = sum of chlorophyll *a* and phaeopigment contents; e.g. Neira et al. 2001] in sediments of the abyssal seafloor in the sub- and equatorial Pacific (at depths of about 4,000–5,000 m) on a transect running along 140°W from 12°S do 9°N, and reported contents averaging 0.36–9.8 µg/g dry sediment. Fluorometric assays made on the sediment samples collected in the eastern part of CCFZ in April–May 1997, after patches of phytodetritus had been observed on the core sediment surface, showed CPEs reaching 4.75 µg/g dry sediment (Radziejewska 2002).

The near-bottom currents were observed to vary greatly in direction and speed, the variations reflecting surface conditions produced by, i.a. wind-driven processes (hurricanes), and local modifications resulting from the seafloor relief (Tkatchenko and Stoyanova 1998). The CCFZ water dynamics shows periodic occurrence of

wind-driven surface gyres the energy of which is transferred, as benthic storms, down to the near-bottom water (Kontar and Sokov 1994; Nikitin 1997; Sokov and Demidova 1992). Overall, Morgan et al. (1999) point out to the presence of 3 dynamic regimes in CCFZ: calm periods, with minimum current speeds and low tidal activity; intermediate, with mostly tidal periods, characterized by alteration of current speed (0 to 5–6 cm/s) and direction; and benthic storms, with current speeds increasing to 24-h averages of 8 cm/s. Effects of intensified dynamics of the near-bottom current were visible as levelling off and erosion of anthropogenically disturbed sediment surface (Tkatchenko and Radziejewska 1998): 22 months after the sediment surface was altered by about 5–10 cm deep grooves flanked by mounds of overturned sediment, the grooves appeared to have been partially filled by the sediment and mound contours smoothed out (cf. Fig. 4.5 in Chap. 4).

The CCFZ seafloor is slightly inclined westwards, as evidenced by average depths increasing from about 4,000 m in the eastern part to about 5,400 m in the western part. The abyssal bottom relief shows a number of linearly arranged depressions, terraces, and elevations. Characteristic of the seafloor in the area is the presence of topographic structures that are volcanic in origin (IOM 1993; Kotliński 1998b). Active volcanism and /or hydrothermal venting is detectable in the patterns of physical and chemical characteristics of water masses overlying the CCFZ bottom, e.g. metal contents (Tkatchenko et al. 1997). Generally, however, the area is characterised by the depositional type of seafloor relief; the slope angle does not exceed 3°, the elevation difference averaging 100–200 m (IOM 1993; Kotliński 1998b). The sedimentary cover is relatively thin: it varies in thickness from about 50 to about 200 m. The surface layer is formed by recent sediments in the form of semi-liquid siliceous ooze, with up to 0.56 % organic carbon content (IOM 1993), and is strongly bioturbated (Pope et al. 1996; Radziejewska, pers. obs.).

As already pointed out above, the stretch of the abyssal plain seafloor flanked by the Clarion and Clipperton Fractures is a gigantic field of mineral deposits known as polymetallic nodules (x. 2). A characteristics of the field, including the description of the origin and the assessment of the nodule resources was provided by Kotlinski (1998b, 1999), Andreev and Gramberg (1998), and Morgan (2000). It has to be pointed out, however, that research aimed at detailed assessment of resources of nodules and metals and minerals they contain is in progress and is a main focus of contracts for exploration concluded by individual contractors with ISA (Kotliński, pers. comm.). Polymetallic nodules that cover the bottom at estimated abundances frequently averaging about 15 kg/m² and occasionally reaching 75 kg/m² lie on the surface of the semi-liquid sediment and may be partly embedded in it; some nodules are found buried in the sediment (Andreev and Gramberg 1998; Hein and Petersen 2013; Iljin et al. 1994, 1997; Kotliński 1998b). The conservative estimate of nodule amount in CCFZ, as given by Hein and Petersen (2013) is 21,100 million dry metric tonnes. Vast stretches of nodule deposits on the seafloor are interspersed by larger or smaller nodule-free areas (cf. Fig. 2.2). As shown by geotechnical assays, properties (mean grain size, water content, shear stress, plasticity) of the sediment in nodule-free areas differ from those shown by the nodule-bearing sediment (Radziejewska and Modlitba 1999).

In the uppermost 5 cm layer, the nodule-bearing sediment was found to be coarser (grains > 0.063 mm in diameter accounted for 39 % as opposed to 11.4 % in the nodule-free area), less hydrated, and less plastic than the nodule-free sediment, the nodule-bearing sediment shear stress increasing sharply downcore.

