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Paleoenvironmental analysis of Cretaceous mudstones at Slope Mountain, Alaska using carbon stable isotopes

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ABSTRACT

This project uses field samples, microfacies analysis, and carbon stable isotopes ($\delta^{13}C$) of mudstones to determine past environmental conditions of North Slope, Alaska during the Albian-Cenomanian (Cretaceous). Samples were taken at Slope Mountain, Alaska located north of the Brooks Range. Slope Mountain includes the Torok Formation and the upper and lower Nanushuk Formations that consist of alluvial, deltaic, and shallow marine facies that were deposited into the North Slope foreland basin on the Arctic Alaska micro plate. An exhaustive search for identifiable microfossils, such as pollen, diatoms, and foraminifera in the samples yielded nothing but charcoal and carbon residue. No other fossilized material was identified. $\delta^{13}C$ values are consistent with a mix of algae and terrestrial C_3 plants, suggesting deposition in a shallow marine setting close to shore.

INTRODUCTION

Although North Slope, Alaska located above the Arctic Circle is experiencing a polar climate today (Fig. 1), it was a very different place in the Cretaceous. The strata examined in this study were part of the Arctic Alaska micro plate (AA on Fig. 2, Fig. 3), which contains both the Brooks Range and North Slope (Newman et al., 1979; Witte et al., 1987). Paleomagnetic studies suggest that the Nanushuk Formation was located at least 75 ° north of the equator during the Cenomanian (Spicer and Herman, 2010; Witte et al., 1987), and possibly as far north as 85 °N (Fig. 2; Spicer and Herman, 2010; Witte et al., 1987). Previous work on the Torok and Nanushuk Formations in other areas of Alaska has provided basic information about the paleoenvironment. At 75°N, there are three completely sunless months; while at 80°N, this increases to four months (Witte et al., 1987). However, if the tilt of the Earth's axis was reduced during the Cretaceous, the number of sunless nights would be decreased (Witte et al., 1987).

Despite being located even further above the Arctic Circle, Cretaceous North Slope Alaska was significantly warmer than today. Paleoflora and dinosaur remains within the Albian-Cenomanian Nanushuk Formation of the North Slope indicate a warm temperate climate (Witte et al., 1987). The preserved floras from the North Slope during the Cretaceous consist entirely of deciduous plants, suggesting the region, was then covered in a temperate deciduous forest (Spicer and Parrish, 1986).

At 60 °N during the Aptian through Albian, the mean annual temperatures were determined to be 16 °C (Huber et al., 1995; 2002) and 10–13 °C in the Late Albian (Fassell and Bralower, 1999), compared to -11°C today. Vegetation composition, wood anatomy, and angiosperm leaf margin analysis indicate that the temperature during the Cenomanian was approximately 10 °C, but could have ranged from 20 °C to −11 °C, throughout the year (Spicer and Parrish, 1986; Parrish et al., 1987; Spicer and Parrish, 1990). Model rainfall estimates suggest that during the Late Albian, the North Slope received around 485mm/yr of rain (Ufnar et al., 2004).

LePain et al. (2009) researched the extent of exposure of the Nanushuk formation throughout Alaska, including Slope Mountain. However, none of these sites were comprehensively examined. The outcrops in this study have not been examined extensively until now and, therefore, can help provide more in-depth information on the paleoenvironment.

During the mid to Late Cretaceous, arctic Alaska experienced great tectonic and climatic change (Bird and Molenaar, 1992). The Torok and Nanushuk Formations (Albian-Cenomanian) were deposited during a period of exhumation and extension south of the Brooks Range (Bird and Molenaar, 1992), filling most of the Colville Basin (Fig. 4, Fig. 5) by the Late Albian (LePain et al., 2009). The Colville Basin formed along the ancestral Brooks Range and Herald Arch (Bird and Molenaar, 1992).

The Albian-Cenomanian was a known period of greenhouse conditions in the Cretaceous Arctic. Sea level was higher and the earth was much warmer than today throughout the Cretaceous (DeConto et al., 1999; Spicer and Corfield, 1992). The Middle Cretaceous (Late Albian) had unusual periods of warm polar temperatures, repeated reef drownings in the tropics, and many oceanic anoxic events (Wilson and Norris, 2001).

I use carbon stable isotopes of mudstones to determine past environmental conditions in the Colville Basin at this time. Information about both atmospheric and oceanic chemistry, along with information about precipitation can be obtained from $\delta^{13}C$ analyses. Samples were taken from both the Torok and Nanushuk Formations at Slope Mountain (Fig. 1) and consist of both nonmarine and alluvial, deltatic, and shallow marine facies based on field observations of large-scale features. The study described below uses carbon stable isotope analysis to better understand changes in the paleoenvironment and paleoclimate for this time period.

BACKGROUND / GEOLOGIC SETTING

Slope Mountain, Alaska (N68.75º W149.03º), is located in the northern foothills of the Brooks Range. It sits in the northwestern Philip Smith Mountains quadrangle near Mile 305 of the Dalton Highway, just west of the Trans Alaska Pipeline System (Mull et al., 2003). Situated on the proximal margin of the North Slope foreland basin (Fig. 4: Colville foreland basin), Slope Mountain consists primarily of strata from the Albian-Cenomanian Nanushuk and Torok Formations (Johnsson and Sokol, 2000; LePain et al., 2009).

TECTONIC SETTING

During the Paleozoic and Early Mesozoic, the Arctic Alaska micro plate was part of a passive margin that subsequently experienced rifting during the Jurassic and Cretaceous (Bird and Molenaar, 1992). This rifting created the separation of the Arctic Platform from the North American craton and produced a series of rifts beneath the present Beaufort Shelf and Canadian Beaufort margin (Plafker and Berg, 1994). Concurrently, the Arctic platforms collided with an island arc producing the Brooks Range and North Slope foreland basin, also known as the Colville Basin (Fig.4; Bird and Molenaar, 1992). In the Early Cretaceous, rotational rifting led to the formation and drifting of the Arctic Alaskan Plate, which separated from the Canadian Arctic Islands, forming the Canada Basin and the Beaufort passive margin (Bird and Molenaar, 1992). This rifting was nearly synchronous with the end of the Brooks Range formation (Plafker and Berg, 1994).

The south of the basin is bounded today by the Brooks Range, while the north is bounded by the Beaufort Sea where the Barrow Arch, a rift shoulder, separates the foreland basin from the extensional Canada basin to the north (Fig. 4; Bird and Molenaar, 1992). The west of the basin continues to the Herald Arch and the eastern edge of the basin narrows as the Brooks Range extends almost to the northern coastline near the Canada-Alaska border (Bird and Molenaar, 1992).

The age of the Colville Basin fill ranges from Middle Jurassic to Tertiary or Quaternary, and it consists of deposits from the ancestral Brooks Range (Fig 5.; Bird and Molenaar, 1992). The basin fill includes the Torok and Nanushuk Formations, deposited between 120 and 95 Ma, that are the focus of this study.

DEPOSITIONAL ENVIRONMENTS AND LITHOLOGIES

The upper portion of Slope Mountain (Fig. 1) consists of dominantly nonmarine sandstone, conglomerate, carbonaceous mudstone, and to a lesser extent coal from the upper Nanushuk Formation (LePain et al., 2009), which overlies the lower Nanushuk of predominantly marine sandstone(Johnsson and Sokol, 2000; LePain et al., 2009).

The Nanushuk Formation is Albian–Cenomanian in age, while the Torok Formation is dated further back to the Aptian–Cenomanian; (Fig. 5; Mull et al., 2003). The Torok Formation is a thick, easily-eroded sequence of sedimentary rocks that underlie the Nanushuk formation and is generally poorly exposed (Mull et al., 2003).

The Nanushuk and Torok Formations are genetically coupled units (Decker, 2007). The Nanushuk prograded over the silty mudstones of the Torok Formation (Mull et al., 2003), which consists of marine shelf and slope deposits that are the coeval lateral equivalents of the Nanushuk Formation (Mull et al., 2003). The Nanushuk was deposited in topset, marine to shelf environments, while the Torok was deposited in deepwater, slope to basin environments (Decker, 2007).

The Nanushuk Formation prograded west to east along the axis of the Colville Basin and established a west-east axial fill that continued from the Cretaceous into the Tertiary (Houseknecht and Schenk, 2005; Decker, 2007; Houseknecht et al., 2009; LePain et al., 2009), which suggests a major sediment source to the south-west. McCarthy (2003) suggested that this prograding succession was formed by a large river dominated deltaic complex known as the Corwin Delta, which is comparable in size to the modern Mississippi Delta. Sandstone components of the Nanushuk suggested another source area from the south; this was likely the Umait Delta which had very little impact on the Corwin Delta (McCarthy, 2003). A large volumetric fraction of the Colville Basin is made of the Nanushuk and Torok Formations, along with the partly time equivalent Fortress Mountain Formation (Decker, 2007). This major sediment influx corresponded with the mid-Cretaceous uplift and erosion of the ancestral Brooks Range (Decker, 2007).

VEGETATION, PALEOCLIMATE, AND PALEOLATITUDE

Rich fossil floras present in the Cretaceous sediments of northern Alaska provide information about past environments (Spicer and Herman, 2001). Albian to Cenomanian floras are abundant and diverse in strata along the North Slope of Alaska (Spicer and Parrish, 1986), and plant fossils are common in the nonmarine beds of the Nanushuk Formation (Mull et al., 2003). Regional vegetation from the Latest Albian to Cenomanian consisted of large coniferous trees and moderately diverse understory of angiosperms and ginkgoes, as well as abundant ground cover of horsetails, ferns, and deciduous cycads (Parrish and Spicer, 1988).

During much of the Mesozoic and Paleogene, polar deciduous forests were an important biome that occupied upwards of 40% of the total land surface of this region (Royer et al., 2005). The proportion of deciduous plants is evidence for strong seasonality, which could be dependent on either light or temperature or both (Spicer and Parrish, 1986). Deciduousness is one of the most important adaptations of woody plants to climates that have periods unfavorable to growth because they can tolerate heat, dryness, and cold (Wolfe, 1987).

These floral records are critical in reconstructing and understanding global climate change because of their unique near-polar location and their capacity for high carbon sequestration during this time of global warmth (Spicer and Herman, 2001). The temperature of the Late Albian to Cenomanian of Arctic North Slope Alaska was around 10 °C as indicated by the physiognomy of the flora of the time period (Parrish and Spicer, 1988).

The floral records represent vegetation that has no modern analogues; the closet analogue is 'low montane mixed coniferous forest' (Spicer and Parrish, 1990). Plant fossils from the Late Albian include the first occurrence of angiosperms at high latitudes in Alaska (Spicer and Herman, 2001). Fossil plant records can provide an abundance of information, but samples collected for this study were not of the right type to make identification of plant fossils possible.

CARBON STABLE ISOTOPES ($\delta^{13}C$)

$\delta^{13}C$, an isotopic signature, is a measure of the ratio of the stable isotopes of ^{13}C : ^{12}C (Bocherens et al., 1993). Isotope values in this study are reported using conventional delta notation ($\delta^{13}C$, $\delta^{15}N$) in parts per mil (‰) relative to Vienna Pee-Dee Belemnite (VPDB).

The value of $\delta^{13}C$ varies depending on primary productivity, the rate of carbon burial, and vegetation types (Bocherens et al., 1993). Therefore, some factors that control $\delta^{13}C$ may be local and some may be global. The source of organic matter, selective partial degradation during diagenesis, and environmental conditions (e.g., ρCO_2, salinity, CO_2 recycling, and temperature) can all affect $\delta^{13}C$ values of bulk sedimentary organic matter (Gröcke, 2002).

Carbon isotopes have many uses in helping to understand more about certain rocks than visual observation alone. $\delta^{13}C$ analyses can provide information about past environments and can help differentiate fine-grained facies into marine, marginal marine, or terrestrial environments when grain size and sedimentary structures alone prove inadequate. Sequence stratigraphic features, such as transgressive flooding surfaces can also be identified by $\delta^{13}C$ analysis. Furthermore, $\delta^{13}C$ analysis can help to determine the different types of organic matter contributing to the system (Bocherens et al., 1993; Gröcke, 2002). Several studies have shown that carbon isotope ratios in higher-plant organic matter are closely related to the carbon isotope composition of the ocean-atmosphere carbon reservoir (Gröcke, 2002).

VARIATIONS IN TIME AND SPACE

Due to limited sampling of mudstones at Slope Mountain, correlation to other studies around the global is difficult. Nevertheless, studies from other locations provide a foundation of expected values for this study. Comparison substantiates values from this study and provides comparative information for negative and positive excursions in samples from this study. The carbon stable isotope values from this study also provides information about the environment of deposition and changes in stratigraphy.

Sediments from the Cretaceous have shown a variety of $\delta^{13}C$ signatures from different places around the world. Many of the $\delta^{13}C$ values show similar patterns of positive and negative excursions that can be correlated to global events. Aptian marine sediments from central Hokkaido, northern Japan, showed a positive $\delta^{13}C_{wood}$ excursion from -25.4‰ to -21.8‰ following a remarkably negative anomaly in the Early Aptian, and a small positive anomaly in the latest Aptian (Ando, 2002). These values have been correlated to other sites around the world, including Italy and England (Fig. 6).

Often large changes in isotopic signatures, such large positive and negative excursions are the result of global, not local, events. A study of Isle Wight in Britain found $\delta^{13}C_{wood}$ to vary based on isotopic composition of global CO_2, not local environmental impacts Britain (Gröcke et al., 1999) and found the $\delta^{13}C_{wood}$ from the Isle of Wight to parallel known values of $\delta^{13}C_{carbonate}$ from the Tethyan Sea.

Bulk sedimentary organic matter and charcoal from the Dakota Formation sampled in Roe Creek Pit (RCP), Nebraska had $\delta^{13}C$ values of -24‰ to -23‰ during the Cenomanian (Gröcke et al., 2006).Values for Slope Mountain would likely be similar to this study because they occur around the same time. In general, Slope Mountain values are expected to range between -20‰ to -28‰, which is the expected range for terrestrial plants with C_3 photosynthesis during the Late Cretaceous (Salazar Jaramillo et al., 2016).

Younger Middle Maastrichtian (Late Cretaceous) samples from the Lower Cantwell Formation, Alaska have $\delta^{13}C_{bulk}$ values that range from -22.95‰ to -27.10‰ and $\delta^{13}C_{wood}$ range from -22.42‰ to -27.85‰ (Salazar-Jaramillo et al., 2016). This study showed that the bulk and wood values parallel each other, suggesting the bulk samples can be useful when wood is not easily accessible. Bulk sedimentary samples provide information for observing nuanced changes in stratigraphy and the environment of deposition.

