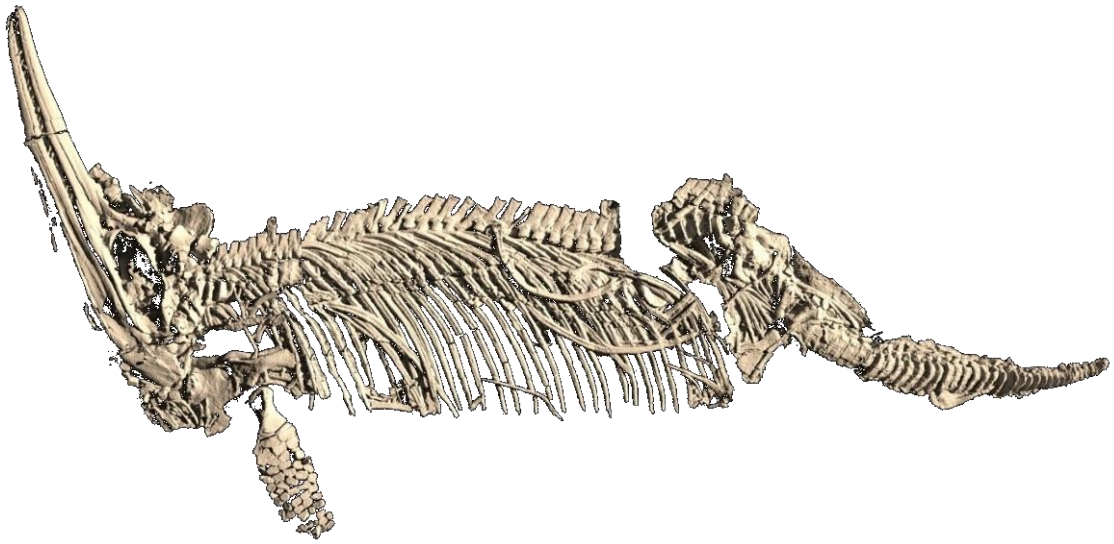
EAVP 2024

Short introduction to the vertebrate paleontology of Svalbard, with excursions to the Triassic and Jurassic



Cryopterygius kristiansenae, Slottsmøya Mb, Janusfjellet

Natural History Museum of Oslo
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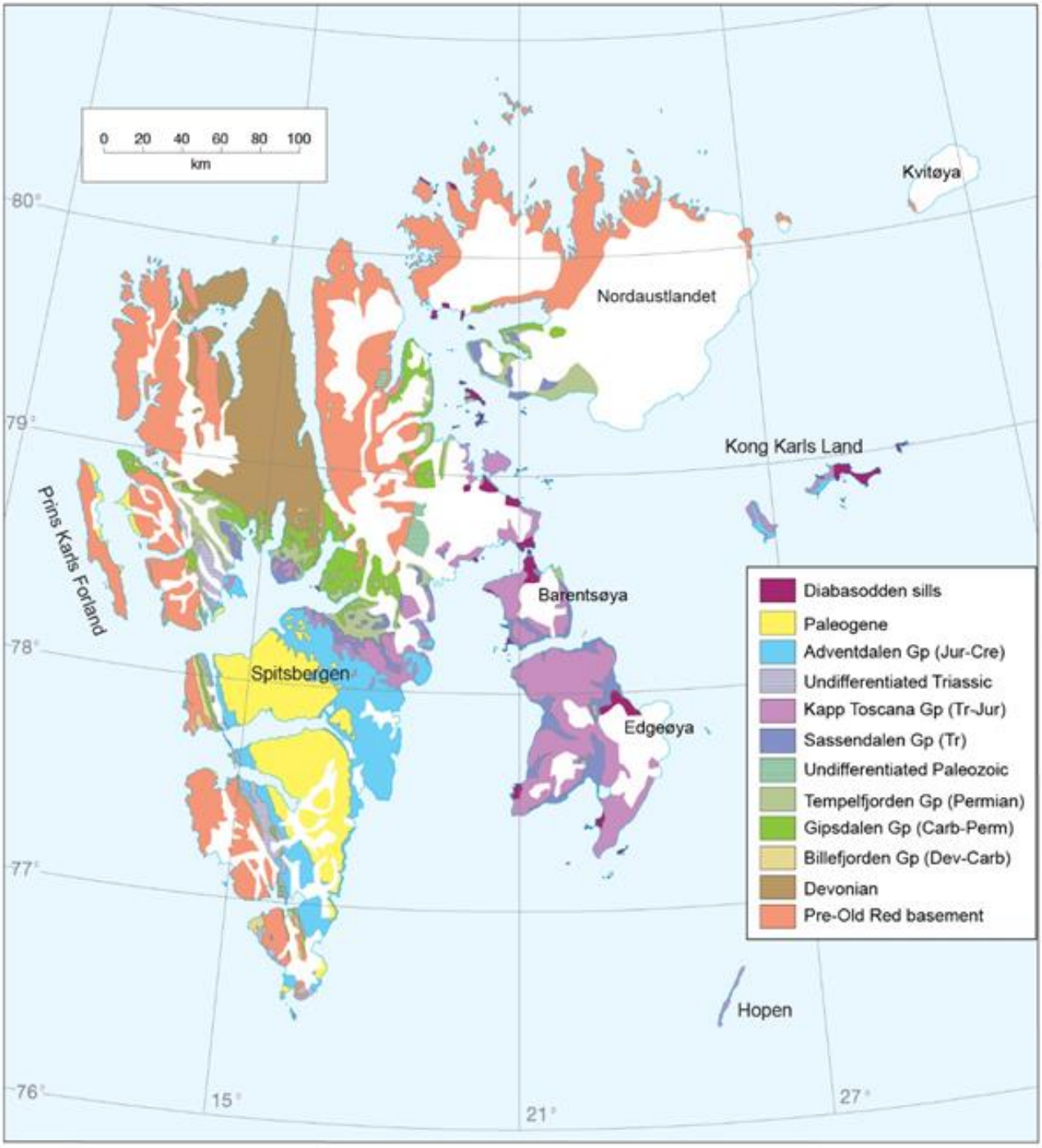

Figure 1. Simplified geological map of Svalbard (excluding Bjørnøya). Modified from Dallmann (1999). See *The Geology of Svalbard*: https://brage.npolar.no/npolar-xmlui/handle/11250/173141

Introduction to the stratigraphy and paleontology of Svalbard

The Svalbard archipelago consists of many islands, the largest being Spitsbergen. Svalbard has a varied geology, with a sedimentary record from the Precambrian to the Paleogene. Parts of the succession are highly fossiliferous. Despite the high latitude, localities are relatively accessible, and there is a well-developed civil infrastructure with modern research facilities. Svalbard is therefore an ideal place for studying the paleontology of the Arctic.

Although the structural geology is complex, as a first approximation we can regard the island of Spitsbergen as a large-scale NNW-SSE syncline, asymmetric, with steeply dipping strata on the western flank but low dip on the eastern flank (fig. 1). In central Spitsbergen, outcrops of the youngest strata, of Paleogene age, are therefore mainly found in the central part of the syncline, south and west of Longyearbyen. Going further west or east, we encounter successively older rocks (Cretaceous, Jurassic, Triassic, Permian, Carboniferous, Devonian), although this pattern is complicated by faults. The pre-Devonian succession is more seriously disturbed by tectonics and metamorphism (the "Hecla Hoek" complex), but fossiliferous rocks are found both in the Proterozoic and in the Cambrian-Ordovician.

We will here focus on units with a documented vertebrate fossil record.

Ordovician

A more than 800 m thick, fossiliferous Lower to Middle Ordovician succession is exposed along Hinlopenstredet in northernmost Spitsbergen (review in Kröger et al. 2016). The controversial vertebrate *Anatolepis heintzi* was described from the Valhallfonna Formation at this locality by Bockelie and Fortey (1976) as fragments of a heterostracan fish.

Devonian

Fossiliferous Devonian strata are mainly found north of Isfjorden, especially from near the Russian settlement at Pyramiden and northwards into the peninsula between Woodfjorden and Wijdefjorden (Andrée Land). The facies are predominantly fluvial, lacustrine, and marginal marine, and are considered to belong to the widespread Old Red Sandstone province (Harland, 1997). The oldest fish-bearing beds are found in the Red Bay Group of Early Devonian (Lochkovian) age, and the rich succession of heterostracans, osteostracans, placoderms, and thelodonts continues into the Pragian-Emsian Wood Bay Formation (e.g., the classic works by Stensiö 1927; Kiær and Heintz 1935; and modern work like Pernègre and Blieck 2016).

