Quantifying large-scale continental shelf margin growth and dynamics across middle-Cretaceous Arctic Alaska with detrital zircon U-Pb dating

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ABSTRACT

Sequence stratigraphy provides a unifying framework for integrating diverse observations to interpret sedimentary basin evolution; however, key time assumptions about stratigraphic elements spanning hundreds of kilometers are rarely quantified. We integrate new detrital zircon U-Pb (DZ) dates from 28 samples with seismic mapping to establish a chronostratigraphic framework across 800 km and ~20 m.y. for the middle-Cretaceous Torok-Nanushuk clinothem of Arctic Alaska (USA). Shelf-margin DZ dates indicate continent-scale sediment routing with Russian Chukotka provenance and provide reliable maximum depositional ages derived from arc volcanism. Shelf-margin advance rates display a clear relationship to toplap trajectories and provide empirical support for long-held inferences linking sediment supply to margin architecture. Two distinct shelf-margin growth regimes are evident: (1) a ca. 115–107 Ma phase of rapid ~50 km/m.y. shelf advance rates with mainly progradational trajectories; and (2) a ca. 107–98 Ma phase of moderate ~13 km/m.y. shelf advance rates with progradational-retrogradational-aggradational trajectories. We established a subsequent shelf-to-deep water correlation by independently dating ca. 98–95 Ma low shelf accommodation and basin-floor deposition as far as 240 km east that indicate lowstand shedding and a change to localized routing with Brooks Range provenance. Finally, we dated a ca. 95 Ma basin-wide transgression at deep-water to shelfal settings across 350 km that exhibits apparent synchronity consistent with an event-significant surface. In one of the world’s largest foreland basin clinothems, our work constrains the timing and duration of key depositional elements to test large-scale sequence stratigraphic assumptions, enables reliable correlation and quantification of sediment dynamics across 800 km, and captures the chronology of a giant regressive-transgressive cycle.

INTRODUCTION

Clinothems are the building blocks of siliciclastic continental margins and originate by the build-out of a sediment prism from a basin margin into deeper water, with continued growth by frontal accretion and vertical aggradation (Patruno and Helland-Hansen, 2018). Sequence stratigraphy and trajectory analysis provide powerful conceptual frameworks for reconstructing clinothem and basin evolution, but key assumptions commonly remain untested because absolute age control is elusive. A primary goal of sequence stratigraphy is to correlate systems tracts of facies associations deposited during specific phases of relative sea level, which relies on the identification of bounding stratigraphic surfaces assumed to approximate time lines (Mitchum et al., 1977; Catuneanu, 2006). However, large-scale correlation can be fraught with uncertainty because high-relief continental margins encompass diverse depositional processes, sedimentation rates that span several orders of magnitude, unconformities of unknown duration and spatial extent, and a periodic physical disconnect between deep-water and shelf systems (Posamentier and Kolla, 2003; Catuneanu, 2006). Despite the value of a basin-wide chronostratigraphic framework for establishing correlations, quantifying deposition rates, and illuminating controls on stratigraphic architecture (e.g., Daniels et al., 2018, 2019; Herrriott et al., 2019; Sharman and Malkowski, 2020), absolute age control is rarely attained at sufficient spatial and temporal resolution to quantify continental margin growth over several hundred kilometers.

We present a case study from one of the world’s largest foreland basin clinothems. The enormous middle-Cretaceous Torok-Nanushuk clinothem stretches ~1000 km across Arctic Alaska from the U.S.-Russia maritime boundary to the U.S.-Canada border and has a volume of 1.2 × 10⁶ km³ (Fig. 1; Houseknecht, 2019). However, imprecise age control has hampered correlation; chronostratigraphic uncertainties are >5–10 m.y. due to rapid sedimentation, low diversity at high paleolatitudes, and diachronous zonal boundaries (McMillen, 1991; Mickey et al., 2006). In this study, we establish a new detrital zircon U-Pb (DZ) maximum depositional age (MDA)–based chronostratigraphy that spans ~20 m.y. and quantifies Torok-Nanushuk clinothem growth across 800 km, greatly expanding the spatial scope of recent outcrop-based DZ MDA studies of foreland clinothems (e.g., Sickmann et al., 2018; Daniels et al., 2019). We tie dates directly to stratigraphic elements imaged seismically over hundreds of kilometers across the continental margin from shelf to deep-water settings to ascertain their temporal significance, quantify sediment dynamics, and discern controls on clinothem architecture.