The Late Albian is marked by a roughly negative 3% excursion in the Dakota Formation, while the Albian/Cenomanian Boundary is preceeded by a quick positive excursion (Gröcke et al., 2006). Positive $\delta^{13}C$ excursions of up to +2% mark Albian/Cenomanian Boundary (Jarvis et al., 2006). Samples from Slope Mountain could potential show these excursions. However, samples from this study cannot be definitively correlated without more detailed sampling. Isotope data from English Chalk and Italian Scaglia showed a negative excursion at the Cenomanian/Turonian Boundary, which marks an anoxic extinction event (Jenkyns et al., 1994). Positive excursions are generally attributed to increased organic carbon burial, while negative excursions are often linked to mass extinctions and decreased oxygen (Gröcke et al., 2006).

Modern day C_3 plants have an upper limit of -20‰ with values higher than -23‰ being typical of plants growing under stress, such as water stress or salt stress (Salazar Jaramillo et al., 2016). In Alaska, recent sediments of the north Bering- south Chukchi seas from the Alaskan-Soviet Arctic Shelf have been found to have $\delta^{13}C$ signatures that increase from western river deltas (<-25‰) in the east to sound areas (-23‰ to -22‰) to open shelf in the west (-21‰ to -20‰) (Naidu et al., 1993). While these studies are modern, they suggest that changes seen in $\delta^{13}C$ signatures could be the result of changing depositional environment.

VARIATIONS AMONG PLANTS

Crassulacean acid metabolism (CAM), $C_{3,\ \text{and}}$ C_4 are the three types of modern terrestrial vegetation. CAM plants evolved recently between 20 and 30 Ma (Keely and Rundel, 2003) as an adaption to arid climates. C_4 plants evolved somewhere between the Late Cretaceous to 7 Ma (Gröcke, 2002; Ehleringer et al., 1991; Bocherens et al., 1993). Most geologic evidence suggests they evolved during the Miocene, with some isotopic evidence for sporadic earlier origins (Spicer, 1989; Robinson and Hesselbo, 1998). In any case, neither CAM nor C_4 plants had a significant effect on the environment until 6 to 7 million years ago (Gröcke, 2002; Ehleringer et al., 1991). Since land plants first developed in the Ordovician, plant have been using C_3 carbon fixation. C_3 plants are temperate, cool season plants that reduce CO_2 directly using the Calvin Benson cycle. In contrast, C_4 plants are warm-season plants and use the Hatch-Slack cycle to convert CO to oxaloacetate before they use it (Robinson and Hesselbo, 1998). These different mechanisms result in distinguishable $\delta^{13}C$ values in modern plants; C_3 plants range between -

23‰ and -34 ‰ in C_3 plants with an average of -27‰; -8‰ to -16‰ in C_4 plants with an average of -13‰ (Gröcke, 2002).

$\delta^{13}C$ values can further be used to differentiate between the types of plants contributing to the carbon source. The Mesozoic Era is assumed to be dominated by C_3 plants with an average $\delta^{13}C$ of -27‰, due to the lack of fossil evidence indicating the presence of C_4 plants (Gröcke, 2002). Alaska North Slope during the mid-Cretaceous was composed of C_3 plants, possibly including both angiosperms and conifers (Spicer and Parrish, 1986). Samples from the Miocene, found angiosperm wood has $\delta^{13}C$ of around -24‰ to -30‰, while conifer wood has $\delta^{13}C$ from around -19‰ to -27‰ (Poole and Bergen, 2006). Variation in values can thus correspond to changes in vegetation.

METHODS

FIELD METHODS

Measurements, descriptions, and photos were all taken collectively as part of the Keck Geology North Slope group. Samples were collected in the field over the course of two weeks. Stratigraphic sections were measured and described. Subsequently, samples were collected from each layer where dark mudstones and carbon rich layers were present (Fig. 7). Sandstones were not sampled because they do not contain much organic matter, and thus would not provide good material for $\delta^{13}C$ analysis. Float samples were collected from areas that contained carbon-rich material of unknown stratigraphic position above and between measured sections (Fig. 7). Note that some float samples were collected higher than our zero datum sample and are numbered -1 and -2.

Measured sections were compiled into stratigraphic columns to observe changes in stratigraphy through time. Information from the measured section were then used for facies analysis to determine the depositional environments experienced at Slope Mountain.

CARBON AND NITROGEN STABLE ISOTOPES

Mudstone samples were collected throughout the measured stratigraphic sections. Most samples were taken in the lower portion of the study section, which likely represents the marine Torok Formation; sample selection was dependent on the lithology of the section as only mudstones were being collected because sandstones do not contain much organic matter. Float samples from carbon-rich locations in the marginal marine to non-marine upper Nanushuk Formation were also collected for comparative purposes.

Each sample was prepared for $\delta^{13}C$ and $\delta^{15}N$ analysis using the methods of Pansu and Gautheyroum, 2006. Each sample was bathed in a 10% HCl solution for 24 hours to remove carbonate. Samples were then put through vacuum filtration to remove the solution, rinsed repeatedly, and placed in the oven overnight to dry.

Samples were then sent to Washington State University - Stable Isotope Core Laboratory for analysis. Samples were weighed out in tin capsules and inserted into a Costech Elemental Analyzer (ECS 4010). A Thermofinnigan Delta PlusXP Mass Spectrometer Isotope was then used to perform mass spectrometry (IRMS) to determine both C and N isotope ratios. These isotope ratios are reported using conventional δ-notation in parts per mil (‰) relative to the Vienna PeeDee Belemnite standard (VPDB).

CALCULATIONS

$\delta^{13}C$ value of land plants were used to determine atmospheric $\delta^{13}C$ with the following equation from Arens et al. (2000):

$$\delta^{13}C_{atm} = (\delta^{13}C_{plants} + 18.67) / 1.10$$

Carbon nitrogen ratios can also be calculated from the data by dividing the percent carbon by the percent nitrogen. This provides information about depositional environment and plant types contributing to the system. For example, C_3 plants usually have a C/N ratio above 25, while algae has a lower C/N ratio of less than 10.

MICROFOSSIL IDENTIFICATION

Three procedures were used to detect microfossils, such as pollen, diatoms, and foraminifera. The presence of specific fossils and other material can provide additional information about the paleoenvironment that might corroborate isotopic data. Hand samples were initally examined with hand lens and under the microscope. Heavy liquid separation, freeze-thaw separation, and thin sections were then utilized to look for possible fossils other than plant remains and carbonaceous debris.

HEAVY LIQUIDS SEPARATION

LST heavy liquid was used to separate out organic matter and bone fragments. A piece of fossil bone (hydroxyapatite at about 3.6 g/cm^3) and quartz (2.65 g/cm^3) were used to test the density of the heavy liquid before processing a sample. The proper density was achieved when the apatite sank and the quartz floated. The heavy liquid was added to a separatory funnel (Fig. 8); then the sample was added and stirred vigorously until combined with the heavy liquids. It was then left to allow for the sample to settle. Stirring was repeated in two three-hour intervals or after most of the sample had settled. It was then left to sit for 3 additional hours or until everything was separated. The lower portion of settled sample was then released from the separation funnel and collected on filter paper for repeated rinsing. This was then repeated with the upper portion. The upper portion was then left to air dry overnight. Both portions were was then observed under the microscope for possible microfossils and other material.

FREEZE-THAW

The freeze – thaw technique of Kennedy and Coe (2014) was used to extract microfossils from the samples through rapid heating and cooling of the sample. Each sample was submerged in cold water for 24 hours after which the cold water was decanted off. The sample was put into a plastic container and was then placed in a freezer at -18°C for 3 hours. Subsequently, boiling water was added to the sediment in the container and the mixture was poured into a beaker. Borax detergent was added to the beaker to prevent flocculation of clays, and the samples were left to sit in the boiling water for between 5 to 10 minutes. At this point samples were sieved, using a 500µm and a 63µm sieve. The portion of the sample that fell between 500-63µm was collected to look for microfossils. The sample greater than 500µm was returned to the plastic container and placed back in the freezer to repeat this process. Other samples that appeared less disaggregated were not sieved after the freeze-thaw cycle. The water was decanted off and the samples were returned to the plastic containers and the freezer. This cycle was then repeated between 5-10 times per sample.

THIN SECTIONS

Thin sections of each sample were made to look for microfossils. These were also useful to identify basic sedimentary textures of the samples (grain size, small scale lamination) and other indicators of environment.

RESULTS

FIELD RESULTS

Figure 9 shows the likely environment of deposition. The sediments seen at Slope Mountain are likely the result of a prograding delta. The lowest measured section was likely a distributary channel system or a lowstand fan. However, because the strata underneath cannot be observed, it is difficult to prove either interpretation. This was followed by prodelta deposits, delta front deposits, then an interdistributary bay.

The lower portion of Slope Mountain is composed of primarily mudstones, then alternating mudstone sandstone beds (Fig. 10 and Fig. 11). Trace fossils are visible in these lower beds. The Torok and the lower Nanushuk Formations occupy the lower portion of Slope Mountain, while the upper portion is composed of predominately sandstones from the upper Nanushuk Formation (see Appendix 1 for complete Stratigraphy Column of Slope Mountain, including measured sections not analyzed here).

Facies analysis suggests that samples taken from the first 10 meters of SM2 are from channel and channel fill (Fig. 9, Fig. 10, Fig. 11). This was likely a lowstand fan or distributary channel. The environment then progresses to an offshore, prodelta setting as suggested by samples from upper portion of measured section SM2, which contain mudstones and alternating mudstone and sandstone sections. Samples from measured section SM1 are delta front deposits that follow the prodelta environment observed in the previous section. Samples from SM1.1 indicate an interdistributary, bay/lagoon setting. Float samples taken in the upper portion of Slope Mountain, significantly above previously discussed measured sections, suggest a more terrestrially influenced environment.

Figure 12 shows a combination of the results discussed above. It provides a view of the entirety of Slope Mountain along with corresponding close-up photos of measured sections SM1 and SM2 and their corresponding stratigraphy columns.

$\delta^{13}C$ AND $\delta^{15}N$ ANALYSIS

Sample isotope values in this study are reported using conventional delta notation ($\delta^{13}C$, $\delta^{15}N$) in parts per mil (‰) relative to Vienna Pee-Dee Belemnite (VPDB). Samples processed at Washington State University - Stable Isotope Core Laboratory have 2-sigma uncertainty of carbon isotopic results of 0.5 per mil.

The $\delta^{13}C$ values $\delta^{15}N$ values and C/N ratios are included in Table 1. The $\delta^{13}C$ values range between - 22.5‰ and -26.1‰, with an average of -24.7‰ which falls within expected values for terrestrial organic carbon from Cretaceous C_3 plants. Figure 12 shows the relationship between $\delta^{13}C$ values and stratigraphy for the first 25m of measured section SM2. The C/N ratios range from 2.3 to 45.6 (Fig. 13). Lower C/N ratios, less than 10, are indicative of marine environments, while much higher C/N ratios, above 25, suggest terrestrial plants. Values that fall between the two suggest a marine environment with terrestrial material inflow.

Stratigraphic Position	δ^{13}C% (VPDB)	C/N	δ^{13}Catm
Float -2	-24.9	45.6	-5.7
Float -1	-22.5	11.3	-3.5
Float 0	-25.0	18.3	-5.7
Float 1	-25.0	32.3	-5.8
Float 2	-26.1	32.5	-6.8
SM1.1-6	-22.6	11.3	-3.6
SM1.1-4	-24.6	10.8	-5.4
SM1-24	-25.2	3.2	-6.0
SM2-51	-23.9	2.3	-4.7
SM1-14	-25.5	3.0	-6.2
SM2-42	-24.7	12.1	-5.4
SM1-4	-25.1	17.0	-5.8
SM2-32	-24.7	10.0	-5.5
SM2-22	-25.1	11.1	-5.8
SM2-18	-24.9	10.6	-5.7
SM2-16	-24.8	11.8	-5.5
SM2-14	-24.6	10.3	-5.4
SM2-12	-24.8	10.2	-5.6
SM2-10	-24.9	11.9	-5.6
SM2-9.2	-25.0	17.5	-5.8
SM2-8	-24.8	10.0	-5.5
SM2-6	-24.9	15.0	-5.7
SM2-5.8	-25.6	41.6	-6.3
SM2-4	-24.3	10.4	-5.1

Table 1 – The δ^{13}C values, C/N ratios, and $\delta^{13}C_{atm}$ for samples from Slope Mountain. Samples are presented in relative stratigraphic position. Measured sections SM2, SM1, and SM1.1 could not be coordinated. However, SM2 is known to be the lowest, followed by SM1, then SM1.1. The colors in the C/N column indicate the likely carbon source; green indicates C3 plants, purple indicates algae, while blue indicates a mixed source.

Sample SM2-5.8 has a more negative value of -25.6 than its surrounding samples. This is coupled with a substantially higher C/N ratio of 41.6. This sample is a baseline for expected values for terrestrial C_3 plant values because this layer consists of mostly preserved plant remains. Figure 13 shows the relationship between δ^{13}C values and C/N ratios and the corresponding source material.

Samples SM1-14, SM2-51, and SM1-24 have lower C/N ratios than the surrounding samples of 3.1, 2.4, and 3.2, respectively (Table 1). SM1-14 and SM1-24 also have slightly more positive than average δ^{13}C values, while SM2-51 have a slightly more negative value. SM2-51 is also a friable, tan-colored layer and not a mudstone.

Samples SM1.1-6 and Float – 1 both have low δ^{13}C values of -22.6‰ and -22.5‰ respectively, and are followed by Float 2 and Float -2 with values of -26.1‰ and -24.1‰ respectively. These positive excursions could be related to changes in the local or global environment, such as global oceanic anoxic events.

Float 1 and Float 2 have high $\delta^{13}C$ values of -25.04 and -26.1 and high C/N ratios of 32.3 and 32.50 respectively. Float -2 also has a high C/N ratio of 45.6. These higher C/N ratios are indicative of C_3 terrestrial plants. These samples fall within the C_3 terrestrial plants half oval shown in Figure 13.

Figure 14 graphically depicts the relationship between calculated $\delta^{13}C_{atm}$ values and $\delta^{13}C$ values. Unlike Figure 13, the graph in Figure 14 does not include $\delta^{15}N$ values. The points on the two graphs do not correlate and the two figures are showing different relationships. One based on $\delta^{13}C$ values and $\delta^{15}N$ values and one based solely on $\delta^{13}C$. Samples SM1.1-6 and Float -1, which both have more positive $\delta^{13}C$ values, are the two dots above the C_3 grassland/shrub seen in Figure 14. These two samples both have lower $\delta^{13}C$ values, but each sample has different $\delta^{15}N$ values.

MICROFOSSIL ANALYSIS

Few recognizable microfossils were found in the samples. Heavy liquid separation and freeze-thaw techniques revealed only small pieces of charcoal and no bone fragments or microfossils. Thin sections appear typical for mudstones with angular grains of siliciclastics. Siliciclastic material is observed in all samples. The float samples are dense mudstones that contain large amounts of carbonaceous material. Opaque carbon-rich layers are also visible in most samples (e.g., samples SM2-9.2 and SM1-24; Fig. 15). These areas range in size from small areas in some of the SM2 samples to the majority of the sample for some of the float samples. However, no obvious microfossils or bone fragments were found.