Figure 2. *Lyktaspis*, a Devonian placoderm from Svalbard

Devonian – Permian

The Upper Devonian (Frasnian or Famennian) to Carboniferous (Viséan) Billefjorden Group is exposed in western Spitsbergen and northeast of Isfjorden, and consists of deltaic, fluvial and floodplain deposits. The paleolatitude was 0–20°N. Coal seams in the Billefjorden Group were previously mined in the Russian settlement at Pyramiden. Plant remains are relatively common, including one of the oldest known fossil forests with dense stands of lycopsid trees in Mimerdalen (Berry and Marshall 2015).

Holtedahl (1926) found early Carboniferous fish fossils in northwest Spitsbergen. Lindemann et al. (2013) reported a Late Devonian or early

Carboniferous vertebrate bone bed in the Hørbyebreen Formation, central Spitsbergen, with fragmentary sarcopterygian and tetrapod remains.

The younger Gipsdalen Group represents a progressively more marine setting, culminating with the lower Permian (Artinskian) evaporitic sabkha deposits of the Gipshuken Formation followed by the marine cherts, carbonates, sands and shales of the Kapp Starostin Formation (Tempelfjorden Group). To our knowledge, no vertebrate fossils have been reported from these units, but micro invertebrates like fish teeth, thelodonts and conodonts have been found (Nakrem, unpubl.).

Triassic

The Triassic in Spitsbergen is more or less continuous (Dallmann et al. 1999; Vigran et al. 2014), with a rich vertebrate fossil record (Hurum et al. 2018). In the Early Triassic, the western areas were shallow marine, even intertidal (Wignall et al. 2015), while the central and eastern parts were progressively offshore. The lithological development is therefore different in the west compared with central and eastern Spitsbergen, leading to different formation names. We follow here the nomenclature for central Spitsbergen, with the Lower Triassic Vikinghøgda Formation followed by the Middle Triassic Botneheia Formation.

The lowermost Triassic (Deltadalen Member, Induan) is not highly fossiliferous but yields invertebrates and fish teeth, especially in the lower part. The succeeding Lusitaniadalen Member is of early Olenekian (Smithian) age, and highly fossiliferous especially in the upper part. This is the so-called Fish Niveau, with a relatively rich invertebrate and vertebrate fauna. Actinopterygians (especially *Saurichthys*), sarcopterygians, and temnospondyls are common. The oldest known ichthyosaur was recently recovered from the Lusitaniadalen Member in Flowerdalen (Kear et al. 2023).

The Vendomdalen Member is of late Olenekian (Spathian) age. As detailed below (Excursion 2), this member also contains a rich vertebrate record. In the lower part, the Grippia Niveau is found, with well-preserved fossils of early ichthyopterygians in concretions, and an extremely rich and diverse marine bonebed at Marmierfjellet near Flowerdalen. The latest Spathian Lower Saurian Niveau consists of large and small ichthyopterygians and rare temnospondyls.

The black-shale Botneheia Formation is believed to span the entire Middle Triassic (Anisian and Ladinian). Spitsbergen was situated at ca. 45°N and had a relatively dry and warm climate and increasingly restricted marine conditions (fig. 3; Mueller et al. 2015). The so-called Upper Saurian Niveau is an interval in the upper part of the formation (Blanknuten Member) with abundant marine reptile remains, mostly ichthyosaurs. Conodonts are also well known from the Lower and Middle Triassic successions (Nakrem et al. 2008).

The Upper Triassic in Spitsbergen is prodeltaic to deltaic. Ichthyosaur remains have been reported from the Tschermakfjellet Formation (Carnian), but at least some of these finds should probably rather be placed in the uppermost Botneheia Formation (discussion in Maxwell and Kear 2013). The sandy De Geerdalen Formation (Carnian-Norian) contains only scattered vertebrate elements (Cox and Smith 1973). The climate became increasingly humid, and the depositional environment was described as a humid delta plain by Mueller et al. (2015).

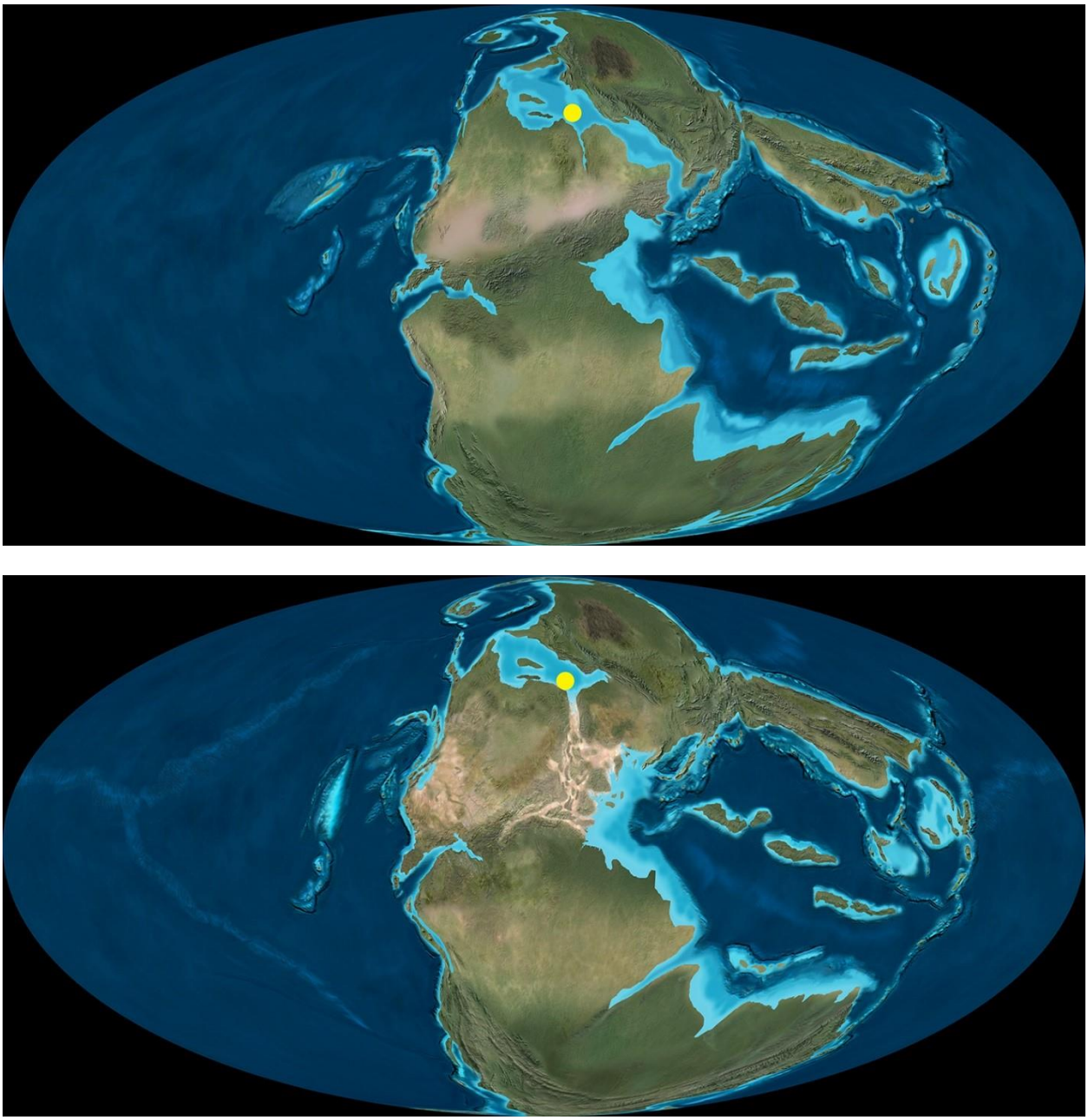

Figure 3. Paleogeographic position of Svalbard (yellow dot) in the Early and Middle Triassic (250 and 240 Ma; paleolatitude 40–45°N).

