

**Carbonate deposition in the Arctic during the Paleocene Eocene Thermal Maximum (PETM)
and Early Eocene Climatic Optimum (EECO), 2D seismic data**

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Abstract

Recently-acquired, high-quality seismic reflection profiles document the presence of possible carbonate deposition on the Mendeleev Rise in the Arctic Ocean during the Paleocene-Eocene Thermal Maximum and the Early Eocene Climatic Optimum. These deposits are concentrated at the crests of bathymetric highs and consist of clusters of platforms comprising small patch reefs overlain by larger, coalesced platforms, followed by back-stepped higher-relief platforms. The small buildups commonly are ~100-500m in diameter and 50-100m in height. The larger platforms are up to 3-7km wide and up to 400m thick. Some of the larger buildups are characterized by internal horizontally layered architecture, whereas others are characterized internally by clinoforms suggesting progradation. A common characteristic of these buildups is that they tend to achieve a common height, typical of buildups sensitive to growth within the photic zone and whose upward growth is limited by sea level. The succession of buildup styles indicates carbonate factories under the influence of accelerating relative sea-level rise, which culminated in drowning and ultimate abandonment.

Introduction

Cenozoic shallow-water carbonates in the Arctic Ocean and Arctic islands and adjacent land have not been previously documented (e.g. Stein, 2019). However, the presence of deep-water mud-bearing biosiliceous ooze deposits has been documented by sampling of the Lomonosov Ridge during the (Moran et al., 2006; Brinkhuis et al., 2006; Backman et al., 2008) Russian Arctic Coring Expedition (ACEX). The age of these deposits are Eocene (Ypresian), 50-45.4 Ma.

It is well known that the Arctic was likely ice free during the Paleocene Eocene Thermal Maximum (PETM) (Sluijs et al., 2006, 2008; Moran et al., 2006; Backman and Moran, 2009; Stein 2019). Sluijs et al. (2006, 2008, 2009) suggest that these anomalously warm periods were characterized by annual temperatures that were in the order of 21-22C. Biostratigraphic evidence suggests the presence of **temperate to subtropical** flora on the fringing coastal and alluvial plains in Siberia, Canada, and Alaska during the late Paleocene and early Eocene (e.g., **Akhmetiev, 2015; West et al., 2015; Suc et al., 2020; Bondarenko, Utescherm 2022; Blumenberg et al., 2024**). This markedly warm period of time has been described as a “hothouse” or “greenhouse” time (Moran et al., 2006; Backman and Moran, 2009; Stein, 2019), though until the present study, there has been no evidence for widespread shallow-water carbonate deposition.

Plate reconstructions suggest that the Arctic Amerasia Basin was in a post-rift phase (Stein, 2019; Nikishin et al., 2021c) with somewhat restricted oceanic circulation during the Paleocene-Eocene (Stein, 2019). Likewise, plate reconstruction indicates that this area then as now was situated over the North Pole (O'Regan, 2008a). Several bathymetric highs were present at that time, including the Lomonosov Ridge and the Mendeleev Rise (Nikishin et al., 2021b.c) (Fig. 1). The present study will show that possible carbonate production created buildups of various sizes with diagnostic internal seismic character that has been recognized in other carbonate platforms globally. The platforms were especially active on the Mendeleev Rise paleo-bathymetric high.

The Mendeleev Rise is located within the Amerasia Basin between the Podvodnikov-Makarov and Toll-Mendeleev-Nautilus deep-water basins (Fig. 1). Recent review of its structure was done by Nikishin et al. (2021a, 2021b, 2021c, 2023) where it was suggested that the Mendeleev Rise consisted of possible stretched continental crust terrane covered by basalts. The Mendeleev Rise is characterized by a relatively thickened crust up to 20-30 km comprising shallow-marine and continental volcanics with documented isotopic ages of 127-80 Ma (Coakley et al., 2016; Mukasa, 2020; Skolotnev et al., 2019, 2023; Nikishin et al., 2021b, 2021c, 2023) overlying a Paleozoic sedimentary cover (Skolotnev, 2019, 2023; Nikishin et al., 2021b, 2021c, 2023). Post-rift and post-volcanic regional subsidence started during the late Cretaceous and current water-depth is 1-2 km. Nikishin et al. (2023) presented an interpretation of seismic 2D data for the Alpha-Mendeleev Rise. They hypothesized that at least one buried high contained Eocene carbonates, a hypothesis that is considered in this paper using all possible new seismic data (Nikishin et al., 2021a, 2023; Shimeld et al., 2021).

Data and methods

Recent geophysical surveys have yielded a regional grid of high-quality multi-channel seismic reflection data across the Arctic (Fig. 1) (Bruvold et al., 2010; Weigelt et al., 2014; Coakley et al., 2016; Piskarev et al., 2019; Nikishin et al., 2021a, 2021b, 2021c, 2023; Shimeld et al., 2021). The dominant frequency, 50-60 Hz, allowed for resolution of approximately 10m (i.e., 1/4 seismic wavelength). Seismic analyses of these data have formed the basis for a new comprehensive stratigraphic framework as well as plate reconstruction for the area (Brinkhuis et al., 2006; O'Regan et al., 2008b; Shephard et al., 2013; Weigelt et al., 2014; Nikishin et al., 2021a, 2021b, 2021c, 2023). Extensive coring and bottom sampling provided ground truth and calibration for these age models (Moran et al., 2006; Backman et al., 2008; Coakly et al., 2016; Homza and Bergman, 2019; Skolotnev et al., 2019; Nikishin, et al., 2021b, 2021c). Key data are results of the ASEX project (e.g. Moran et al., 2006; Backman et al., 2008) and deepwater geological expeditions in 2014 and 2016 (Mendeleev-2014 and Mendeleev-2016) using special submarine equipment to collect deepwater samples from outcrops (Skolotnev et al., 2019, 2023; Nikishin et al., 2021a). Recently a few shallow stratigraphic boreholes were drilled by the Geologic

Survey of Russia and oil company Rosneft in the Laptev, East-Siberian and Chukchi Sea with first results presented by Malyshev et al. (2024a, 2024b) and Petrov et al. (2023). Cenozoic to Jurassic strata were drilled and samples studied. Coal-bearing deposits were observed to be common within the Paleocene and Eocene sections.

Seismic stratigraphic analyses highlighted in the present study focused on evaluation of seismic reflection architecture and provide strong evidence for active shallow-water carbonate deposition over at least some of the paleo-bathymetric highs. The approach taken was that outlined by Mitchum and Vail (1977) wherein 1) reflection terminations were identified and related to stratigraphic discontinuities, 2) the form and shape of individual seismic reflections were evaluated and related to stratigraphic architecture and ultimately to depositional elements, and 3) seismic reflection continuity and amplitude were evaluated as an indication of lithologies present. Depositional features that were identified were subsequently age-dated by relating them to the available stratigraphic framework.

Results

1. Regional stratigraphy

The stratigraphy of the Mendeleev Rise is based upon two data sets: borehole data integrated with the regional seismic grid and sample collections using special underwater vehicles. Two regional seismostratigraphic units are recognized: HARS-1 and HARS-2 (Nikishin et al, 2021b). These units can be traced around main parts of the Eurasia and Amerasia basins (for details see Nikishin et al., 2021b). The level of possible carbonates in the Mendeleev Rise coincides with HARS-1 (56-45 Ma). The seismic section shown in Figure 2 provides a tie between the ACEX well and the Mendeleev Rise and provides age calibration for the target section. This tie to available borehole data strongly suggests an age for the possible carbonate section close to 56-45 Ma. Another borehole that provides age data is the recently drilled well SSDCH-11 in the Chukchi Sea to the North-East of Wrangel Island (Malyshev et al., 2024b). That borehole penetrated an angular unconformity between Cenozoic and Lower Cretaceous deposits (Fig. 3). Within the

section correlative with the possible shallow-water deposits, early Paleocene and younger deposits were documented by microfossils (Malyshev et al., 2024b).