DISCUSSION

Previous studies of the Middle to Late Cretaceous Arctic have indicated that the environment was very different from today. Evidence suggests that the mid-Cretaceous had a reduced gradient between the equator and the polar regions (Barron and Washington, 1982; Spicer and Corfield, 1992; Ufnar et al., 2004). It is also suggested that the mid-Cretaceous had decreased annual temperature variations, diminished seasonal temperature extremes, and limited below freezing temperatures in the arctic (Sloan and Barron, 1990; Ufnar et al., 2004).

Assuming a paleolatitude between 71 °N and 89 °N (Fig. 2), the Northern Alaska winter likely had almost 5 months of continuous darkness bounded by months of continuous twilight during the Late Cretaceous (Spicer and Herman, 2010). Based on wood anatomy, leaf margin analysis, and vegetation composition, the Cenomanian North Alaska had an air temperature of approximately 10°C (about the same as northern Ohio) with a mean annual range of over 20°C, but no lower than -11 °C (Spicer and Parrish, 1986; Parrish et al., 1987; Spicer and Parrish, 1990; Spicer and Herman, 2010). At 60°N, mean annual temperatures in Aptian to Albian time was around 16°C (Huber et al., 1995; 2002), while the Late Albian had a temperature between 10°C and 13°C (Fassell and Bralower, 1999; Ufnar et al., 2004). Both of these temperatures, are significantly higher than the mean annual temperature today (-10°C).

Large amounts of coal accumulation seen in Aptian-Cenomanian sediments indicates that precipitation was high (Spicer and Herman, 2010). Precipitation estimation models for North Slope, Alaska, during the Albian indicate between 485–626 mm/yr, which is consistent with precipitation in modern peat-forming environments (Ufnar et al. 2004).

CARBON STABLE ISOTOPES

Bulk samples were used for the carbon stable isotopes in this study. Wood would be ideal; however, it was not present throughout the study location in a form that was useful for analysis. For stratigraphic purposes, carbon isotope values from bulk organic matter in dark mudstones can still provide valuable information about variations in paleoenvironment throughout the stratigraphic section.

The $\delta^{13}C_{bulk}$ values range from -22.5‰ to -26.1‰ (Table 1) with an average of -24.7‰, which is expected for Late Cretaceous C_3 terrestrial plants, which usually range in $\delta^{13}C$ values from -20‰ to -28‰ (Salazar Jaramillo et al., 2016). The values in this study fall within the expected range, but are slightly lower than other studies from around the same time period. The $\delta^{13}C$ values also show some variation throughout the section suggesting changes in environment, both globally and locally. Differences in atmospheric CO_2 over time could affect the $\delta^{13}C$ values. Figure 14 uses the relationship between atmospheric carbon and plant carbon sources to determine environmental conditions. The carbon stable isotope value for the atmosphere ($\delta^{13}C_{atm)}$ can be derived using an empirical relationship based on a regression of $\delta^{13}C_{plants}$ and $\delta^{13}C_{atm}$ values (Arens et al., 2000). The $\delta^{13}C_{atm}$ values can be plotted against the $\delta^{13}C$ values to visually show this relationship (Fig. 14).

Temperature and plant type could also have an effect on values. For example, the expected value of a C_3 plant is different than that of algae; this is a result of the different mechanisms within the plants that process CO_2. Similarly, $\delta^{13}C$ values for leaves can be used to differentiate between forest type, such as deciduous, evergreen, etc (Diefendorf et al., 2010). Modern leaves from cool cold deciduous forests had $\delta^{13}C$ values of -21.1‰. A study of Miocene plant fossils found gymnosperm species to be slightly less depleted when compared to angiosperms (Van Bergen and Poole, 2002). Values from this study are most similar to values for C_3 plants. Many of the plant fragments observed in the field were horsetails (equisetum), which are spore-bearing plants, with a modern $\delta^{13}C$ values range from -25.0‰ to -28.8‰ (Milligan et al., 2010). Green algae has $\delta^{13}C$ values between -20.3‰ to -8.8‰. The values observed in this study fall between these two plant types suggesting a mix of both marine and terrestrial plant sources contributing to the system. A marine setting that is receiving terrestrial plant material could explain this mixed signal.

A phenomenon of general enrichment over time is also observed with samples and suggests earlier fossils would have less negative $\delta^{13}C$ values when preserved in sandstone. However, when preserved in mudstone, the opposite effect is observed and values tend to be more negative with time and, plant values tend to be more similar to modern equivalents (Gröcke, 1998). This suggests that samples seen at Slope Mountain will be similar to modern $\delta^{13}C$ values or slightly more negative. This would suggest that many samples included a mix of algae and C_3 plant material.

COMPARISON TO OTHER STUDIES

Age	**Location**	**$\delta^{13}C$% (VPDB)**	**Source**
Middle Maastrichtian	Lower Cantwell Formation, Alaska	Wood: -22.42‰ to -27.85‰ Bulk: -22.95‰ to -27.10‰	(Salazar-Jaramillo et al., 2016)
Cenomanian	Dakota Formation, Nebraska	Bulk: -24‰ and -23‰	(Gröcke et al 2006)
Albian-Cenomanian	North Slope, Alaska	Bulk: -22.5‰ to -26.1‰	This study
Late Albian	Western Atlantic	Range of sources: range of values (~ -27‰ to ~ -9‰)	(Wilson and Norris, 2001)
Aptian	Isle of Wight, England	Wood: range of values (~ -29‰ to ~ -19‰)	(Gröcke et al 1999).
Aptian	Hokkaido, northern Japan	Wood: -25.4‰ to -21.8‰	(Ando et al., 2002)

Table 2: This table shows different $\delta^{13}C$ values for different locations and ages that are comparable to Slope Mountain.

Studies from other locations provide a foundation of expected values for this study and increases the legitimacy of values from this study. Comparison also helps provide information for negative and positive excursions overserved in samples from this study. Correlation to other studies around the global is difficult because of the limited amount of mudstones at Slope Mountain.

Many of the $\delta^{13}C$ signatures from the Cretaceous have different values, but show similar patterns of positive and negative excursions that can be correlated to global events. The Aptian (mid-Cretaceous) marine sediments from central Hokkaido, northern Japan have a $\delta^{13}C_{wood}$ range from -25.4‰ to -21.8‰, which is slightly more positive than North Slope; this could be caused by differences in latitude, temperature, or plant type. $\delta^{13}C_{wood}$ values also tend to be more positive than $\delta^{13}C_{bulk}$, as shown in recent studies (Salazar et al., 2016). Thus, it would be expected for Slope Mountain values to be slightly more negative than other similar studies of wood. Salazar et al. (2016) measured $\delta^{13}C$ for both bulk and wood samples and found these values have a similar range, suggesting that bulk samples can be a good substitute when wood and other plant material is unavailable.

During the Cenomanian, $\delta^{13}C_{bulk}$ values from the Dakota Formation in Rose Creek Pit, Nebraska range between -24‰ and -23‰ (Gröcke et al., 2006). Younger Middle Maastrichtian (Late Cretaceous) samples from the Lower Cantwell Formation, Alaska had $\delta^{13}C_{bulk}$ range from -22.95‰ to -27.10‰ and $\delta^{13}C_{wood}$ range from -22.42‰ to -27.85‰ (Salazar-Jaramillo et al., 2016). These bulk values are very similar to the North Slope values and have significant overlap. The $\delta^{13}C_{bulk}$ values from the Dakota Formation (Nebraska) are from a similar time to the North Slope samples, and the Lower Cantwell Formation $\delta^{13}C_{bulk}$ values are from a similar geographical location (also Alaska).

An Aptian (Early Cretaceous) study of Isle Wight in Britain found $\delta^{13}C_{wood}$ to vary based on isotopic composition of global CO_2, not local environmental impacts Britain (Gröcke et al., 1999). $\delta^{13}C_{wood}$ from the Isle of Wight paralleled known values of $\delta^{13}C_{carbonate}$ from the Tethyan Sea. This suggests that changes in values from this study could similarly be due to differences in climate rather than local effects.

The curve of $\delta^{13}C_{wood}$ from the Aptian Hokkaido, Japan samples paralleled the known $\delta^{13}C_{carbonate}$ curve from a Pacific guyot (Fig. 6; Ando et al., 2002), suggesting that the change in variation throughout their stratigraphic section was caused by global events and not local factors. This study also included a figure linking studies of $\delta^{13}C_{carbonate}$ from Piobbico and Cismon, Italy, Roter Sattel, Switzerland, and the Isle of Wight, England. All studies had similar negative excursions for the Aptian.

The Albian-Cenomanian boundary is marked by a roughly negative 3% excursion in the Late Albian, which is seen in the Dakota Formation in Nebraska. Samples from Slope Mountain likely cross this Albian to Cenomanian boundary, and a few negative excursions are observed between samples with the largest occurring between samples SM1.1-6 and Float 2, another significant negative excursion occurs between Float -1 and Float -2. These excursions could be indicative of the transition between Albian-Cenomanian. However, a more thorough sampling at these levels would be needed to conclusively determine this possibility.

Modern studies indicate that $\delta^{13}C_{atm}$ values can depend on depositional setting and diagenesis. Nearshore environments tend to have more negative values than offshore (Dickens et al., 2004). Recent sediment from the Alaskan-Siberian arctic was found to have more positive $\delta^{13}C$ values in sediments from estuarine environments, while C/N ratio was lower towards estuarine environments (Naidu et al., 1993). Near river deltas had a value of ~ -25‰, sounds ranged from ~ -23‰ to -22‰, and open shelf was ~ -21‰. This suggests that a prograding delta would result in values moving from more to less positive.

PALEOENVIRONMENT AND DEPOSITIONAL ENVIRONMENT CHANGES THROUGH STRATIGRAPHY

The facies model suggests that the environment transitioned from lowstand fan or distributary channel to prodelta to delta front to interdistributary bay (Figure 8). Figure 12 provides a view of the entirety of Slope Mountain along with corresponding close-up photos of measured sections SM1 and SM2 and their corresponding stratigraphy columns.

Lowstand Fan / Distributary Channel (SM2: 0-10m)

The first 10m of measured section SM2 are likely a lowstand fan or distributary channel based on facies analysis siltstone (Fig. 9, Fig. 10, Fig. 11). Sample SM2-4 is weakly bedded dark grey. The first 5 meters of SM2 was likely formed form suspension settling that was interrupted by bed load deposition under low flow regime currents in a moderately well oxygenated setting, allowing for bioturbation.

Samples SM2-5.8, SM2-6, SM2-8, SM2-9.2, and SM2-10 were soft clay-rich mudstones that occurred between sandstone layers. The sandstones were likely caused by bedload deposition in a low energy subaqueous setting, while the mudstones were the result of suspension settling.

Sample SM2-5.8 is a carbonaceous mudstone with large fragmented and intact plant fossils (Figure 7). 5.8m up section SM2 was dense layer of carbonaceous material and large plant fragments. Due to the unique nature of the SM2-5.8 layer, it has a more negative $\delta^{13}C$ value and a larger C/N ratio than other samples, which indicates the presence of terrestrial C_3 plants (Figure 13). This sample is a baseline for expected values for terrestrial C_3 plant values because this layer consisted of mostly preserved plant remains. Most of the plant fragments observed in the field were horsetails (equisetum). The more negative $\delta^{13}C$ value at this stratigraphic position is likely caused by the increase in preserved terrestrial matter in this sample.

Samples, SM2-6, SM2-8, SM2-9.2, and SM2-10 all have similar $\delta^{13}C$ value and C/N ratios with SM2-6 and SM2-9.2 having only slightly more positive C/N ratios, suggesting they had more

$\delta^{13}C$ input from C_3 plant source compared to the other samples (Table 1). These slight variations are due to changes in the amount of nitrogen compared to carbon and are likely caused by minor shifts in carbon source. The slightly more positive C/N ratios occur when there is an increase in C_3 plant material, suggesting the depositional environment moved closer to shore, allowing for the preservation of more terrestrial organic matter. This four meter sequence could be the result of progradation over the previous 5.8m of SM2.

The carbonaceous mudstones collected throughout SM2 represent low-energy settings with high inorganic input relative to the amount of organic material accumulated. Because of visible plant material preserved throughout the first 5.8 meters, and especially at the 5.8m boundary, there was likely a larger amount of mud compared to plant matter entering this system. Burial rather than decay, would explain the presence of still visible plant remains. Rapid burial can also explain the lack of microfossils in these samples. Large amounts of fragmentation of the plant remains suggest they were transported over a large distance, with the exception of 5.8m, where whole plant fossils were observed. These whole fossils suggest deposition closer to the source, such as a floodplain

Prodelta (SM2: 10m +)

The samples from measured section SM2 between 12m and 51m range from silty shale to siltstone (Fig. 9; Fig. 10). Facies analysis suggests that the silty shale likely resulted from settling from suspension in an oxygen limited setting below fair-weather wave base, interrupted by intervals of bed load deposition. This likely occurred in an offshore, prodelta setting. The facies model provides little to separate among these samples. However, $\delta^{13}C$ values and C/N ratios suggest more nuanced variation.

Samples SM2-12, SM2-14, SM2-16, SM2-18, SM2-22, SM2-32, and SM2-42 all have similar $\delta^{13}C$ values and C/N ratios (Table 1), which are also similar to SM2-8 and SM2-10. The $\delta^{13}C$ values are all around -24.8‰ and C/N ratios around 10.5. The comparison of the $\delta^{13}C$ values with the C/N ratios (Fig. 13) indicates that most of the bulk organic matter in the samples are a combination of algae and C_3 plant material from land. These results are expected for an offshore prodelta environment. They indicate a predominance of marine carbon and less terrestrial carbon.

Sample SM2-51 has a very low C/N ratio around 2.8 and a more positive $\delta^{13}C$ value (Table 1), which is indicative of marine algae. These values indicate a significant change in carbon source, and indicate a lack of C_3 plant material and more marine algae. This tan friable sample is different from the other mudstone. The different $\delta^{13}C$ values and C/N ratios could be a false signal due to post-depositional processes or evidence of a temporarily more marine setting.

Delta Front (SM1)

Measured section SM1 is above SM2. There may be a small stratigraphic gap or even a small overlap. In the following section, note that these measurements are from the bottom of SM1, which might overlap with the top of SM2, but the relationship cannot be discerned.

The samples from measured section SM1 range from silty shale to siltstone (Fig. 10; Fig. 11). Similar to the above prodelta environment, facies analysis suggests that the silty shale likely resulted from settling from suspension in an oxygen limited setting below fair-weather wave base, interrupted by intervals of bed load deposition. This likely occurred in a delta front setting.

