Chapter 13
Echinoderms at Ancient Hydrocarbon Seeps and Cognate Communities

Jamie Brezina, Neal L. Larson, and Neil H. Landman

13.1 Introduction

Today, echinoderms are found in every corner of the seas and oceans, even on the seafloor below the ice in the Arctic and Antarctica. They are relatively common at modern hydrocarbon seeps, including, for example, the Gulf of Mexico (Pawson et al. 2015), the Mediterranean Sea (Zeppilli et al. 2011) and off the coast of California and Oregon (Torres et al. 2009). Echinoderms and other animals are attracted to these sites because they furnish a source of nutrients, both on the seafloor and in the overlying water column. Indeed, in a recent video, a brittlestar was observed preying upon a swimming squid (NOAA ship Okeanos Explorer expedition in 2017). Most echinoderms are mobile, allowing them to search for food at seep sites. In addition, echinoderms are attracted to hydrocarbon seeps due to the presence of carbonate crusts and structures that provide a hard substrate.

In contrast to their modern counterparts, echinoderms are rare at ancient hydrocarbon seeps, with only a few reported occurrences. Their rarity may be related to environmental parameters including water chemistry, oxygen levels, food availability and presence or absence of a hard substrate. In addition, echinoderms may not have been preserved as fossils due to their low preservation potential. In general, after death, echinoderms rapidly decay, and their skeletons become disarticulated

J. Brezina (✉)
Department of Mining Engineering, South Dakota School of Mines and Technology, Rapid City, SD, USA

N. L. Larson
Larson Paleontology Unlimited, Keystone, SD, USA

N. H. Landman
Department of Invertebrate Paleontology, American Museum of Natural History, New York, NY, USA
e-mail: landman@amnh.org

A. Kaim et al. (eds.), *Ancient Hydrocarbon Seeps*, Topics in Geobiology 53,
https://doi.org/10.1007/978-3-031-05623-9_13

(Hess et al. 2011; T. Oji, pers. comm., 2020). However, it is possible that the high rate of calcium carbonate precipitation at many seeps promoted their fossilization. Collecting bias might also be a factor in the low number of reported occurrences, as specimens may not be visible on the surface of the outcrop. Many new species of echinoderms have been discovered by screening and washing sediments and then examining the washed sediments for small fragments known as ossicles (spines, arms, plates and columnals). This chapter provides a brief overview of reported occurrences of echinoderms at ancient hydrocarbon seeps and cognate communities (e.g. wood falls). The list is organized alphabetically by region and will be more fully expanded upon in the future.

13.2 Occurrences

13.2.1 Antarctica

Occasional crinoid ossicles have been reported by Kelly et al. (1995) from the Late Jurassic (Tithonian) seep deposit in Alexander Island, Antarctica, which otherwise is dominated by gastropods and lucinid bivalves (Kaim and Kelly 2009).

13.2.2 England

An ichthyosaur fall was discovered in the Upper Jurassic (Oxfordian) Ringstead Clay Member in Dorset, England, by Danise et al. (2014). The ichthyosaur has been identified as a species of *Ophthalmosaurus*. Prior to burial, the skeleton was colonized by a benthic community—including echinoids. However, it is unlikely to have represented a fully formed chemosynthetic community because the sulfophilic stage was lacking and the scavenger stage was followed directly by the reef stage—this is rarely observed in modern examples of vertebrate falls (compare Smith and Baco (2003)). Simms (1999) also described several occurrences of crinoids associated with wood falls in Jurassic sediments of England. Most likely, as already suggested by Buckland (1837), these crinoids could have been pseudoplanktonic, living on driftwood for many years before it sank to the seafloor.

13.2.3 France

Upper Jurassic (Oxfordian) seep deposits have been documented from the Terres Noires Formation near Beauvoisin in Southeast France (Rolin et al. 1990). The seep deposits occur in grey to black marly shale similar to the Pierre Shale in North

America. The deposits contain concentrations of the irregular echinoid *Tithonia oxfordiana* Gaillard et al. 2011. According to Gaillard et al. (2011), the seeps may have acted as a refuge for this species.