The environmental variability in the abyss, although known to be much more extensive than previously thought, is still far below the variability that can be induced by human activities. How resilient are abyssal communities to such variability remains unknown, although they have been presumed (and perceived) to be relatively poorly resilient (Davies et al. 2007; Ramirez-Llodra et al. 2011). And yet, as already indicated, plans are underway with which to effect the anthropogenic intervention into the deep sea (Lodge et al. 2014; Van Dover et al. 2014). It is therefore advisable to look for proxies which would provide an aid in the assessment of the degree of resilience, including the biotic community recovery potential. The next chapter will introduce the meiobenthos, a category of seafloor-dwelling organisms which—as already indicated in the previous chapter—has a potential of being used as such a proxy.

References

- Allredge AL, Silver MW (1988) Characteristics, dynamics and significance of marine snow. *Prog Oceanog* 20:41–82
- Aller JY (1997) Benthic community response to temporal and spatial gradients in physical disturbance within a deep-sea western boundary region. *Deep-Sea Res I* 44:39–69
- Amador JA, Alfaro EJ, Liyano OG et al (2006) Atmospheric forcing of the eastern tropical Pacific: a review. *Prog Oceanog* 69:101–142
- Andreev SI, Gramberg IS (1998) The explanatory note to the metallogenic map of the world ocean. VNIIOkeangeologiya, St. Petersburg
- Angel MV (1984) Detrital organic fluxes through pelagic ecosystems. In: Fasham MJ (ed) *Energy and materials in marine ecosystems. Theory and practice*. Plenum Press, London
- Angel MV, Rice TL (1996) The ecology of the deep ocean and its relevance to global waste management. *J Appl Ecol* 33:915–926
- Ballance LT, Pitman RL, Fiedler PC (2006) Oceanographic influences on seabirds and cetaceans of the eastern tropical Pacific: a review. *Prog Oceanog* 69:360–390
- Barash MS, Kruglikova SB, Mukhina VV (2000) Stratigraficheskiye osobennosti osadochnykh obrazovaniy provintsii Klarion-Klipperton (Vostochnaya ekvatorialnaya Patsifika). *Okeanologia* 40:424–433
- Billett DSM, Lampitt RS, Rice AL et al (1983) Seasonal sedimentation of phytoplankton to the deep sea benthos. *Nature* 302:520–522
- Brown J, Colling A, Park D et al (1989) *Ocean chemistry and deep sea sediments*. The Open University, Milton Keynes
- Coxall HK, Wilson PA, Pälike H et al (2005) Rapid stepwise onset of Antarctic glaciation and deeper calcite compensation in the Pacific Ocean. *Nature* 433:53–57
- Davies AJ, Roberts JM, Hall-Spencer J (2007) Preserving deep-sea natural heritage: emerging issues in offshore conservation and management. *Biol Conserv* 138:299–312
- Demidova T (1999) The physical environment in nodule provinces of the deep sea. In: *Deep-seabed polymetallic nodule exploration: development of environmental guidelines*. Proceedings of International Seabed Authority's workshop held in Sanya, Hainan Island, People's Republic of China, 1–5 June 1998. International Seabed Authority, Kingston, Jamaica