$\delta^{13}C$ values and C/N ratios provide more nuanced information about changes in stratigraphy that the facies model cannot provide.

Sample SM1-4 has a slightly higher C/N ratio, similar to SM2-6 and SM2-9.2 (Table 1). This higher ratio suggests a larger amount of C_3 plant material contributing to the system. The larger amount of C_3 plant material could be caused by the natural progradation and retogradation. Progradation can occur during periods of sea-level fall and when there is extremely high sediment input, while retrogradation is caused by periods of sea level rise caused by global warming and very low sediment input. The larger amount of C_3 plant material was likely preserved during a time of rapid progradation because the extra sediment allowed for it to be preserved.

SM1-14 and SM1-24 have very low C/N ratios, around 2.83 (Table 1) and are on the border of both marine and lacustrine algae shown in Figure 13. These values indicate a significant change in carbon source, and indicate a lack of C_3 plant material and more marine and lacustrine algae, suggesting an environment further offshore away from terrestrial carbon. This could have occurred during a period when less sediment was entering the system. Between SM1-14 and SM1-24 there are some intervening sandstones that show cross-stratification (Fig. 10).

Interdistributary bay (SM1.1)

Measured section SM1.1 is above SM, with a small stratigraphic gap between the two sections. The exact relationship between SM1 and SM1.1 cannot be discerned.

Samples from SM1.1 were fissile mudstone which weathered into cm-scale platy fragments, with some occasional carbonaceous fragments on bedding surfaces (Fig. 10). Facies analysis indicates this formed in a suspension settling in an oxygen-limited setting that was likely an interdistributary, bay/lagoon setting.

SM1.1-4 has similar $\delta^{13}C$ values and C/N ratios as the majority of other samples with a $\delta^{13}C$ value of 24.56‰ and a C/N ratio of around 10.83, which are similar to the average of the SM2 samples, indicating that these samples likely had similar carbon source material (Table 1).

SM1.1-6 has a more positive $\delta^{13}C$ values than the other samples, but a similar C/N ratio (Table 1). This positive excursion in the $\delta^{13}C$ values could be the result of global changes. The C/N ratio could have remained similar to others seen throughout the stratigraphy because the contributors to the system were not being altered. However, a larger scale change, such as an ocean anoxic event or mass extinction, resulted in the more positive $\delta^{13}C$ values.

Terrestrial (Float Samples)

A large jump in stratigraphy occurs between samples from measured sections (SM2, SM1, and SM1.1) and samples collected from loose float higher up on Slope Mountain. The true stratigraphic position of the float samples was undetermined. However, their general stratigraphic placement is with Float 2 lowest and Float -2 highest.

Float 2 has a more negative $\delta^{13}C$ value of -26.1‰ and a high C/N ratio of 32.50 (Table 1). This is most similar to SM2-5.8, suggesting that this float sample was composed of primarily C_3 plant material. Float 1 also have a similar, but slightly more positive, $\delta^{13}C$ value and C/N ratio to SM2-5.8. This suggests these samples contain mostly terrestrial C_3 plant material.

Float 0 has a similar $\delta^{13}C$ value to Float -1, and these samples were taken near each other (Fig. 1, Table 1). However, it has a much lower C/N ratio, suggesting it had carbon from both a marine and a terrestrial source.

Float -2 has a similar $\delta^{13}C$ value and C/N ratio to Float 2, Float 1, and SM2-5.8, indicating that most of its plant material is from C_3 plants. These higher C/N ratios observed in float samples suggest that C_3 terrestrial plants were influencing the highest part of the study section where the float was likely sourced.

The upper portion of Slope Mountain is composed of the upper Nanushuk Formation which is mostly sandstone that experienced gradual transgressive back stepping in its uppermost portions (Decker 2007). The dark mudstone samples of Float 2, Float 1, Float 0, and Float -2 indicate periods of slow moving water very nearshore.

COMPARISON OF SLOPE MOUNTAIN VALUES

The different $\delta^{13}C$ value and C/N ratio in sample SM1.1-6 is also seen in Float -1. SM1.1-6 has a $\delta^{13}C$ value of -22.6‰ and a C/N ratio of 11.29, while Float -1 has a $\delta^{13}C$ value of -22.5‰ and a C/N ratio of 11.3. These values are very similar, despite occurring very far apart in the stratigraphy. Both samples have a more dark grey brown color than the other samples. The more positive $\delta^{13}C$ value could be the result of changes in the environment that changed the preservation of these samples, resulting in more positive $\delta^{13}C$ value. The lower $\delta^{13}C$ values suggest a possibly drier, warmer environment than the other samples. These are the two samples above C_3 grassland on Figure 14.

SM1.1-4 had a $\delta^{13}C$ value of -24.6‰, which was followed by SM1.1-6 with the more positive $\delta^{13}C$ value of -22.6‰. Float 0 had a $\delta^{13}C$ value of -25.0‰, which was followed by Float -1 with the $\delta^{13}C$ value of -22.5‰. These positive excursions could have been related to changes in the local or global environment. A positive excursion can indicate the rapid burial of large amounts of carbon, which is rich in ^{12}C on a global scale. The burial of ^{12}C results in the increased concentration of ^{13}C. The Albian-Cenomanian boundary is proceeded and marked by a positive excursion (Gröcke et al., 2006; Jarvis et al., 2006). To determine the true cause of these excursions more thorough sampling would need to be done due to the large stratigraphic gap between each sample.

Both SM1.1-6 and Float – 1 had more positive $\delta^{13}C$ values, followed by more negative $\delta^{13}C$ values. The negative excursion could be related to the increased amount of terrestrial plant material in the sample, which is indicated by higher C/N ratios in these samples. It could also be indicative of the Late Albian, similar to the negative excursion observed in the Dakota Formation (Gröcke et al., 2006). Negative excursions often mark mass extinctions and can be caused by ocean anoxic events and decrease in primary productivity. However, these samples could not indicate the Late Albian if the previous samples indicate the Albian-Cenomanian boundary. More thorough sampling is needed to find their true correlation to world-wide events during the Albian and Cenomanian.

OCEAN ANOXIC EVENTS

Ocean anoxic events refer to when the oceans become depleted in oxygen (O_2) and usually correspond with mass extinctions. These events have not occurred in recent years. They are often associated with greenhouse Earth because they are believed to be linked to the slowing of ocean circulation and climatic warming.

During the Cretaceous, two major ocean anoxic events (OAEs) occurred; one ~120Ma during the Early Aptian (known as the Selli Event or OAE 1a) and another at the Cenomanian – Turonian boundary ~93Ma (known as the Bonarelli Event or OAE 2). Samples from Slope Mountain were deposited between these two larger events. The Middle Cretaceous (120 to 80 Ma) had a series of smaller known OAEs. (Wilson and Norris, 2001).

Potentially, these smaller events could result in smaller scale negative excursions in carbon isotope data because negative excursions have been linked to large scale ocean anoxic events and mass extinctions. However, the breadth of these impacts is currently unknown and more research into their significance is needed. The lack of microfossils in these samples would support the idea of an ocean anoxic event (OAE). Without oxygen, microfossils could not flourish in this environment. These ocean anoxic events would also be conducive to the formation of black shale. However, the mechanism for their formation is still debated between 'high productivity' models and 'ocean stagnation' models (Wilson and Norris, 2001).

FURTHER CONSIDERATIONS

When considering $\delta^{13}C$ values of plant material, diagenesis needs to be considered because it can affect the preservation of plant material. Diagenesis refers to change caused by physical, biological or chemical factors in sediments during lithification. During early diagenesis of lignified plant tissues, isotopic changes can occur, which result in fossil wood having slightly more depleted $\delta^{13}C$ compared to modern plants, resulting in more negative $\delta^{13}C$ values (Benner et al., 1987). However, in Miocene to Holocene sediments, diagenesis has been shown to not cause a significant shift in $\delta^{13}C$ (Dean et al., 1986) and indicates that it is unlikely to affect values of sediments from the Cretaceous.

The comparison of the $\delta^{13}C$ values with the $\delta^{13}C_{atm}$ values (Fig. 14) shows that the environment was most likely somewhere between a cool mixed hardwood and conifer forest and a modern C_3 grassland and shrub environment. C_3 grassland environments did not exist until the Cenozoic, but these values are indicative of a warmer Cretaceous environment. Many of the plant fragments observed in the field were horsetails (equisetum), spore-bearing plants, which can range from temperate, evergreen to tropical climates (Milligan et al., 2010).

The $\delta^{13}C$ values, $\delta^{13}C_{atm}$ values, the C/N ratios imply that Arctic Alaska was warm and wet, during the Albian to Cenomanian. The comparison of the $\delta^{13}C$ values with the C/N ratios indicates changes in carbon source contribution throughout the stratigraphy and implies a changing environment. The majority of samples indicate a mix of terrestrial C_3 plants and algae, suggesting a marine environment with terrestrial material entering the system (Figure 13). Carbon stable isotopes provide information about subtle changes in carbon sources throughout the stratigraphy. Some of these changes were possibly caused by local environmental factors, while others were the result of broader global events.

This data supports previous research and adds new details to the developing image of greenhouse Arctic conditions. $\delta^{13}C$ values provide nuanced information about variation in the stratigraphy that is not clear when only examining the facies. These results demonstrate the utility of stable isotope analysis of bulk organic matter in mudstones, and show that an increase in sampling resolution would provide dramatic insight into the evolution of local depositional patterns and global environmental conditions throughout the Albian-Cenomanian.

CONCLUSIONS

This study provides detailed information about the sequence stratigraphy based on $\delta^{13}C$ and $\delta^{15}N$ values. $\delta^{13}C$ values, $\delta^{13}C_{atm}$ values, and C/N ratios provide information about carbon source material and the likely depositional and paleoenvironment.

FUTURE RESEARCH

A more global image of the Albian-Cenomanian Arctic could be obtained with more thorough sampling. The Nanushuk and Torok Formations are present throughout northern Alaska. To gather a more complete picture, samples of mudstones would need to be taken at other locations. Slope Mountain had considerably less fossils and less mudstones than other locations were Nanushuk and Torok were previously studied. Thus, carbon stable isotope analysis of other areas with Torok and Nanushuk Formations can provide a more detailed dataset for changes in the formations geographically and potentially correspond to other carbon isotope datasets globally.

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FIGURES

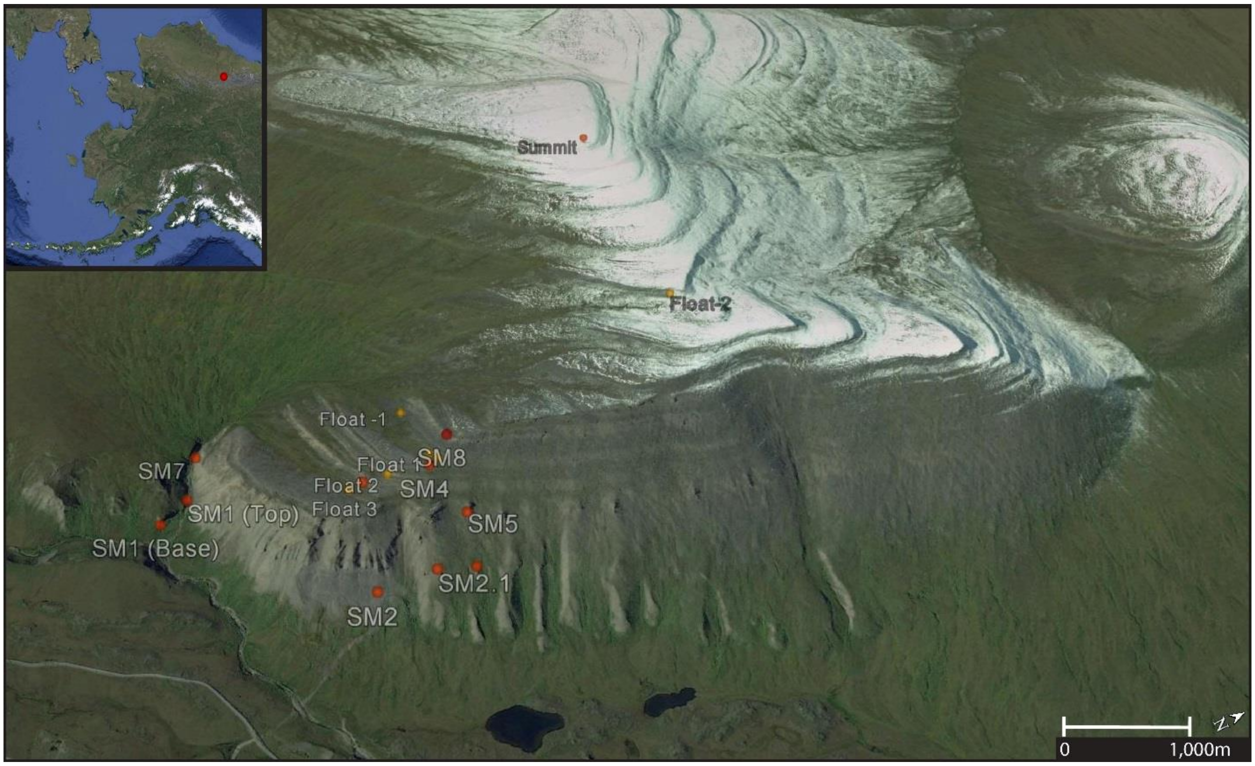


Figure 1 – A North-west view of Slope Mountain with the location of the specific sites measured in the field. The inset shows the location of Slope Mountain in Alaska (Source: Google Earth).