13.2.4 Germany

The Jurassic (Toarcian) Posidonia Shale in Germany contains several examples of crinoids in close association with wood logs (e.g. Hess (1999)). The crinoids were apparently attached to the logs while they were still floating or after they sunk to the seafloor (Seilacher and Hauff 2004), thus forming a pseudoplanktic rather than a chemosynthetic community (Hunter et al. 2020).

13.2.5 Greenland

Lower Cretaceous seep deposits are present in Wollaston Foreland, Northeast Greenland, as described by Kelly et al. (2000) and Nakrem et al. (2020). Large echinoid spines have been observed at some of these sites (C.T.S. Little, pers. comm., 2019).

13.2.6 Italy

Numerous echinoid ossicles have been reported by Peckmann et al. (1999) from Miocene lucinid-dominated methane seep deposits in Marmorito, Northern Italy.

13.2.7 Japan

A number of ancient seep deposits are exposed in Japan but not all of them are fully explored. Crinoids have been documented from Cretaceous seep deposits in the Yezo Group in Hokkaido (Kato and Oji 2015; Kato 2019). The crinoids belong to the Isocrinidae (see Hess (2011)). They are not endemic to the seeps but occur elsewhere in the basin. In addition, *Isselicrinus* sp. has been discovered by Kazutaka Amano near or at a wood fall in the Katsuhira Formation in Urahoro Town, Eastern Hokkaido (Amano et al. 2018; A. Hunter, pers. comm. 2020).

13.2.8 Morocco

Several seep deposits are present in the Silurian and Devonian of Morocco (Jakubowicz et al. this volume). However, the origin of these deposits is unclear and they may reflect a mixture of cold and hydrothermal seepage. Stalked crinoids have been reported from some of these sites, although it is unknown if they were seep-obligate or opportunistic.

13.2.9 Namibia

Some crinoid ossicles have been reported from Upper Carboniferous seep carbonates in Southern Namibia (Himmler et al. 2008).

13.2.10 New Zealand

Some echinoid spines have been reported by Saether (2011) from Miocene seep deposits at Wanstead and Rocky Knob in New Zealand. The specimens from Rocky Knob have been identified as cidaroids (Saether 2011).

13.2.11 Novaya Zemlya

Hryniewicz et al. (2015) researched seep deposits from the Arctic Island of Novaya Zemlya. The deposits appear to date from the Late Jurassic/Early Cretaceous. Skeletal plates of echinoderms were identified in thin sections. Further research is needed at these localities to understand the paleoenvironment and composition of the seep communities.

13.2.11.1 Poland

The Bathonian (Middle Jurassic) clays in Poland contain several logs of wood supporting rich benthic communities (Kaim 2011). These communities include crinoids, echinoids, asteroids and ophiuroids. Kaim (2011) argued that the crinoids (*Balanocrinus* and *Chariocrinus*) settled on the wood when it was already on the sea bottom. Therefore, the crinoids were benthic rather than pseudoplanktonic. These associations represent Jurassic wood-fall communities, which, in contrast to their modern counterparts, do not contain chemosymbiotic animals. This disparity results from the absence of xylophagain wood-boring bivalves. These bivalves produce significant numbers of faecal pellets, the decomposition of which increases the amount of sulphide around sunken driftwood.

13.2.12 Svalbard

Numerous fossil seep deposits are present in Spitsbergen in the Svalbard Archipelago (Hammer et al. 2011; Hryniewicz et al. 2014). The deposits occur in the uppermost Volgian-Ryazanian (Jurassic-Cretaceous) Slottsmøya Member of the Agardhfjellet Formation. The carbonate bodies occur in a dark shale, similar to sites in France and the USA. Crinoid ossicles belonging to the Isocrinidae and echinoid test plates are present but rare, in these deposits.

