Chapter BS (Brookian Sequences)

SEISMIC FACIES ANALYSIS AND HYDROCARBON POTENTIAL OF BROOKIAN STRATA

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ABSTRACT

Seismic facies analysis was performed on approximately 700 line-miles of data from the Arctic National Wildlife Refuge (ANWR) and approximately 900 line-miles of data from the adjacent offshore as a basis for assessing the petroleum potential of Brookian and related strata in the ANWR 1002 area. Seven seismic sequences, representing a spectrum of depositional systems, were defined and mapped.

Two Cretaceous sequences (defined as G and F) represent a composite of depositional systems that accumulated during flooding of the Lower Cretaceous Unconformity (sequence G) and during progradation of one or more Brookian clastic wedges into the Colville foreland basin to the west (sequence F). Sequence G contains potential reservoir facies (Thomson and Kemik sandstones) and a condensed section (Hue Shale) that includes significant oil-prone source-rock facies. The Thomson and Kemik sandstones are the basis for two hydrocarbon plays assessed in the 1998 USGS assessment of ANWR. Sequence F consists of distal turbidite and basin plain facies; it has little hydrocarbon potential, although it is included in the turbidite play for assessment purposes.

Five Tertiary sequences represent a spectrum of depositional systems that reflect dynamic interactions among sediment influx, basin subsidence, and eustasy. These five sequences are Paleocene (sequence E), Paleocene-Eocene (sequence D), Eocene (sequence C), Oligocene (sequence B), and Miocene (sequence A) in age. Within the ANWR 1002 area, sequences E, C, and B contain turbidite, slope, and shelf facies whereas sequences D and A contain only shelf through non-marine facies. Seismic facies identified within these five sequences are the basis of three hydrocarbon plays assessed in the 1998 USGS assessment of ANWR: the turbidite, lowstand wedge, and topset plays. Potential reservoir and trap combinations typical of the turbidite play are present in sequences E and C, typical of the wedge play are present in sequence C, and typical of the topset play are present in sequences E, D, C, B, and A. Although no oil-prone source-rock facies have been observed directly in these Tertiary sequences, indirect evidence suggests they may be present in parts of sequence E and/or C. All plays defined within Tertiary sequences are in favorable positions to be charged by older source rocks, especially the Hue Shale.

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INTRODUCTION

Late Cretaceous through Tertiary strata in the 1002 Area of the Arctic National Wildlife Refuge (ANWR) are part of a synorogenic clastic wedge shed from the Brooks Range and deposited to the north in a foreland basin and on the Arctic continental margin. These strata represent the largest volume of sedimentary rocks within the undeformed part of the 1002 Area and, therefore, are of critical importance to assessing the petroleum potential of the region.

During the decade since the publication of results of the last comprehensive study of ANWR petroleum potential (Bird and Magoon, 1987), the subdisciplines of seismic facies analysis and sequence stratigraphy have emerged as unifying concepts of sedimentary geology. The former involves interpretation of depositional facies from seismic reflection data whereas the latter attempts to recognize genetically related volumes of strata deposited during discrete intervals of geologic time. Combining these tools provides the potential to define mappable volumes of lithofacies deposited in genetically related depositional systems, which enables geologists to reconstruct basin evolution as a function of sea level, subsidence, and sediment supply.

This paper presents the results of a seismic facies analysis of Brookian strata of the ANWR and adjacent areas, lays the foundation for the development of a sequence stratigraphic framework for those strata, and summarizes the implications of this analysis to petroleum potential of the region.

METHODS

Seismic facies analysis was performed on approximately 700 line-miles of data from ANWR, mostly within the western (i.e., relatively undeformed) part of the 1002 area (Fig. BSG1). Interpretation was conducted on workstations using seismic data that had been reprocessed and converted to depth as described by Lee and others (Chap. SP). However, none of that reprocessed and depth-converted data can be included in this paper because of confidentiality restrictions. In addition, seismic facies analysis was extended to the adjacent offshore through interpretation of approximately 900 line-miles of data, including public domain seismic data collected by the USGS during 1977-80 (see Grantz and others, 1994 for summary) and industry

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seismic data published by Craig and others (1985) and Scherr and others (1991).

Seismically mappable units representing either individual or composite depositional sequences were defined and correlated throughout the study area. To the extent possible, depositional sequences were defined based on unconformities and their correlative conformities. However, the resolution of seismic data combined with the small scale heterogeneity of some stratigraphic intervals caused us to define sequences known to be composites in some cases. Within each sequence, seismic facies were interpreted using criteria of the sort summarized by Sangree and Widmier (1977).

Depositional sequences and inferred seismic facies were correlated directly to well data and outcrops wherever possible. Because relatively few exploration wells have been drilled on or near seismic lines available for this study, correlation to well data is limited to a handful of wells in the State lands west of the ANWR and offshore north of the ANWR. Attempts to project seismic interpretations to outcrops generally were successful, although the pervasive influence of permafrost on near-surface seismic expression limited the resolution of seismic-to-outcrop correlations.

STRATIGRAPHY

Cretaceous and Tertiary strata of the North American margin of the Arctic Ocean collectively have been called the “Brookian sequence” (Lerand, 1973; Molenaar, 1983; Molenaar and others, 1987; Bird and others, 1987; McMillen and O’Sullivan, 1992) or “Brookian plate sequence” (Hubbard and others, 1987) to emphasize their common lithologic properties and their inferred tectonic significance, particularly in contrast to older strata of the North Slope of Alaska and Canada. Although recognition of this large volume of strata deposited as a synorogenic clastic wedge during the Brookian orogeny is of fundamental importance, in this paper we avoid referring to Brookian strata collectively as a “sequence” to avoid confusion with the smaller scale seismic sequences defined in this study.

Brookian strata of the eastern Alaska North Slope previously have been divided into five units of formational status, including (1) the Hue Shale, (2) the Arctic Creek facies, (3) the Canning Formation, (4) the Jago River Formation, and (5) the Sagavanirktok Formation (Molenaar and others, 1987). The stratigraphy of these units is discussed by Bird and Molenaar

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(1987) and by Bird (Chap. GG). This study also includes Cretaceous strata that lie above the LCU and below the Hue Shale, even though these are not formally included in the Brookian (Bird and Molenaar, 1987; Bird, Chap. GG).

This study has resulted in the recognition within Brookian strata of several distinct depositional sequences that reflect dynamic interactions among sediment influx, basin subsidence, and eustasy. This paper summarizes the seismic and outcrop characteristics of these sequences and correlates them to previously defined stratigraphic units.

CRETACEOUS - TERTIARY DEPOSITIONAL SEQUENCES

Seven depositional sequences were defined on reflection seismic data and mapped throughout the ANWR 1002 Area and the adjacent State lands and offshore areas (Fig. BSG1). The depositional sequences are named sequence A through G in order of increasing age (Fig. BSG2). Each sequence is described in the following sections in chrono-stratigraphic order, and the regional scale characteristics of each sequence are schematically summarized in Figure BSG2 and illustrated on seismic sections in Plates BS1, BS2, BS3, and BS4. Relationships of these newly defined depositional sequences to previously defined stratigraphic units are shown in Figure BSG3. Breakout of five plays (topset, turbidite, wedge, Thomson, and Kemik) used to assess the petroleum potential of these depositional sequences is summarized in Figure BSG4.

Sequence G

Sequence Definition and Boundaries. Sequence G is defined on seismic sections in the westernmost part of the ANWR 1002 Area and is tied to well control in the State lands just west of the Canning River. The base of sequence G is defined in most areas as the boundary between a very high amplitude reflection below and a relatively transparent interval of low amplitude, laterally discontinuous reflections above (Plates BS1, BS2, BS3, and BS4). This seismic boundary marks the Lower Cretaceous Unconformity (LCU), with either pre-Mississippian rocks of the “Franklinian sequence” or Mississippian through Triassic rocks of the “Ellesmerian sequence” below the unconformity and Cretaceous rocks above the unconformity (for description of Franklinian and Ellesmerian strata see Bird and Molenaar, 1987; Bird, Chap. GG). The top of sequence G is defined as

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the boundary between high amplitude, laterally continuous reflectors in the upper portion of sequence G and a relatively transparent interval of low amplitude, laterally discontinuous reflections above (Plates BS1 and BS2). This boundary is characterized either by parallelism of underlying and overlying reflectors or by subtle downlap of reflectors in sequence F onto the top of sequence G; it appears to be conformable where observed on seismic sections.

Seismic Facies. Internally, sequence G is characterized by a basal zone of very low amplitude, laterally discontinuous reflections that collectively define a relatively transparent zone typically less that a few hundred feet thick on most seismic sections (Plate BS2). Most of sequence G is characterized by high amplitude reflectors that are generally parallel to one another and laterally continuous over many miles (Plates BS1 and BS2); these define a distinctive, highly reflective zone whose maximum thickness is approximately 1,000 feet.

Thickness and Distribution. Sequence G and the overlying sequence F cannot be distinguished from one another throughout the study area because of structural complications and limited seismic resolution, so the two sequences have been combined for mapping purposes. The combined thickness of the two sequences ranges from zero to more than 4,000 feet in the undeformed part of the 1002 Area (Fig. BSG5). Sequence G attains maximum thickness of 1,000 to 1,500 feet in the southwestern part of the 1002 Area, where it is distinguishable on many seismic sections. The sequence displays subtle thinning northward towards Point Thomson (Figs. BSG1 and BSG5), apparently as the result of depositional thinning onto the Mikkelsen high (east-plunging extension of Barrow Arch that trends through Point Thomson and enters the northwesternmost corner of the ANWR 1002 area; see Bird, Chap. GG).

However, the most dramatic thinning of sequence G occurs along a northwest-southeast oriented zone where the typical seismic expression of sequence G (and that of overlying sequence F) is truncated by erosion at the base of sequence E. Sequence G is thinned notably across a broad area (e.g., Plate BS2) and truncated completely along a northwest - southeast trend (Plate BS1). The location and orientation of this zone of truncation is clearly defined by the isopach map of the combined thickness of sequences G and F (Fig. BSG5). East of this zone, the typical seismic expression of sequence G is recognized only in relatively small, isolated “outliers” (Plate BS1).