SETTING

The Torok-Nanushuk clinothem (Aptian–Cenomanian) in the Brookian tectonostratigraphic sequence of Arctic Alaska comprises sediment eroded from the Brooks Range and Chukotka orogens. The clinothem filled relic flexural accommodation generated by earlier tectonic loading that formed the Colville foreland basin and by coeval rift-shoulder uplift related to opening of the Canada Basin.
Deposition occurred during greenhouse conditions at ∼80°N paleolatitude (Spicer and Herman, 2010). The architecture of the Torok-Nanushuk clinothem is well known from decades of study (e.g., Huffman, 1985; Molenaar, 1988; McMillen, 1991). Recent interpretations of sequence stratigraphic surfaces and systems tracts inferred from seismic reflection, well-log, core, and outcrop studies provide a rich framework for our work, and are summarized below (Figs. 1 and 2; Houseknecht et al., 2009; LePain et al., 2009; Pemberton, 2016; Ramon-Duenas et al., 2018; Houseknecht, 2019, and references therein). The base and top of the clinothem are defined by regionally extensive, high-amplitude seismic reflections marking flooding surfaces capped by condensed shale of the gamma-ray zone (GRZ) of the Hue Shale and the lower Seabee Formation, respectively. Deep-water GRZ bottomset facies interfinger westward with and are overlain by foresets of Torok Formation silty mudstone and local sandstone that were deposited on a slope. Topset facies consist of Nanushuk...
Formation sandstone, siltstone, mudstone, and coal that were deposited in shelf through non-marine environments. The base and top of the Torok foresets are clearly defined in seismic data as downlap and toplap surfaces, respectively.

Within the clinothem, dozens of lowstand shelf margins are recognized in seismic data via discrete foreset surfaces draped by transgressive mudstone that form high-amplitude reflections and abrupt basinward termination of correlative topset reflections (Houseknecht, 2019). Nanushuk shelf-margin orientation and foreset dip indicate the foreland basin filled mainly by eastward axial sediment transport (Fig. 1), whereas outcrop paleocurrents indicate minor transverse transport in the foredeep. Decompacted depositional relief of individual shelf margins ranges from 1.0 to 2.5 km basin wide as approximated by the vertical distance from toplap to downlap along individual foresets.

The progradational limits of Nanushuk toptset and Torok upper foreset strata (Fig. 1, ultimate shelf margin) are marked by a regressive surface of erosion (RSE). In deep water to the east, the RSE is overlain by basin-floor fan deposits in lower foreset and bottomset strata (Fig. 1; terminal lowstand systems tract [LST]), which is exposed in the eastern Brooks Range as the lower Juniper sandstone and Arctic Creek unit (Fig. 1; Mull and Decker, 1993; Waltzes et al., 2011; Houseknecht, 2019).

Regional termination of the clinothem is marked by a transgressive surface of erosion on the relict upper slope and outer shelf, which commonly merges with the RSE as a composite surface. A transgressive systems tract (TST) comprising Seabee Formation condensed shale was deposited overlying the terminal LST on the slope and basin floor. The TST on the relict shelf comprises the Ninuluk sandstone (uppermost Nanushuk Formation) grading up into Seabee condensed shale (Houseknecht and Schenk, 2005; LePain et al., 2009; Houseknecht, 2019).

METHODS

We used DZ geochronology to determine clinothem provenance and MDAs. Torok and Nanushuk core samples were collected within an average 150 m vertical distance of the toplap surface to constrain shelf-margin age and advance rates. Outcrop samples were collected through Juniper and Arctic Creek lower fan successions to constrain the age of the terminal LST. Ninuluk sandstone core and outcrop samples were collected to constrain the age of the terminal transgression that drowned the relict Nanushuk shelf. Samples were projected along relict shelf margins and stratigraphic elements (Fig. 2). DZ dates were obtained via laser ablation–inductively coupled–plasma mass spectrometry with 100–565 grains analyzed for each of 28 samples from 17 sites (6700 grains in total; see the Supplemental Material1; Lease et al., 2022). MDAs were calculated as the weighted mean of the youngest three or more dates that overlap within $2\sigma$ age uncertainty (youngest grain cluster at $2\sigma$ method; Coutts et al., 2019). MDAs include both analytical and systematic uncertainties (Horstwood et al., 2016).