Recently acquired sample collections using special underwater vehicles on the slopes of seamounts (Skolotnev et al., 2019, 2022, 2023; Nikishin et al., 2021a, 2023) provided further insights into the stratigraphy of the Mendeleev Rise. The Mendeleev Rise is characterized by Pre-Cenozoic horsts and half-grabens (Nikishin et al., 2023). As illustrated by Figure 3 the upper part of the pre-Cenozoic structured section is characterized by high-amplitude seismic reflections that are interpreted as volcanics. Half-graben sections within this pre-Cenozoic section are wedge-shaped and similar in geometry to seaward-dipping reflectors (SDRs) of continental passive volcanic margins. Rock sampling has shown that the horsts are composed of sedimentary rocks of Paleozoic age, penetrated by intrusions (Skolotnev et al., 2023). Aptian-Albian sections containing volcanics (basalts, trachybasalts, trachyandesites) were identified on the horsts. U/Pb dating of igneous rocks showed that typical age of rocks is 110-114 Ma (possible ages are between 127 and 80 Ma) (Skolotnev et al., 2023). The first strata overlying the volcanics on the Mendeleev Rise are shallow-marine sandstones characterized by Barremian to Aptian fossils (Skolotnev et al., 2019, 2022; Nikishin et al., 2021a). Mukasa et al. (2020) obtained isotopic ages of basalts dredged from Chukchi Borderland northern slope with ages close to 118-70 Ma. Isotopic data show that the possible carbonates lie between the documented Cretaceous volcanics and the sea floor, which currently lies at over 1500m water depth. Consequently, a major flooding event, likely tectonic related, must have occurred between deposition of the shallow-water deposits immediately overlying the volcanic basement and the modern sea floor, which lies in deep water.

2. *Possible carbonates of the Mendeleev Rise*

All regional seismic data were evaluated for the presence of possible carbonate buildups across the Mendeleev Rise. Because of the variable quality of the seismic data and the relatively sparse coverage, systematic mapping of potential buildups was not possible. However, we

interpret numerous possible carbonate buildups based on one-line interpretations over several tectonic highs in the vicinity of the Mendeleev Rise (Figs. 3-7). The principal conclusion is that there are carbonate buildups across this structurally high setting and that they have are of the same age (i.e., Eocene). Figure 8 illustrates the map distribution of the observed possible buildups.

Features observed exclusively at the top of early Cenozoic paleo-bathymetric highs along the Mendeleev Rise reveal the presence of features (Figs. 3A and 4) that are interpreted as shallow-water carbonate patch reefs and platforms very similar to Miocene platforms observed on seismic data in today's tropics and sub-tropics (Figs. 4, 5) (Posamentier et al., 2010; Bashir et al., 2021; Makhankova et al., 2021). Two types of mounded features are observed: small conical-shaped mounded features approximately 100-500m in diameter and 50-100m in height, and larger massive mounds or platforms up to 3-7km in diameter and up to 400m in thickness. The smaller mounded features are observed to overlie a continuous, essentially featureless (i.e., likely planar horizontal at the time of deposition) high-amplitude reflection and are widespread across the area of the paleo-bathymetric high. Internally, the larger interpreted buildups or platforms are characterized by internal horizontal reflections indicative of aggradational accretion of shallow-water carbonate deposits. Temporally, the small, mounded features are overlain by much larger mounded or platform features, which in places are conically-topped and in other places are flat-topped, and in places, characterized by internal horizontal reflections. Again, it is worth noting that these interpreted high-relief buildups lie directly above a package of planar parallel seismic reflections, which, in turn lie above likely volcanic basement, suggesting that these high-relief features significantly post-date basement structuring.

The overall succession represents a trend that has been observed in past studies (Posamentier et al., 2010): 1) platform dominated by patch reefs, 2) coalescence of patch reefs into a large "mega-platform", 3) rapid aggradation (due to sea level rise) and eventual drowning.

Nonetheless, their location directly above basement uplifts is consistent with the interpretation that these high-relief features, interpreted as carbonate buildups, nucleated on these bathymetric highs.

Although direct borehole calibration is not available at this time, we nonetheless interpret a carbonate origin for these features based upon observed seismic geometry and reflection character compared with analogs of known carbonate buildups that are strikingly similar, as well as based upon first principles regarding the stratigraphy of carbonate deposits (Burgess et al., 2013; Hendry et al., 2021). Figure 5 illustrates a comparison between the features observed here and documented Miocene carbonate buildups from southeast Asia (compare Fig. 4a and 4c) (Posamentier et al., 2010). Despite the differences in local climate and age, the two features are virtually identical from a stratigraphic architectural perspective. In both instances we observe small cone-shaped features overlain by larger mounded platform stratigraphic architecture (Figs. 4 and 5). Internal to the larger platform facies, horizontal seismic reflections, and possible progradation can be observed (Figs. 4 and 6).

The scale of the observed features and the analog features is strikingly similar. In both instances, the buildups grade from small buildups at the base to overlying intermediate buildups to larger platform buildups at the top. The analog features, when mapped in 3D, are circular in outline and interpreted as small patch reefs (Figs. 5d and 5e). Unfortunately, without available 3D seismic data coverage, we cannot be certain of the map view of the features described here and can only infer their circular map pattern. The crests of these small, interpreted patch reefs as well as the larger platform buildups reach a common level, which is a characteristic common to shallow-water carbonate buildups. A modern analog that bears a striking resemblance to the Mendeleev Rise interpreted carbonate buildups is the Maldives islands. Here, too, a bathymetric basement high has allowed for the establishment of shallow-water carbonate buildups in the form of various sized patch reefs and platforms.

The section overlying the interpreted buildups is characterized by predominantly isopachous, continuous, moderate to high amplitude reflections that extend from over the Mendeleev Rise down the flanks on either side. This pattern is consistent with the process of pelagic and hemipelagic drape sedimentation that characterized this area subsequent to cessation of carbonate deposition, suggesting a drowning event related to accelerated subsidence that terminated carbonate production. Because of this drape style of deposition (Fig. 4), the modern sea floor topography mirrors that of the PETM so that the irregularity of the modern sea-floor represents a proxy for the PETM paleotopography. Isolated platforms mapped in this way are up to 50km wide (Fig. 1).

Because of the greater thickness of the upper platform buildups relative to the smaller underlying interpreted patch reefs, internal architectural characteristics can be observed. In places, possible horizontal reflections within the interpreted platforms can be observed (Figs. 4 and 6). Internal horizontal reflections are a characteristic typical of shallow-water carbonate platforms and indicate aggradation occurring in response to relative sea-level rise. This is an architectural characteristic that differentiates carbonate buildups from volcanic edifices, which are commonly characterized by cone-in-cone rather than horizontally bedded internal stratigraphic architecture (Burgess et al., 2013; Posamentier et al., 2014; Hendry et al., 2021). Another differentiating characteristic of carbonate vs. volcanic edifices is that shallow-water carbonates tend to build simultaneously and top out at a common level (i.e., sea level), whereas volcanic construction is not constrained vertically by sea level. As Figure 4 illustrates, especially for the many small patch reefs present towards the base of the interpreted carbonate complex, these features are tightly clustered and reach approximately the same height. The presence of both horizontal coupled with locally progradational internal seismic reflections internal to the larger interpreted buildups further argues against these being of volcanic origin. The presence of continuous reflections of minimal relief just below the small, interpreted patch reefs as well as above is also consistent with an interpretation of a period of stasis prior and subsequent to initiation of carbonate production. Finally, the context of observing these features exclusively above paleo-bathymetric highs is consistent with a

carbonate rather than a volcanic origin, inasmuch as volcanoes need not be local only to paleo-bathymetric highs.

The succession of smaller buildups followed by progressively larger, higher-relief buildups can be interpreted as carbonate sedimentation under the influence of accelerating relative sea-level rise that culminated in a drowning event, which resulted in total cessation of carbonate sedimentation. That drowning event likely occurred during the middle Eocene, coincident with accelerated tectonically driven subsidence that was associated with rapid subsidence of the North Chukchi Basin and major transgression in the order of 400-500km (Nikishin et al., 2021b). This was also a time when climatic change towards cooler temperatures began. A similar stratigraphic succession of smaller buildups followed by progressively larger, higher-relief buildups offshore Madura, Indonesia, has been interpreted as being driven by accelerated relative sea-level rise (Posamentier et al., 2012).