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Truncation of lithostratigraphic equivalents of sequence G ("radioactive zone") has been recognized to occur regionally at the base-of-slope associated with several Brookian progradational wedges (Noonan, 1987; his Fig. 19).

Two possible interpretations are offered to explain the truncation of sequence G in ANWR. The irregular relief at the top or complete truncation of sequence G (Plate BS1) can be interpreted to be the result of erosion at the base of depositional sequence E. Such erosion may have been subaerial or submarine (although the latter is favored), and may have been induced by an abrupt lowering of base level, either as the result of tectonic activity or eustatic fall of relative sea level. The age of the erosional surface is approximately coincident with the onset of known thrust faulting and piggyback basin development in the eastern part of the 1002 Area (i.e., the Sabbath Creek facies; Bird, Chap. GG; Potter and others, Chap. BD; Houseknecht and Schenk, 1998), so a tectonic influence is certainly reasonable.

Alternatively, the seismic features illustrated in Plate BS1 can be interpreted to be the result of one or more massive failures of a marine slope related to deposition of the overlying sequence E. In this interpretation, slope instability may have induced mass failure, slumping, and associated submarine erosion that extended downward and laterally into previously deposited sediments of sequences F and G. The presence of large scale, rotational slump features (e.g., Plate BS1) in slope (i.e., foreset) facies of sequence E just west of the zone of truncation provides evidence of the instability of the muddy slope and lends credence to this interpretation. Similar features have been described in older, lithostratigraphically analogous facies of the Lower Cretaceous Torok Formation in the National Petroleum Reserve, Alaska (NPRA) by Weimer (1987).

The two interpretations presented above carry significantly constrasting implications regarding source-rock potential in the 1002 Area because sequence G includes the Hue Shale, an oil-prone source rock believed to have generated oil across the eastern North Slope (Magoon and others, Chap. PS). In the case of the first interpretation, sequence G may be absent over part of the 1002 Area as the result of erosion and, north and east of the zone of truncation, may be present only in isolated outliers such as those illustrated in Plate BS1. This scenario would reduce source-rock potential over a portion of the 1002 Area.

In the case of the second interpretation, kerogen indigenous to the Hue Shale may be preserved among the slumped sediments that comprise the lower portions of sequence E. In fact, this scenario may provide an explanation for the unknown source rock(s) associated with the “Canning - Sagavanirktok petroleum system” (Magoon and others, Chap. PS). Mass failure and slumping involving sequences E and G could have resulted in facies containing a mix of oil-prone kerogen from the Hue Shale and more gas-prone kerogen typical of the Tertiary-aged portion of the Canning Formation. Thus, east of the zone where sequences F and G are truncated, sequence E may contain a mixture of kerogen types that could include the source for the oils attributed to the Canning - Sagavanirktok petroleum system.

Ties and Age. Sequence G has been tied to several wells and outcrops. Seismic control permits direct correlation to four key wells just west of the Canning River, including the Beli, Alaska State J-1, Leffingwell, and West Staines #2 (Fig. BSG1). These correlations indicate the basal, relatively transparent part of the sequence represents the stratigraphic interval that includes the Kemik Sandstone, the Thomson sand of the Point Thomson area, and the Pebble Shale Unit, all of which are Early Cretaceous (Hauterivian to Barremian) in age, and that the volumetrically predominant, highly reflective part of the sequence represents the stratigraphic interval of the Hue Shale, which is Early through Late Cretaceous (Aptian(?) through Campanian or Maestrichtian) in age (Bird and Molenaar, 1987). It should be emphasized that seismically defined sequence G includes strata (Kemik Sandstone, Thomson sand, and Pebble Shale Unit) that are not formally assigned to the Brookian (Bird and Molenaar, 1987; Bird, Chap. GG).

Depositional Facies. Based on outcrop studies, the Kemik Sandstone and Pebble Shale Unit are thought to represent shallow marine facies deposited during marine transgression of the Lower Cretaceous Unconformity. The Hue Shale is interpreted as a condensed section, likely deposited during times that included maximum flooding of this area by marine waters. However, considered in a regional context, the Hue Shale is part of a package of strata that spans a considerable interval of geologic time (Aptian(?) to Campanian or Maestrichtian; Bird and Molenaar, 1987), and chronostratigraphically equivalent strata to the west (in NPRA) include multiple progradational clastic wedges. Considering these relationships, this interval is likely a distal composite of several progradational and flooding events. The presence of multiple depositional sequences in strata of this age has been demonstrated by

Schenk and Bird (1993), Phillips and others (1990), and Myers and others (1993).

The inferred depositional facies described above indicate that seismic sequence G is a composite of several depositional systems that may not be related genetically. Additional details are provided by Schenk and Houseknecht (Chap. TK). Nevertheless, we use sequence G as a seismically mappable unit for purposes of this work.

Hydrocarbon Potential. Sequence G contains important source rocks and reservoir rocks. The Hue Shale is considered to contain some of the best, oil-prone source rocks on the eastern Alaska North Slope and has been demonstrated to have generated oil through geochemical correlations (Magoon and others, Chap. PS).

The large scale, lenticular geometry of the Kemik sandstone and well exposed folding and faulting that involves the Kemik suggest the potential for both stratigraphic and structural traps within the 1002 Area. However, the very fine grain size and pervasive quartz cement observed in the Kemik appear to place limits on the potential for reservoir quality. The petroleum potential is assessed in the *Kemik play*.

In contrast, the Thomson sand, an apparent stratigraphic tongue of the Kemik, displays excellent reservoir quality and is a know hydrocarbon reservoir in the Point Thomson field. The Thomson sand is an areally restricted facies that consists largely of clastic carbonate grains apparently eroded from Franklinian sedimentary strata truncated by the LCU. Significant reservoir potential may exist within the ANWR where similar conditions may have resulted in erosion of Franklinian strata and accumulation of clastic carbonate grains above the LCU. Petroleum potential of this unit is assessed in the *Thomson play*.

Sequence F

Sequence Definition and Boundaries. Sequence F is defined on seismic sections in the westernmost part of the ANWR 1002 Area and is tied to well control in the State lands just west of the Canning River. The base of sequence F is defined as the boundary between high amplitude, laterally continuous reflectors in the upper part of sequence G and a relatively transparent interval of low amplitude, laterally discontinuous reflections above

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(Plates BS1 and BS2). This boundary is characterized by parallelism of underlying and overlying reflectors or by subtle downlap of reflectors within the lower part of sequence F onto the top of sequence G. The boundary appears to be conformable where observed on seismic sections. The top of sequence F is defined by a marked erosional discontinuity and a less erosive, seemingly conformable, correlative surface. The erosional surface is recognized by truncation of characteristic seismic facies of both sequence F and the underlying sequence G beneath reflectors that define the base of the overlying sequence E (Figs. BSG2 and Plates BS1 and BS4). The zone of truncation of sequence F is displayed clearly on seismic lines in the northwestern part of the 1002 Area (Plates BS1 and BS2) and trends southeastward into the 1002 Area, as defined by the thinning of sequences F and G from more than 2,000 feet to zero (Fig. BSG5). South and west of that zone of truncation, the top boundary of sequence F is a slightly undulating surface defined by either parallelism between underlying and overlying reflectors or by subtle truncation of underlying reflectors by overlying reflectors (Plate BS3).

Seismic Facies. Internally, sequence F is characterized by low to moderate amplitude, laterally discontinuous reflectors that collectively define a relatively transparent zone on most seismic sections. The reflectors are generally parallel, giving an overall impression of beds that were deposited horizontally, although subtle downlap is locally observable and broad mounding is suggested by some reflectors that display gently convex-upward geometries (Plate BS2, label “b”). Collectively, these characteristics suggest sequence F represents bottomset seismic facies deposited as pelagic or hemi-pelagic muds and distal turbidite sands at, or beyond, the toe of a marine slope.

Thickness and Distribution. The combined thickness of sequences F and G ranges from zero to more than 4,000 in the undeformed part of the 1002 Area (Fig. BSG5). South and west of the zone of truncation discussed above, sequence F displays a maximum thickness of about 2,000 feet where it is clearly distinguishable in the southwestern corner of the 1002 Area. It generally thins to the north and east. This thinning appears to be depositional, although subtle erosional thinning cannot be ruled out. Within the zone of truncation, sequence F thins from nearly a thousand feet to zero over a lateral distance of a few miles. Seismic interpretations suggest this abrupt thinning and truncation is the result of erosion or slumping at the base of the overlying sequence E.

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Ties and Age. Sequence F has been correlated to several wells and outcrops. Seismic control permits direct correlation to four key wells just west of the Canning River, including the Beli, Alaska State J-1, Leffingwell, and West Staines #2 (Fig. BSG1). These correlations indicate sequence F occurs in the lower part of the Canning Formation, which has been dated as late Cretaceous (Campanian - Maestrichtian) in age in these wells (Bird and Molenaar, 1987). Within the 1002 Area, sequence F has been correlated southward across the Marsh Creek anticline to outcrops of the Canning Formation that have yielded late Maestrichtian ages based on palynology (Frederiksen, personal communication). Based on this control, we believe sequence F is late Cretaceous in age, and most likely Maestrichtian within the 1002 Area.

Depositional Facies. In western ANWR and adjacent State lands, the lower part of the Canning Formation has been interpreted as muds and sands deposited at the toe of a prograding muddy slope (Molenaar and others, 1987), and our analysis confirms that interpretation. Outcrops of strata considered to be part of sequence F comprise parallel bedded mudstones, siltstones, and very fine grained sandstones that display sedimentary structures that indicate deposition in a distal turbidite environment (Fig. BSP1). Vertical association of these facies suggest deposition on a basin plain and as distal fringes of submarine fan lobes, and generally suggest deposition in a position at the base-of-slope or farther basinward.