- Fang J, Barcelona MJ, Nogi Y et al (2000) Biochemical implications and geochemical significance of novel phospholipids of the extremely barophilic bacteria from the Marianas Trench at 11,000 m. *Deep-Sea Res I* 47:1173–1182
- Fiedler PC, Talley LD (2006) Hydrography of the eastern tropical Pacific: a review. *Prog Oceanog* 69:143–180
- Fileman TW, Pond DW, Barlow RG et al (1998) Vertical profiles of pigments, fatty acids and amino acids: evidence for undegraded diatomaceous material sedimenting to the deep ocean in the Bellingshausen Sea, Antarctica. *Deep-Sea Res I* 45:333–346
- Fowler SW, Knauer GA (1986) Role of large particles in the transport of elements and organic compounds through the oceanic water column. *Prog Oceanog* 16:147–194
- Gage JD, Tyler PA (1985) Growth and reproduction of the deep sea urchin *Echinus affinis*. *Mar Biol* 90:41–53
- Gage JD, Tyler PA (1991) *Deep-sea biology: a natural history of organisms at the deep-sea floor*. Cambridge University Press, Cambridge
- Gooday AJ (1994) The biology of deep-sea foraminifera: a review of some advances and their applications in paleoceanography. *Palaios* 9:14–31
- Hammond DE, McManus J, Berelson WM et al (1996) Early diagenesis of organic material in Equatorial Pacific sediments: stoichiometry and kinetics. *Deep-Sea Res* 43:1365–1380
- Hannides AK, Smith CR (2003) The northeastern Pacific abyssal plain. In: Black KD, Shimmield GB (eds) *Biogeochemistry of marine systems*. Blackwell, Oxford
- Hein JR, Petersen S (2013) The geology of manganese nodules. In: Baker E, Beaudoin Y (eds) *Deep sea minerals: manganese nodules, a physical, biological, environmental, and technical review*, vol 1B. Secretariat of the Pacific Community, GRID-Arendal
- Hochachka PW (ed) (1976) *Biochemistry at depth. Pressure effects on biochemical systems of abyssal and midwater organisms: the 1973 Kona expedition of the "Alpha Helix"*. Pergamon Press, Oxford
- Hyun J-H, Kim K-H, Jung H-S et al (1998) Potential environmental impact of deep-seabed manganese nodule mining on the *Synechococcus* (Cyanobacteria) in the Northeast Equatorial Pacific: effect of bottom water-sediment slurry. *Mar Geores Geotechnol* 16:133–143
- Ilijin AV, Ivakin AN, Lysanov YP (1994) O raspredelenii zhelezomargantsevykh konkreciy na poligone Klarion-Klipperton. *Okeanologia* 34:911–914
- Ilijin AV, Bogorov GB, Skorniakova NS (1997) O prostranstvennoy izmenchivosti zaleganiya zhelezo-margantsevykh konkretsiu (na poligone Klarion-Klipperton). *Okeanologiya* 37:285–294
- IOM (1993) *Geologiya, konkrecyonosnost' i prirodnye usloviya raiona pervonachalnoy deyatel'nosti SO Interokanmetall*. IOM, Szczecin
- Johnson GC, Toole JM (1993) Flow of deep and bottom waters in the Pacific at 10° N. *Deep-Sea Res I* 40:371–394
- Kalogeropoulou V, Bett BJ, Gooday AJ et al (2010) Temporal changes (1989–1999) in deep-sea metazoan meiofaunal assemblages on the Porcupine Abyssal Plain, NE Atlantic. *Deep Sea Res II* 57:1383–1395
- Khripounoff A, Vangriesheim A, Crassous P (1998) Vertical and temporal variations of particle fluxes in the deep tropical Atlantic. *Deep-Sea Res I* 45:293–316
- Kolosov VP (1988) Chlorofill "a" i pervichnaya produkcija. In: Simonov AI (ed) *Ekologicheskiye usloviya vostochno-ekvatorialnoy oblasti severnoy chasti tikhogo okeana*. Gidrometeoizdat, Moskva
- Kontar EA, Sokov AV (1994) A benthic storm in northeastern tropical Pacific over the fields of manganese nodules. *Deep-Sea Res* 41:1069–1089
- Kotliński R (1998a) Konkrecje polimetaliczne. In: Depowski S, Kotliński R, Rühle E et al (eds) *Surowce mineralne mórz i oceanów*. Wydawnictwo Naukowe Scholar, Warszawa
- Kotlinski R (1998b) The present state of knowledge on oceanic polymetallic ores as exemplified by Interoceanmetal Joint Organization's activity. *Mineral Pol* 29:77–89
- Kotliński R (1999) Metallogenesis of the world's ocean against the background of oceanic crust evolution. Special Paper 4, Polish Geological Institute