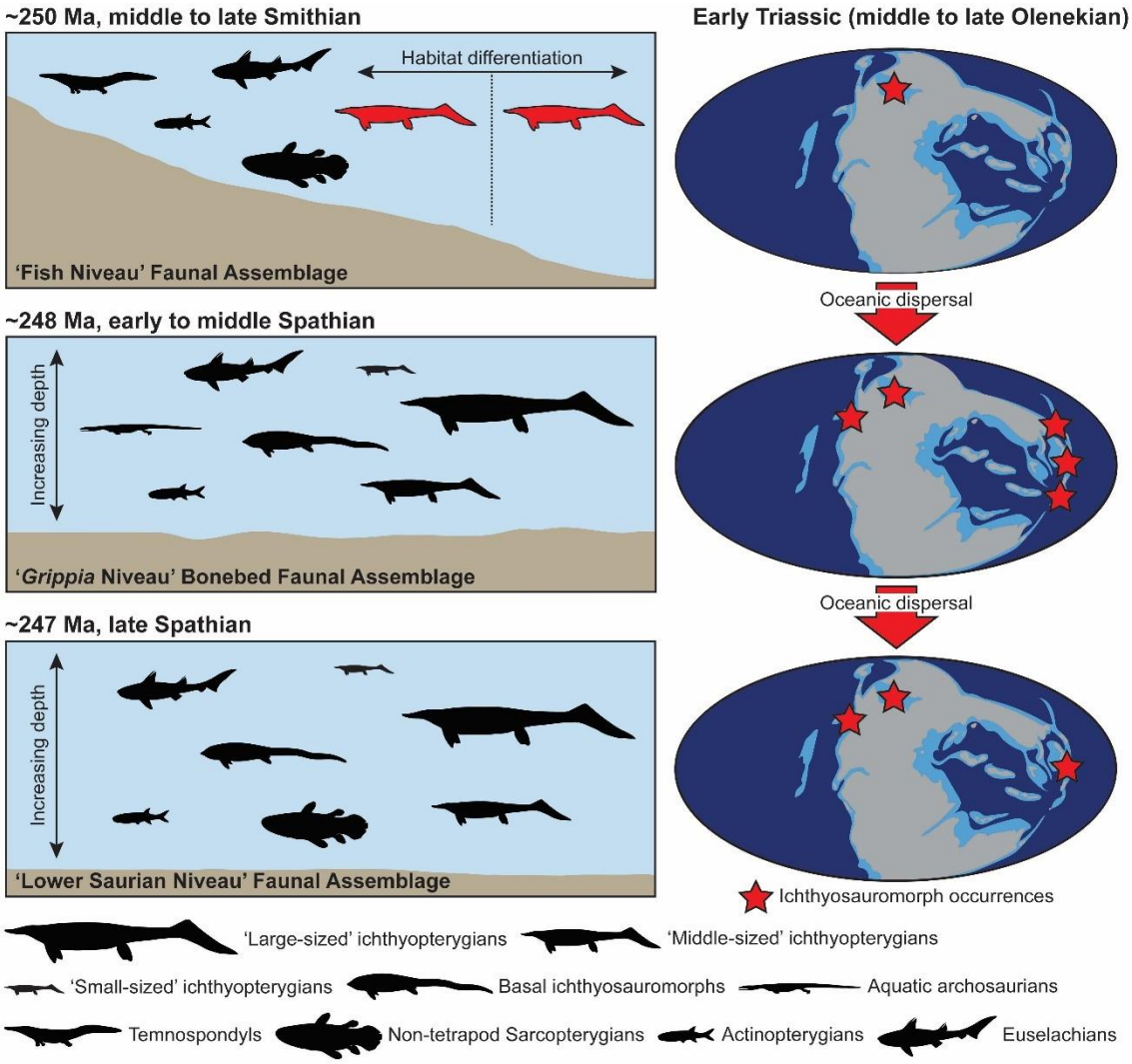

Figure 4. The three Early Triassic vertebrate faunal assemblages at Svalbard. The earliest ichthyosaur is found in the "Fish Niveau" (red). The dispersal of ichthyopterygians with worldwide localities shown on the globes.

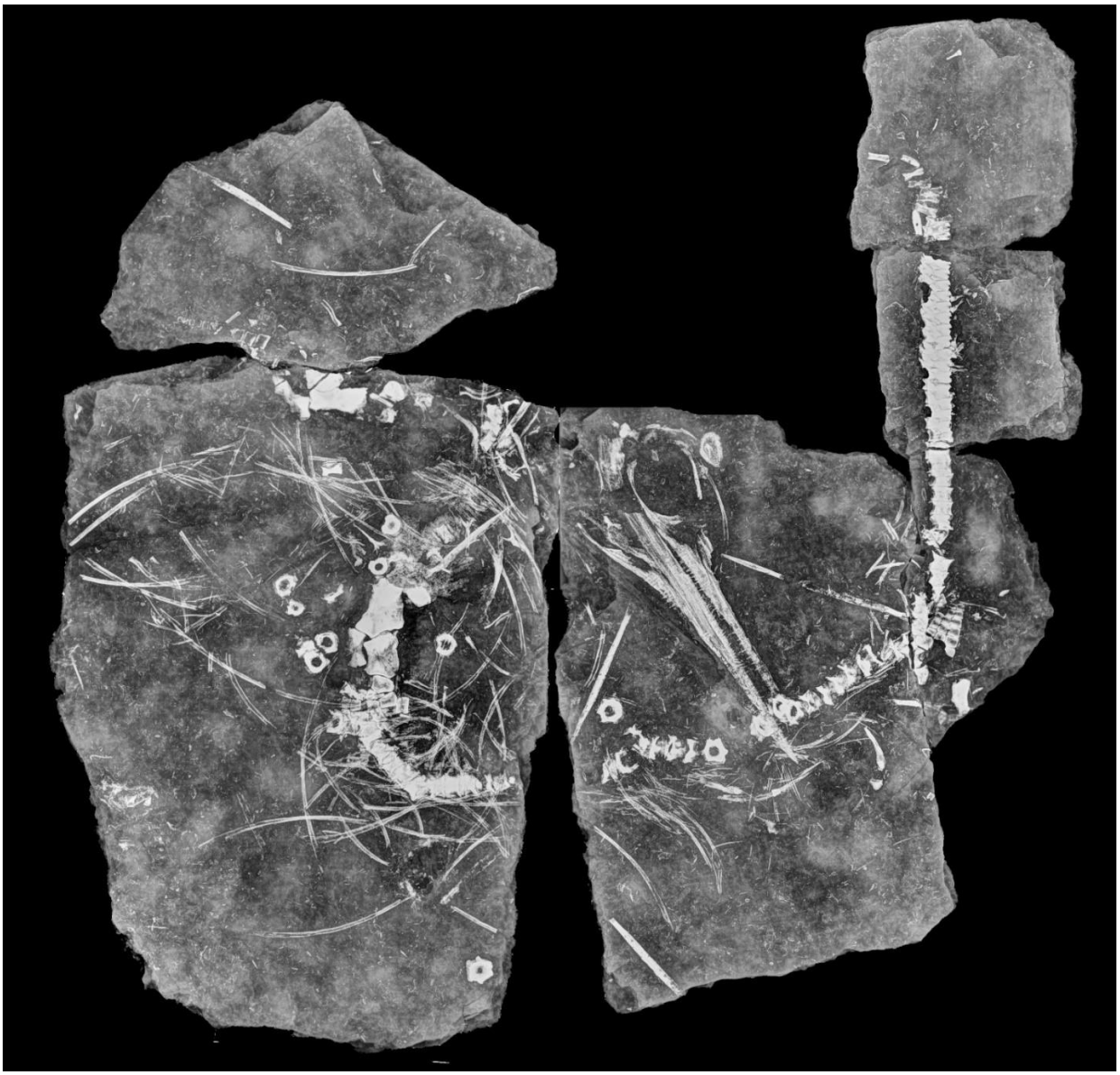

Figure 5. X-ray radiograph of a mixosaur from the Upper Saurian niveau, Edgeøya (Engelschiøn et al. 2023).

Jurassic

The uppermost Triassic (upper Norian to Rhaetian) to Lower Jurassic in central Spitsbergen is represented by the strongly condensed and discontinuous Knorringfjellet Formation, with sandstones, shales and conglomerates deposited in a shallow marine environment (Nagy and Berge 2008).

The Middle and Upper Jurassic is represented by the Agardhfjellet Formation (fig. 8), which is a succession of dark to black shales with subordinate sands and carbonates, typically ca. 200 m thick. While fish elements are found throughout the Agardhfjellet Fm (Koevoets et al. 2018), and marine reptile skeletal elements (mainly vertebrae) are occasionally found in the lower part, it is mainly the upper part (Slottsmøya Member, Tithonian) that has become famous for abundant vertebrate fossils, especially ichthyosaurs (fig. 6) and plesiosaurs (Hurum et al. 2012; Delsett et al. 2016). This fauna is described in more detail under Excursion 1, below. The climate was probably temperate (fig. 8).

Figure 6. The excavation of a large ichthyosaur in 2009 at Janusfjellet.

Figure 7. A plesiosaur with 60 neck vertebrae: *Spitrasaurus wensaasi*. Janusfjellet, Svalbard.