RESULTS

Detrital zircon U-Pb analyses effectively characterize provenance for the Cretaceous Torok-Nanushuk clinothem because the prospective Chukotka source area to the west has distinctive <350 Ma ages that are generally absent in the Brooks Range to the south (Fig. 3). Torok-Nanushuk shelf-margin samples have significant 200–700 Ma and 1700–2100 Ma DZ ages that match those of Chukotka Triassic strata (Fig. 3; Amato et al., 2015; Miller et al., 2018) and suggest eastward, axial transport in a >1000-km-long continental-scale sediment routing system with headwaters in Russian Chukotka. In addition, 95–160 Ma shelf-margin DZ ages were likely sourced from Chukotka Mesozoic arc volcanism that includes airfall (Akinin et al., 2020). In contrast to shelf-margin samples, Juniper–Arctic Creek basin-floor fan samples generally lack 100–350 Ma DZ ages and instead are characterized by 350–700 and 900–2000 Ma DZ ages consistent with Brooks Range provenance (Fig. 3; Strauss et al., 2017) and minor

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1Supplemental Material. Zircon U-Pb methods and data. Please visit https://doi.org/10.1130/GEOL.S.1904929 to access the supplemental material, and contact editing@geosociety.org with any questions.
95–100 Ma airfall volcanic input. The terminal lowstand DZ data suggest northward, transverse transport in more localized sediment dispersal systems emanating from the Brooks Range.

Climothen strata contain rare young zircons (e.g., Sharman and Malkowski, 2020), likely derived from the Okhotsk-Chukotka and precursor volcanic arcs (Akinin et al., 2020), which we use to calculate clinothem MDAs. We demonstrate a test case in Nanushuk upper topset deltaic facies where DZ MDAs of 98.2–98.4 ± 1.3–1.4 Ma (n = 3 samples) coincide with the 98.4 ± 1.3 Ma zircon U-Pb crystallization age of interbedded volcanic ash (Fig. 1B). We establish a chronostratigraphic framework for the entire clinothem with DZ MDAs (Figs. 2 and 4A). MDAs young from 114.7 to 97.6 Ma west to east for the Torok-Nanushuk shelf margins (n = 14 sites; ± 1.4–2.2 m.y.), from 98.4 to 95.5 Ma upsection through the terminal lowstand fans (n = 2 sites, 6 samples; ± 1.3–1.5 m.y.), and from 95.4 to 95.0 Ma in the transgressive Nuluk sandstone (n = 4 sites; ± 1.3–1.6 m.y.). We interpret MDAs to approximate true depositional ages given the consistent test case result (Fig. 1B), nearby presence of coeval volcanic arc sources throughout deposition of the succession (Fig. 3), and regional younging of MDAs basinward and upsection (Figs. 2 and 4A). Clinothem MDAs suggest that forest facies overtopped the Northern Alaska anticlinorium accommodation sill between ca. 107.5 and 105.4–104.5 Ma (sites To, E, I, and S in Fig. 1; Homza et al., 2020).

DISCUSSION
We integrate DZ MDAs with seismic mapping to provide unprecedented absolute age control on the dynamics of a large-scale shelf-margin clinothem across 800 km (Fig. 2). This new chronostratigraphic framework indicates an initial stage of rapid Torok-Nanushuk shelf-margin growth during ca. 114.7–107.5 Ma with a horizontal advance rate (i.e., progradation rate) of ∼10 km/m.y. (Fig. 4A; n = 5 sites). Shelf-margin trajectories during rapid growth are strongly progradational with only minor aggradational and retrogradational segments (Figs. 2A and 2B); clinothem foresets are gently dipping with little erosion, and stacking patterns resemble those of normal regression (Catuneanu et al., 2011; Houseknecht, 2019). An abrupt reduction in shelf-margin growth and change in trajectory occurred ca. 107 Ma, followed by slower shelf-margin advance during ca. 105.4–97.6 Ma at a rate of only ∼13 km/m.y. (Fig. 4A; n = 9 sites). Shelf-margin trajectories during slower growth have a sawtooth form characterized by short progradational, significant retrogradational, and large aggradational segments (Figs. 2B and 2C); foresets are steeply dipping with evidence of gravity mass failure, and stacking patterns suggest forced regression. No major changes in clinothem height or provenance (Fig. 3) occur across the transition in shelf-margin growth.