Hydrocarbon Potential. Sequence F is inferred to have modest hydrocarbon potential within the ANWR. Mudstones within the sequence are generally lean in organic carbon and kerogen composition suggests they are gas-prone. Sandstones are generally very thinly bedded (typically a few inches thick - Fig. BSP2) and very fine grained, and are characterized by low porosity. Favorable trapping geometries may be present, both as stratigraphic traps formed by broad lenses of sandstone encased in mudstone and as structural closures associated with the Marsh Creek anticline and compressional structures farther north. However, the apparent absence of reservoir-quality sandstones within sequence F minimizes the likelihood for the presence of recoverable hydrocarbons in this sequence.

Sequence E

Sequence Definition and Boundaries. Sequence E is defined on seismic sections throughout the ANWR 1002 Area, as well as adjacent State lands and offshore areas where it is tied to well control. The base of sequence E is

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defined as a marked erosional or slump surface and a correlative, slightly undulating surface that may or may not be erosional (Plates BS1, BS2, BS3, and BS4). A northwest-southeast zone of truncation, in which underlying strata of sequences F and G are truncated beneath the erosional or slump surface, separates areas where the character of this sequence boundary contrasts significantly. West of the zone of truncation, the base of sequence E is defined by a moderate to high amplitude reflector that undulates mildly and locally appears to truncate one or two underlying reflectors (Plates BS1 and BS3). Otherwise, the general parallelism between reflectors in the upper part of sequence F and lower part of sequence E makes this a subtle sequence boundary. However, within and northeast of the truncation zone the basal sequence E boundary displays the characteristics of an unconformity with significant relief (Plates BS1, BS2, and BS4). As discussed previously (see section on Sequence G, Thickness and Distribution), this sequence boundary can be interpreted as either an erosional surface or as a mass failure (i.e., slump) surface. Whichever the case, this sequence boundary truncates both the underlying sequence F *and* sequence G below that (Plate BS1). In areas where sequence G has been completely removed, it appears that even the LCU has been truncated and the surface that defines the base of sequence E rests directly on pre-Mississippian rocks (Plate BS1). In this case, the base of sequence E may represent a *basal Tertiary unconformity* (BTU - Fig. BSG2), which may be equivalent to the “breakup unconformity” of offshore usage (Craig and others, 1985; Scherr and others, 1991). North and east of the zone of truncation, seismic evidence suggests that either (a) there exists significant relief on the erosional surface so that apparent outliers of Cretaceous strata and the underlying LCU are preserved beneath sequence E or (b) most Cretaceous strata (i.e., sequences F and G) have been chaotically slumped and only isolated areas of non-slumped Cretaceous strata remain intact (Plate BS1).

In the westernmost part of the 1002 Area, the top of sequence E is defined by a mildly undulating boundary between parallel reflectors within sequences D and E (Plates BS1, BS2, and BS3). Eastward, the top of sequence E is defined by a zone of truncation where the base of sequence C cuts down through sequence D and truncates reflectors in the upper part of sequence E. This zone of truncation trends from the Point Thomson area southeastward into the 1002 Area and is well defined by the truncation edge of sequence D (Fig. BSG7). East of the zone of truncation, the boundary between sequence E and the overlying sequence C is characterized by one or more moderate to high amplitude reflectors and there is generally parallelism between reflectors

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within the two sequences (Plates BS1 and BS4). This part of the sequence boundary could be interpreted to be conformable and, if so, the upper part of sequence E may include facies that are distal equivalents of sequence D.

Seismic Facies. Sequence E displays internal reflections that represent a composite of smaller scale depositional sequences that cannot be mapped throughout the study area because of insufficient seismic resolution. It is clear that sequence E contains a complete spectrum of bottomset, foreset, and topset facies. Bottomset seismic facies lie immediately above the lower sequence boundary and display a variety of characteristics. To the north and east (i.e., distal facies), bottomset facies display low amplitude, discontinuous, somewhat hummocky and locally chaotic reflectors (e.g., Plates BS1 and BS4) scattered randomly through a relatively transparent section that lacks distinct reflectors (Plates BS1 and BS4). These seismic facies likely represent basin plain mudstones and distal turbidites deposited at, and beyond, the toe of a prograding muddy slope, although the presence of a lowstand systems tract cannot be ruled out. This inferred distal bottomset facies grades southward and westward into a seismic facies that contains abundant high amplitude reflectors that display mounded (convex upward) geometries (Plate BS1). Internally, many mounds display subtle low amplitude reflections that suggest downlapping strata within the mounds. In some mounds, the internal reflections define bi-directional downlap, suggesting aggradation of submarine fan facies. In others, the internal reflections define uni-directional downlap, suggesting lateral accretion or progradation of submarine fan lobes or related facies. Multiple horizons of mounded facies are present within sequence E, each overlain by downlapping clinoform foresets that generally display northward and eastward apparent dips (Plate BS1). These complex relationships suggest sequence E contains facies deposited during multiple episodes of relative base level fluctuation and/or slope and shelf progradation. It is possible that the mounded submarine fan facies is part of a lowstand systems tract that may be present in the lower part of sequence E, particularly if the basal sequence boundary represents an erosional surface rather than a massive slump surface.

Foreset seismic facies within sequence E are represented by low to moderate amplitude reflectors that display low apparent dips to the north and east (Plates BS1 and BS4). They downlap northward and eastward onto inferred bottomset facies and display southward and westward toplapping relationships to topset facies. Locally, the foresets are laterally discontinuous and display deformed geometries, suggesting slumping of the muddy slope.

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The position and geometry of the foreset seismic facies suggest they were deposited as part of one or more, progradational highstand systems tracts.

In the southwesternmost corner of the 1002 Area, more than half the total thickness of sequence E is composed of topset seismic facies. These are mostly low to medium amplitude, parallel reflectors (Plate BS3). Northward and eastward, individual topset reflectors either terminate near up-dip terminations of foresets or display rollover mergence into foresets; both features define positions of ancient shelf edges (Plate BS3). These shelf edges display an up-section basinward migration (Plate BS3) indicating that sequence E was, at least in part, deposited as the result of basinward migration of a shelf-slope depositional system. The shelf edge facies migrate up-section to near the top of sequence E a short distance into the ANWR, suggesting that most of the 1002 Area was occupied by marine slope and basin depositional systems during accumulation of sequence E. The shelf edge mapped at the base of sequence E trends nearly north - south and is located just west of the Canning River (Fig. BSG11). In contrast, the shelf edge mapped at the top of sequence E trends northwest - southeast from Point Thomson into the ANWR and displays a marked embayment near the western 1002 boundary (Fig. BSG11).

Thickness and Distribution. Sequence E is present throughout most of the 1002 Area and ranges from as little as 1,000 to as much as 7,000 feet thick (Fig. BSG6). Sequence E is thickest along the southern part of the undeformed area and thins northward onto the Mikkelsen high (Fig. BSG6), which perhaps acted as an accommodation sill during deposition of sequence E, and it is locally thin where eroded at the base of sequence D. The overall isopach pattern suggests that the original, depositional thickness of sequence E increased to the south and southeast (Fig. BSG6). Sequence E appears to be consistently at least several thousand feet thick in the eastern part of the ANWR 1002 area, where it is deformed by folding and thrust faulting. Sequence E appears to be at least 2,000 feet thick offshore, although thicknesses are uncertain because of poor resolution at depth of public domain seismic data.

Ties and Age. Sequence E has been tied to numerous wells and several outcrops. Seismic control permits correlation into several wells in State lands west of ANWR, including the Beli, Alaska State J-1, Leffingwell, and West Staines #2, and approximate correlation to a handful of wells offshore, including the Alaska State A-1 (Fig. BSG1). These correlations indicate

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sequence E is equivalent to the upper part of the Canning Formation and the lower part of the Sagavanirktok Formation. Paleontological control from those wells indicates sequence E is Paleocene in age. Sequence E also has been correlated to outcrops along the Canning River just south of the southwestern corner of the 1002 Area, and those outcrops have yielded Paleocene palynomorphs (Frederiksen, personal communication). Based on these correlations, we believe sequence E is Paleocene in age.

Depositional Facies. Outcrops along the Canning River that have been correlated to sequence E display sedimentary facies that are interpreted to represent most of the seismic facies described above. The lowermost exposures consist of sandstones thought to be the deposits of turbidite channels. Internally, these are amalgamated sandstones consisting of individual beds that average about three feet thick (Fig. BSP3). Each bed displays an erosive base and a finer grained top, suggesting that each is the deposit of a single depositional event. The amalgamated nature and apparently limited lateral extent of the sandstones suggest they accumulated within incised channels, which may have formed either on the lower slope or in the proximal parts of submarine fans or turbidite aprons.

Above the turbidite channel deposits is a thick section of mudstone, siltstone, and sandstone inferred to represent slope deposits (Fig. BSP4). This section displays a range of sedimentary features, including intervals of chaotic mudstone interpreted to be slump (slope failure) deposits, intervals of thinly laminated silty mudstone interpreted to be marine slope deposits, and intervals of thin bedded sandstones interpreted to be unconfined turbidites and/or contourites deposited on the marine slope. Subtle angular truncations of beds occurs within this interval (Fig. BSP4), and these may reflect either rotational slumping of slope deposits and/or episodes of erosion on the slope.

Overlying the slope deposits are intervals of interbedded sandstones, mudstones, and siltstones interpreted to be marine shelf deposits (Fig. BSP5). The sandstones display hummocky cross-stratification, suggesting deposition of sand by storm events (Fig. BSP6). Some hummocky bedded sandstones fine abruptly into overlying siltstones and mudstones that display vertical burrows and pelecypod faunas, apparently reflecting a return to relatively low energy marine shelf to shoreface conditions following storm events.