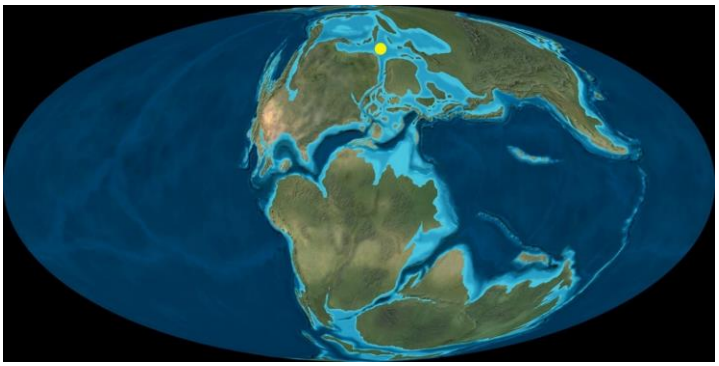

Figure 8. Paleogeographic position of Svalbard (yellow dot) in the Late Jurassic (150 Ma), paleolatitude ca. 60°N. © 2013 Colorado Plateau Geosystems Inc.

Cretaceous

The Cretaceous in Spitsbergen is represented mainly by the Rurikfjellet Formation (?Valanginian–Barremian), the Helvetiafjellet Formation (Barremian) and the Carolinefjellet Formation (Aptian–Albian). The Upper Cretaceous is missing in Svalbard.

The Rurikfjellet Formation is a dark shale with siderite nodules, coarsening upwards into siltstones and sandstones, typically ca. 200 m thick. The depositional environment was an

open marine shelf, oxic, grading up into shallow shelf/prodelta. No vertebrate fossils have been described from this formation, but marine invertebrates are abundant.

The regressive phase of the Rurikfjellet Formation is capped by the fluvio-deltaic sandstones of the Helvetiafjellet Formation. No vertebrate body fossils are known from this formation, but dinosaur tracks have been described from several localities in Spitsbergen (fig. 9; Lapparent 1962; Hurum et al. 2006; Hurum et al. 2016a). All these tracks are now ascribed to ornithopods (Hurum et al., 2016a). Plant fossils are also abundant.

The Carolinefjellet Formation represents a return to a marine depositional environment. The only fossil vertebrate known from this formation is a small femur tentatively identified as avian by Hurum et al. (2016b).

Abundant glendonites especially in the Rurikfjellet and Carolinefjellet formations are interpreted as indicative of cold (< 7°C) events (Vickers et al. 2019).

A phase of tectonic uplift started already in the Barremian and continued into the Cenozoic, leading to the large hiatus spanning the Cenomanian to the early Danian.

Figure 9. Cretaceous dinosaur tracks at the East side of Spitsbergen.

Paleogene

The Van Mijenfjorden Group of Paleocene (probably late Danian) to Eocene age is mainly confined to the "Central Cenozoic Basin" of central Spitsbergen and represents a deltaic to prodeltaic setting. Sands and shales with coal seams dominate. The coal seams and mines around Longyearbyen are part of the Lower Paleocene Firkanten Formation, which is exposed in the Central Cenozoic Basin. This was a deltaic coastal plain, with delta front and prodelta environments, and includes peat swamp, lacustrine, lagoonal and barrier deposits.

Plant fossils are abundant in some horizons and indicate a temperate and humid climate at high latitude. Vertebrate fossils are virtually unknown, except for pantodont tracks (fig. 10) reported by Lüthje et al. (2010) from the Firkanten Formation (Paleocene) and an amiid fish (Lehman 1951). The plant fossils found around Longyearbyen are from the Eocene Aspelintoppen Formation. The Aspelintoppen Formation sediments represent crevasse splay, backswamp and ephemeral lake deposits in a broad lowland floodplain that was subject to frequent flooding. In the aftermath of the Paleocene-Eocene Thermal Maximum these forests grew at a paleolatitude of 75°N.

Figure 10. Pantodont tracks in the roof of Mine 7, Longyearbyen.

Practical information

Transportation

Both excursions are full-day and will take place relatively close to Longyearbyen. Transport will be by open speedboat (RIB). These boats are very safe, but the ride can be bumpy and windy. All passengers are required to use a survival suit. More information will be given at a briefing before the trip.

Clothing and what to bring

The temperature in Svalbard in August is typically between 0 and 10 degrees Celsius. Wind and light rain can be expected, but heavy rain is rare. The terrain can be wet and soggy on the strand flat, and steep and rocky at the outcrops. Good hiking boots are recommended. Also bring a pair of dry socks just in case. Don't forget a camera! Mobile phone coverage is not guaranteed. Lunch will be provided. Bring a water bottle, as the water in streams is unsafe to drink due to a parasite (*Echinococcus multilocularis*).

Safety

Both trips are relatively easy. More information will be given before the trip, but we ask you to pay particular attention to the following:

Although we will avoid dangerous heights, some of the exposures are in steep cliffs. Know your limitations with respect to these cliffs, and do not hesitate to tell us if you feel uncomfortable. Rocks can be loose, so do not traverse a steep slope directly above others (or signal clearly if you do so). Also make sure to not walk directly underneath others at outcrops. We will supply hard hats if necessary.

There is much talk about polar bears in Svalbard. There is no need to be overly concerned. We will bring experienced polar bear guards, and fatal bear attacks on well-prepared groups on day trips have basically never happened in Svalbard. However, bears are common in the area. Both for your own safety, and to ensure safe shooting background, it is therefore *very important that we keep together as a group*. If you need a moment of privacy (euphemism), then please inform security staff.

Preserving nature

The nature in Svalbard is vulnerable. Do not litter – even paper decomposes slowly in the cold, dry climate. All waste (including used paper) must be brought back to Longyearbyen. Be gentle to the vegetation. Driftwood and other old objects on the beach are protected as cultural heritage, and it is also illegal to collect whale bones and reindeer antlers.

Both field trips are outside national parks, and you can collect moderate amounts of loose fossils and rocks. If significant discoveries are made, they will be included in the Paleontological collections at the Natural History Museum in Oslo (NHM-PMO).

Excursion 1: The Upper Jurassic Slottsmøya Member Lagerstätte at Janusfjellet

Introduction

The Janusfjellet area has long been known for scattered finds of marine reptile remains. In 1931, a partial skeleton of a plesiosaur, now referred to *Colymbosaurus*, was excavated here by American medical doctors (fig. 6; Knutsen et al. 2012a). Extensive field work by the University of Oslo from 2004 to 2012 uncovered a large number of complete or partly articulated marine reptiles in the Upper Jurassic Slottsmøya Member of the Agardhfjellet Formation, both at Janusfjellet and several other localities some 20 km along the outcrop (Hurum et al. 2012; Delsett et al. 2016; 2019b).

The finds include several species of ichthyosaurs (Druckenmiller et al. 2012, Roberts et al. 2014; Delsett et al. 2017; 2018; 2019a), pliosaurs (Knutsen et al. 2012b), and long-necked plesiosaurs (Knutsen et al. 2012c; 2012d; Liebe and Hurum 2012; Roberts et al. 2017; 2020). Usually, the skeletons are found by prospecting for individual bones on the surface, followed by excavation into the hillside, often into the permafrost. Frost wedging has caused some fragmentation of the bones, especially near the surface.

In this excursion, we will visit one of the most productive sites of the "Slottsmøya Lagerstätte". While we cannot guarantee finding vertebrate remains, we will get a good overview of the stratigraphy and the invertebrate paleontology of the Agardhfjellet Formation (Koevoets et al. 2019a; 2019b).

Figure 11. Excavation of a partial plesiosaur skeleton in the Slottsmøya Member near Janusfjellet, 1931.

The boat trip

As we leave Longyearbyen and head northwest out Adventfjorden (fig. 13), we see the Lower Cretaceous (Aptian to Albian) Carolinefjellet Formation in outcrops along shore to the left (southwest). This unit is followed by a considerable hiatus – the whole of the Upper Cretaceous and the lowermost Paleocene is missing. Above the low-angle unconformity, the Van Mijenfjorden Group (Paleocene to Eocene, possibly Oligocene) continues up to the local mountain peaks. The Firkanten Formation is partly sandy and forms steep cliffs in the lower parts of the mountains, typically followed by the shales of the Basilika Formation and then the thick sands of the Grumantbyen Formation.

On the right side (northeast), the marine Lower Cretaceous (Berriasian to Barremian) Rurikfjellet Formation is exposed along the shore. Further up the mountain sides we see the fluvio-deltaic sandstones of the Helvetiafjellet Formation (Barremian). Above this, the succession mirrors that on the left side of the fjord, with the Paleogene sands on the mountain peaks.

As we round the Revneset point and turn northeast towards Deltaneset, we observe a gentle westward dip in the strata, reflecting the eastern flank of the central Spitsbergen syncline. We therefore encounter progressively older strata along the shore. As we pass the small valley Carolinedalen, we cross the Jurassic-Cretaceous boundary, and enter the Agardhfjellet Formation, which is our main excursion target.