3. Possible carbonate caps on eroded tops of Cretaceous and Paleocene volcanoes

Using seismic data, Funck and Shimeld (2023) described a buried seamount on the Alpha Ridge characterized by a truncated top and a size approximately 40x20 km (Fig. 9a). Samples containing hyaloclastics were collected from the seamount slope. The age of the volcanics is approximately 90 Ma (Funck and Shimeld, 2023). This volcanoclastic mound likely was eroded, possibly by subaerial processes, and was later flooded in response to accelerated subsidence and then buried by marine sediments. We propose that a carbonate platform developed during the transition from the possibly subaerial volcanic seamount to deep-marine seafloor (Fig. 9a). This possible carbonate platform lay above the late Cretaceous volcano, consistent with an Eocene age, including the Paleocene Eocene Thermal Maximum (PETM) and Early Eocene Climatic Optimum (EECO).

Nikishin et al. (2021b, c) analyzed seismic data for the Laptev Sea Eurasia Basin continental margin and recognized a break-up unconformity with an age close to 56 Ma. A few possible magmatic features like intrusions and possible buried volcanos were described just below this unconformity suggesting that the age of magmatism is Paleocene or latest Cretaceous to Paleocene (Nikishin et al., 2021b). Several buried conical-type structures were discovered. (e.g., Fig. 9b). We suggest that here too, a Paleocene submarine massif with erosional truncation at its top and overlying deposits of possible carbonates. The age of the carbonates was post-Paleocene with an Eocene age including PETM and EECO levels most likely.

4. Why not volcanoes

Differentiating between carbonates and volcanics can be challenging and some examples of carbonates shown in this study may be equivocal. However, in those instances where the putative carbonates overlay horizontal reflections such as illustrated in Figure 4d, a rejuvenated volcanic terrain overlying these horizontal reflections would not be a reasonable interpretation. Volcanic buildups subsequent to deposition of these horizontal reflections would have required the volcanics to have penetrated these reflections and re-established a volcanic terrain. Rather, we interpret the horizontal reflections as uniform (shallow?) marine sedimentation subsequently overlain by carbonate buildups (see discussion above).

Discussion

Numerous seismic stratigraphic units with a distinctive geometry suggestive of shallow-water carbonates have been observed on the Mendeleev Rise. Regional seismic and ACEX borehole-based studies from the nearby Lomonosov Ridge have recently shown that the section that is the focus of this study is approximately equivalent to the Paleocene Eocene Thermal Maximum (PETM) and the Early Eocene Climatic Optimum (EECO) approximately 56-45 Ma (Sluijs et al., 2006, 2008; Backman and Moran, 2009; Shephard et al., 2013; Stein, 2019; Nikishin et al., 2021c). Largely based on Oxygen isotopes extracted from benthic foraminifera, temperatures

were inferred to have been significantly higher than that of today. Annual temperatures up to 22C with ice-free conditions have been suggested for the PETM. Faunal assemblages suggest “exceptionally warm and humid conditions” at that time (Stein, 2019; Salpin et al., 2019; Suc et al., 2020). Mollusk-derived stable isotopes from the Prince Creek Formation, Alaska, suggest annual shallow marine temperatures between 11-22C (Brice et al., 1996; Singh et al., 2013). It is noteworthy that evidence of anomalously higher global temperatures at this time come from locations even far from the Arctic (Pollitt et al., 2012). Up until now, no evidence for active shallow-water carbonate deposition has been observed from any boreholes drilled in the Arctic. However, these boreholes were drilled primarily in locations where shallow-water carbonates would not have been deposited.

The presence of significant shallow-water carbonates in the Arctic that are strikingly similar to what is currently observed in warmer-water oceans, will have major significance to the greater scientific community. 1) it is the first time that the presence of a carbonate-friendly environment has been documented for the Arctic, with carbonate platform buildups – e.g., patch reefs and platforms – observed on paleo bathymetric highs, 2) the presence of these active carbonate factories on the Mendeleev Rise during the Paleocene/Eocene adds a significant data point to the discussion of climate change in general, 3) the presence of active shallow-water carbonate growth in a location that is characterized by periods of no daily sunlight for part of the year potentially opens up a new area of research regarding shallow-water carbonate growth in general, and 4) discovery of these examples of shallow-water carbonate growth highlights the need to better understand the paleo-tectonic and associated paleogeographic-driven oceanographic controls that allowed for a brief period of sufficiently warm water temperatures conducive to this growth (Fig. 10). Again, while it is known that the climate during this brief period of the PETM allowed for the development of temperate-type vegetation in the circum-Arctic environment, this paper presents the first documented examples for the presence of significant shallow-water carbonate development in this region. Discovery of possible Eocene shallow-water carbonates in the Arctic Ocean is a challenge for Earth science. 2D seismic data is not sufficient to unequivocally confirm this interpretation. Rather, a borehole project to obtain samples from proposed carbonate bodies is required.

Consequently, we propose a holistic international project to further study the Cenozoic climate history of the Arctic with special emphasis on confirming the presence of shallow-water carbonates.

Globally, carbonate structures for the timing of PETM and EECO are well known (e.g., Perrin, 2002). They were mainly located in the equatorial and tropical regions (Fig. 11). The dominant reef biota were algae, foraminifera, corals, bivalves, bryozoans, and worms (e.g., Perrin, 2002). We can only speculate on the presence of reef biota in the Arctic. They may have been bryozoans, algae and other organisms. The carbonate structures of the Mendeleev Rise are similar to the carbonate structures of the Offshore Indus Basin in the Indian Ocean in terms of probable age and character of the geological structure based on seismic data. Drilling data and numerous seismic profiles are available for them (Shahzad et al., 2018; Shahzad et al., 2019). The carbonate structures of the Mendeleev Rise are similar in their geological structure to the well-studied Late Oligocene-Early Miocene carbonate platforms for offshore Myanmar (Paumard et al., 2017; Teillet et al., 2020)

Conclusions

For the first time, shallow-water carbonate deposition in the Arctic during the Paleocene Eocene Thermal Maximum (PETM) and the Early Eocene Climatic Optimum has been documented based on seismic stratigraphic analyses of recently-acquired 2D seismic data. These deposits are observed on paleo-bathymetric highs associated with the Mendeleev Rise. Carbonate deposition evolves from small 100-500m diameter patch reefs at the base, to larger 3-7km wide platforms at the top. The stratigraphic architecture of these deposits is strikingly similar to analogous known shallow-water carbonate deposits elsewhere (Bachtel et al., 2004; Posamentier et al., 2010; Bashir et al., 2021; Makhankova et al., 2021). The carbonate deposits are interpreted to have evolved in response to accelerating relative sea-level rise that culminated in complete cessation of carbonate sedimentation during the early Eocene (Lutetian, 45Ma), as this area ultimately became a deep-water environment, currently at a depth of 1.5-2.0km. The results presented here are preliminary and require ground truth in the

form of borehole data for confirmation. To this end, we propose an international project to drill locations favorable for Arctic Cenozoic shallow-water carbonate bodies. Further focused research into Arctic depositional environments has the potential to change current models of the Cenozoic climatic history of this area.

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Figure captions

Figure 1. Map showing key topographic elements of the Arctic region (Jakobsson et al., 2020) as well as the location of key seismic lines (Nikishin et al., 2021a). Inset illustrates detailed bathymetry that can serve as a proxy for PETM carbonate platforms.

Figure 2. Composite seismic profile from the ACEX borehole on the Lomonosov Ridge to carbonates on the Mendeleev Rise. Data from (Nikishin et al., 2021a; Nikishin et al., 2021b; Nikishin et al., 2023). A and B – details of the profile. A – detailed seismic section with ACEX borehole data, ACEX borehole data from (Bruvoll et al., 2010); B – detailed seismic section with possible carbonates. Seismic stratigraphic correlations suggest that the age of the interpreted shallow-water carbonates is between 56 Ma and 45 Ma.

Figure 3. Composite seismic profile from the Chukchi Sea borehole (SSDCH11) to carbonates on the Mendeleev Rise. Data from (Nikishin et al., 2021a; Nikishin et al., 2021b; Nikishin et al., 2023; Malyshev et al., 2024b). A, B, C, D – details of the seismic profile. Segment A – possible carbonates; segment B – clinoform complex and MTD; segment C – possible SDRs with basalts (~125-100 Ma); segment D – correlation with borehole SSDCH11 data. Seismic stratigraphic correlation supports the interpretation of an age between 56 Ma and 45 Ma.

Figure 4. a) Multi-channel seismic section (ARC20-24) across the Mendeleev Rise (see Fig. 1 for location). b) Detail of interpreted carbonate buildups illustrating various size patch reefs and platforms. c and d) Detailed view of interpreted small and intermediate patch reefs characterized by small patch reefs at the base, culminating in larger platforms at the top.