The abrupt fourfold decrease in shelf-margin advance rates and change from strongly progradational to progradational-rettrogradational-aggradational toplap trajectories (Figs. 2 and 4A) coincided with changes in tectonics, sediment partitioning, and eustasy. First, sediment supply from the Chukotka–Brooks Range orogen may have decreased due to a transition from crustal thickening to extension and translation, though the timing and details along the orogen length are debated (Amato et al., 2015; Till, 2016; Miller et al., 2018; Akinin et al., 2020). Second, a reduction in sediment flux feeding eastward shelf-margin growth in the Colville foreland basin likely occurred once forest facies overtopped the Northern Alaska anticlinorium accommodation sill, which increased sediment partitioning and bypass to the deep, rifting Canada Basin to the north. Third, a middle-Albian rise in the long-term envelope of eustatic sea level (Haq, 2014) may have influenced shelf-margin trajectories. We conjecture a ∼0.4 m.y. average shelf margin duration based on the ∼47 margins discernible in two-dimensional seismic during ca. 115–98 Ma (Fig. 2) and speculate pacing by long-period orbital eccentricity, as is common for fourth-order sequences at lower latitudes during the middle-Cretaceous greenhouse (Haq, 2014).

The new chronostratigraphic framework enables reliable correlation over hundreds of kilometers and quantifies a ca. 98–95 Ma third-order terminal LST with low to negative shelfal accommodation and bypass to deep water followed by a ca. 95 Ma terminal transgression (Figs. 2 and 4A). The ultimate shelf margin was established at ca. 97.9–97.6 Ma (sites Ka, Cd, K in Fig. 1), and a coeval switch from GRZ condensed marine shale to submarine fan deposition occurred at ca. 98.4–97.6 Ma (sites J, A). The stalling of Nanushuk shelf-margin advance and shift to localized Brooks Range provenance (Fig. 3) suggests a significant decrease in sediment flux as Chukotka continental-scale sediment routing was disrupted during a major reorganization. Upsection, our data demonstrate the apparently synchronous establishment (at ±1σ internal uncertainty) of a terminal TST across a 350-km-long transect (Figs. 2 and 4B), with
the ca. 95.6–95.5 Ma maximum regression of basin-floor fans (n = 2 sites) coinciding with the ca. 95.4–95.0 Ma transgression of the relict shelf (n = 4 sites). The similar ca. 95 Ma timing of a reconnection between the Arctic Ocean and Gulf of Mexico 5000 km to the south (Elldritt et al., 2017) following isolation since ca. 98 Ma suggests gateway influences impacted late-stage Torok-Nanushuk sedimentation.

We are unaware of a better-dated clinothem of this scale (20 m.y. duration, 800 km length, 1–2.5 km relief) where dates can be tied to basin-wide stratigraphic elements to quantitatively reconstruct clinothem growth and test large-scale sequence stratigraphic assumptions. First, whereas links between sediment supply and shelf-margin architecture are commonly inferred by comparing different margins (e.g., Carvajal et al., 2009), here we illuminate the coevolution of shelf-margin advance rates and toplap trajectories within a single clinothem. Rapid shelf advance rates of ~50 km/m.y., among the fastest in the world (Carvajal et al., 2009; Patruno and Helland-Hansen, 2018), and strongly progradational trajectories are sustained for ~8 m.y.; a subsequent fourth decrease in advance rate coincides with an abrupt change to sawtooth trajectories, engendering a well-constrained target for stratigraphic modeling (e.g., Zhang et al., 2020).

Second, whereas shelf to deep-water correlation is typically hampered by a physical disconnect and inadequate age control, here we independently date a 98–95 Ma period of low shelfal accommodation and bypass to deep water that is consistent with longstanding expectations from a canonical sea-level cycle (Posamentier and Kolla, 2003; Catuneanu et al., 2011). Third, using six dates across 350 km, we document the opening of the middle Albian–Cenomanian Nanushuk Formation in outcrop, central North Slope, Alaska: Alaska Division of Geological and Geophysical Surveys Report of Investigations 2009-1, 78 p., https://doi.org/10.14509/20091761.

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