13.2.13 Turkey

Kiel et al. (2017) reported echinoderm fragments in methane seep deposits from the Upper Triassic (upper Carnian-lower Norian). The sites are located within the Kasımlar Basin from the Anamas Akseki autochthon in the Taurus Mountains in Southern Turkey.

13.2.14 Washington State, USA

Hybersten and Kiel (2018) described a middle Eocene cold seep deposit at the Weatherwax site in the basal Humptulips Formation along the West Fork of Satsop River in Washington State. The deposit contains silicified fossils including echinoid spines. Goedert and Squires (1993) noted spatangoid echinoids and crinoid ossicles (*Isocrinus*?) in an Oligocene seep deposit at Murdock Creek, and Goedert and Peckmann (2005) also reported echinoderms from an Eocene seep deposit near Knappton, both in Washington State. In addition, Goedert and Campbell (1995) documented seep deposits containing echinoid spines in the Lower Oligocene Makah Formation in the northwestern Olympic Peninsula of Washington State near Shipwreck Point.

13.2.15 Western Interior, USA

Methane seep deposits are very abundant in the Northern Great Plains of North America (Larson et al. 2013; Landman et al. this volume). The seeps developed in the Late Cretaceous Western Interior Seaway (WIS). Hundreds of metres of organic-rich sediments extending from the Middle to Upper Jurassic Sundance Formation up through the Upper Cretaceous Pierre Shale and Bearpaw Shale are the likely sources of hydrocarbons. Due to plate tectonics, the western and central regions of the USA were slowly uplifted, creating fractures and faults during the Laramide orogeny. These fractures and faults probably provided pathways for pore waters, hydrocarbons, minerals and gases to escape towards the surface. These underlying mechanisms are the key to understanding seep development in the WIS.

In general, echinoderms are rare in the Upper Cretaceous of the Western Interior of North America. However, the rapid rate of carbonate precipitation at the sediment-water interface at some methane seeps probably increased the chances of echinoderm preservation. Indeed, many of the fossils from these sites are preserved in exquisite detail. Exploration, mapping and research are ongoing in this region as new species and new localities are discovered (Brezina et al. in preparation). Future exploration will also yield additional clues to understanding the formation of these seep deposits.

Gill and Cobban (1966) documented fragments of asteroids (starfish) near seep deposits in the Pierre Shale on the Old Woman Anticline in eastern Wyoming. Subsequently, several species of echinoderms have been reported from seep deposits in the upper Campanian *Didymoceras cheyennense* Zone of the Pierre Shale in South Dakota (Figs. 13.1 and 13.2). These include a regular echinoid (*Gauthieria* sp.), an irregular echinoid (*Hemiaster* sp.) a feather star comatulid crinoid (*Glenotremites brezinai* (in press)), a brittlestar (ophiuroid) (*Brezinacantha tolis* Thuy et al., 2018), a starfish (asteroid) (*Betelgeusia brezinai* Blake et al., 2018), and a stalked crinoid (*Lakotacrinus brezinai* Hunter et al., 2016). Many of these same species also occur in seep deposits in the overlying upper Campanian *Baculites compressus* and *B. cuneatus* Zones of the Pierre Shale in South Dakota (Larson et al. 2013; Landman et al. 2010; Larson et al. 1997; Hunter et al. 2016; Kato et al. 2017). A few additional specimens of echinoids (*Hemiaster humpreysanus* and *Eurysalenia minima*) have also been discovered near or at seep deposits in the lower Maastrichtian *B. eliasi* and *B. baculus* Zones of the Pierre Shale on the Cedar Creek Anticline in Montana (Ryan et al. 2020).

The brittlestar (ophiuroid) *Brezinacantha tolis* is present in a methane seep deposit in the Pierre Shale of western South Dakota (Fig. 13.2a–c). The specimens are concentrated at the edge of the seep deposit. They appear as a mass occurrence, all cemented together. The individuals at the top of the mass are articulated whereas those at the bottom are disarticulated, consisting of fragments and ossicles. Thuy et al. (2018) suggested that these brittlestars may have inhabited the same area for an extended period of time and, following death, were cemented together by seep carbonates.