Figure 5. Comparison between Miocene carbonate buildups (a and b) from offshore Madura, Indonesia (Posamentier et al., 2010) and c) Mendeleev interpreted buildups. 3D seismic time slices through small patch reefs with numerous small patch reefs (e) evolving into larger patch reefs (d) through time.

Figure 6. Seismic section (ARC12-03) illustrating carbonate buildups (a) from the Mendeleev Rise (see Fig. 1 for location). b) Detail of the seismic section highlighting the interpreted shallow-water carbonate deposits. c) Interpretation of the detailed seismic section focused on the shallow-water carbonates. Note the internal platform top inferred from the internal horizontal reflections.

Figure 7. Additional seismic profiles with possible shallow-water carbonates (see Fig. 8 for location). Possible shallow-water carbonate buildups are between 56 Ma and 45 Ma, based on seismic stratigraphic correlation with available borehole data. Seismic data from (Nikishin et al., 2021a, Nikishin et al., 2021b, Nikishin et al., 2023).

Figure 8. Basement topography of the Mendeleev Rise region (modified after Nikishin et al., 2023, with new data added) and location of possible carbonate build-ups (stars). Green stars – possible carbonates on tectonic highs, red stars - possible carbonates on volcanic tops.

Figure 9. A. Alpha Ridge with Fedotov Cretaceous Volcano and carbonate cap. Seismic section from Funck and Shimeld (2023) with our interpretation of shallow-water carbonates. B. Laptev Sea continental slope and Paleocene volcano with possible carbonate cap. See Fig. 8 for location.

Figure 10. Cenozoic paleoclimate (Westerhold et al., 2020; Planke et al., 2021) and interval of possible carbonate buildups.

Figure 11. Paleogeographic map for the PETM (Thanetian/Ypreccian) time (Scotese, 2014) and global reef (carbonate build-ups) distribution (circles). Mainly after Perrin (2002) and Shahzad et al. (2019). Star – location of possible Mendeleev Rise carbonates.

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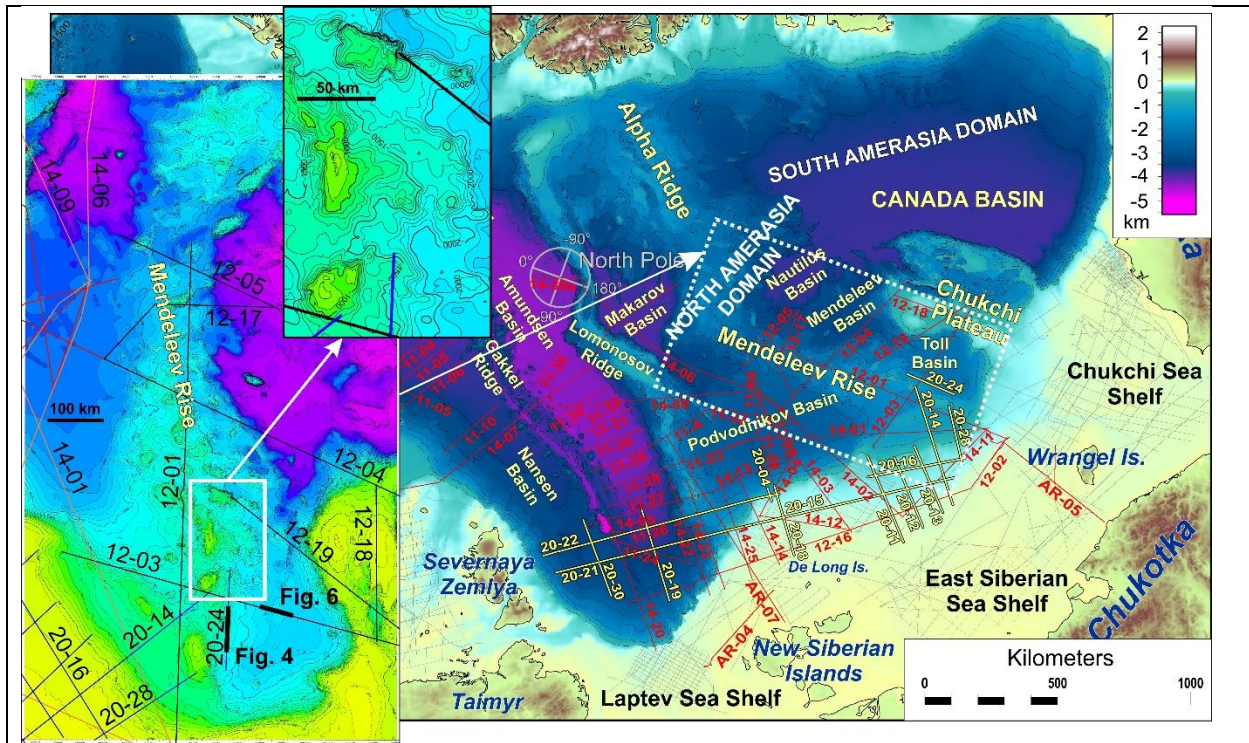


Figure 1. Map showing key topographic elements of the Arctic region (Jakobsson et al., 2020) as well as the location of key seismic lines (Nikishin et al., 2021a). Inset illustrates detailed bathymetry that can serve as a proxy for PETM carbonate platforms.

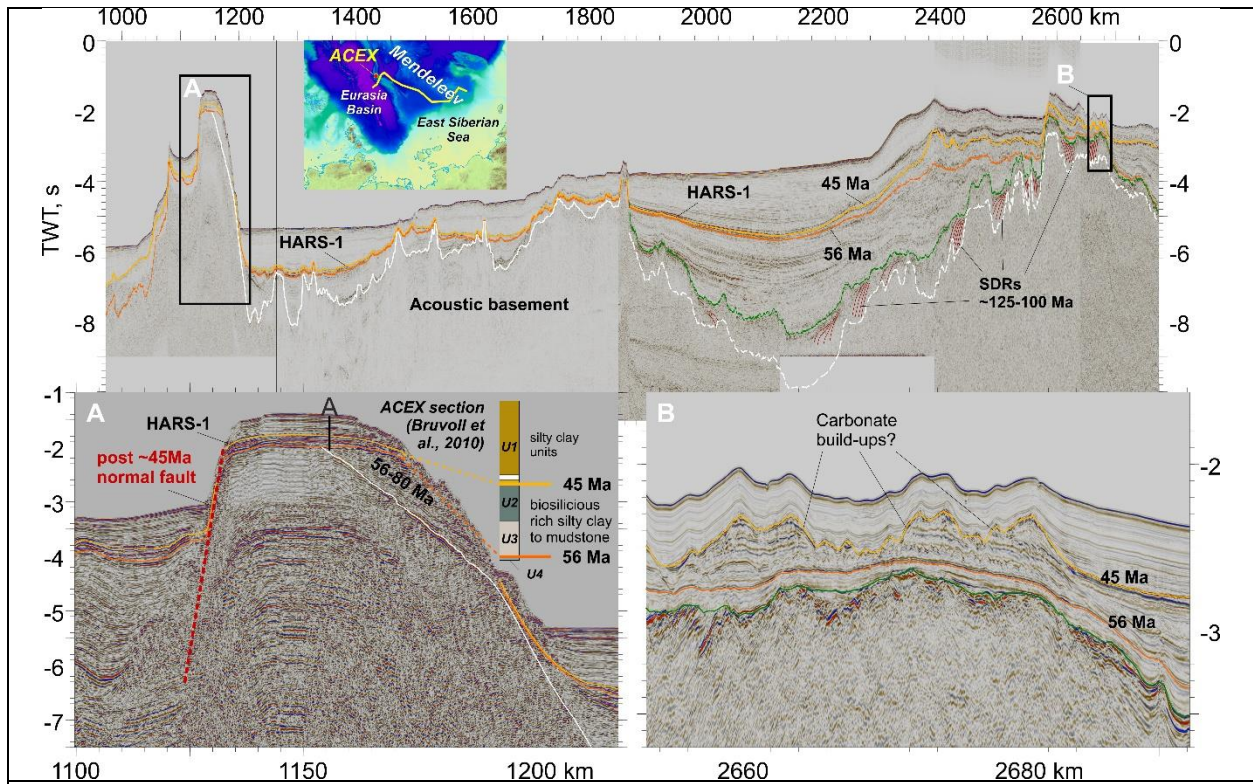


Fig. 2. Composite seismic profile from the ACEX borehole on the Lomonosov Ridge to carbonates on the Mendeleev Rise. Data from (Nikishin et al., 2021a; Nikishin et al., 2021b; Nikishin et al., 2023). A and B – details of the profile. A – detailed seismic section with ACEX borehole data, ACEX borehole data from (Bruvoll et al., 2010); B – detailed seismic section with possible carbonates. Seismic stratigraphic correlations suggest that the age of the interpreted shallow-water carbonates is between 56 Ma and 45 Ma.