Near the top of Paleocene outcrops along the Canning River, sandstones that display erosional bases and internal accretionary bedding (Fig. BSP7) suggest

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meandering fluvial deposition within the topset seismic facies. However, it is not known whether these apparently fluvial facies are part of sequence E or part of the overlying sequence D.

In outcrops west of the Canning River (including sections along the Kavik River and Kadleroshilik River), exposed sections that have been dated as Paleocene comprise intervals containing hummocky bedded sandstones, which are interpreted as shelf deposits, and intervals containing cross-bedded sandstones and coal beds, which are interpreted as deltaic and fluvial deposits.

The outcrop characteristics summarized above, combined with the seismic facies described earlier, confirm that sequence E includes unconfined turbidites and incised turbidite channels (perhaps part of a lowstand systems tract), as well as muddy slope and marine shelf facies (likely parts of a highstand systems tract).

Hydrocarbon Potential. Sequence E appears to have significant hydrocarbon potential in the ANWR 1002 Area and in the adjacent State lands and offshore. Within the turbidite facies, a number of wells have encountered oil shows or have tested oil. For example, the Alaska State A-1 well (Fig. BSG1) tested more than 2,500 barrels per day of oil from sandstones that correlate to sequence E. We believe the sandstones from which oil was tested in the Alaska State A-1 well represent amalgamated turbidite channel sands similar to those described in outcrop along the Canning River. The inferred turbidite depositional systems are ideal stratigraphic traps because turbidite channels incised into lower slope and proximal fan facies likely onlap the depositional slope, and sandstones within submarine fan lobes at the downdip termini of channels likely downlap the basin floor (Lemley, 1998).

Several wells drilled during the past five years apparently have tested mounded features within sequence E and some have been classified as discoveries. Among these, some information has been released regarding the Badami field (located about 15 miles west of Point Thomson, Fig. BSG1; Lemley, 1998) but most remain proprietary so neither the exact intervals of successful oil tests nor the facies of the successfully tested intervals can be confirmed. The oil potential within the turbidite facies of sequence E is assessed as part of the *Turbidite play* described elsewhere in this report.

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Sequence E also appears to have oil potential within the topset seismic facies. In one outcrop section along the Canning River, marine shelf facies correlated to sequence E include a 24 ft thick sandstone that is heavily oil stained (Fig. BSP5), thereby confirming the presence of reservoir quality sandstones and favorable charge potential within the topset seismic facies. This outcrop is downthrown to the Sadlerochit Mountains frontal thrust fault, indicating the oil stained sandstone is in the position of a footwall fault trap. No clear evidence of stratigraphic trapping geometries have been observed within the topset seismic facies, although our interpretation of depositional environments raises the potential for stratigraphic traps within shelf and fluvial facies. The presence of topset seismic facies within sequence E is limited to a small part of the southwestern corner of the 1002 Area, southwest of the "top sequence E" shelf edge shown in Figure BSG11. The topset seismic facies of sequence E are included in the *Topset play* of this assessment.

The direct and abundant evidence of oil within sequence E occurs despite the apparent absence of oil-prone source rocks within sequence E. Geochemical analysis of oils sampled from outcrops of this sequence suggests an older source rock, probably the Hue Shale (Magoon and others, Chap. PS). Therefore, the presence of oil within both turbidite and topset facies indicates the presence of favorable migration pathways from the Hue Shale.

As discussed previously, it also is possible that distal facies of sequence E may contain source rocks for the "Canning - Sagavanirktok petroleum system." This petroleum system has been identified on the basis of oil recovered from well tests offshore, a core from the Tenneco Aurora well, and surface shows along the coast (Magoon and others, Chap. PS). The geochemical characteristics of these oil samples indicate a Tertiary source kerogen, although no source rock has been sampled that matches these characteristics. We suggest that sequence E bottomset facies are possible candidates to contain this source rock, particularly if the interpretation is accepted of mass failure (slump) and mixing of indigenous Paleocene kerogen with oil-prone kerogen from the Hue Shale.

Sequence D

Sequence Definition and Boundaries. Sequence D is defined on seismic sections in the westernmost part of the ANWR 1002 Area, as well as adjacent State lands where it is tied to well control. The base of sequence D is defined as a mildly undulating erosion(?) surface. This sequence boundary is distinct

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where it separates the up-dip portions of clinoform foresets within the underlying sequence E from parallel reflectors within sequence D (Plates BS1 and BS2); in fact, truncation of the former beneath the latter is locally apparent. The sequence boundary is less distinct where it separates low to medium amplitude, parallel reflectors within the topset seismic facies of sequence E from overlying low to high amplitude, parallel reflectors within sequence D (Plate BS3).

The top of sequence D is defined by a parallel to mildly undulating surface in the westernmost part of the 1002 Area and by erosional truncation of the entire sequence D at the base of the overlying sequence C in an area that trends southeastward into the 1002 Area from Point Thomson (Plate BS1).

Seismic Facies. Internally, sequence D is characterized by low to high amplitude reflectors that range from laterally discontinuous to continuous (Plates BS1, BS2, BS3, and BS4). The reflectors are mostly parallel, giving the impression of beds that were deposited horizontally. The entire sequence D is considered to represent topset facies deposited on a marine shelf and in associated deltaic and fluvial environments.

Thickness and Distribution. Sequence D displays a thickness of 1,500 to nearly 3,000 feet (Fig. BSG7), except where thinned by truncation at the base of the overlying sequence C. Truncation of the entire sequence from a thickness of more than 1,000 ft to zero occurs over a lateral distance of 3 to 5 miles (Fig. BSG7). Because of this erosional truncation, sequence D is limited in extent to the southwestern corner of the 1002 Area (Fig. BSG7).

Ties and Age. Sequence D has been tied via seismic control to several wells in the State lands west of the Canning River, including the Beli, Alaska State J-1, Leffingwell, and West Staines #2 (Fig. BSG1). These ties reveal that sequence D correlates to the Staines tongue of the Sagavanirktok Formation (Bird and Molenaar, 1987). The Staines tongue was formerly inferred to pinch out depositionally to the north and east, based primarily on well-log correlations (Bird and Molenaar, 1987). Our new seismic interpretations indicate the pinch-out of the Staines tongue is actually erosional truncation of sequence D at the base of sequence C.

Ties to well control indicate that sequence D is late Paleocene to early Eocene in age.

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Depositional Facies. Neither seismic control nor paleontological information permits identification of specific outcrop sections that correlate uniquely to sequence D. However, it is likely that sequence D is present in a number of exposures of the Sagavanirktok Formation along, and west of, the Canning River. Outcrops that have yielded late Paleocene to Eocene ages (based on palynology) display a variety of deltaic to fluvial depositional facies. These include sandstones and pebbly sandstones deposited as point bars in delta plain or fluvial environments and as transverse and longitudinal bars in braided fluvial environments. Westward from the Canning River, coal beds and carbonaceous mudstones become more common in this stratigraphic interval, indicating the presence of delta plain to alluvial plain swamps and marshes. Considering this limited range of depositional facies, we infer that sequence D is composed of sandstone-rich, deltaic through alluvial deposits, although we cannot rule out the possible occurrence of marine shelf facies within the sequence.

Hydrocarbon Potential. The limited presence of sequence D in southwestern 1002 Area translates into modest hydrocarbon potential. Clearly, sequence D does not contain oil-prone source rocks, and gas-prone source rocks (i.e., coaly facies) are present in significant volumes only in the State lands west of the Canning River.

Sequence D contains sandstones and pebbly sandstones that display high porosity and permeability, so good quality reservoir rocks are present. Trapping potential exists in three distinct geometries: (1) sequence D locally is truncated up dip (regional structural dip) at the base of sequence C, (2) structural closure involving sequence D may be present as the result of folding and/or faulting along and north of the Marsh Creek anticline, and (3) stratigraphic sandstone pinch-outs (e.g., isolated point-bar sandstones) may occur throughout sequence D. Petroleum potential of sequence D is evaluated as part of the *Topset play.*

Sequence C

Sequence Definition and Boundaries. Sequence C is defined on seismic sections throughout the ANWR 1002 Area, as well as adjacent State lands and offshore areas where it is tied to well control. The base of sequence C is defined as a marked erosional surface and correlative surfaces that may not be erosive. A zone of truncation, defined as the area where underlying strata are truncated beneath the erosional surface, separates areas where the character of

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this sequence boundary contrasts significantly. This zone of truncation extends from Point Thomson southeastward into the ANWR 1002 Area, as defined by the thinning from more than 1,000 ft to zero of sequence D (Fig. BSG7). West of the zone of truncation, the base of sequence C is defined by a low to moderate amplitude reflector that undulates mildly and locally appears to truncate one or two underlying reflectors of sequence D (Plates BS1 and BS2). Otherwise, parallel reflectors in the upper part of sequence D and lower part of sequence C make this a subtle boundary.

Within the zone of truncation, the basal boundary of sequence C displays the characteristics of an erosional surface with significant relief. This boundary is characterized by termination of underlying reflectors along a surface defined by low to high amplitude, gently dipping reflectors that are laterally continuous over distances ranging up to a few miles (Plate BS1). This basal boundary of sequence C truncates the entire sequence D and is erosive down into the upper part of sequence E (Plate BS1).

East of the zone of truncation, the boundary between sequence C and the underlying sequence E is characterized by one or more moderate to high amplitude reflectors and there is generally parallelism between reflectors within sequences C and E (Plate BS1).

Throughout the western part of the 1002 Area and the adjacent offshore (i.e., Camden Bay), the top of sequence C is defined by a mildly undulating surface between parallel topset reflectors in the upper part of sequence C and lower part of sequence B (Plates BS1, BS2, BS3, and BS4), or a subtle surface of truncation between the up-dip parts of clinoform foresets of sequence C and overlying topset reflectors of sequence B (Plate BS1, eastern part). In the eastern part of the 1002 Area and the adjacent offshore, a similar upper sequence boundary is present in structurally low “sub-basins” but a distinct erosional surface forms the upper sequence boundary across structural highs (Plate BS5), indicating a phase of compressional deformation between deposition of sequences C and B.