The stalked crinoid *Lakotacrinus brezinai* is present in upper Campanian seep deposits in the Pierre Shale of Nebraska, South Dakota, Montana, and Colorado (Fig. 13.2f–h). It has, so far, not been reported from elsewhere in the basin and may have been restricted to the seeps. Because it lacks a holdfast, it may have drifted from one area of a seep to another or even to an adjacent seep in the same seep field. It is preserved in small concretions (SACs) or loose in the shale. It also occurs in

Fig. 13.1 Echinoderms from hydrocarbon seep deposits, Upper Cretaceous (upper Campanian) Pierre Shale, western South Dakota, USA. (**a**) Irregular echinoid *Hemiaster* sp., AMNH 82711, AMNH loc. 3420. (**b**) Irregular echinoid *Hemiaster* sp., AMNH 82710, AMNH loc. 3419. (**c**) Irregular echinoid *Hemiaster* sp., AMNH 82713, AMNH loc. 3419. (**d**) Regular phymosomatoid echinoid, AMNH 82705, AMNH loc. 3509. (**e**) Regular phymosomatoid echinoid, AMNH 82706, AMNH loc. 3509. (**f**) Regular phymosomatoid echinoid, AMNH 82707, AMNH loc. 3509. (**g**) Regular phymosomatoid echinoids, AMNH 82716, AMNH loc. 3654. (**h**) Comatulid crinoid (feather star) *Glenotremites brezinai*, calyx, AMNH 164729, AMNH loc. 3529. See Appendix Table 13.1 for locality details