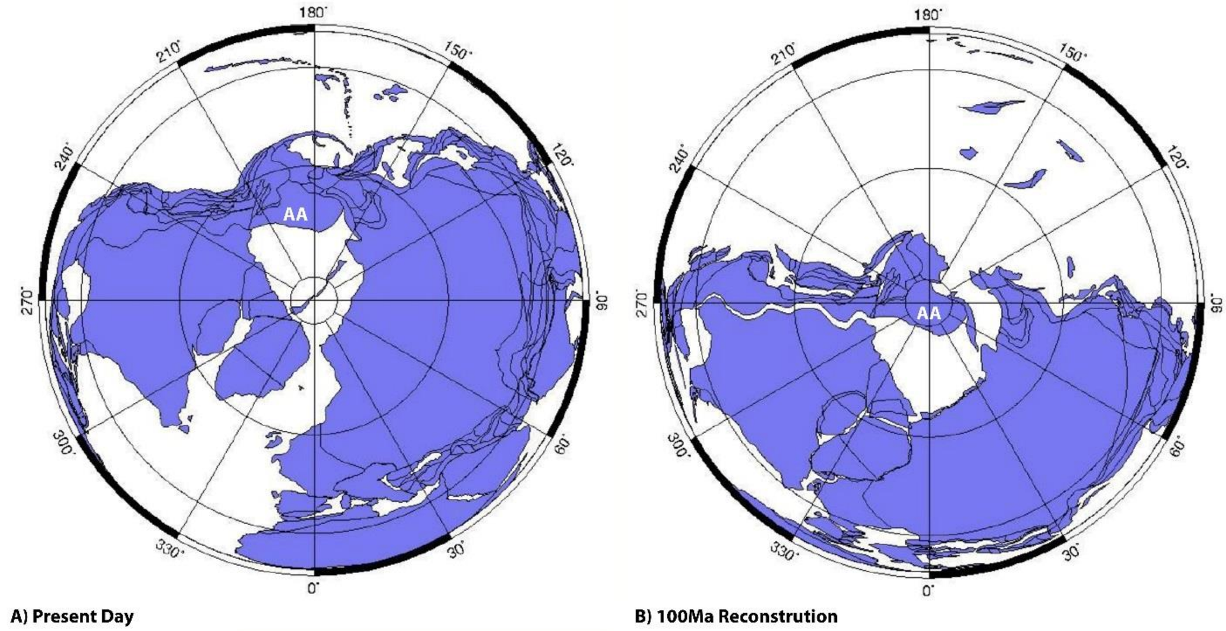


Figure 2 – Plate projections with polar view of the Northern Hemisphere A) Present-day and B) 100 Ma. Longitude is shown around the equator. AA indicates the Arctic Alaska terrane. Reconstruction made using Ocean Drilling Stratigraphic Network (ODSN) website (http://www.odsn.de/).

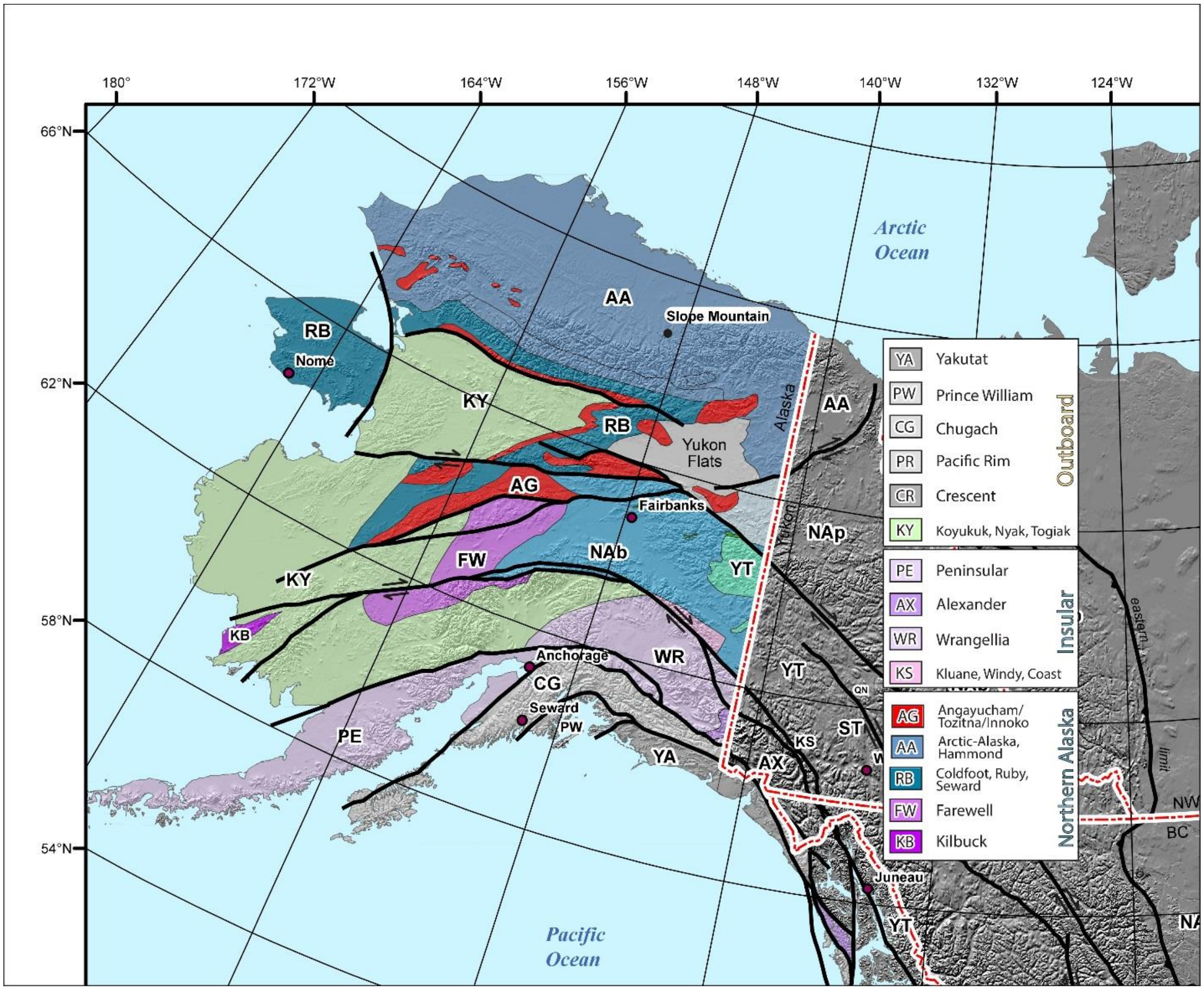


Figure 3 – Map of the bedrock terranes of Alaska, modified from Yukon Government website (http://www.geology.gov.yk.ca/bedrock_terrane.html). The Arctic Alaska terrane (AA), and Slope Mountain are indicated.

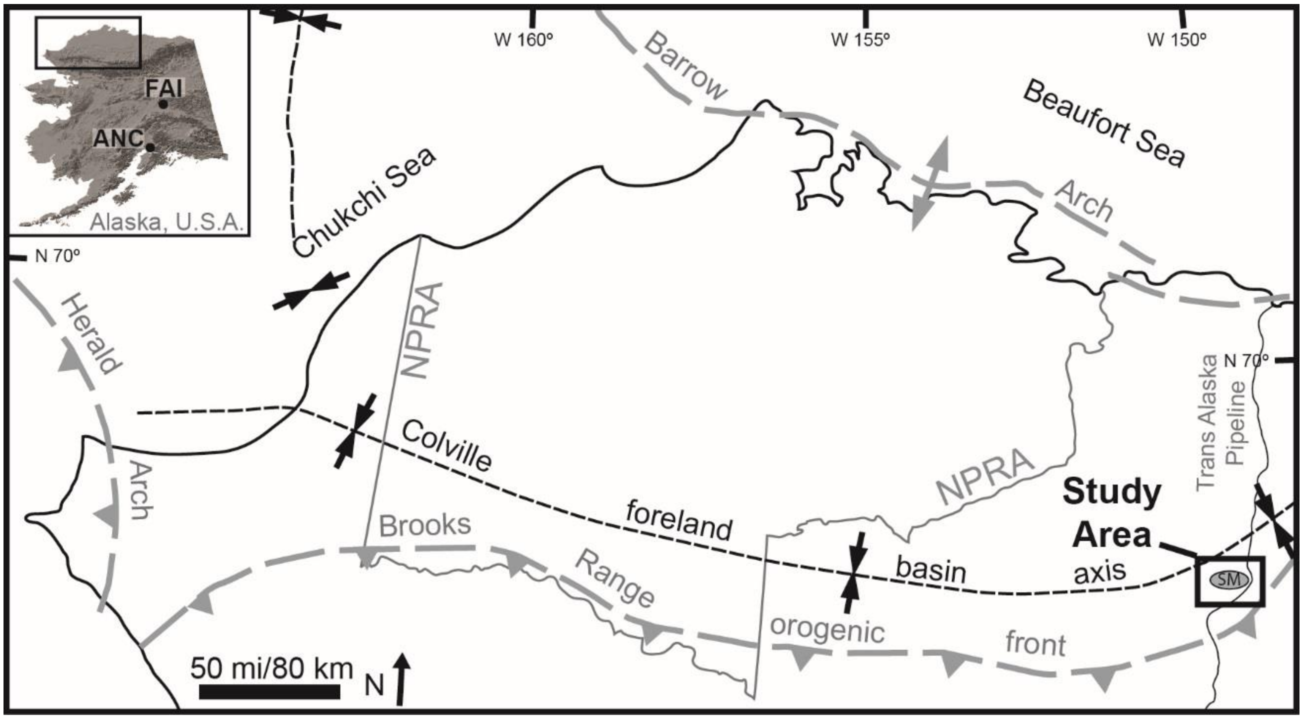


Figure 4 – Map of north Alaska with structural features (from Grant Shimer), including Colville Basin, Brooks Range, Herald Arch, Barrow Arch, and passive margin. Slope Mountain (circle) is situated at the border between the Arctic National Wildlife Refuge (ANWR) and the National Petroleum Reserve – Alaska (NPRA) with the Trans Alaska Pipeline to the east.; just north of the Brooks Range.

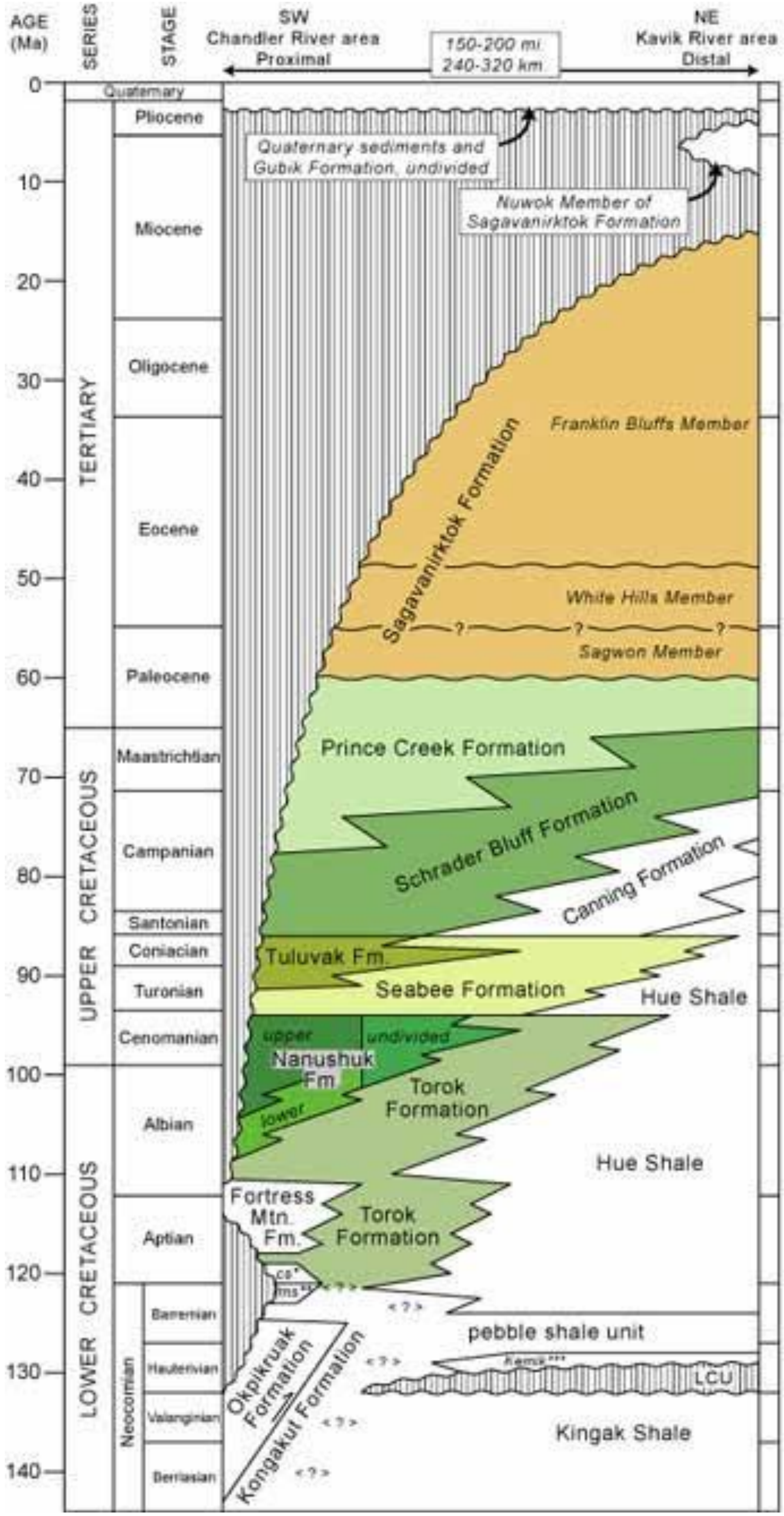


Figure 5 – Stratigraphy Column of Colville Basin sediments taken from Mull et al., 2003. Formations are shown with ages and coeval units. Slope Mountain contains sediments from the Aptian to Cenomanian Torok and Nanushuk Formations.

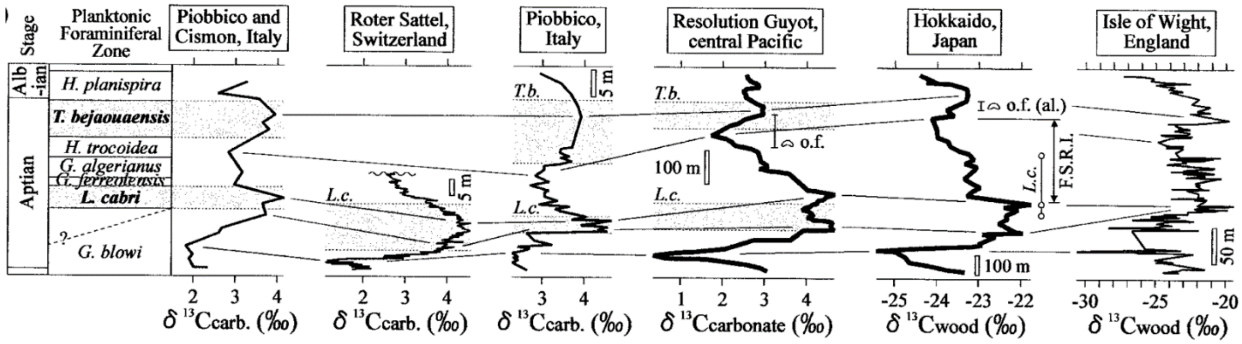


Figure 6 – Correlations of Aptian δ^{13}C profiles from Ando et al. (2002). Positive excursions from the Aptian are linked in studies from Italy, Switzerland, the Pacific Guyot, Japan, and England. δ^{13}C values include carbonate and wood.