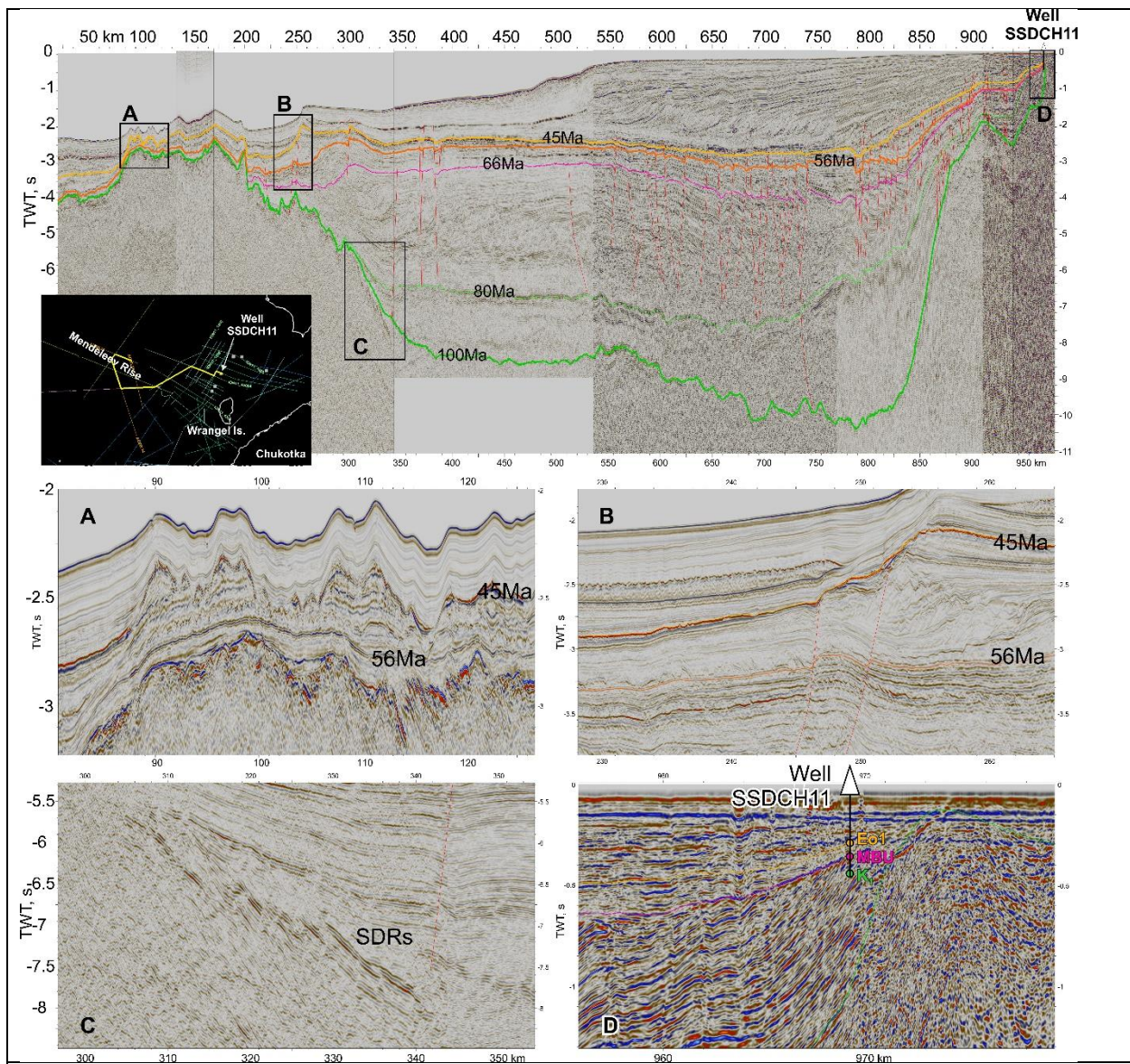


Figure 3. Composite seismic profile from the Chukchi Sea borehole (SSDCH11) to carbonates on the Mendeleev Rise. Data from (Nikishin et al., 2021a; Nikishin et al., 2021b; Nikishin et al., 2023; Malyshev et al., 2024b). A, B, C, D – details of the seismic profile. Segment A – possible carbonates; segment B – clinof orm complex and MTD; segment C – possible SDRs with basalts (~125-100 Ma); segment D – correlation with borehole SSDCH11 data. Seismic stratigraphic correlation supports the interpretation of an age between 56 Ma and 45 Ma.

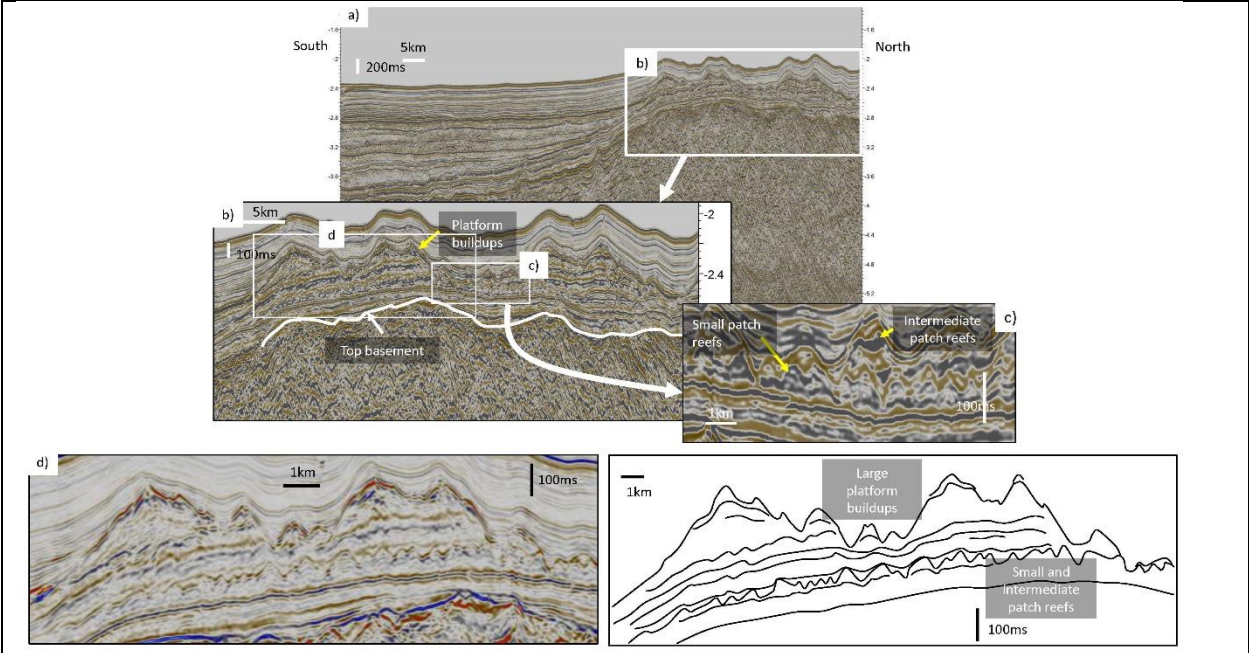


Figure 4. a) Multi-channel seismic section (ARC20-24) across the Mendeleev Rise (see Fig. 1 for location). b) Detail of interpreted carbonate buildups illustrating various size patch reefs and platforms. c and d) Detailed view of interpreted small and intermediate patch reefs characterized by small patch reefs at the base, culminating in larger platforms at the top.