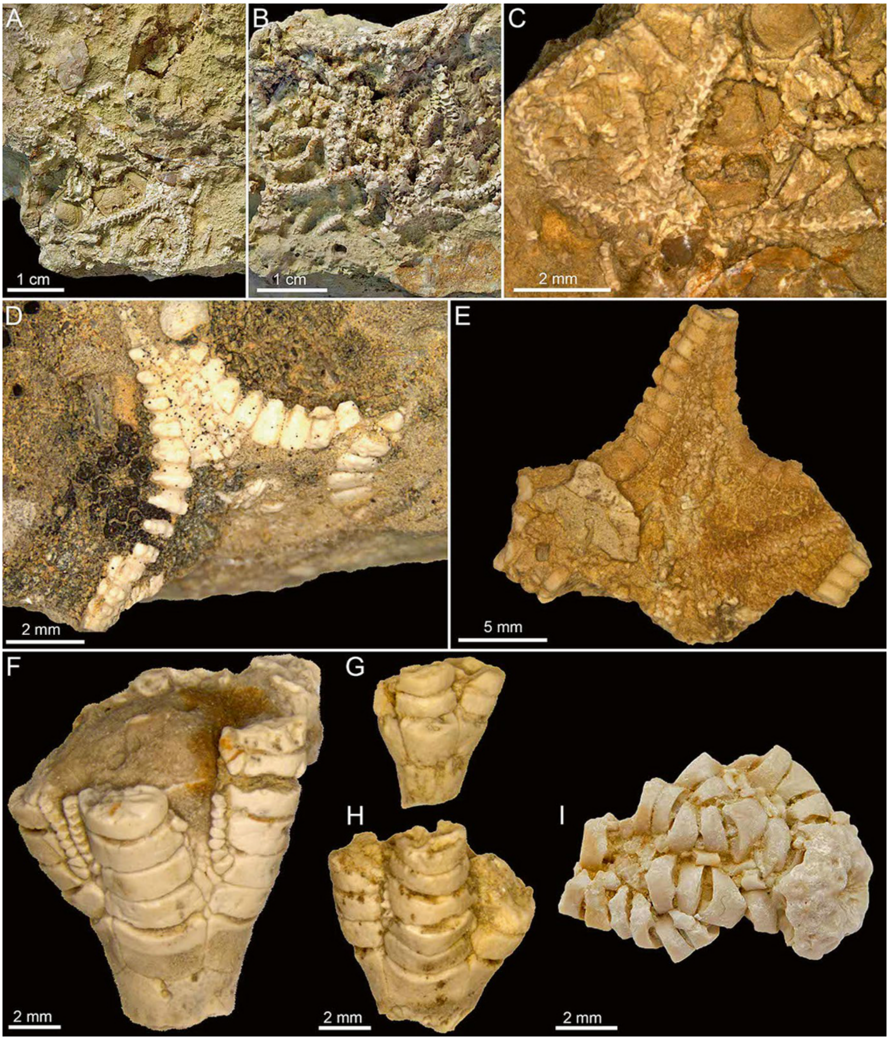

Fig. 13.2 Echinoderms from methane seep deposits, Upper Cretaceous (upper Campanian) Pierre Shale, western South Dakota, USA. (**a**) Brittlestar (ophiuroid) *Brezinacantha tolis* Thuy et al., 2018, AMNH 164730, AMNH loc. 3509a. (**b**) Brittlestar (ophiuroid) *Brezinacantha tolis* Thuy et al., 2018, AMNH 113585, AMNH loc. 3509a. (**c**) Brittlestar (ophiuroid) *Brezinacantha tolis* Thuy et al., 2018, AMNH 164731, AMNH loc. 3509a. (**d**) Asteroid (starfish) *Betelgeusia brezinai* Blake et al., 2018, AMNH 164732, AMNH loc. 3529. (**e**) Asteroid (starfish) *Betelgeusia brezinai* Blake et al., 2018, AMNH 111823, AMNH loc. 352. (**f**) Stalked crinoid *Lakotacrinus brezinai* Hunter et al., 2016, juvenile partial crown, AMNH 84500, AMNH loc. 3509b. (**g**) Stalked crinoid *Lakotacrinus brezinai* Hunter et al., 2016, juvenile partial crown, AMNH 84495, AMNH loc. 3509b. (**h**) *Lakotacrinus brezinai* Hunter et al., 2016, juvenile partial crown, AMNH 84499, AMNH loc. 3509b. (**i**) Comatulid crinoid (feather star) *Glenotremites brezinai*, partial crown, AMNH 161016, AMNH loc. 3529. See Appendix Table 13.1 for locality details

association with large tabular plates consisting of whole or broken inoceramid shells. These plates probably formed a carbonate crust that was rapidly cemented together at the time, producing a hard substrate. *Lakotacrinus brezinai* persisted for at least 3 Myr of the 6–7 Myr of recorded seepage around the Black Hills and eastern Rocky Mountain Region.

Kato et al. (2017) analysed the carbon isotopic composition of *Lakotacrinus brezinai* for clues to its mode of life. The values of $\delta^{13}C$ of the skeletal material are very low and range from −32‰ to −11‰. Given the highly specialized morphology of *L. brezinai*, in combination with its low $\delta^{13}C$ values, Kato et al. (2017) argued that it was adapted to cold seep environments, in agreement with the earlier suggestion of Hunter et al. (2016) that this species was probably an obligate member of the chemosynthetic community. In contrast, the morphology and carbon isotopic composition of the echinoids at the same seep sites are not significantly different from those at non-seep sites, suggesting that the echinoids were opportunistic rather than obligate members of the chemosynthetic community (Kato et al. 2017). It is worth noting, however, that the isotopic composition of echinoderms as well as other fossil materials from the Upper Cretaceous Western Interior is sometimes subject to alteration due to post-depositional processes (Hunter et al. 2018; Kato et al. 2018).

13.3 Conclusions

Echinoderms are rare in ancient hydrocarbon seep deposits and other unique environments, possibly due to several factors like low preservation potential. Most of them represent background fauna that colonized the seep from elsewhere in the seaway or oceanic basin. Modern hydrocarbon seeps, hydrothermal vents and cognate communities host a wide range of echinoderms including starfish, brittlestars, feather stars, holothuroids and echinoids. New species are regularly being described from these sites. Future exploration of ancient methane seep deposits will also lead to new discoveries and a better understanding of the paleoenvironments in which these communities developed.