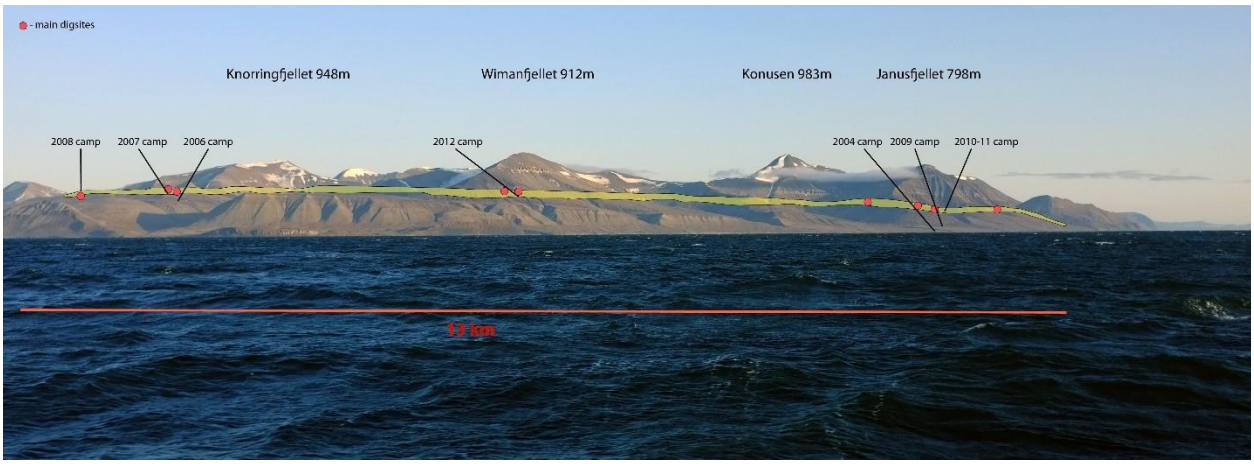

Figure 12. Campsites and main excavation sites along the mountains during the Spitsbergen Mesozoic Research Group's field work (2004-12). Deltaneset where we will disembark is just below Janusfjellet (2004 camp).

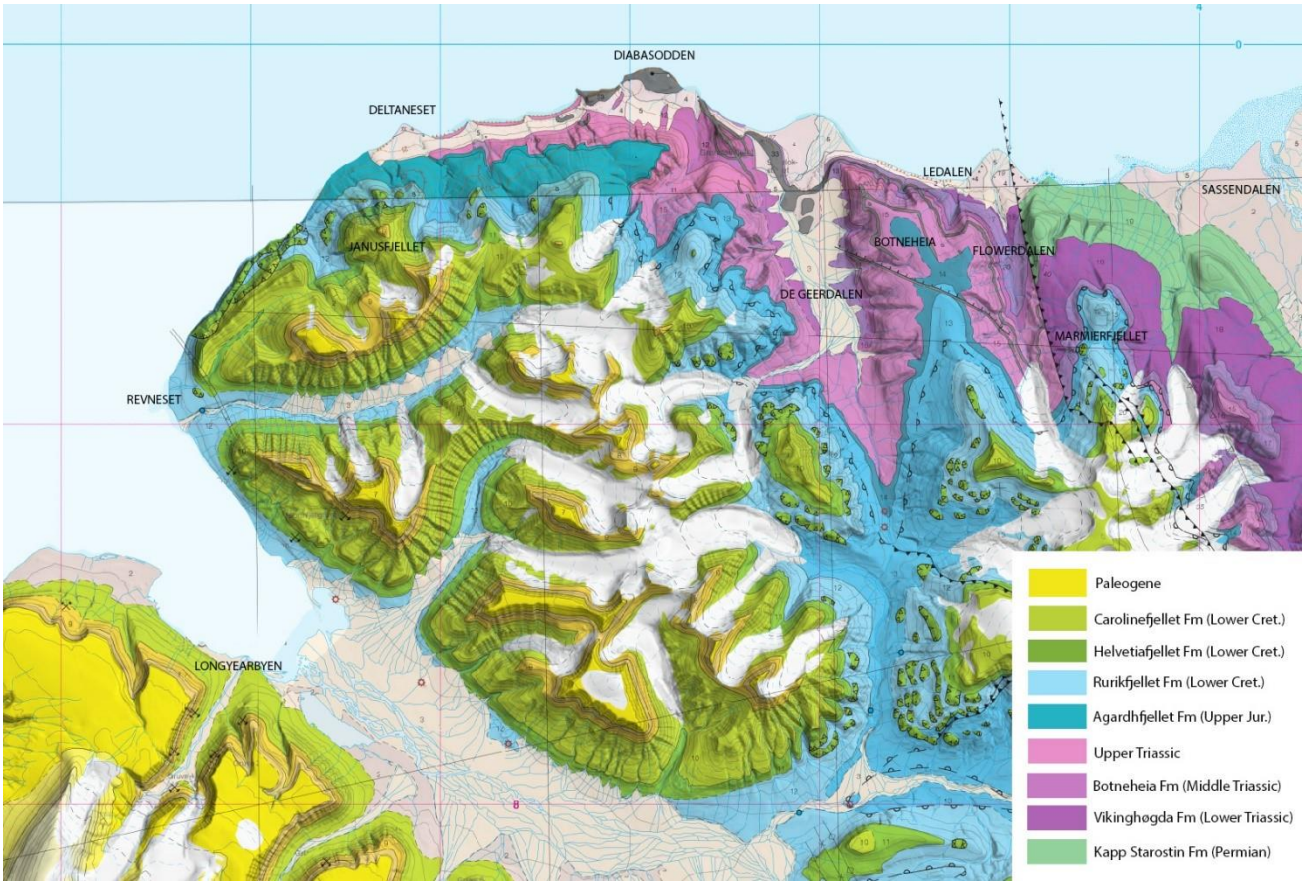

Figure 13. Geological map of the area between Longyearbyen (west) and Sassendalen (east). Map data by Norsk Polarinstiutt/GeoSvalbard.

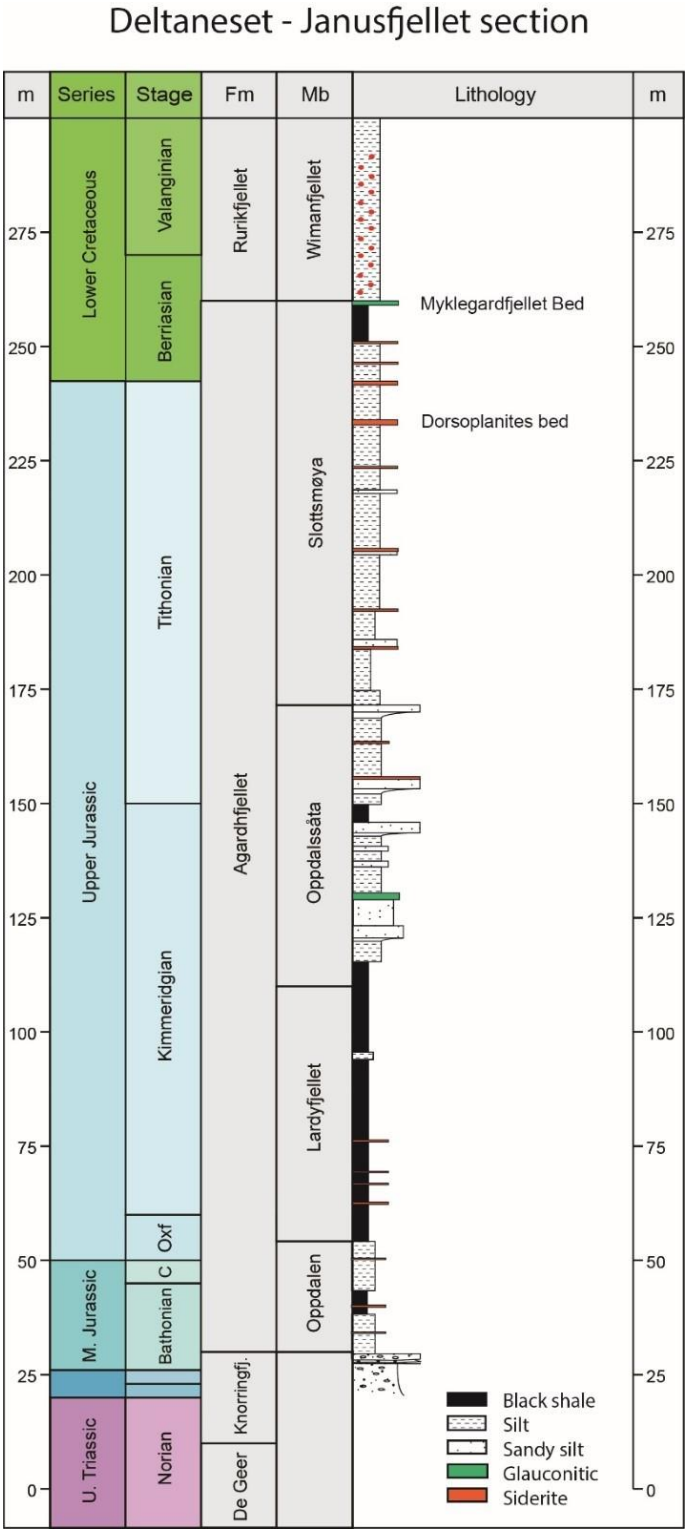

Figure 14. Stratigraphy of the lower slope at Janusfjellet (after Koevoets et al. 2019a). Some correlations are approximate.