- Kotliński R, Rühle E (1998) Geneza i geologia oceanów. In: Depowski S, Kotliński R, Rühle E et al (eds) *Surowce mineralne mórz i oceanów*. Wydawnictwo Naukowe Scholar, Warszawa
- Kotliński R, Stoyanova V, Tkatchenko G (1996) Environmental studies on a reference transect in the IOM pioneer area. In: Chung JS, Das BM, Roesset J (eds) *Proceedings of 6th ISOPE Conference*, vol 1. Los Angeles, USA, pp 54–57
- Lodge M, Johnson D, Le Gurun G et al (2014) Seabed mining: International Seabed Authority environmental management plan for the Clarion-Clipperton Zone. A partnership approach. *Mar Policy* 49:66–72
- Mantyla AW, Reid JL (1983) Abyssal characteristics of the World Ocean waters. *Deep-Sea Res* 30:805–833
- Menzies RJ (1965) Conditions for the existence of life on the abyssal sea floor. *Oceanog Mar Biol Ann Rev* 3:195–210
- Mestas-Nunez AM, Miller AJ (2006) Interdecadal variability and climate change in the eastern tropical Pacific: a review. *Prog Oceanog* 69:267–284
- Morgan CL (2000) Resource estimates of the Clarion-Clipperton manganese nodule deposits. In: Cronan DS (ed) *Handbook of marine mineral deposits*. CRC Press, Boca Raton
- Morgan CL, Oduntun NA, Jones AF (1999) Synthesis of environmental impacts of deep seabed mining. *Mar Geores Geotechnol* 17:307–356
- Neira C, Sellanes J, Levin LA et al (2001) Meiofaunal distributions on the Peru margin: relationship to oxygen and organic matter availability. *Deep-Sea Res I* 48:2453–2472
- Nienstedt JC, Arnold AJ (1988) The distribution of benthic foraminifera on seamounts near the East Pacific Rise. *J Foram Res* 18:237–249
- Nikitin OP (1997) Vertikalnaya struktura sinopticheskikh techeniy v severo-vostochnom tropikal'nom Tikhom okeane. *Okeanologia* 37:819–831
- Ozturgut E, Anderson GD, Burns RE et al (1978) Deep ocean mining of manganese nodules in the North Pacific: pre-mining environmental conditions and anticipated mining effects. NOAA Techn Mem, ERL MESA-33
- Pennington TJ, Mahoney KL, Kuwahara VS et al (2006) Primary production in the eastern tropical Pacific: a review. *Prog Oceanog* 69:285–317
- Pfannkuche O, Boetius A, Lochte K et al (1999) Responses of deep-sea benthos to sedimentation patterns in the North-East Atlantic in 1992. *Deep-Sea Res I* 46:573–596
- Pope RH, DeMaster DJ, Smith CR et al (1996) Rapid bioturbation in equatorial Pacific sediments: evidence from excess ^{234}Th measurements. *Deep-Sea Res II* 43:1339–1364
- Rabalais NN, Diaz RJ, Levin LA et al (2010) Dynamics and distribution of natural and human-caused hypoxia. *Biogeosci* 7:585–619
- Radziejewska T (2002) Responses of deep-sea meiobenthic communities to sediment disturbance simulating effects of polymetallic nodule mining. *Int Rev Hydrobiol* 87:459–479
- Radziejewska T, Modlitba I (1999) Vertical distribution of meiobenthos in relation to geotechnical properties of deep-sea sediment in the IOM pioneer area (Clarion-Clipperton Fracture Zone, NE Pacific). In: Chung JS, Sharma R (eds), *Proc 3rd Ocean Mining Symposium*, Goa, India
- Ramirez-Llodra E, Brandt A, Danovaro R et al (2010) Deep, diverse and definitely different: unique attributes of the world's largest ecosystem. *Biogeosci* 7:2851–2899
- Ramirez-Llodra E, Tyler PA, Baker MC et al (2011) Man and the last great wilderness: human impact on the deep sea. *PLoS ONE* 6:e22588
- Scharek R, Tupas LM, Karl DM (1999) Diatom fluxes to the deep sea in the oligotrophic North Pacific gyre at Station ALOHA. *Mar Ecol Prog Ser* 182:55–67
- Schlitzer R (2004) Ocean Data View. <http://odv.awi-bremerhaven.de>
- Seibold E, Berger WH (1993) *The sea floor. An introduction to marine geology*, 2nd edn. Springer, Berlin
- Semina HI, Mikaelyan AS, Belyaeva GA (1997) Fitoplankton raznykh razmernykh grupp v severnoy subtropicheskoy zone Tikhogo okeana. *Okeanologia* 37:730–738
- Smith CR (2013) Biology associated with manganese nodules. In: Baker E, Beaudoin Y (eds) *Deep sea minerals: manganese nodules, a physical, biological, environmental, and technical review*, vol 1B. Secretariat of the Pacific Community, GRID-Arendal