Acknowledgments The authors would like to thank the private landowners, ranchers and farmers for allowing access to seep sites, the USDA Forest Service for allowing research permits, the private collectors for allowing access to collections and their donations and the countless fellow worldwide researchers that made this collaboration and research possible. We would also like to thank all of the teachers, professors and students involved in this ongoing project. Special thanks to ranchers in western South Dakota, Wyoming and Montana, granting J. Brezina access to private property. The authors thank J. Kirk Cochran (Stony Brook University) and Andrzej Kaim (Institute of Paleobiology, Polish Academy of Science) for help in editing the manuscript and organizing the bibliography. We also thank Selina R. Cole (US National Museum of Natural History) for reviewing the manuscript and making many helpful suggestions.

Appendix

Table 13.1 AMNH localities, Pierre Shale. Abbreviations: *B. comp.= Baculites compressus; D. chey. = Didymoceras cheyennense;* study number is a way point number (WPT) assigned by J. Brezina

Loc.	Study no. (WPT)	Zone	State	County	TRS	Latitude (N)	Longitude (W)
3419	61	*B. comp.*	SD	Custer	SEC 30 T3S, R11E	43° 45′ 41″	102° 51′ 9″
3420	61	*D. comp.*	SD	Custer	SEC 19, T3S, R11E	43° 46′ 15″	102° 51′ 26″
3509	130A, B	*D. chey.*	SD	Pennington	SEC 15, T2S, R10E	43° 52′ 39″	102° 54′ 40″
3529	140	*D. chey.*	SD	Pennington	SEC 3, T2S, R10E	43° 54′ 22″	102° 54′ 27″
3654	136	*D. chey.*	SD	Custer	SEC10, T5S, R9E	43° 37′ 50″	103° 2′ 26″

References

Amano K, Jenkins RG, Kurita H (2018) New and Mesozoic-relict mollusks from Paleocene wood-fall communities in Urahoro Town, eastern Hokkaido, northern Japan. J Paleontol 92:634–647

Blake DB, Halligan WK, Larson NL (2018) A new species of the asteroid genus *Betelgeusia* (Echinodermata) from methane seep settings, Late Cretaceous of South Dakota. J Paleontol 92(2):196–206

Brezina et al (in preparation) Fossil echinoderms in methane seep deposits from the Upper Cretaceous Pierre Shale in the Western Interior of North America

Buckland W (1837) Geology and mineralogy, considered with respect to natural theology: v. 6, The Bridgewater treatises: pt. 1: 1–618; pt. 2: 1–129, 69 pl., London, Wm. Pickering

Danise S, Twitchett RJ, Matts K (2014) Ecological succession of a Jurassic shallow-water ichthyosaur fall. Nature Commun 5:4789

Gaillard C, Neraudeau D, Thierry J (2011) *Tithonia oxfordiana*, a new irregular echinoid associated with Jurassic seep deposits in south-east France. Palaeontology 54:735–752

Gill JR, Cobban WA (1966) The Red Bird section of the Upper Cretaceous Pierre Shale in Wyoming. USGS Prof Pap 393-A:1–73

Goedert J, Campbell KA (1995) An early Oligocene chemosynthetic community from the Makah Formation, northwestern Olympic Peninsula, Washington. Veliger 38:22–29

Goedert JL, Peckmann J (2005) Corals from deep-water methane-seep deposits in Paleogene strata of Western Oregon and Washington, U.S.A. In: Freiwald A, Roberts JM (eds) Cold-water corals and ecosystems. Springer, Berlin, pp 27–40

Goedert JL, Squires RL (1993) First Oligocene records of *Calyptogena* (Bivalvia: Vesicomyidae). Veliger 36:72–77

Hammer O, Nakrem HA, Little CTS, Hryniewicz K et al (2011) Hydrocarbon seeps from close to the Jurassic–Cretaceous boundary, Svalbard. Palaeogeogr Palaeoclimatol Palaeoecol 396:15–26