Figure 15. Upper part of the succession at Janusfjellet. **S**: Slottsmøya Mb in the Agardhfjellet Fm, Upper Jurassic (Tithonian-Berriasian). **R**: Rurikfjellet Fm, Lower Cretaceous (Berriasian-Barremian). **H**: Helvetiafjellet Fm with the Festningen Mb sandstone, Barremian. **C**: Carolinefjellet Fm (Aptian-Albian). **F**: Firkanten Fm (Paleocene).

Locality 1: The Lardyfjellet and Oppdalssåta members (Oxfordian to Kimmeridgian)

When we land the boat at Deltaneset, we see the Upper Triassic De Geerdalen Fm in beach outcrops to the east (fig. 13). The coastal flat corresponds approximately to a highly condensed sequence (the Knorringfjellet Fm) spanning the Lower to Middle Jurassic, mostly covered.

As we walk up the hillside from Deltaneset, with the Janusfjellet mountain towering in front (figs. 14–15), we are first passing through the lowermost part of the Agardhfjellet Formation, the Oppdalen Member, of Bathonian to Oxfordian age (ca. 25 m thick). The exposure is, however, poor. Further up, we enter the Lardyfjellet Member, a black shale of mainly early Kimmeridgian age, ca. 60 m thick. The Lardyfjellet Member is high in organic carbon, reaching 12% TOC (Dypvik et al. 1991; Koevoets et al. 2019a). It is considered to mainly represent an anoxic to dysoxic depositional environment, but many horizons contain a relatively abundant and diverse benthic fauna, especially bivalves, indicating episodic oxygenation (Koevoets et al. 2019b). The nektonic fossils include flattened ammonites (especially *Amoebites* spp. and *Rasenia cymodoce*), onychites (belemnoid arm hooks), and teleost skeletal elements (Koevoets et al. 2018). Marine reptile vertebrae are occasionally found in the scree.

The silty to sandy Oppdalssåta Member, of late Kimmeridgian age, is ca. 60 m thick. Fossils are weathering out on the slopes, although usually with poor preservation. Bivalves and belemnoids are relatively common, together with wood. Ammonites, onychites and fish remains are much rarer than in the Lardyfjellet Member, while gastropods increase in the upper part. Bioturbation is intensive. Both the sedimentological and the paleontological evidence indicate a regressive phase.

The lack of reported marine reptiles in this lower part of the Agardhfjellet Formation is probably partly due to poorer exposure and less intensive collecting than in the overlying Slottsmøya Member, so keep your eyes open!

Locality 2: The Slottsmøya Member (Tithonian to lowermost Cretaceous)

After climbing through the Lardyfjellet and Oppdalssåta members, we reach a small plateau near the base of the Slottsmøya Member (Tithonian). This locality has yielded an astonishing number of marine reptiles (ichthyosaurs and plesiosaurs; figs. 16–17). This includes an almost complete, articulated skeleton of the ichthyosaur *Cryopterygius kristiansenae*, exhibited at the Natural History Museum in Oslo (Druckenmiller et al. 2012; front page of this excursion guide). A skeleton of the plesiosaur *Ophthalmothule cryostea* from nearby Wimanfjellet is also part of the exhibit there (Roberts et al. 2020). Productive excavations have been made at the same stratigraphic level almost 20 km along strike towards the east (figs. 12–13), so the true fossil density is probably not particularly high here at Janusfjellet but is rather a result of favorable topography.

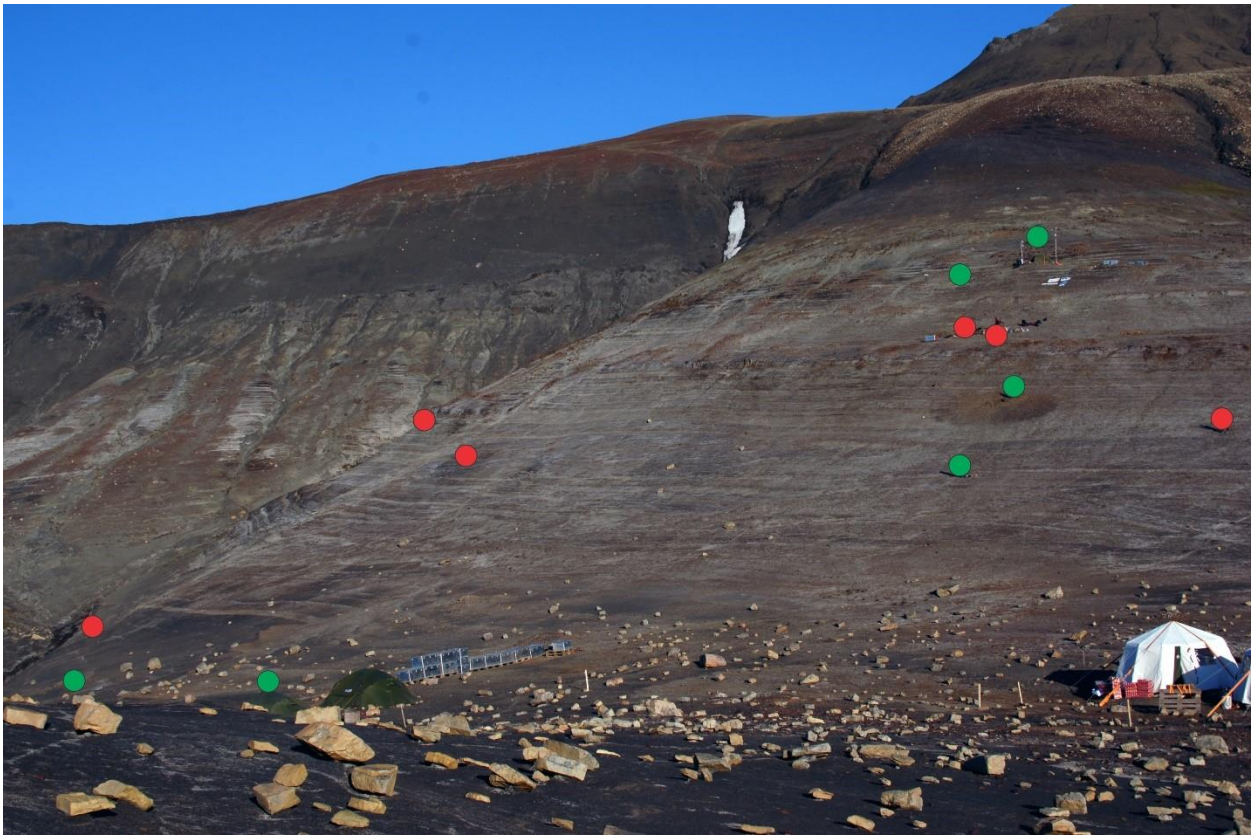

Figure 16. The hillside below Janusfjellet with marked collected skeletons. Green ichthyosaurs, red plesiosaurs.