- Smith CR, Baco AR (2003) The ecology of whale falls at the seep-sea floor. *Oceanog Mar Biol Ann Rev* 41:311–354
- Smith CR, Hoover DJ, Doan SE et al (1996) Phytodetritus at the abyssal seafloor across 10° of latitude in the central equatorial Pacific. *Deep-Sea Res II* 43:1309–1338
- Smith CR, Berelson W, DeMaster DJ et al (1997) Latitudinal variations in benthic processes in the abyssal equatorial Pacific: control by biogenic particle flux. *Deep-Sea Res II* 44:2295–2317
- Smith CR, Maybaum HL, Baco AR et al (1998) Sediment community structure around a whale skeleton in the deep Northeast Pacific: macrofaunal, microbial and bioturbation effects. *Deep-Sea Res II* 45:335–364
- Snelgrove RVP, Butman CA (1994) Animal-sediment relationships revisited: cause versus effect. *Oceanog Mar Biol Ann Rev* 32:111–177
- Sokov AV, Demidova TA (1992) Ob antitsiklonicheskom vikhre v severo-vostochnoy chasti tropicheskoy zony Tikhogo okeana. *Meteorolog Gidrolog* 3:57–64
- Stoecker DK, Gustafson DE, Verity PG (1996) Micro- and mesoprotozooplankton at 140°W in the equatorial Pacific: heterotrophs and mixotrophs. *Aquat Microb Ecol* 10:273–282
- Thiel H, Pfannkuche O, Schriever G et al (1988/1989) Phytodetritus on the deep-sea floor in a central oceanic region of the northeast Atlantic. *Biol Oceanog* 6:203–239
- Thistle D (1998) Harpacticoid copepod diversity at two physically reworked sites in the deep sea. *Deep-Sea Res II* 45:13–24
- Thistle D, Levin LA (1998) The effect of experimentally increased near-bottom flow on metazoan meiofauna at a deep-sea site, with comparison data on macrofauna. *Deep-Sea Res I* 45:625–638
- Thistle D, Levin LA, Gooday AJ et al (1999) Physical reworking by near-bottom flow alters the metazoan meiofauna of Fieberling Guyot (northeast Pacific). *Deep-Sea Res I* 46:2041–2052
- Tholosan O, Garcin J, Bianchi A (1999) Effects of hydrostatic pressure on microbial activity through a 2000 deep water column in the NW Mediterranean Sea. *Mar Ecol Prog Ser* 183:49–57
- Tivey MK, Bradley AM, Joyce TM et al (2002) Insights into tide-related variability at seafloor hydrothermal vents from time-series temperature measurements. *Earth Planet Sci Lett* 202:693–707
- Tkatchenko GG, Radziejewska T (1998) Recovery and recolonization processes in the area disturbed by a polymetallic nodule collector simulator. In: Chung JS, Ollagnon M, Kim CH et al (eds) *Proceedings of 8th ISOPE Conference*, vol 2. Montreal, Canada, pp 282–286
- Tkatchenko G, Stoyanova V (1998) The scale and nature of water column variability in an area designated for polymetallic nodule mining. In: Chung JS, Ollagnon M, Kim CH et al (eds) *Proceedings of 8th ISOPE Conference*, vol 1. Montreal, Canada, pp 39–43
- Tkatchenko G, Kotlinski R, Stoyanova V et al (1997) On the role of geologic factors in determining peculiarities of water mass structure in the Clarion-Clipperton ore field. In: Chung JS, Das BM, Matsui T et al (eds) *Proceedings of 7th ISOPE Conference*, vol 1. Honolulu, Hawaii, pp 959–961
- Tsuchiya M, Talley LD (1996) Water property distributions along an eastern Pacific hydrographic section at 135°W. *J Mar Res* 54:541–564
- Tyler PA (1988) Seasonality in the deep sea. *Oceanog Mar Biol Ann Rev* 26:227–258
- Tyler PA (1995) Conditions for the existence of life at the deep-sea floor: an update. *Oceanog Mar Biol Ann Rev* 33:221–244
- Van Dover CL, Aronson J, Pendleton L et al (2014) Ecological restoration in the deep sea: *Desiderata*. *Mar Pol* 44:98–106
- Wang C, Fiedler PC (2006) ENSO variability and the eastern tropical Pacific: a review. *Prog Oceanog* 69:239–266
- Whitmarsh RA, Bull JM, Rothwell RG et al (1996) The evolution and structure of ocean basin. In: Sommerhayes CP, Thorpe SA (eds) *Oceanography. An Illustrated Guide*. Manson Publishing, London
- Wijffels SE, Toole JM, Bryden HL et al (1996) The water masses and circulation at 10°N in the Pacific. *Deep-Sea Res I* 43:501–544

- Willett CS, Leben RR, Lavin MF (2006) Eddies and tropical instability waves in the eastern tropical Pacific: a review. *Prog Oceanog* 69:281–283
- Wishner KF, Ashjian CJ, Gelfman C et al (1995) Pelagic and benthic ecology of the lower interface of the eastern tropical Pacific oxygen minimum zone. *Deep-Sea Res I* 42:93–115
- Yamazaki T, Kajitani J (1999) Deep-sea environment and Impact Experiment to It. In: Chung JS, Matsui T, Koterayama W (eds) *Proceedings of 9th ISOPE Conference*, vol 1. Brest, France, pp 374–381
- Young CM, Tyler PA (1993) Embryos of the deep sea echinoid *Echinus affinis* require high pressure for development. *Limnol Oceanog* 38:178–181

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