Hess H (1999) Lower Jurassic Posidonia Shale of Southern Germany. Fossil Crinoids:183–196

Hess H (2011) Isocrinida. In: Hess H, Messing CG, Ausich WI (eds) Treatise on invertebrate paleontology, Part T, Echinodermata 2 revised, Crinoidea, vol 3. University of Kansas Press, Lawrence, pp 42–69

Hess H, Ausich WI, Brett CE, Simms MJ (2011) Fossil Crinoids. Palaeontology 54:735–752

Himmler T, Freiwald A, Stollhofen H, Peckmann J (2008) Late Carboniferous hydrocarbon-seep carbonates from the glaciomarine Dwyka Group, southern Namibia. Palaeogeogr Palaeoclimatol Palaeoecol 257:185–197

Hryniewicz K, Nakrem HA, Hammer Ø et al (2014) The palaeoecology of the latest Jurassic-earliest Cretaceous hydrocarbon seep carbonates from Spitsbergen, Svalbard. Lethaia 48:353–374

Hryniewicz K, Hagström J, Hammer Ø et al (2015) Late Jurassic–Early Cretaceous hydrocarbon seep boulders from Novaya Zemlya and their faunas. Palaeogeogr Palaeoclimatol Palaeoecol 436:231–244

Hunter AW, Larson NL, Landman NH et al (2016) A new crinoid from cold methane seep deposits in the Upper Cretaceous Pierre Shale. J Paleontol 90(3):506–524

Hunter AW, Larson NL, Brezina J (2018) Comment to Kato et al. (2017), "Paleoecology of echinoderms in cold seep environments revealed by isotope analysis in the Late Cretaceous Western Interior Seaway". Palaios 33:282–283

Hunter AW, Casenove D, Mayers C, Mitchell EG (2020) Reconstructing the ecology of a Jurassic pseudoplanktonic raft colony. R Soc Open Sci 7(7):200142

Hybertsen F, Kiel S (2018) A middle Eocene seep deposit with silicified fauna from the Humptulips Formation in western Washington State, USA. Acta Palaeontol Pol 63:751–768

Jakubowicz M, Berkowski B, Hryniewicz K, Bełka Z (this volume) Middle Paleozoic of Morocco: the earliest-known Methane Seep Metazoan Ecosystems. In: Kaim A, Cochran JK, Landman NH (eds) Ancient Hydrocarbon Seeps. Topics in Geobiology, vol 50. Springer, New York

Kaim A (2011) Non-actualistic wood-fall associations from Middle Jurassic of Poland. Lethaia 44:109–124

Kaim A, Kelly SRA (2009) Mass occurrence of hokkaidoconchid gastropods in the Upper Jurassic methane seep carbonate from Alexander Island, Antarctica. Antarct Sci 21:279–284

Kato M (2019) Crinoids lived around the Cretaceous seeps: the second example from cold-seep deposit in the Yezo Group in Hokkaido, Japan. Zoosymposia 15:88–97

Kato M, Oji T (2015) Comparison of fossil echinoderms from Upper Cretaceous cold seep environments between Japan and central United States. Paper presented at Japan Geoscience Union Meeting, Makuhari, Chiba, Japan, 24–28 May 2015

Kato M, Oji T, Shirai K (2017) Paleoecology of echinoderms in cold seep environments revealed by isotope analysis in the Late Cretaceous Western Interior Seaway. Palaios 32:218–230

Kato M, Oji T, Shirai K (2018) Reply to comment on Kato et al. (2017) "Paleoecology of echinoderms in cold seep environments revealed by isotope analysis in the Late Cretaceous Western Interior Seaway". Palaios 33:284–285

Kelly SRA, Ditchfield PW, Doubleday PA, Marshall JD (1995) A late Jurassic methane-seep limestone from the Fossil Bluff Group forearc basin of Alexander Island, Antarctica. J Sediment Res A65:274–282