Seismic Facies. Based on internal reflection geometries, sequence C appears to be a composite of multiple, smaller scale depositional sequences that cannot be individually distinguished throughout the study area because of the low density and locally poor resolution of seismic data. Nevertheless, seismic facies within sequence C are divided into two broad categories for

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ease of presentation, lowstand systems tract and highstand systems tract (e.g., Posamentier and others, 1988).

Lowstand systems tract - At stratigraphic positions that can be correlated to the lower portion and base of the erosional slope defined by truncation of reflectors in sequence D and the upper part of sequence E, sequence C displays seismic facies suggesting the presence of a lowstand systems tract (Plate BS1), which has three components, submarine fan mounds, lowstand wedge, and bottomset facies. At the base of the erosional slope, above a basal sequence C boundary that is broadly parallel with reflectors within the underlying sequence E, sequence C displays multiple, vertically stacked, high amplitude reflectors that define convex-upward bodies two to five miles wide (Plate BS1, near east end of seismic record). These are interpreted to be lowstand submarine fan mounds. Internally, many of these mounds display low amplitude, downlapping reflections, some of which suggest lateral accretion (uniform direction of downlap) and others which suggest vertical aggregation (opposing direction of downlap) of submarine fan mounds or lobes. These inferred mounds may have been deposited as isolated fans or as lobes of a submarine fan apron that formed at the base of the slope.

West of and laterally associated with the lowstand mounds are moderate to high amplitude, basinward-dipping reflectors that onlap the erosional slope in a westward direction and downlap eastward onto the lowstand mound facies (Plate BS1). Collectively these basinward-dipping reflectors are interpreted to represent a lowstand wedge, which may include a variety of depositional systems ranging from shingled turbidites to slope channels to shoreface facies.

A third seismic facies observed east of and laterally associated with the lowstand mounds comprises low to moderate amplitude, laterally discontinuous reflectors that are generally parallel. Locally, these reflectors display subtly mounded and hummocky geometries. This facies is interpreted as bottomsets deposited as pelagic or hemi-pelagic muds and distal turbidites basinward from the lowstand submarine fans.

Highstand systems tract - Above the inferred lowstand systems tract, sequence C displays an internal geometry of reflectors that represents a complete spectrum of bottomset, foreset, and topset seismic facies deposited as one or more prograding clastic wedges. Bottomset seismic facies of the highstand systems tract lie immediately above the lowstand bottomsets and generally display similar characteristics. A boundary between the lowstand bottomsets and highstand bottomsets is recognized locally by the presence of relatively high amplitude reflectors, laterally continuous over a few miles, that appear to represent a downlap surface at the base of highstand foresets. The highstand bottomset facies locally display contorted and truncated reflections interpreted as syndepositional slumps or zones where listric, syndepositional growth faults sole into muddy strata near the base of the marine slope.

Highstand foreset facies generally comprise low to moderate amplitude reflections that display northward and eastward downlap onto lowstand seismic facies and southward and westward toplap against topset facies (Plates BS1 and BS4). However, the foreset facies of sequence C also display locally hummocky and chaotic reflections, truncations of apparently deformed reflections by overlying clinoforms, local dip reversals, and abrupt thickness variations (Plate BS1). Collectively, these characteristics indicate deposition on a predominately muddy marine slope marked by syndepositional slumping and growth faulting. In fact, listric growth faults that sole into foreset facies can be mapped in many areas where dip reversals and abrupt thickness variations are observed.

Highstand topset facies comprise low to moderate amplitude reflections that are generally parallel (Plates BS1, BS2, and BS4). In the southwestern corner of the 1002 Area, topset facies represent nearly the entire thickness of sequence C. Northward and eastward, individual topset reflectors either terminate near up-dip terminations of foresets or display rollover mergence into foresets (Plates BS1 and BS4); both features define positions of ancient shelf edges. These shelf edges display an up-section basinward migration indicating that sequence C was, at least in part, deposited as the result of basinward migration of a shelf-slope depositional system (Fig. BSG11). The shelf edge mapped at the base of sequence C trends from Point Thomson southeastward into the ANWR and displays a broad embayment in the westernmost 1002 Area (Fig. BSG11) The shelf edge mapped at the top of sequence C trends from Flaxman Island southeastward into the ANWR along a trend nearly parallel to the present coastline (Fig. BSG11).

Significantly, topset facies deposited near the shelf edge display dip reversals and abrupt thickness increases indicative of syndepositional growth faulting. A majority of the growth faults dip steeply in the topset facies, become listric in the underlying foreset facies, and sole into bed-parallel zones of contorted reflections in the middle or lower parts of the foreset facies. Most growth

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faults mapped in this study dip to the north or northeast, and many display geometries that suggest spoon-shaped fault planes (i.e., the strike of a fault plane appears concave-northeastward in map view). These growth faults are present in the topset facies of sequence C throughout the western 1002 Area, and they generally increase in throw northward and eastward. Their maximum displacement is hardly discernible on seismic records in the southwest part of the study area (maximum displacement of topsets <100 feet) whereas their displacement is clearly visible (maximum displacement of topsets up to several hundred feet) along the coast and in the central part of the study area. Although the growth faults occur individually in some areas, it is more common for them to occur in swarms of several discrete faults, and total displacement across such a swarm may be as much as 1,000 feet over a lateral distance of one mile, particularly in the area just southwest of the "top sequence C" shelf edge shown in Figure BSG11.

Thickness and Distribution. Sequence C is present throughout most of the 1002 Area and it ranges from less than 3,000 to more than 10,000 feet thick (Fig. BSG8). It is thinnest in the Point Thomson area, from where it thickens south and southeastward towards the deformed part of ANWR. It thickens abruptly in the area where its basal boundary cuts down through underlying strata ("trough" of thickness in Fig. BSG8), and some of the thickening occurs across growth faults.

Sequence C is present throughout the eastern 1002 Area, where commonly it is severely deformed by folding and thrust faulting. Original stratigraphic thicknesses are difficult to estimate because of structural repetitions, but sequence C appears to be at least 7,000 to 10,000 feet thick in structurally low areas and has been thinned by erosion over structurally high areas.

Ties and Age. Sequence C has been tied to numerous wells and several outcrops. Seismic control permits correlation into several wells in State lands west of ANWR, including the Alaska State J-1, Leffingwell, and West Staines #2, and approximate correlation to a handful of wells offshore, including the Alaska State A-1 (Fig. BSG1). These correlations indicate sequence C comprises the upper part of the Canning Formation and the lower part of the Sagavanirktok Formation, and paleontological control from those wells indicate sequence C is Eocene in age. In the Point Thomson area, sequence C represents the Mikkelsen tongue of the Canning Formation and the lower part of the overlying Sagavanirktok Formation (Bird and Molenaar, 1987). Sequence C has been tentatively correlated to the Richards sequence in

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the Beaufort-MacKenzie Basin of Canada (Dietrich and Lane, 1992; Dixon, 1992; Dixon and others, 1992) through common stratigraphic relationships to younger strata displayed on public domain seismic data in the Demarcation sub-basin (area of "3-mile boundary" label in Fig. BSG1).

Sequence C can be correlated to the surface using seismic control in the western 1002 Area. Scattered outcrops along the crest of the Marsh Creek anticline and along the south flank of the syncline just to the south appear to correlate to sequence C. Palynology of samples from those exposures confirms an Eocene age (Frederiksen, personal communication).

Depositional Facies. Depositional facies are difficult to reconstruct because outcrops of sequence C are relatively small, scattered, and severely deformed. Individual exposures in the western 1002 Area display turbidite, marine slope, marine shelf, and perhaps deltaic facies similar to those described for sequence E. However, the lack of vertically continuous outcrops precludes placing these facies into the context of a complete depositional system.

Hydrocarbon Potential. Sequence C appears to have modest source-rock potential but contains significant potential for reservoir and trapping combinations. At all locations sampled, mudstones of sequence C are relatively poor in total organic carbon and contain gas-prone kerogen. However, the presence of oil-prone source rocks in older depositional sequences and the presence of oil in both older and younger depositional sequences in the State lands and adjacent offshore indicate that sequence C occupies a stratigraphic position favorable for oil charging. There is also a possibility that distal facies within sequence C may contain oil-prone kerogen that has contributed to the Canning-Sagavanirktok petroleum system.

The lowstand systems tract of sequence C contains apparent submarine fan mounds as well as lowstand wedge facies that onlap the erosional surface at the base of the sequence. No well penetrations or outcrops are known to include the lowstand systems tract, so no direct evaluation of either reservoir or seal quality is possible. However, seismic interpretations reveal that the lowstand systems tract is located immediately down dip from the truncation edge of topset seismic facies of sequences D and E (Plate BS1), both of which have been demonstrated to contain reservoir quality sandstones in wells and outcrops just to the west. This geometry suggests the lowstand systems tract has good potential to contain sandstones of reservoir quality, both in the submarine fan and lowstand wedge facies. Similarly, the presence

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of good quality seals can be inferred by analogue from sequence E, which contains marine slope and basinal facies that appear to be identical to those in sequence C. The inferred petroleum potential of the submarine fan facies within sequence C is assessed as part of the *Turbidite play* whereas that of the lowstand wedge facies is assessed as the *Wedge play* of this assessment.

Reservoir and trapping geometries also are present in two facies within the highstand systems tract of sequence C. Potential exists in turbidite facies associated with the lower foreset and bottomset seismic facies. Although no known well penetrations of this facies have occurred, the presence of reservoir quality sandstones and stratigraphic trapping geometries can be inferred based on seismic analogy to similar facies within sequence E, which have been tested successfully, and this potential is assessed as part of the *Turbidite play*.