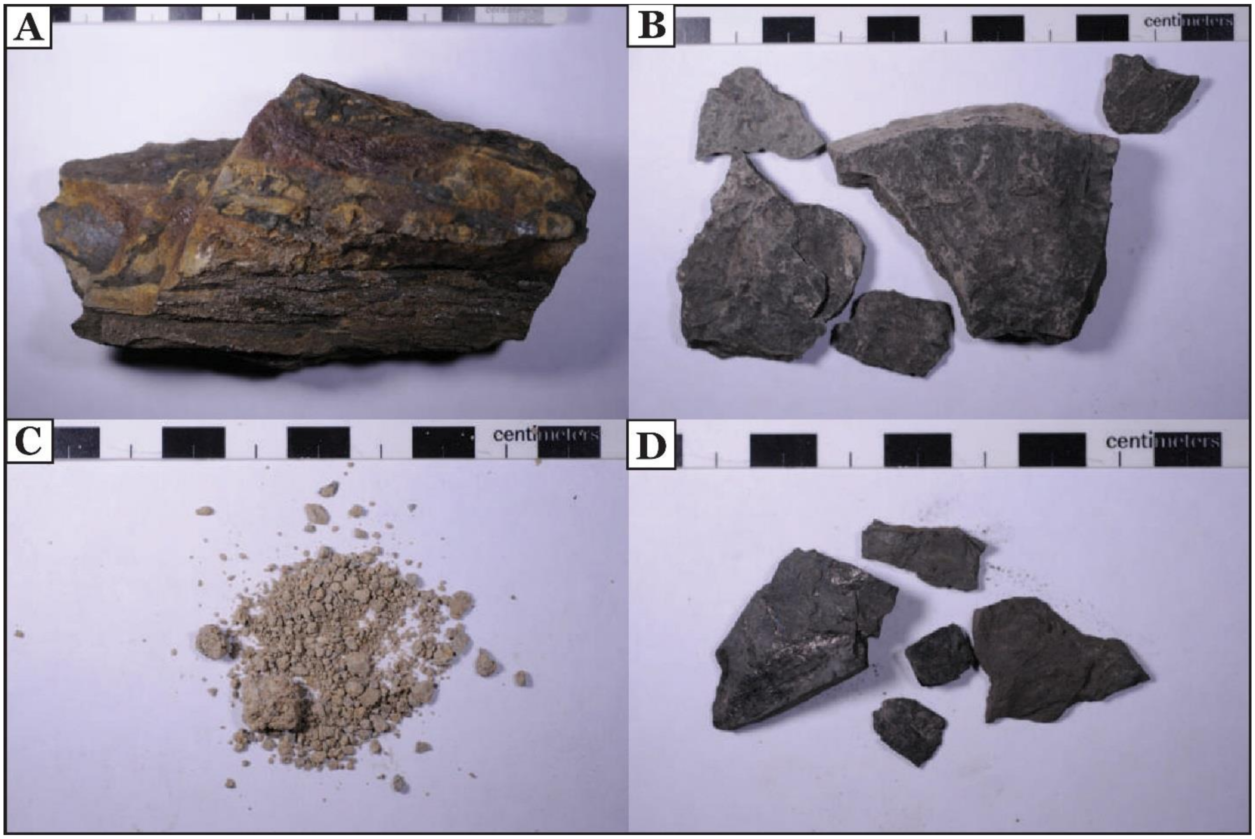


Figure 7 – The samples collected varied from mostly siliciclastic dark mudstones to more carbon rich mudstones, where clear pieces of carbon are visible. **A)** Sample from measured section SM2 at 5.8m. Large piece of fossilized plant material. **B)** Sample from measured section SM2 at 22m, dark fragmented mudstones, similar to other mudstones throughout Slope Mountain. **C)** Sample from measured section SM2 at 51m of tan, friable material. **D)** Float -2 sample, dark fragmented mudstones, similar to other mudstones throughout Slope Mountain.

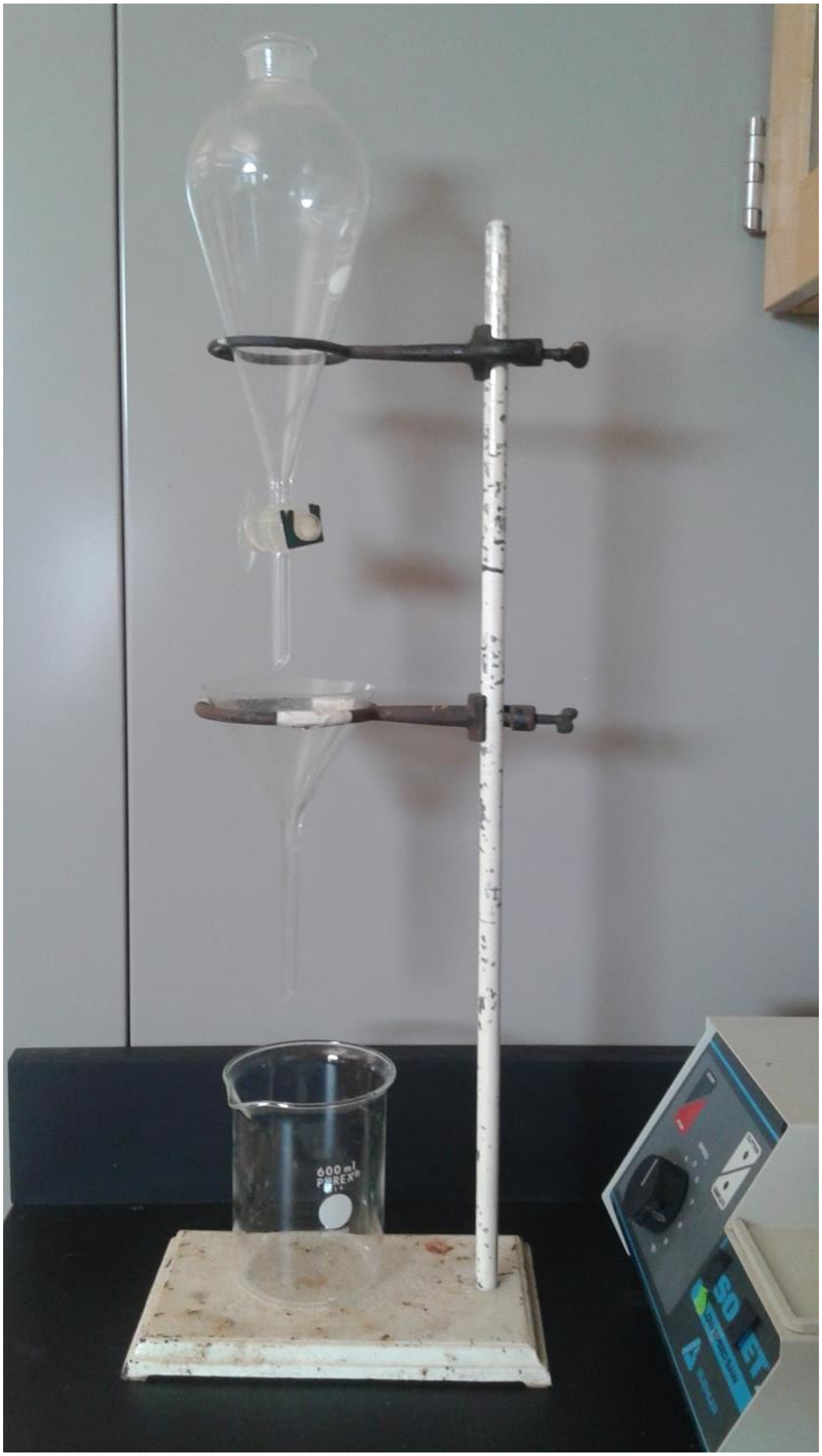


Figure 8 – Block diagram showing depositional environment including subaqueous distributary channel, prodelta, and delta front, and interdistributary bay. The first 10 meters of measured section SM2 corresponds to the area next to the channel, the rest of SM2 suggests a prodelta environment. SM1 was a delta front, while SM1.1 was likely interdistributary bay.

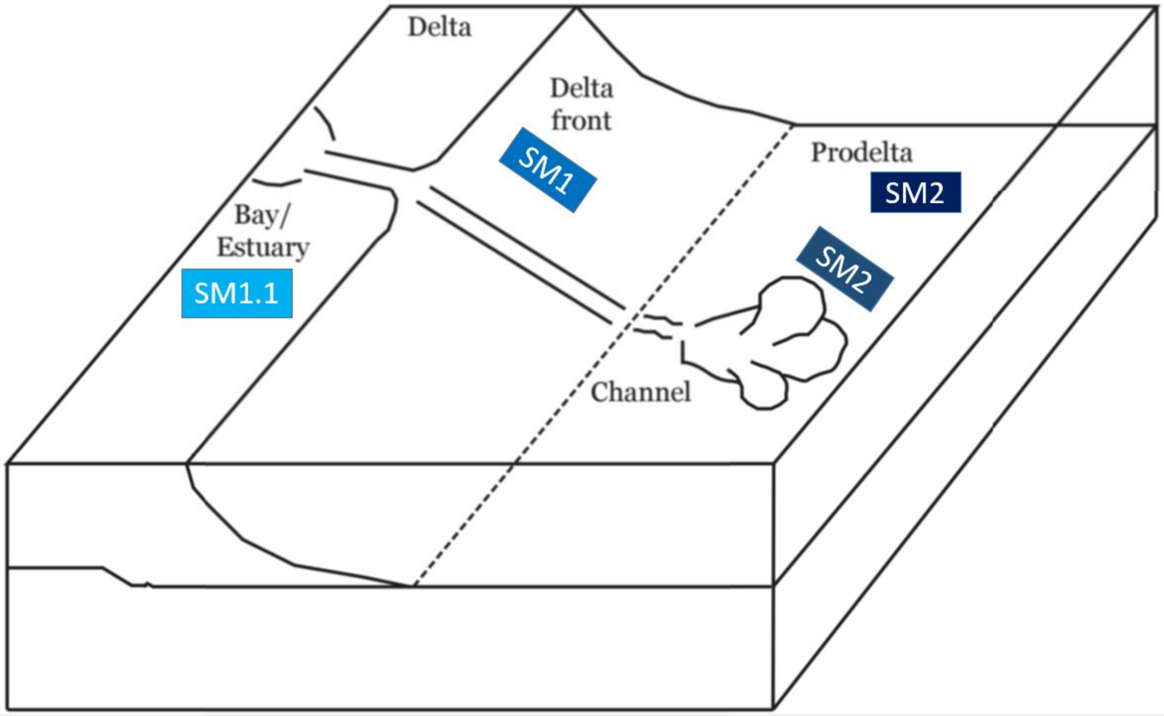


Figure 9 –This image shows the set up for heavy liquid separation. Samples were mixed with the heavy liquid in the separatory funnel, where lighter material (with density similar to quartz) floated to the top and denser material (with density similar to apatite) sank to the bottom. The separated samples were then collected in filter paper in the funnel and the heavy liquid was collected in the beaker below.

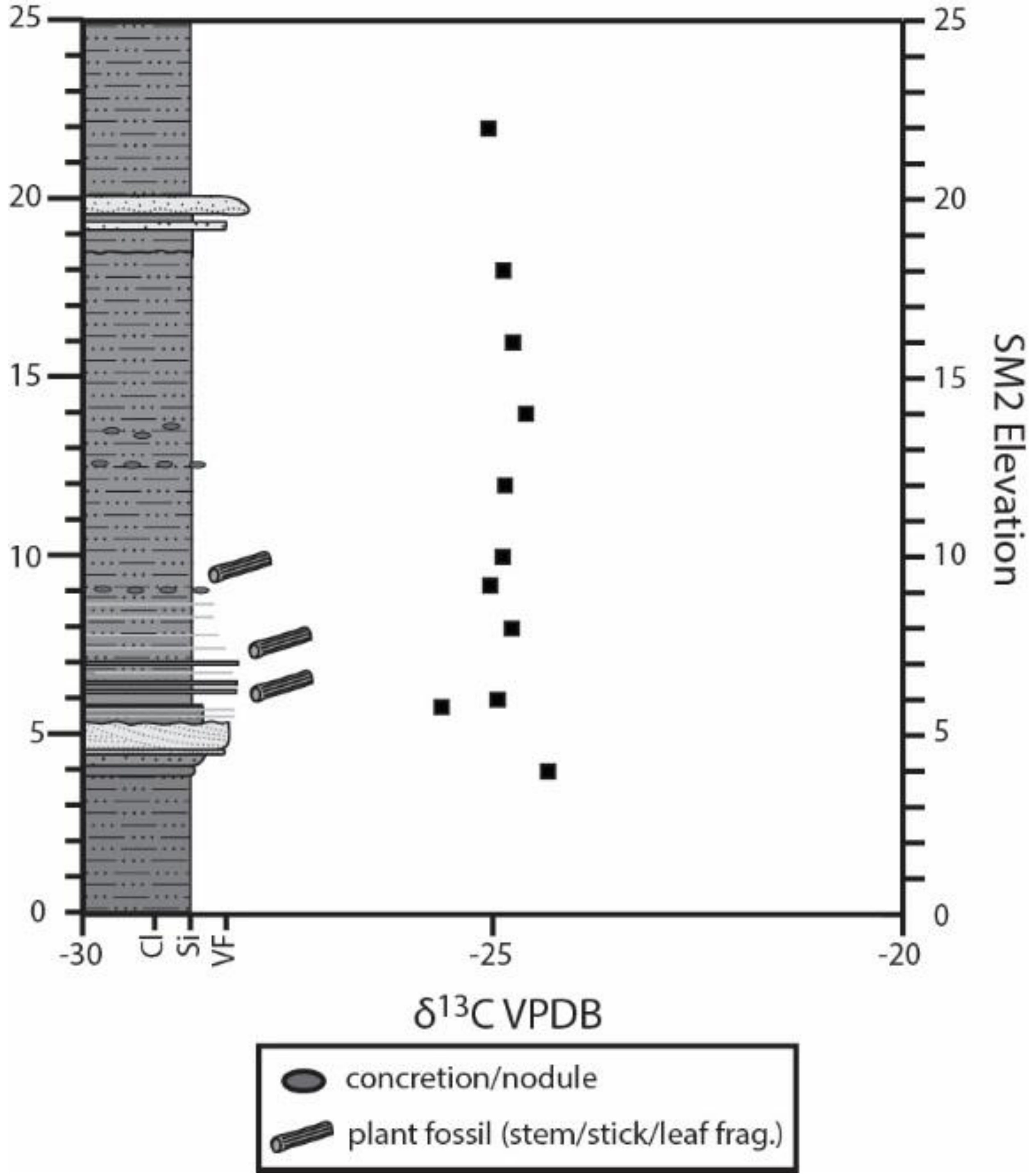


Figure 10 – Stratigraphy column of measured areas of Slope Mountain (modified from Grant Shimer). Only the lower portion of Slope Mountain, measured sections SM2, SM1, SM1.1, is shown because these were the only measured sections where samples were taken for this study. Cl = clay, Si = silt, VFS = very fine sand, FS = fine sand, MS = medium sand, CS = course sand, VCS = very course sand, GR = granule, PB = pebbles, CB = cobbles.