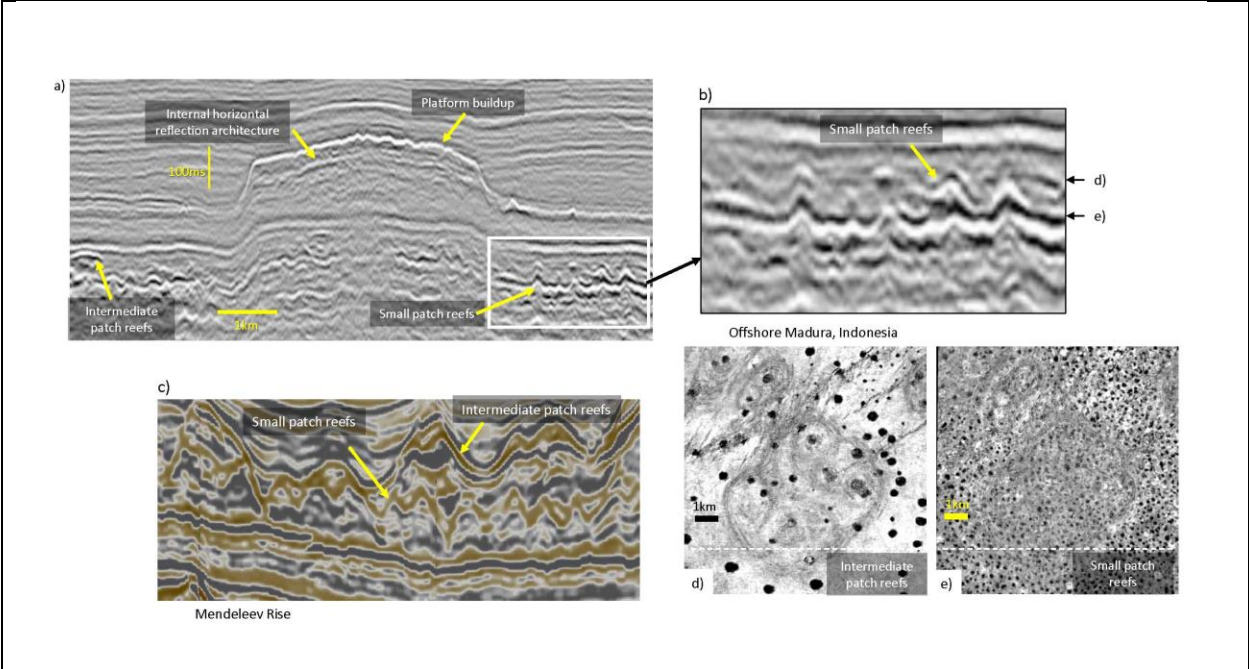


Figure 5. Comparison between Miocene carbonate buildups (a and b) from offshore Madura, Indonesia (Posamentier et al., 2010) and c) Mendelev interpreted buildups. 3D seismic time slices through small patch reefs with numerous small patch reefs (e) evolving into larger patch reefs (d) through time.

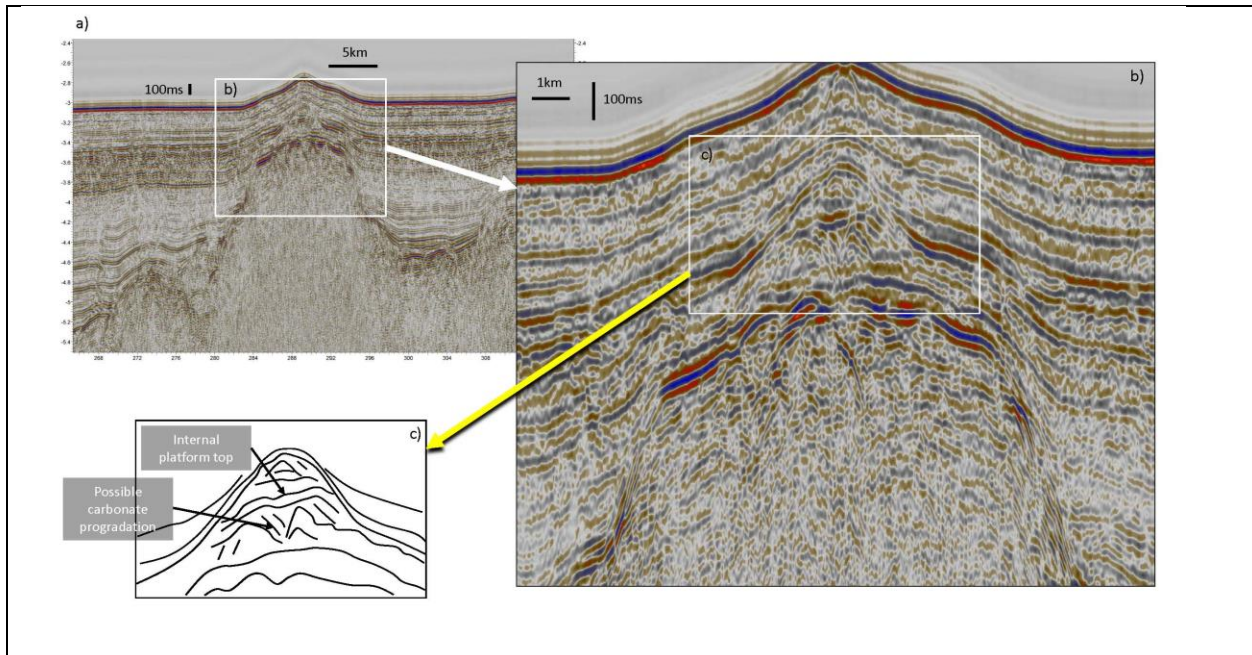


Figure 6. Seismic section (ARC12-03) illustrating carbonate buildups (a) from the Mendeleev Rise (see Fig. 1 for location). b) Detail of the seismic section highlighting the interpreted shallow-water carbonate deposits. c) Interpretation of the detailed seismic section focused on the shallow-water carbonates. Note the internal platform top inferred from the internal horizontal reflections.