There also appears to be significant potential in the basal topset facies of sequence C, particularly where growth faulting has rotated topset facies into geometries that may form traps. One well in the Point Thomson field (Pt. Thomson 2; Nelson and others, Chap. WL, Plate WL34) encountered shows of oil at this stratigraphic horizon but tests failed to recover free oil. In addition, several offshore wells (e.g., Kuvlum and Hammerhead) have successfully tested oil from traps with similar attributes in the overlying sequence B. Those wells tested oil from the basal portion of topset facies in sequence B (Oligocene), which represent the lowermost topset facies of the Tertiary section at those offshore locations. Presumably, those offshore traps were charged by oil migrating up section through underlying foreset seismic facies, perhaps along growth faults. In much of the western 1002 Area, topset facies of sequence C occupy an analogous position (i.e., the lowermost topset facies of the Tertiary section) and appear, therefore, to have significant oil potential. This potential is included in the *Topset play* of this assessment.

Sequence B

Sequence Definition and Boundaries. Sequence B is defined on seismic sections in the western ANWR 1002 Area and locally in the eastern 1002 Area, as well as adjacent State lands and offshore areas where it is tied to well control. In the western 1002 Area, the entire thickness of sequence B is composed of topset seismic facies and the base of the sequence is defined by a mildly undulating surface between parallel topset reflectors in the upper part of sequence C and lower part of sequence B (Plates BS1 and BS2), or by

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subtle truncation between the up dip parts of clinoform foresets within sequence C and overlying topset reflectors of sequence B (Plate BS1, eastern part). Offshore in Camden Bay, the lower part of sequence B is composed of foreset seismic facies, and the base of the sequence is defined by a moderate to high amplitude reflector that forms a downlap surface that is generally parallel to reflections in lower foreset or bottomset facies of the underlying sequence C (Plate BS4, northern end). Locally, the basal sequence B reflection appears to truncate underlying foreset or bottomset reflections of sequence C. In the eastern 1002 Area and the adjacent offshore, the basal reflection of sequence B generally is parallel to underlying reflections of sequence C in structurally low areas and appears to truncate underlying reflections of sequence C across structurally high areas (Plate BS5).

The top of sequence B is defined by a parallel to mildly undulating surface between parallel topset reflectors in the upper part of sequence B and lower part of sequence A throughout the 1002 Area and adjacent State lands and offshore (Plates BS1, BS2, and BS4).

Seismic Facies. Sequence B is composed largely of topset facies characterized by low to moderate amplitude, parallel reflectors (Plates BS1 and BS2). These topsets are interpreted as marine shelf, and perhaps deltaic and fluvial facies. Offshore and in the eastern 1002 Area, the lower part of sequence B is composed of low to moderate amplitude clinoform foresets, which are interpreted as marine slope facies (Plates BS4, northern end, and BS5).

Thickness and Distribution. In the non-deformed part of the 1002 Area and offshore in Camden Bay, sequence B forms a northward thickening wedge ranging from less than 3,000 to more than 6,000 ft thick (Fig. BSG9). Sequence B has been thinned by erosion in the southwestern corner of the 1002 Area and along the crest of the Marsh Creek anticline. It is exposed at the surface or covered by Pleistocene and younger deposits along the north limb and east-plunging nose of the Marsh Creek anticline, and is absent due to erosion or non-deposition south of the axis of that structure. Starting near the coast, sequence B thickens dramatically in an offshore direction across syndepositional growth faults and attains thicknesses in Camden Bay as much as double those observed onshore.

In the eastern 1002 Area, sequence B is more than 5,000 feet thick in some structural lows and appears to thin onto structural highs, where it is either

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exposed at the surface, covered by Pleistocene and younger deposits, or completely absent due to erosion.

Ties and Age. Sequence B has been tied to numerous wells and several outcrops. Seismic control permits correlation into several wells in State lands west of ANWR, including the Alaska State J-1, Leffingwell, and West Staines #2, and correlation to a several wells offshore, including the Alaska State A-1, Wild Weasel, Hammerhead, and Kuvlum (Fig. BSG1). These correlations indicate sequence B comprises part of the Sagavanirktok Formation, and paleontological control from those wells indicate sequence B is Oligocene in age. Sequence B has been correlated to the Kugmallit sequence in the Beaufort-MacKenzie Basin of Canada (Dietrich and Lane, 1992; Dixon, 1992; Dixon and others, 1992) through direct ties to public domain seismic data in the Demarcation sub-basin (area of “3-mile boundary” label in Fig. BSG1).

Within the 1002 Area, sequence B correlates to exposures of the Sagavanirktok Formation near the eastern end of Marsh Creek anticline along Carter Creek. These exposures have been dated as Oligocene by McNeil and Miller (1990).

Depositional Facies. Despite the fact that sequence B occurs at or near the surface over large parts of the 1002 Area, outcrops are small, scattered, and of poor quality. Consequently, relatively little is known about depositional facies although individual exposures in the western 1002 Area display sedimentary structures that suggest deposition in marine shelf through fluvial environments. Fouch and others (1990) studied the exposures of Oligocene strata along Carter Creek and interpreted the facies as marine shelf and prodelta deposits.

Hydrocarbon Potential. Sequence B has essentially no source-rock potential in the 1002 Area and appears to have little source-rock potential in the eastern 1002 Area and offshore.

Sequence B has excellent reservoir and trap potential. Throughout the topset seismic facies, sequence B contains sandstones that display high porosity and permeability. Trapping potential exists as the result of basinward shelf edge migration and growth faulting. The former has resulted in apparent up-dip pinch-out of topset seismic facies, which may be sand prone, and the latter is common where sequence B topset facies directly overlie clinoform foresets of

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either sequence B or sequence C. In those settings, growth faults have locally rotated topset facies into favorable trap geometries (Plates BS4 and BS5). Stratigraphic trapping potential appears to be especially favorable along the trend of a paleo shelf edge that trends along the present coastline from Point Thomson to the southernmost extend of Camden Bay, and then onshore into the eastern part of the 1002 Area (Fig. BSG11). Several offshore wells have tested oil from shelf edge and structural traps in sequence B, and similar potential exists within the 1002 Area.

Sequence B also is involved in several anticlines that appear to have four-way dip. Some of these closures appear to be related to rotation along syndepositional normal faults whereas others appear to be exclusively compressional in origin. These anticlines display two dimensional closure of 1 to 4 miles and represent possible traps with significant volumetric potential.

Petroleum potential of sequence B, including both stratigraphic and structural traps within the non-deformed part of the 1002 Area, is assessed as part of the *Topset play*.

Sequence A

Sequence Definition and Boundaries. Sequence A is defined on seismic sections in the northwestern ANWR 1002 Area and locally in the eastern 1002 Area, as well as adjacent State lands and offshore areas where it is tied to well control. The base of sequence A is defined by a mildly undulating surface between parallel topset reflectors in the upper part of sequence B and lower part of sequence A (Plates BS1, BS2, and BS4).

The top of sequence A is not preserved in the study area. Onshore, sequence A is truncated either by Pliocene-Pleistocene deposits or by the present land surface. Offshore, sequence A is truncated at the base of Pliocene-Pleistocene deposits.

Seismic Facies. Wherever it is present within the 1002 Area and offshore in Camden Bay, the entire thickness of sequence A is composed of topset seismic facies interpreted as marine shelf through non-marine deposits. Offshore from eastern ANWR, sequence A displays progradational clinoform seismic facies within the Barter sub-basin (north of Aurora well in Fig. BSG1), where it is interpreted as marine shelf and slope deposits.

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Thickness and Distribution. Sequence A is exposed at the surface or buried beneath Pliocene-Pleistocene deposits across much of the ANWR coastal plain and no original stratigraphic thicknesses appear to be preserved. The preserved portion of sequence A forms a wedge that thickens from a zero edge onshore to more than 6,000 ft in Camden Bay (Fig. BSG10). In Camden Bay and farther offshore, sequence A thickens dramatically across growth faults.

Ties and Age. Sequence A has been tied to several wells and a few outcrops. Seismic control permits correlation into several wells in State lands near the coast and offshore from ANWR, including the West Staines #2, Alaska State A-1, Wild Weasel, Hammerhead, and Kuvlum (Fig. BSG1). These correlations indicate sequence A comprises the upper part of the Sagavanirktok Formation, and paleontological control from those wells indicates sequence A is Miocene in age. Sequence A has been correlated to the MacKenzie Bay sequence in the Beaufort-MacKenzie Basin of Canada (Dietrich and Lane, 1992; Dixon, 1992; Dixon and others, 1992) through direct ties to public domain seismic data in the Demarcation sub-basin (area of “3-mile boundary” label in Fig. BSG1).

Depositional Facies. Despite the fact that sequence A occurs at or near the surface over large parts of the 1002 Area, outcrops are small, scattered, and of poor quality. Consequently, relatively little is known about depositional facies although individual exposures in the western 1002 Area display sedimentary structures that suggest deposition in marine shelf through fluvial environments.

Hydrocarbon Potential. Sequence A has essentially no source-rock potential in the 1002 Area and offshore.

Sequence A has excellent reservoir potential. Throughout the topset seismic facies, sequence A contains sandstones that display high porosity and permeability. Trapping potential appears to be poor to non-existent within ANWR because of the broad pattern of outcrop across the coastal plain and the absence of trap geometries within the sequence. A possible exception may exist if permafrost provides near surface sealing potential. Sequence A may have trap potential offshore, particularly where it is associated with large displacement growth faults. Petroleum potential of sequence A is assessed as part of the *Topset play.*

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SUMMARY

Brookian strata of the ANWR 1002 Area represent a composite of depositional sequences whose total thickness ranges from 12,000 to 22,000 feet. These strata contain significant source, reservoir, and trap potential in sedimentary facies that range from turbidites through fluvial channels. Brookian strata of the ANWR 1002 Area, and adjacent State lands and offshore areas, have been subdivided into seven seismic sequences that are used as the basis for assessing the petroleum potential of the ANWR non-deformed area.