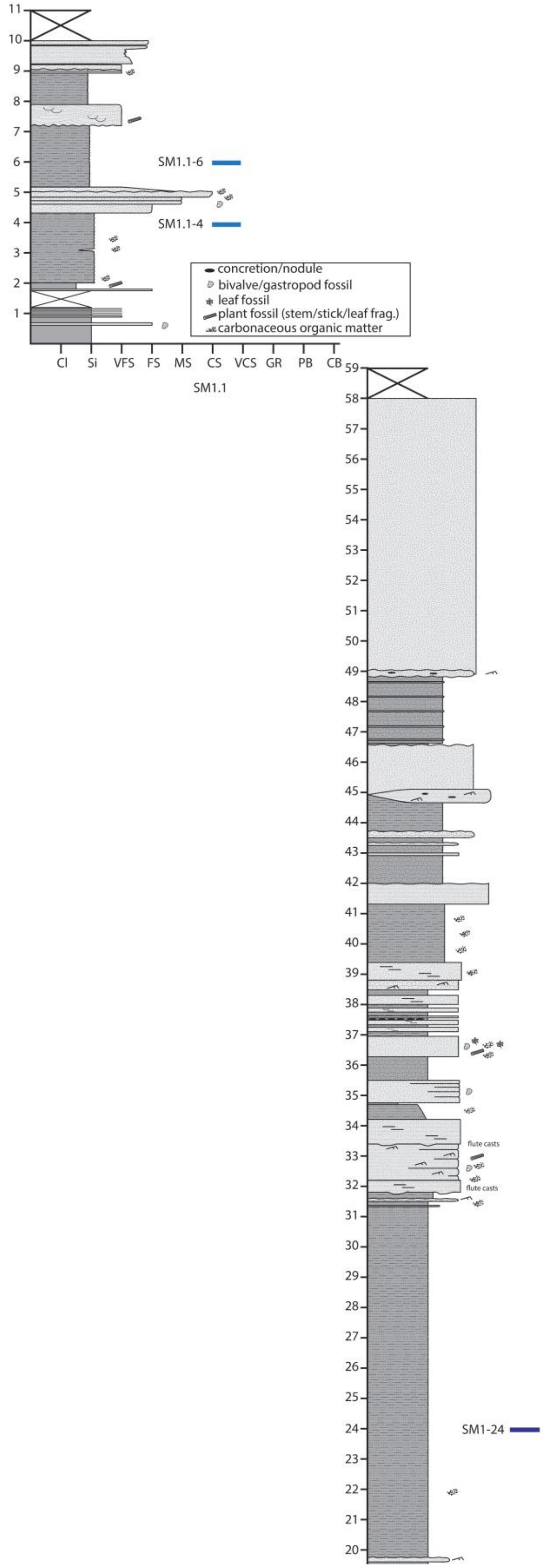


Figure 11 – top

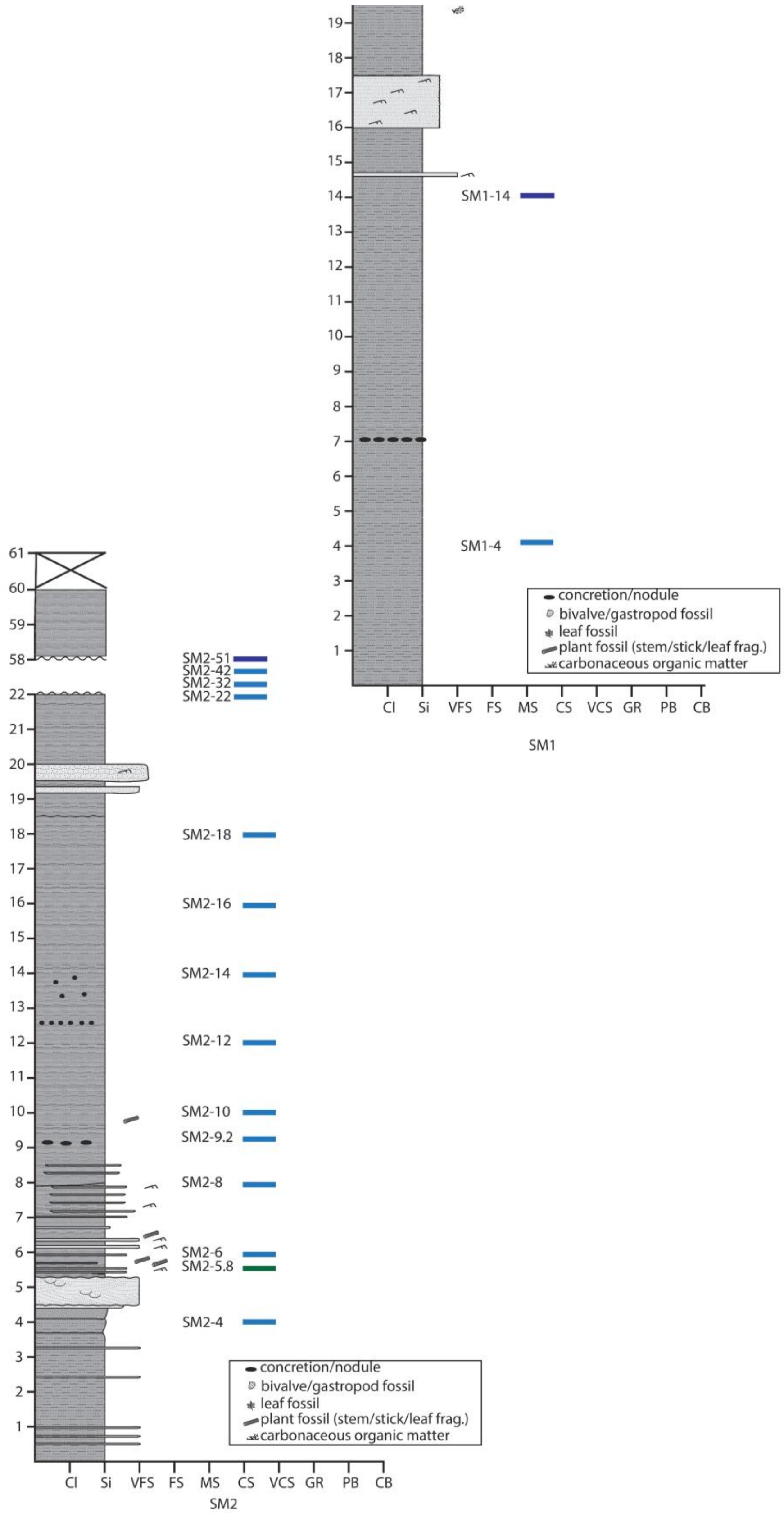


Figure 11 bottom – The changes in δ^{13}C values is shown in comparison to the stratigraphy for the first 25m of measured section SM2. Cl = clay, Si = silt, VF = very fine sand. This area showed the most nuanced variation with certain stratigraphic position.

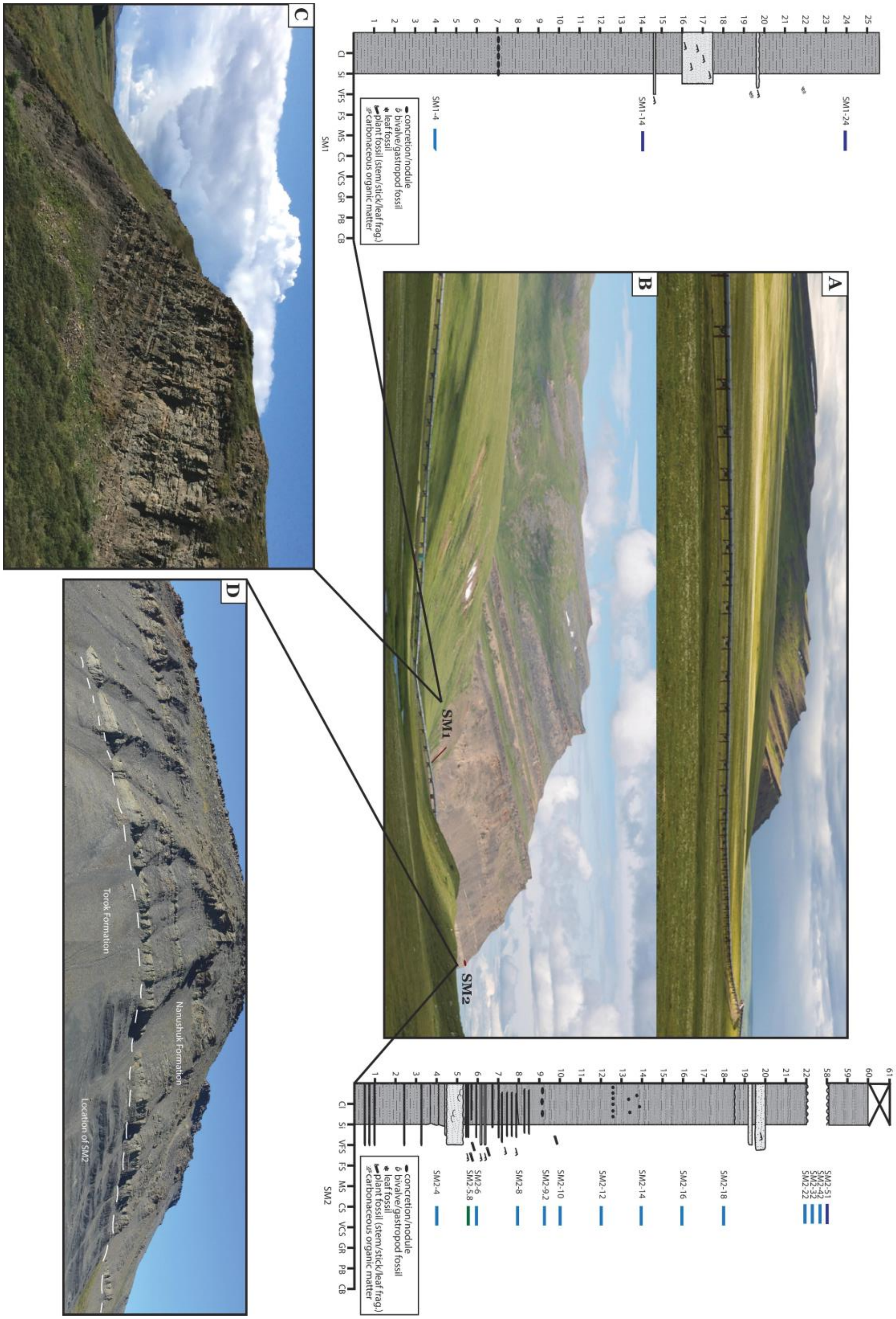


Figure 12 – **A)** North view of entirety of Slope Mountain (www.lucaspaynephotography.com). **B)** North, North-East view of outcrop exposures visible on Slope Mountain (www.lucaspaynephotography.com). Location of SM1 and SM2 marked on photo and corresponding stratigraphy column shown for each location to the side. **C)** West, South-West view of measured section, SM1. **D)** West view of measured section, SM2. Divide between Nanushuk and Torok Formations outlined on photograph.

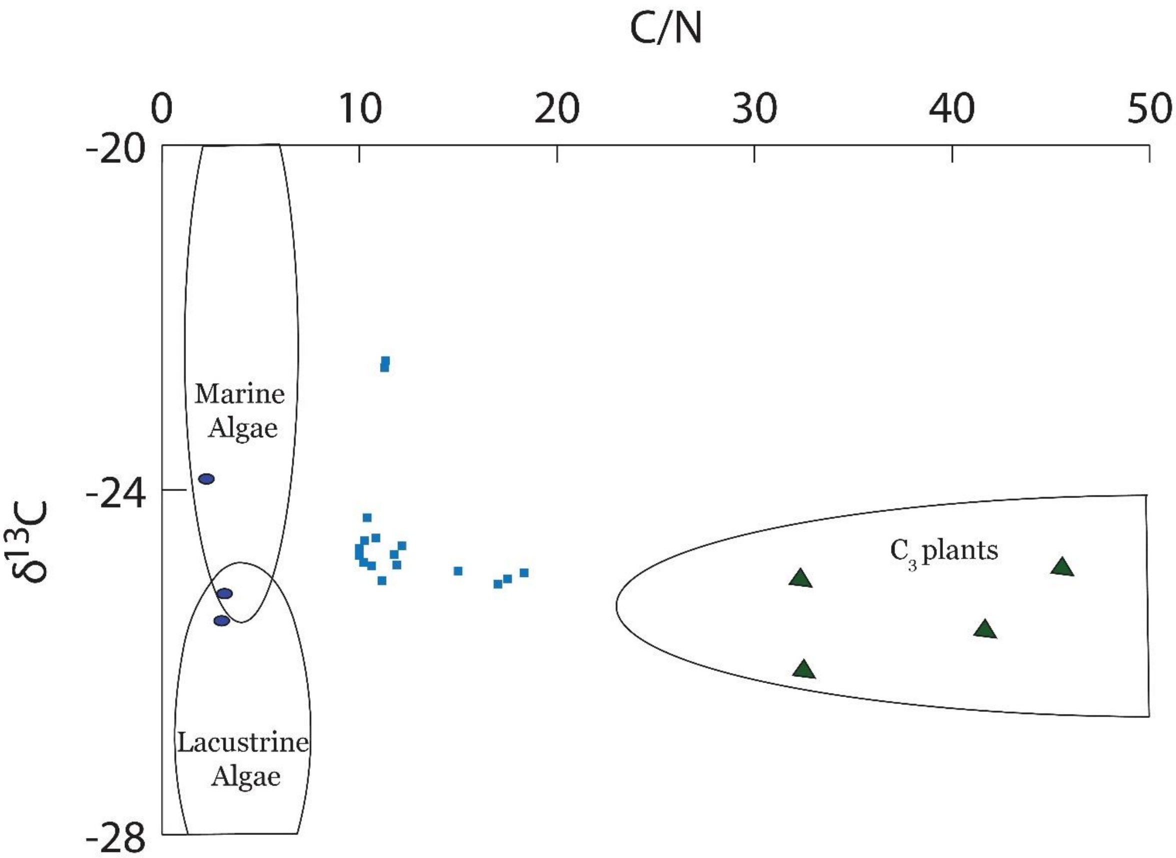


Figure 13 – The relationship between $\delta^{13}C$ values and C/N ratios indicates areas produced by marine algae, lacustrine algae, and C_3 land plants (after Meyers, 1997). Most of the sample is a combination of algae and plant material, as shown by the blue squares, suggesting a mix source of both marine and terrestrial material. The green triangles encompassed by the half oval represent C_3 land plants. And the dark blue ovals represent algae, the upper oval is marine algae, while the other oval indicates lacustrine algae.