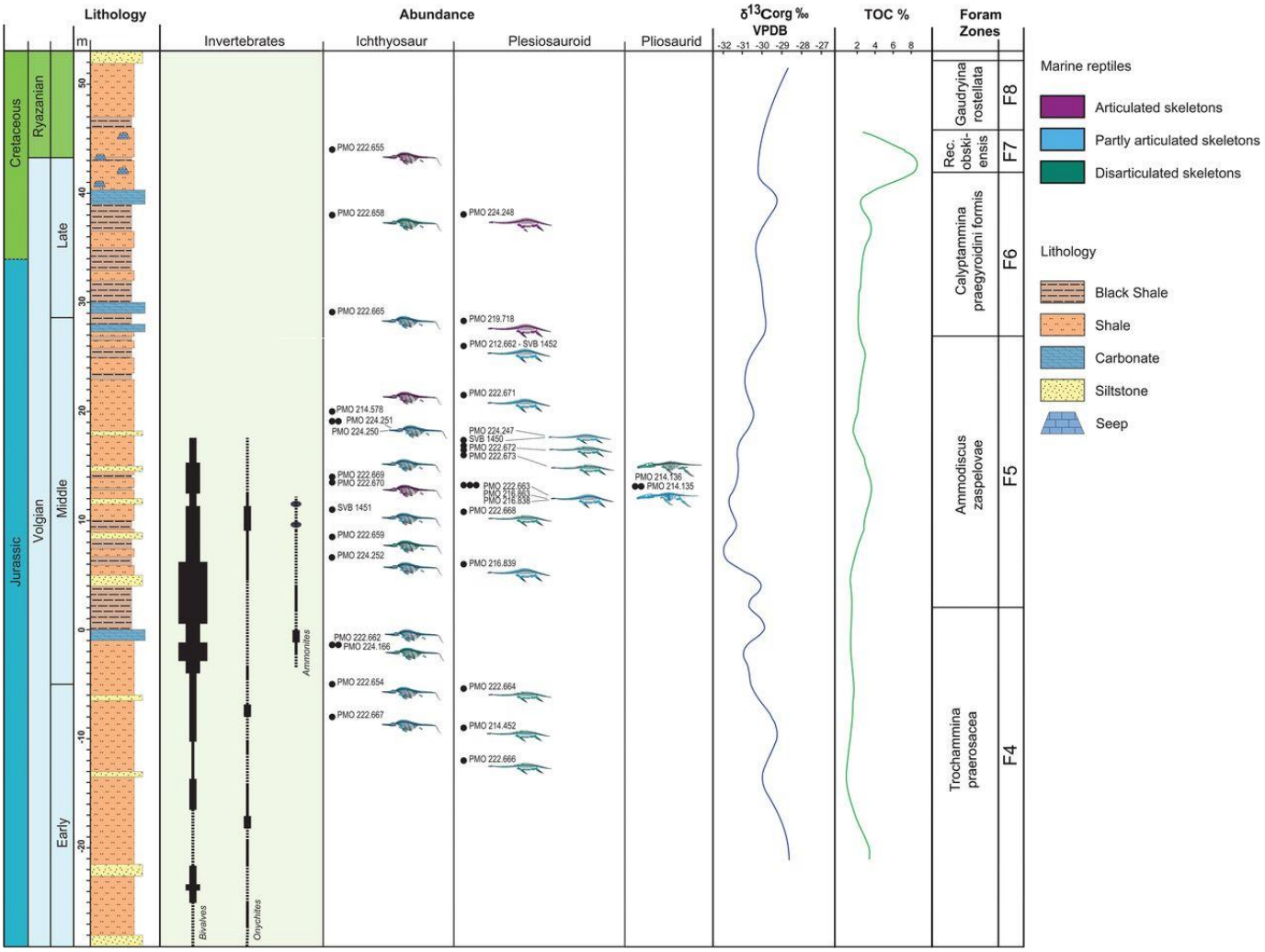

Figure 17. Ichthyosaur and plesiosaur skeletons found in the Slottsmøya Mb from 2004 to 2012. In total 38 specimens are figured, more fragmentary skeletons (about 20 more) not figured. The negative carbon isotope excursion in the middle part of the Slottsmøya Mb is a regional chemostratigraphic marker, known as the Volgian Isotopic Carbon Excursion (VOICE; Hammer et al. 2012; Galloway et al. 2020). Figure from Delsett et al. (2016).

Some red-weathering carbonate beds (siderite) are very rich in ammonite and bivalve imprints (*Dorsoplanites*, *Buchia* etc.). These "Dorsoplanites beds" have been intensively collected here by tourists, and better slabs can be found a few hundred meters to the east.

Between the Dorsoplanites beds and the Myklegardfjellet Bed (see below), hydrocarbon seep carbonates are found across Spitsbergen (Hammer et al. 2011). These carbonates contain a rich, well-preserved invertebrate fauna with bivalves, brachiopods, gastropods, serpulids, ammonites, etc. (Hryniewicz et al. 2015).

Locality 3: The Myklegardfjellet Bed and the Rurikfjellet Formation (Lower Cretaceous)

Further up the hillside we encounter a yellowish-greenish band of plastic clay, often covered in vegetation. This is the somewhat enigmatic Myklegardfjellet Bed, which is a lithological marker throughout much of central Spitsbergen. It is believed to represent a condensed, low-stand unit, probably with a small hiatus, within the lowermost Cretaceous (Dypvik et al. 1992; Koevoets et al. 2019a).

The Myklegardfjellet Bed marks the base of the Lower Cretaceous (Berriasian to lower Barremian) Rurikfjellet Formation, which is a gray shale with abundant siderite nodules, often with well-preserved bivalve fossils (*Buchia*). Vertebrate fossils have not yet been found in this formation.

The light-colored cliffs above the Rurikfjellet Formation are the fluvio-deltaic sandstones of the Helvetiafjellet Formation (Barremian), which contains dinosaur footprints in several places around Spitsbergen (Hurum et al. 2016a).

Excursion 2: The marine reptile explosion after the end-Permian mass extinction, Ledalen

Introduction

The marine, upper Permian Kapp Starostin Formation (chert, shale, limestone, sandstone) in central Spitsbergen is possibly truncated by a Capitanian–Changhsingian hiatus. However, a continuous sedimentary record is present across the Permian–Triassic boundary, as the base of the overlying Vikinghøgda Formation lies within the uppermost Changhsingian (Nakrem et al., 2008; Zuchuat et al., 2020). The marine Lower to Middle Triassic sequence in Spitsbergen is nearly complete, with a thickness of several hundred meters, and with a variety of depositional environments from nearshore in Western Spitsbergen to offshore in central Spitsbergen and eastern Svalbard. The Upper Triassic is prodeltaic to deltaic.

Hurum et al. (2018) give a thorough review of the research on Early to Middle Triassic vertebrates in Svalbard, starting with the earliest finds (e.g., Nordenskiöld 1866; see also Maxwell and Kear 2013). Renewed research activity in the last ten years has confirmed that Svalbard provides a wealth of information about the early evolution of marine reptiles after the end-Permian mass extinction. This includes a rich record of Olenekian marine temnospondyls and sarcopterygians; the oldest known ichthyosaur; well-preserved fossils of *Grippia* and other early ichthyosaurs; and more derived ichthyosaurs in the upper Olenekian and the Middle Triassic. The richest vertebrate-bearing intervals are traditionally known as the Fish Niveau, the Grippia Niveau, and the Lower and Upper Saurian niveaus (essentially from Wiman in the early 1900s; see Hurum et al. 2018). Although it has turned out that these “niveaus” are difficult to define precisely, they are still useful as informal terms.

In this excursion we will visit the Fish Niveau, Grippia Niveau and Lower Saurian Niveau (all Olenekian), and possibly the Upper Saurian Niveau (Ladinian), at least as scree material. The Ledalen locality is easily accessible and clearly demonstrates the stratigraphy (fig. 18).