The oldest two seismic sequences represent flooding of the LCU and the distal facies of depositional systems that prograded into the North Slope foreland basin west of the ANWR. Sequence G (Cretaceous) includes facies deposited during marine transgression of the Lower Cretaceous Unconformity (Kemik Sandstone, Thomson sand, and Pebble Shale Unit) as well as a condensed section (Hue Shale). This sequence contains facies that are potentially important source and reservoir rocks. Sequence F (late Cretaceous) comprises basinal mudstones and turbidite sandstones deposited as the distal toe of one or more clastic wedges. This sequence is thought to have little source and reservoir potential.

Sequence E (Paleocene) includes complex seismic facies that include a complete spectrum of sedimentary facies deposited in deep basin, marine slope, and marine shelf environments. These facies are interpreted as a possible lowstand systems tract and a highstand systems tract that displays evidence of multiple smaller scale, progradational sequences. This sequence has significant hydrocarbon potential. Prospective reservoir and trap combinations occur in turbidite facies throughout the undeformed part of the 1002 Area, and in shelf facies in the southwestern part of the 1002 Area. Sequence E may also contain source-rock potential, both within the ANWR and in the adjacent offshore.

Sequence D (late Paleocene - early Eocene) comprises marine shelf through fluvial facies. It is present only in the southwestern corner of the 1002 Area, owing to erosional truncation prior to the deposition of the overlying sequence C. Sequence D has good reservoir potential and moderate trap potential.

Sequence C (Eocene) is the most voluminous depositional sequence within Brookian strata. It contains both a well defined lowstand systems tract and a

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highstand systems tract. The lowstand systems tract was deposited as an apron against the lower portion of an northeast-dipping erosional surface that truncates older depositional sequences. The lowstand systems tract includes potential reservoir and trap combinations both in turbidite facies at the base of the erosional slope and within a "wedge" of strata that onlaps the erosional slope. The highstand systems tract displays the overall geometry of a progradational clinoform (foreset) and topset couple, although in detail it is a composite of many smaller scale depositional sequences. Potential reservoir and trap combinations within the highstand systems tract include marine sandstone shelf facies involved in growth fault traps, and perhaps turbidite facies deposited at the base of the marine slope. Potential reservoir sandstones of both shelf and turbidite facies also are involved in compressional structures that form favorable trap geometries.

Sequence B (Oligocene) comprises mostly marine shelf through deltaic (and perhaps fluvial) facies, although marine slope facies also are present in the northeastern part of the study area. This sequence displays excellent potential for reservoir and trap combinations, mostly involving marine sandstone shelf facies involved in growth fault traps that apparently formed near ancient shelf edges.

Sequence A (Miocene) comprises exclusively marine shelf through deltaic (and perhaps fluvial) facies throughout the ANWR. This sequence displays excellent reservoir potential, but relatively poor trapping potential.

ACKNOWLEDGMENTS

We appreciate significant input throughout the course of this study from Ken Bird and Gil Mull. We acknowledge the contributions of Myung Lee, Warren Agena, John Miller, and John Grow (seismic processing) as well as Norm Frederiksen and Wylie Poag (paleontology). Discussions with numerous North Slope geologists have helped shape our insights and interpretations; Mark Myers and Dick Garrard have been particularly helpful. Incisive reviews by Linda Smith-Rouch and Kevin Evans helped clarify our presentation. Last but not least, we thank Sami Superdock for her contributions to three successful field seasons.

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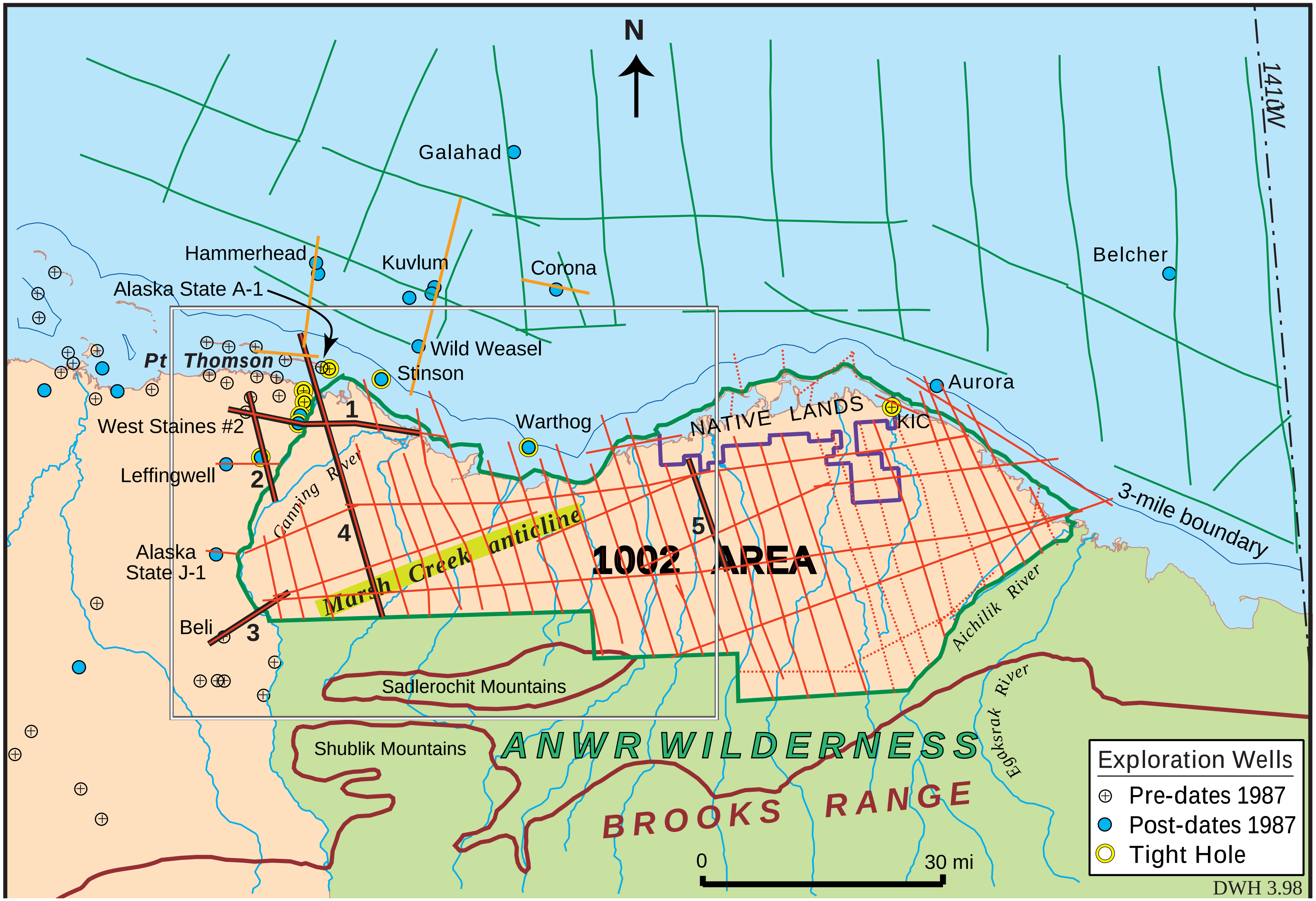

Fig. BSG1. Map of ANWR 1002 Area, key wells (selected well names shown), Marsh Creek anticline, and seismic grid. Red, green and orange lines are approximate locations of seismic lines; red solid lines = proprietary ANWR seismic lines used in this study; green lines = USGS seismic lines (Grantz and others, 1994); and orange lines = published industry lines (Craig and others, 1985; Scherr and others, 1991). Red dotted lines are proprietary ANWR seismic lines not used in this study. White rectangle defines area of maps shown in subsequence figures. Black numbered lines are plates accompanying this paper.

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Fig. BSG2. Schematic summary of depositional sequences defined within Brookian strata. White circles with letters identify sequences defined in this paper. LCU = Lower Cretaceous unconformity; BTU = basal Tertiary unconformity.