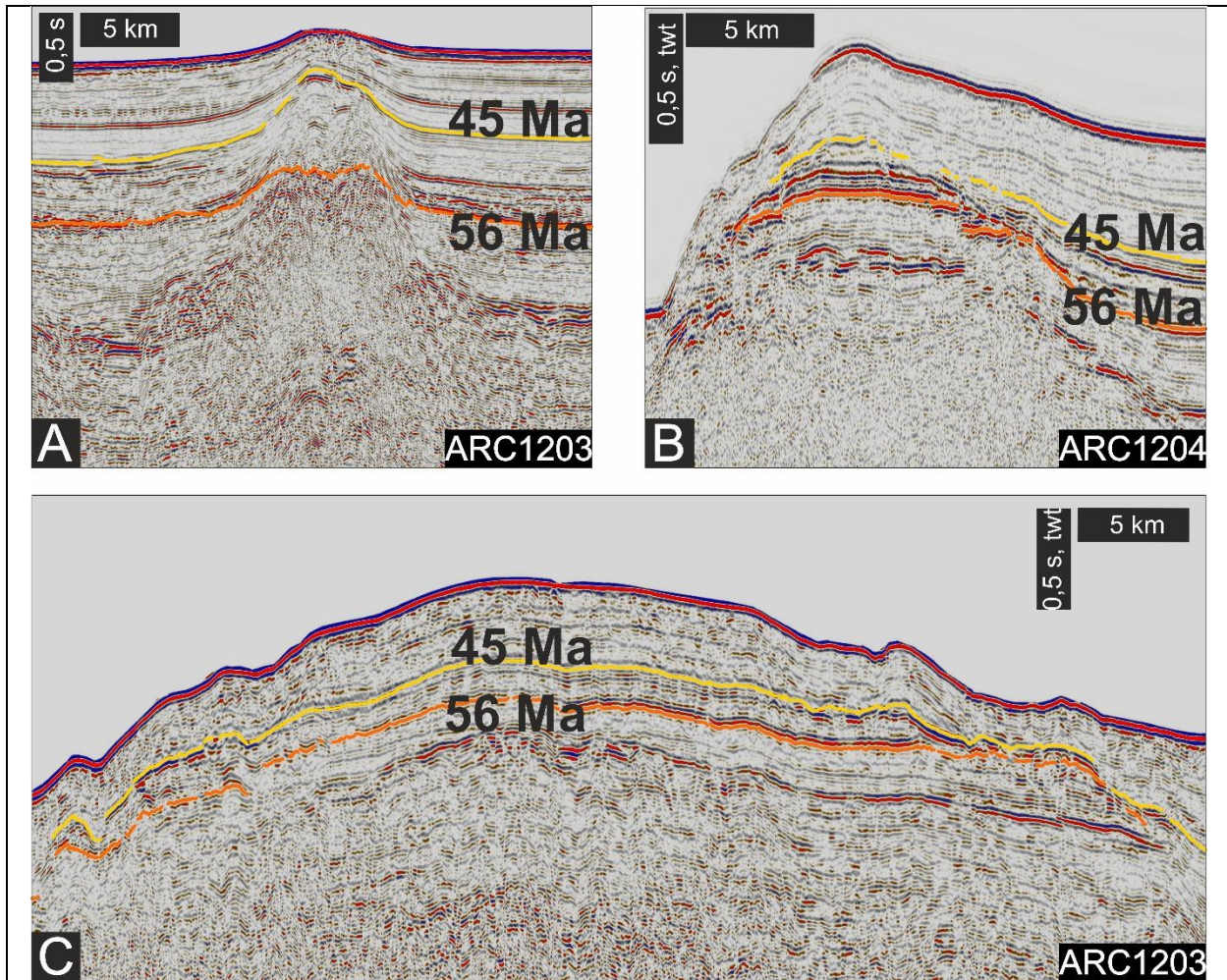
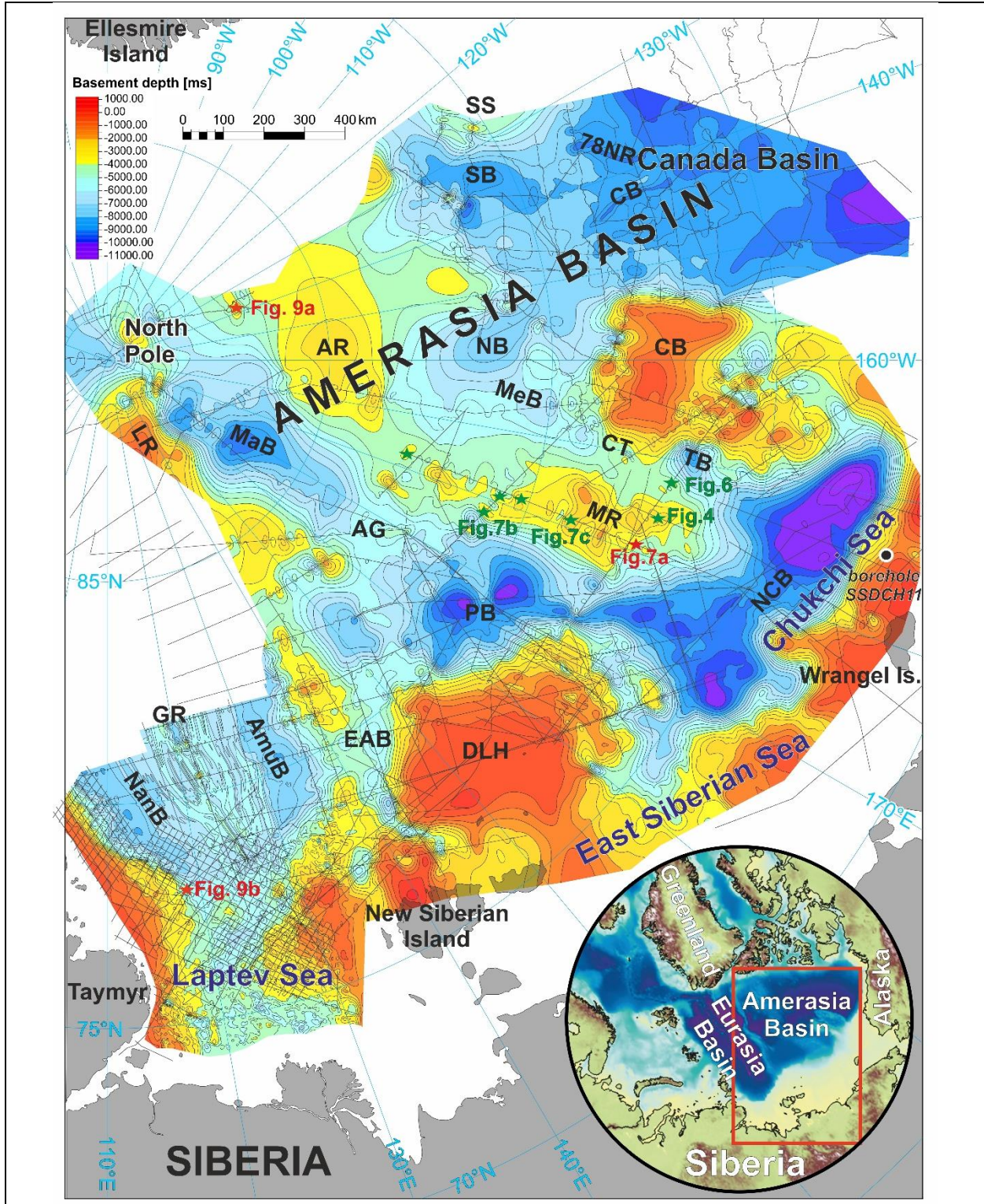


Figure 7. Additional seismic profiles with possible shallow-water carbonates (see Fig. 8 for location). Possible shallow-water carbonate buildups are between 56 Ma and 45 Ma, based on seismic stratigraphic correlation with available borehole data. Seismic data from (Nikishin et al., 2021a, Nikishin et al., 2021b, Nikishin et al., 2023).



- | | | | |
|---------------------------|------------------------------|-------------------------|-----------------------|
| MR - Mendeleev Rise | AR - Alpha Ridge | AG - Arlis Gap | GK - Gakkel Ridge |
| MeB - Mendeleev Basin | NB - Nautilus Basin | LR - Lomonosov Ridge | NanB - Nansen Basin |
| TB - Toll Basin | SS - Sever Spur | PB - Podvodnikov Basin | AmuB - Amundsen Basin |
| CT - Charlie Trough | CB - Canada Basin Axial Rift | ACEX - boreholes | |
| NCB - North Chukchi Basin | 78NR - 78N Rift | MaB - Makarov Basin | |
| DLH - De Long High | SB - Stefansson Basin | EAB - East Anisin Basin | |
| | CB - Chukchi Borderland | | |

Figure 8. Basement topography of the Mendeleev Rise region (modified after Nikishin et al., 2023, with new data added) and location of possible carbonate build-ups (stars). Green stars – possible carbonates on tectonic highs, red stars - possible carbonates on volcanic tops.