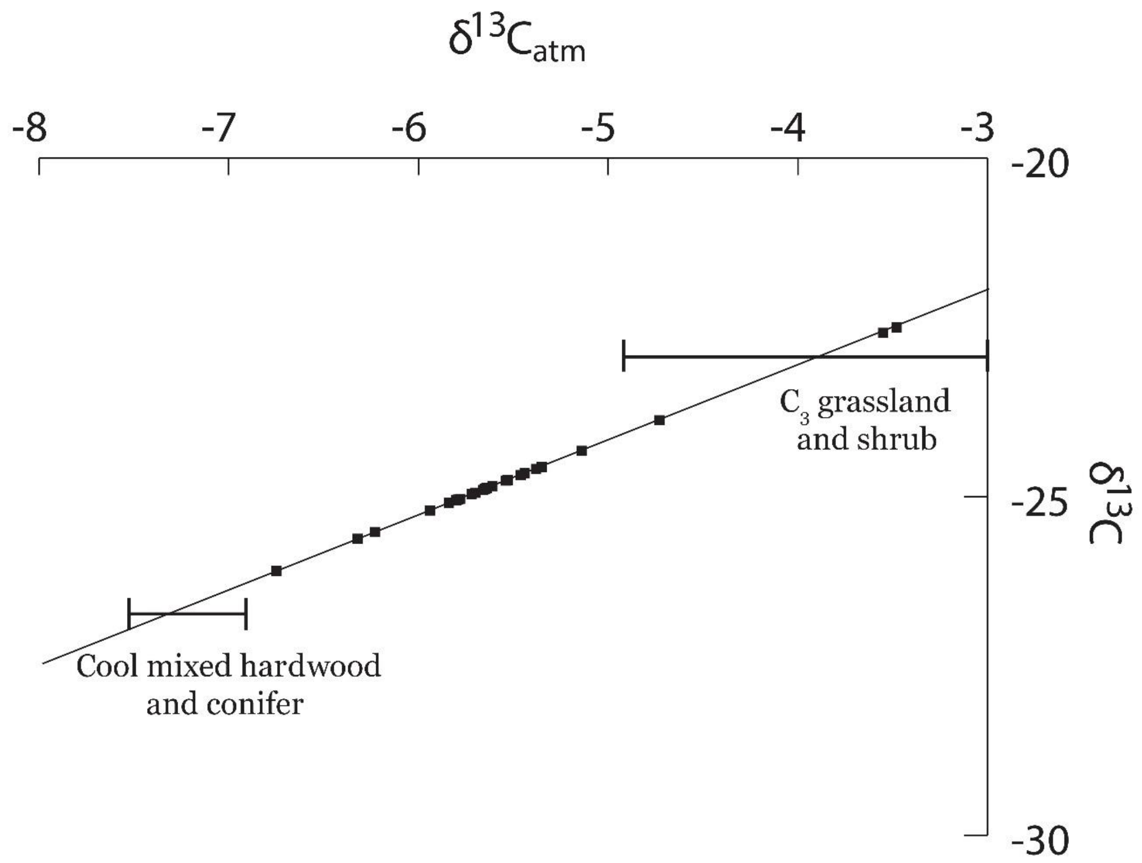


Figure 14 –The comparison of $\delta^{13}C$ values and $\delta^{13}C_{atm}$ (based on Arens et al., 2000) values provides information about the climate. The values from Slope Mountain are between a C_3 grassland/shrub environment and a cool mixed hardwood and conifer environment.

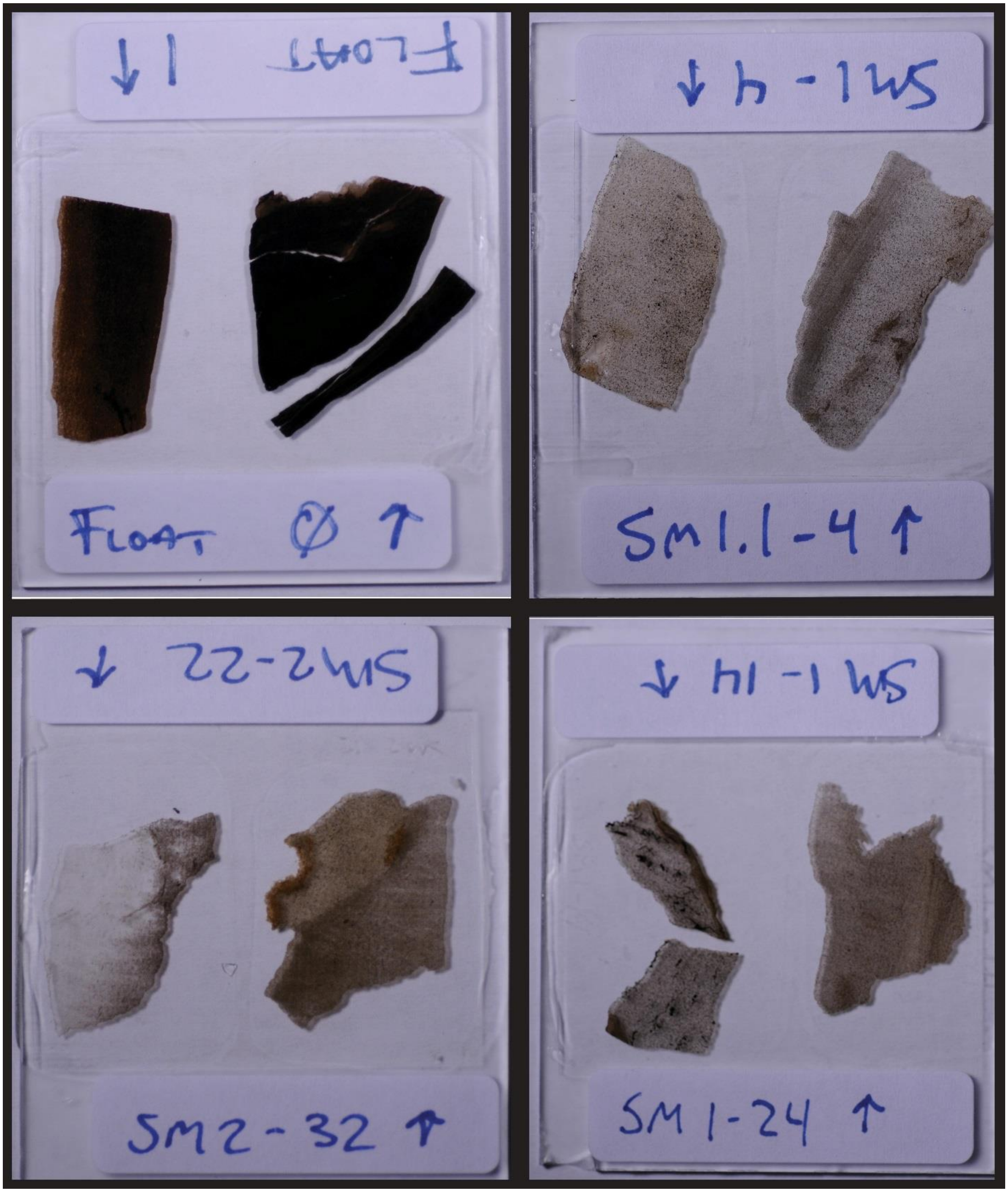
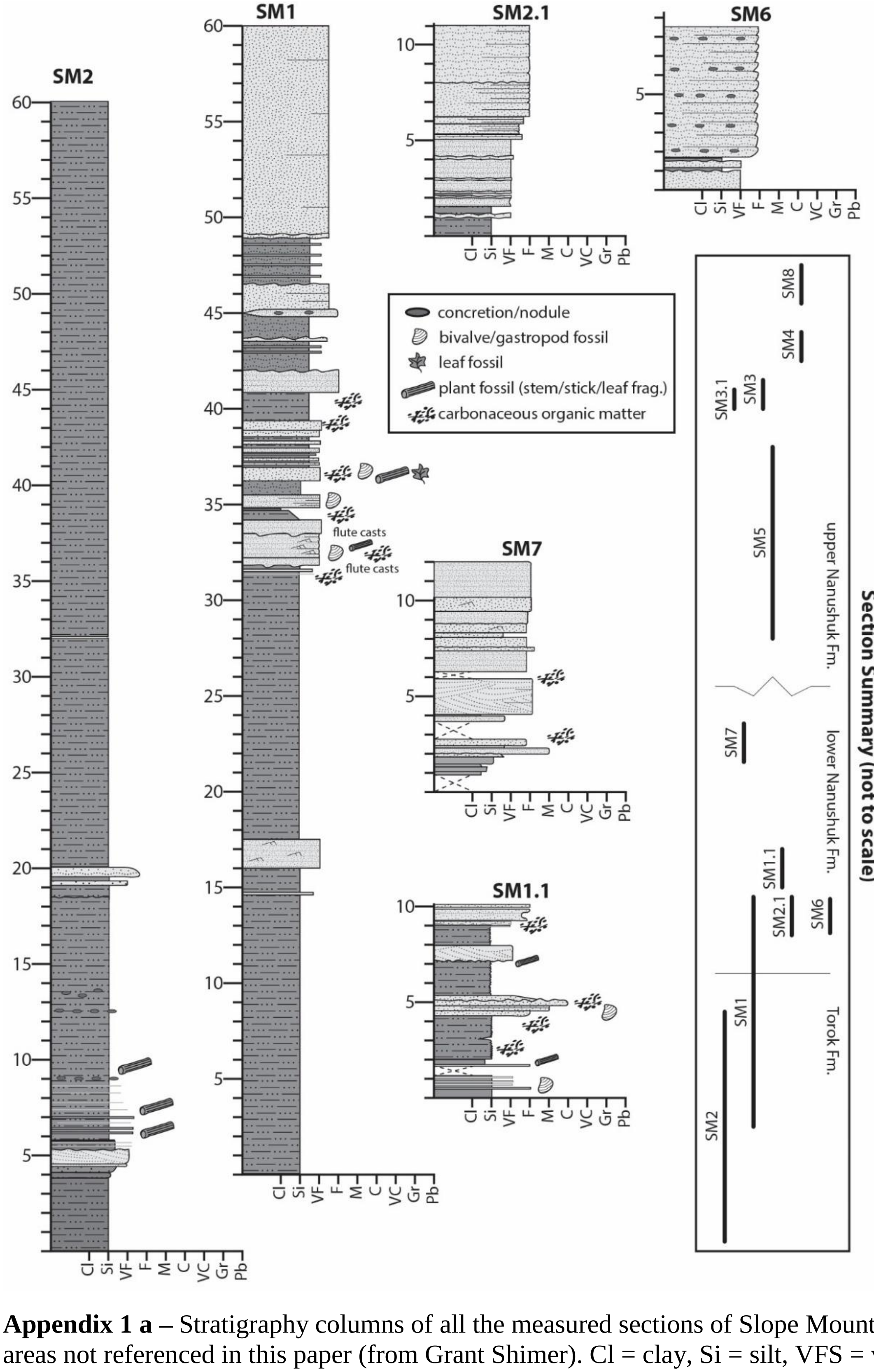
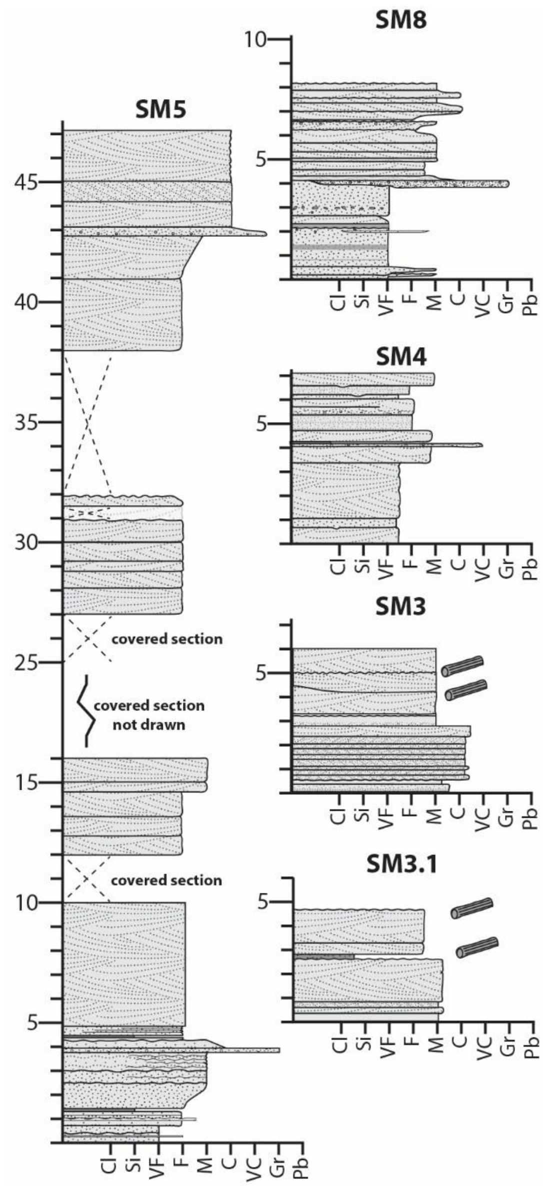


Figure 15 – The variation among samples can be seen in thin section photos. The thin sections of float samples were dark and denser than the other samples. Bedding can be seen in SM1-24 and SM1.1-4. Dark carbonaceous material is also visible as dark layers and dark spots in samples, especially in SM1-14.

APPENDIX



Appendix 1 a – Stratigraphy columns of all the measured sections of Slope Mountain, including areas not referenced in this paper (from Grant Shimer). Cl = clay, Si = silt, VFS = very fine sand, FS = fine sand, MS = medium sand, CS = course sand, VCS = very course sand, GR = granule, PB = pebbles, CB = cobbles. Stratigraphy columns from Torok and lower Nanushuk Formations.



Appendix 1 b – Stratigraphy columns of all the measured sections of Slope Mountain, including areas not referenced in this paper (from Grant Shimer). Cl = clay, Si = silt, VFS = very fine sand, FS = fine sand, MS = medium sand, CS = course sand, VCS = very course sand, GR = granule, PB = pebbles, CB = cobbles. Stratigraphy columns from upper Nanushuk Formations.

Appendix 2 – Outcrop of exposure Nanushuk Formation at Slope Mountain, Alaska North Slope. Photo shows where SM1 was measured. People for scale visible at base of outcrop and top of vegetation.

Appendix 3 - Outcrop exposure of the Torok and Nanushuk Formations at Slope Mountain, Alaska North Slope. Photo shows where SM2 was measured. People visible for scale.

Appendix 4 – Photo showing location of carbonaceous layer 5.8m up measured section SM2. Layer has large amounts of carbonaceous material and plant fossils. Rock hammer for scale.

Appendix 5 – Close up photo showing location of same carbonaceous layer 5.8m up measured section SM2. Mudstone with beds rich in carbonaceous material, coal, and plant fossils. Tape measure for scale.