Kelly SRA, Blanc E, Price SP, Whitham AG (2000) Early Cretaceous giant bivalves from seep-related limestone mounds, Wollaston Forland, Northeast Greenland. Geol Soc London Spec Publ 177:227–246

Kiel S, Krystyn L, Demirtas F et al (2017) Late Triassic mollusk-dominated hydrocarbon-seep deposits from Turkey. Geology 45(8):751–754

Landman NH, Kennedy WJ, Cobban WA et al (2010) Scaphites of the '*nodosus* group' from the Upper Cretaceous (Campanian) of the Western Interior of North America. Bull Am Mus Nat Hist 342:1–242

Landman NH, Cochran JK, Brezina J et al (this volume) Methane Seeps in the Late Cretaceous Western Interior Seaway, USA. In: Kaim A, Cochran JK, Landman NH (eds) Ancient hydrocarbon seeps. Topics in geobiology, vol 50. Springer, New York

Larson NL, Jorgensen SD, Farrar RA et al (1997) Ammonites and the other cephalopods of the Pierre Seaway. Geoscience Press, Tucson

Larson et al (2013) Hydrocarbon Seeps: Unique habitats that preserved the diversity of fauna in the Late Cretaceous Western Interior Seaway

Nakrem HA, Little CTS, Kelly SRA (2020) Early Cretaceous hydrocarbon seep carbonates from Wollaston Forland, Northeast Greenland. NGF Abstr Proc Geol Soc Norw 1:149

Pawson DL, Nizinski MS, Ames CL, Pawson DJ (2015) Deep-sea echinoids and holothurians (Echinodermata) near cold seeps and coral communities in the northern Gulf of Mexico. Bull Mar Sci 91:167–204

Peckmann J, Thiel V, Michaelis W, Clari P, Gaillard C, Martire L, Reitner J (1999) Cold seep deposits of Beauvoisin (Oxfordian; southeastern France) and Marmorito (Miocene; northern Italy): microbially induced authigenic carbonates. Int J Earth Sci 88:60–75

Rolin Y, Gaillard C, Roux M (1990) Ecologie des pseudobiohermes des Terres Noires jurassiques liés à des paléo-sources sous-marine: le site oxfordien de Beauvoisin (Drôme, Bassin du sud-Est, France). Palaeogeogr Palaeoclimatol Palaeoecol 80:79–105

Ryan DR, Witts JD, Landman NH (2020) Palaeoecological analysis of a methane seep deposit from the Upper Cretaceous (Maastrichtian) of the U.S. Western Interior. Lethaia 54:185–203

Saether KP (2011) A taxonomic and palaeobiogeographic study of the fossil fauna of Miocene hydrocarbon seep deposits, North Island, New Zealand. PhD thesis archived at ResearchSpace@ Auckland 7. https://researchspace.auckland.ac.nz/handle/2292/6676

Seilacher A, Hauff RB (2004) Constructional morphology of pelagic crinoids. Palaios 19(1):3–16

Simms MJ (1999) *Pentacrinites* from the Lower Jurassic of the Dorset coast of southern England. In: Hess H, Ausich WI, Brett CE, Simms MJ (eds) Fossil Crinoids. Cambridge University Press, Cambridge, pp 177–182

Smith C, Baco A (2003) Ecology of whale falls at the deep-sea floor. Oceanogr Mar Biol 41:311–354

Thuy B, Landman NH, Larson NL, Numberger-Thuy LD (2018) Brittle-star mass occurrence on a Late Cretaceous methane seep from South Dakota, USA. Sci Rep 8:9617

Torres ME, Embley RW, Merle SG et al (2009) Methane sources feeding cold seeps on the shelf and upper continental slope off central Oregon, USA. Geochem Geophys Geosyst 10:Q11003

Zeppilli D, Mea M, Corinaldesi C, Danovaro R (2011) Mud volcanoes in the Mediterranean Sea are hot spots of exclusive meiobenthic species. Progr Ocean 91(3):260–272