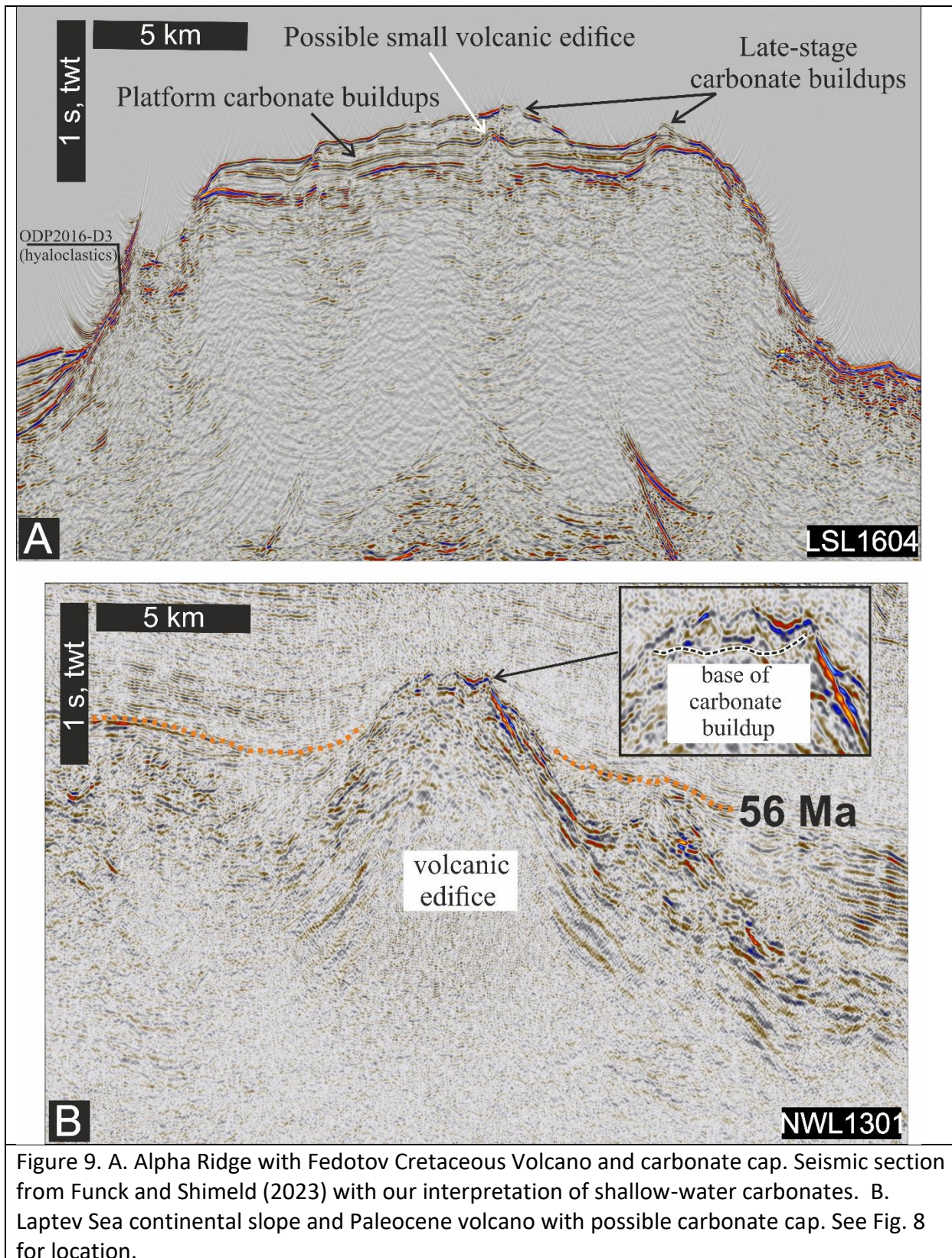


Figure 9. A. Alpha Ridge with Fedotov Cretaceous Volcano and carbonate cap. Seismic section from Funck and Shimeld (2023) with our interpretation of shallow-water carbonates. B. Laptev Sea continental slope and Paleocene volcano with possible carbonate cap. See Fig. 8 for location.

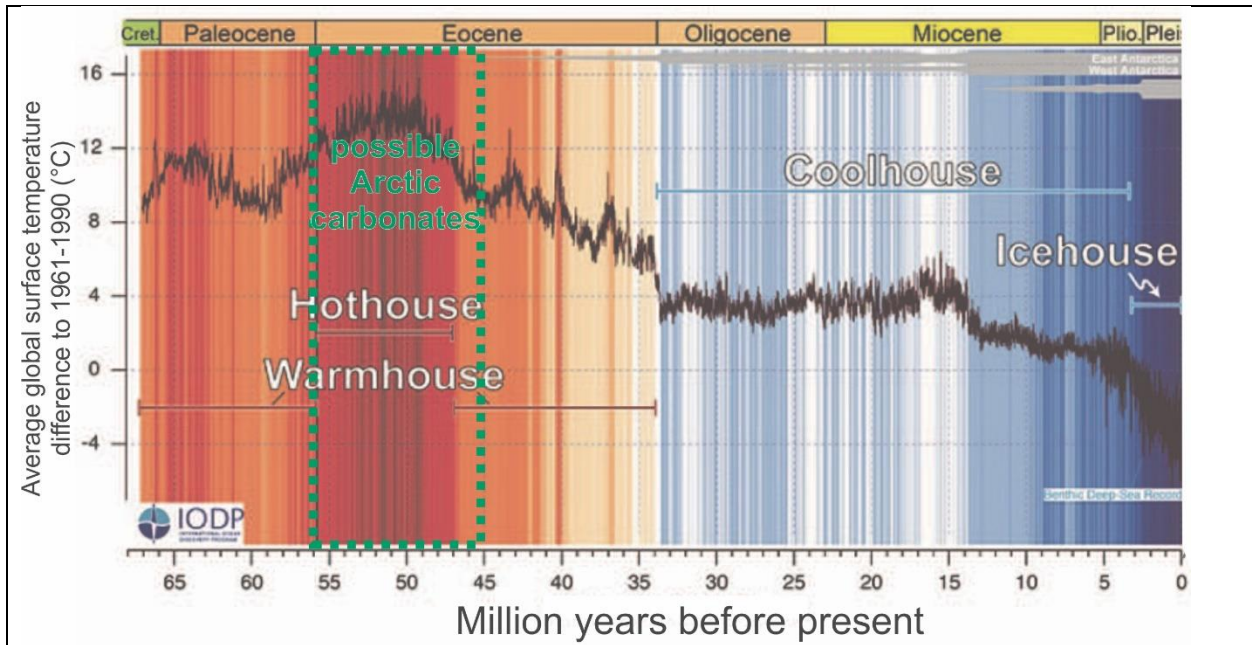
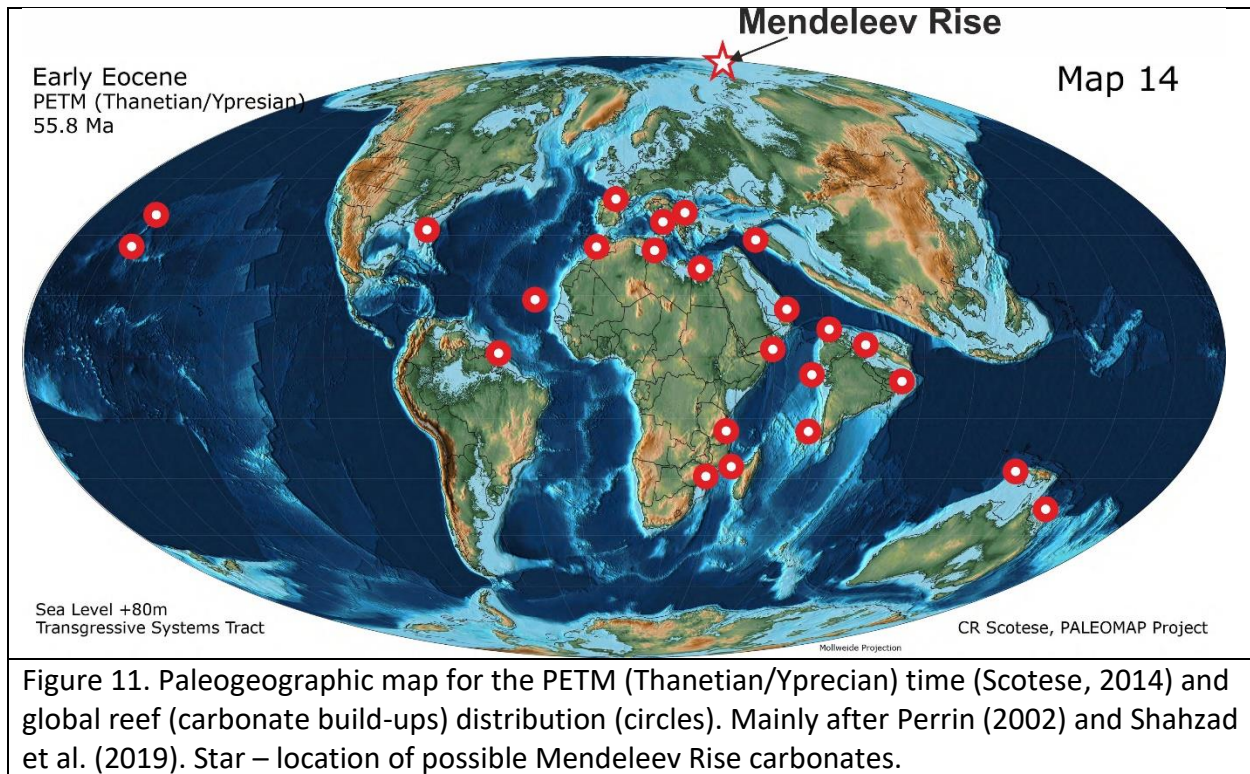


Figure 10. Cenozoic paleoclimate (Westerhold et al., 2020; Planke et al., 2021) and interval of possible carbonate buildups.



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