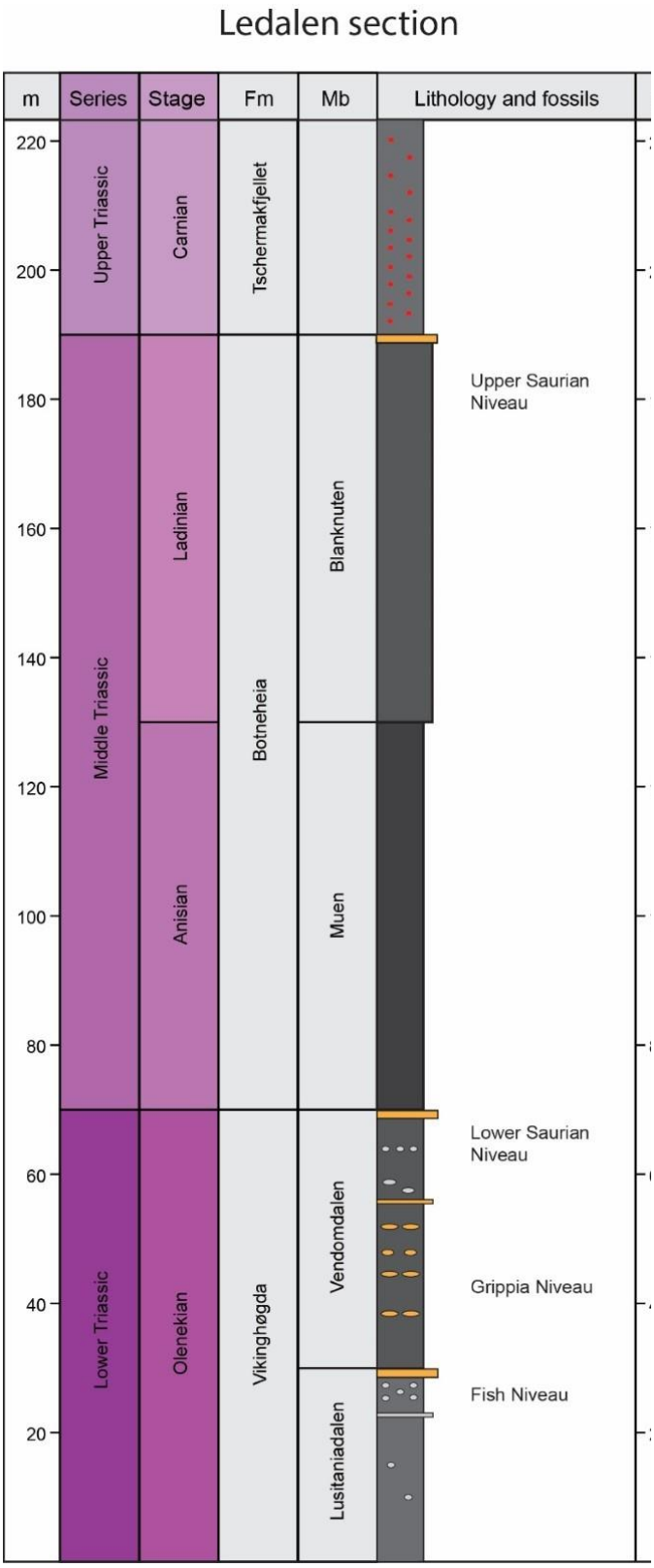

Figure 18. Simplified log of the Ledalen section (after Hansen et al. 2019; Vigran et al. 2014).

Figure 19. The Fish Niveau reconstructed (illustration: Esther van Hulsen).

The boat trip

As described in more detail for Excursion 1, the first part of the boat trip from Longyearbyen provides views of the Lower Cretaceous Carolinefjellet Formation and the Paleogene Van Mijenfjorden Group on the left side. We then move progressively down in the stratigraphy as we continue eastward into Isfjorden. On our right side (south), the shoreline outcrops transition from the Lower Cretaceous Rurikfjellet Formation into the Upper Jurassic Agardhfjellet Formation (with the Slottsmøya Member).

After passing Deltaneset, the Upper Triassic (Carnian-Norian) De Geerdalen Formation is exposed along the shore and in the lowermost hillsides. This is a shallow shelf to deltaic sandstone and shale unit, ca. 250 m thick, with abundant plant fossils.

The imposing, dark cliffs at Diabasodden, with a large seabird colony, is an outcrop of the large magmatic intrusions (dolerite sills) of the Diabasodden Suite, of Early Cretaceous (Barremian) age (Senger et al., 2014). The sill complex continues across the De Geerdalen valley and into the hills further to the east, at increasing elevations.

As we get closer to Botneheia and Ledalen, we have the dark shales of the Botneheia Formation (Middle Triassic) in the lower hillside.

The partly carbonate cemented shales of the Blanknuten Member (Ladinian) form steep cliffs, intruded by the Diabasodden dolerite. The overlying Tschermakfjellet Formation (Carnian) is dominated by gray shales, followed by the Upper Triassic sandstones (De Geerdalen Formation).

We go ashore at Vindodden, below the small Ledalen valley. Further east of Vindodden there are outcrops of the Permian, marine Kapp Starostin Formation along shore. The beautiful cliffs on the northern side of the fjord are also Permian (Gipshuken and Kapp Starostin formations).

Locality 1: The Lusitaniadalen Member, with the Fish Niveau

Only the upper part of the Vikinghøgda Formation (Lower Triassic; Mørk et al. 1999) is exposed at Ledalen. More complete sections are available e.g. in Flowerdalen, 3 km to the southeast, and in Sassendalen. The lowermost outcrops are marine shales of the Lusitaniadalen Member (Olenekian; Smithian). The calcite nodules contain a rich fauna of ammonoids of the *Euflemingites romunduri* Zone (middle Smithian), especially *Arctoceras blomstrandi*, together with abundant bivalves (Hansen et al. 2020; 2024). The uppermost 2-3

m of the Lusitaniadalen Member represents the *Wasatchites tardus* Zone (early part of the upper Smithian), also with abundant fossils in the nodules.

The upper 10-20 m of the Lusitaniadalen Member (upper *E. romunduri* Zone and the *W. tardus* Zone) is traditionally known as the *Fish Niveau* in Svalbard, and represents a globally warm phase, with a temperature peak in the mid-Smithian. The calcite nodules contain relatively abundant but often disarticulated remains of vertebrates. The fishes (actinopterygians and sarcopterygians) were described in detail by Stensiö (1921; 1925). The marine temnospondyls are represented by several species (e.g., Kear et al. 2016; Slodownik et al. 2021). The oldest known ichthyosaur was recently recovered from the Lusitaniadalen Member in nearby Flowerdalen (Kear et al. 2023).

Locality 2: The Vendomdalen Member (Grippia Niveau and Lower Saurian Niveau)

Continuing up slope, we pass into the somewhat darker shales of the Vendomdalen Member (Olenekian; Spathian). A yellow-weathering, carbonate-cemented bed marks the boundary, often with a slight break in terrain slope. This member boundary corresponds approximately to the Smithian-Spathian boundary, with a small hiatus just above the carbonate bed (Hammer et al. 2019). This correlation is tightly constrained by both biostratigraphy and the carbon isotope curve.

The Vendomdalen Member is relatively thin (ca. 40 m) at Ledalen. A deeper setting is inferred for the lower part of the member, relative to the lowstand in the uppermost Lusitaniadalen Member. The fossil abundance in this lower part is relatively low and the preservation is usually poor, with mainly pelagic forms (ammonoids, belemnoid hooks, orthoceratoids, shark scales) and little benthic fauna (Hansen et al. 2024).

This lower part of the Vendomdalen Member is famous for vertebrate remains, usually disarticulated but otherwise well preserved and locally abundant (Stensiö 1928; Wiman 1928; 1933; Maxwell and Kear 2013; Hurum et al. 2018). The lower and upper boundaries for this *Grippia Niveau* have never been precisely determined, and they are probably gradual. At nearby Marmierfjellet, an extremely rich bone bed is found about 12 m above the base of the member (Hansen et al. 2018), with a large diversity of disarticulated vertebrate remains, including ichthyosaurs (Ekeheien et al. 2018), chondricthyans, and conodonts (Nakrem and Orchard 2023). This fauna is presently under study by the NHM in Oslo.

The upper part of the Vendomdalen Member (*Keyserlingites subrobustus* Zone, uppermost Spathian) is richer in fossils, especially in an interval of grey calcite nodules where ammonoids (especially *Svalbardiceras spitsbergense*) and other invertebrates are well preserved. The uppermost ca. 10 m interval, below a conspicuous yellow dolomite bed marking the top of the member (and the top of the Vikinghøgda Fm), is also characterized by abundant vertebrate remains, in particular ichthyosaurs (Ekeheien et al. 2018; Engelschiøn et al. 2018). This is the *Lower Saurian Niveau*.

Locality 3: The Botneheia Formation (Upper Saurian Niveau)

The Botneheia Formation (Middle Triassic) is dominated by black shales with carbonate concretions and calcareous siltstone beds. Small phosphate nodules are common. The formation is divided into two members. The lower Muen Member (Anisian) is a soft, black mudstone, often covered by scree. The upper Blanknuten Member (Ladinian) has a higher carbonate content and usually forms steep cliffs. For safety reasons we will probably not venture up there, but fossils are often found in the scree downslope and we may have a look for those.

The Blanknuten Member, especially its upper part, is highly fossiliferous, with bivalves (*Daonella* etc.), ammonoids (especially the sphaerocone *Aristoptychites*) and other

cephalopods. This interval is also characterized by abundant marine reptile remains, especially ichthyosaur vertebrae and ribs, but also more articulated skeletons (Hurum et al. 2014; Økland et al. 2018; Roberts et al. 2022). This is the *Upper Saurian Niveau*.

Figure 20. Typical ammonoids in the Lower and Middle Triassic of Spitsbergen. Top row: *Euflemingites romunduri*, *Arctoceras blomstrandi*, *Wasatchites tardus* (Lusitaniadalen Mb.). Bottom row: *Svalbardiceras spitsbergense*, *Keyserlingites subrobustus* (Vendomdalen Mb.); *Aristoptychites kolymensis* (Botneheia Fm.)

Figure 21.The Ledalen locality, with the Lusitaniadalen Member (Smithian) in the foreground.

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