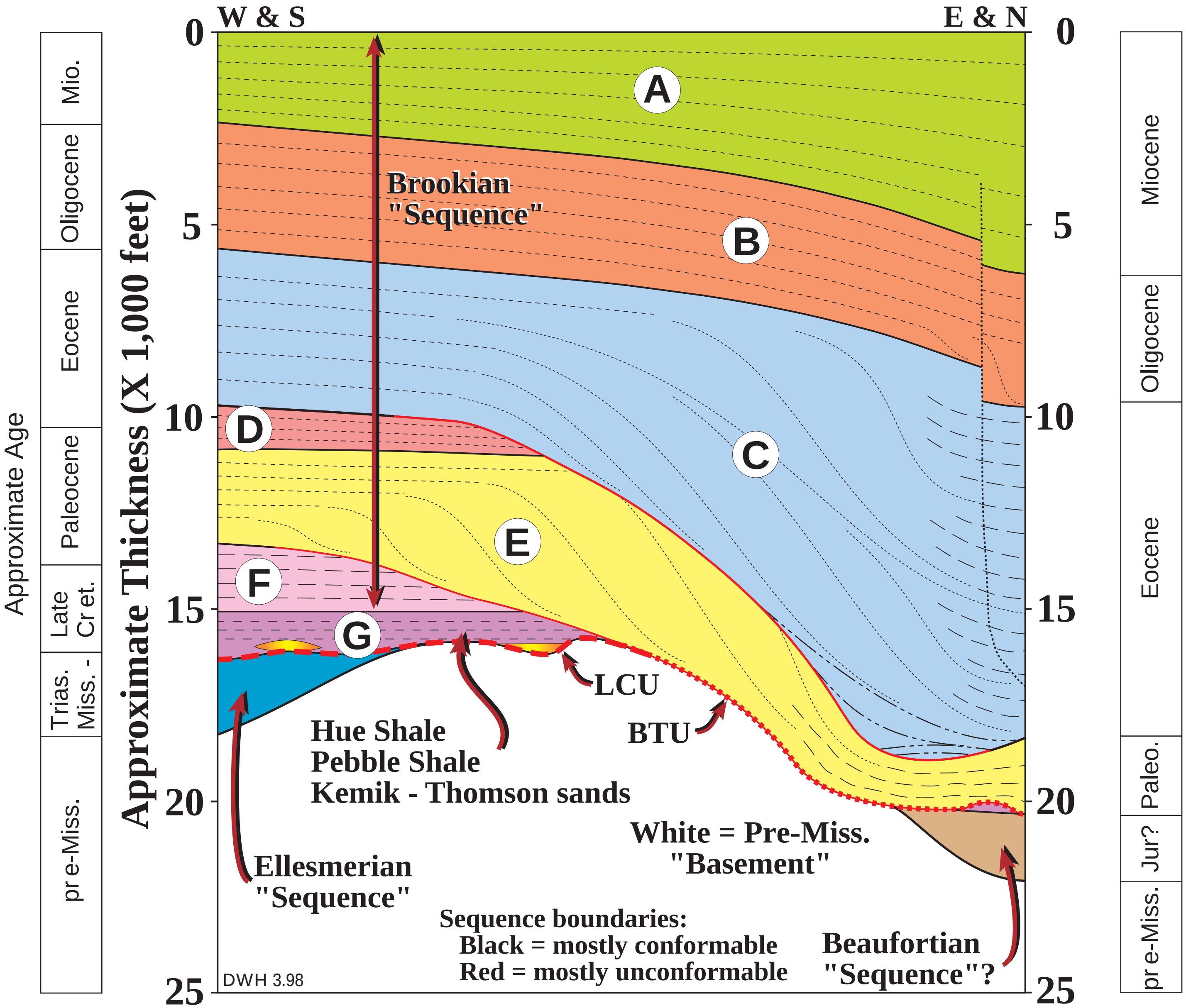

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Fig. BSG3. Schematic illustration of relationships between Brookian depositional sequences defined in this study and previously defined stratigraphic units.

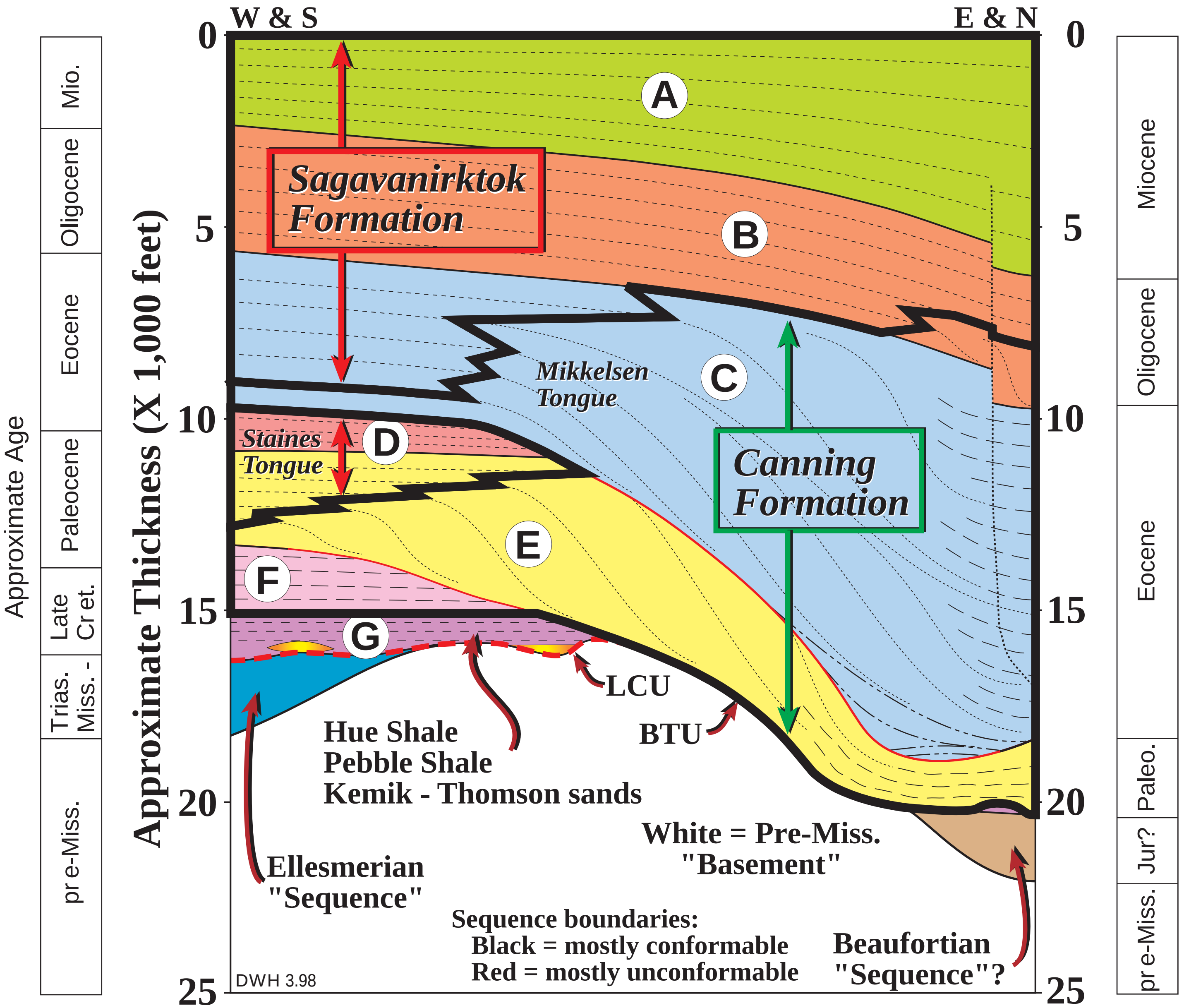

Fig. BSG4. Schematic illustration of topset, turbidite, wedge, Thomson, and Kemik plays defined within Brookian and associated depositional sequences.

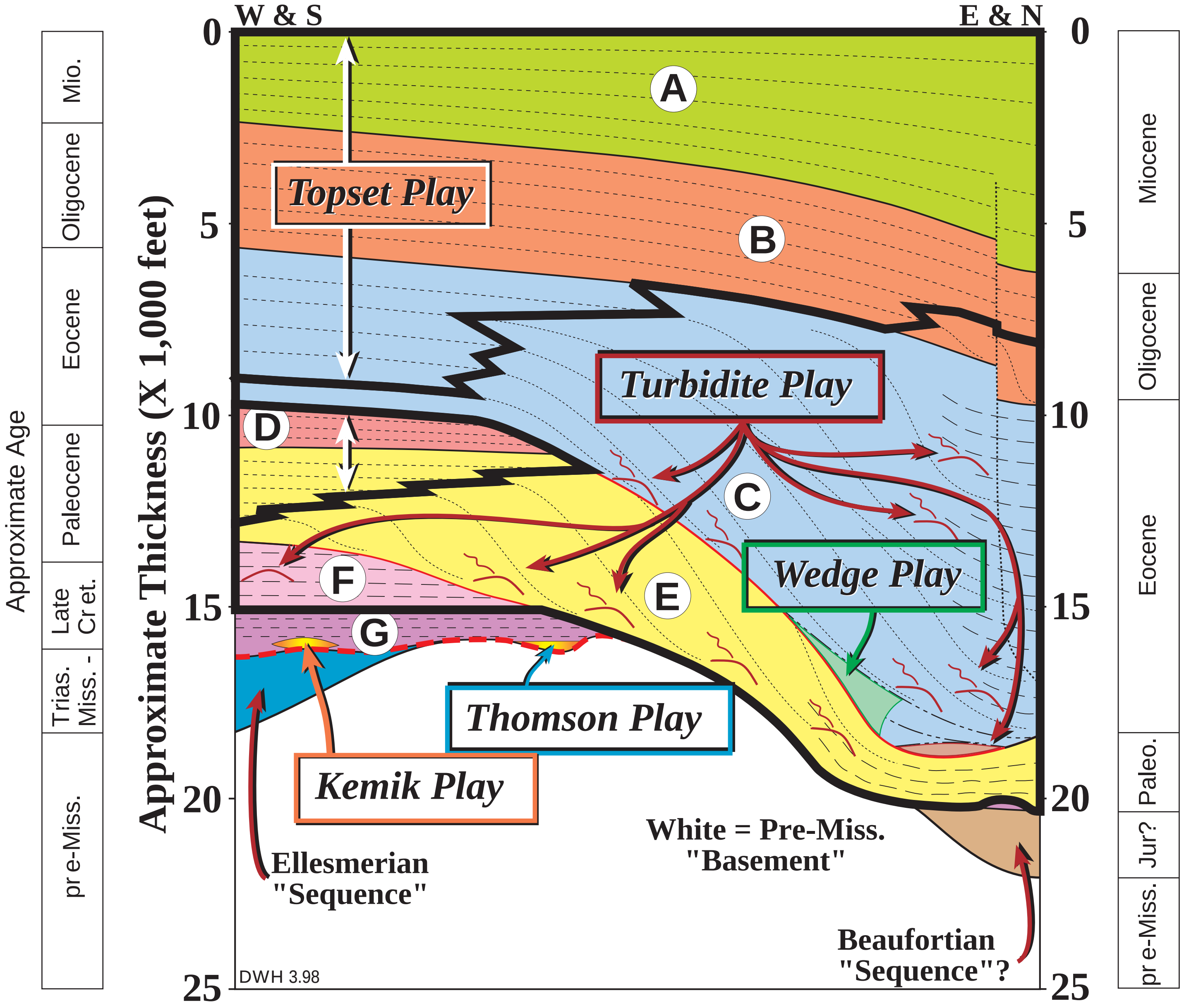

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Fig. BSG5. Isopach map of combined thicknesses of Brookian depositional sequences F and G. MCA = Marsh Creek anticline.

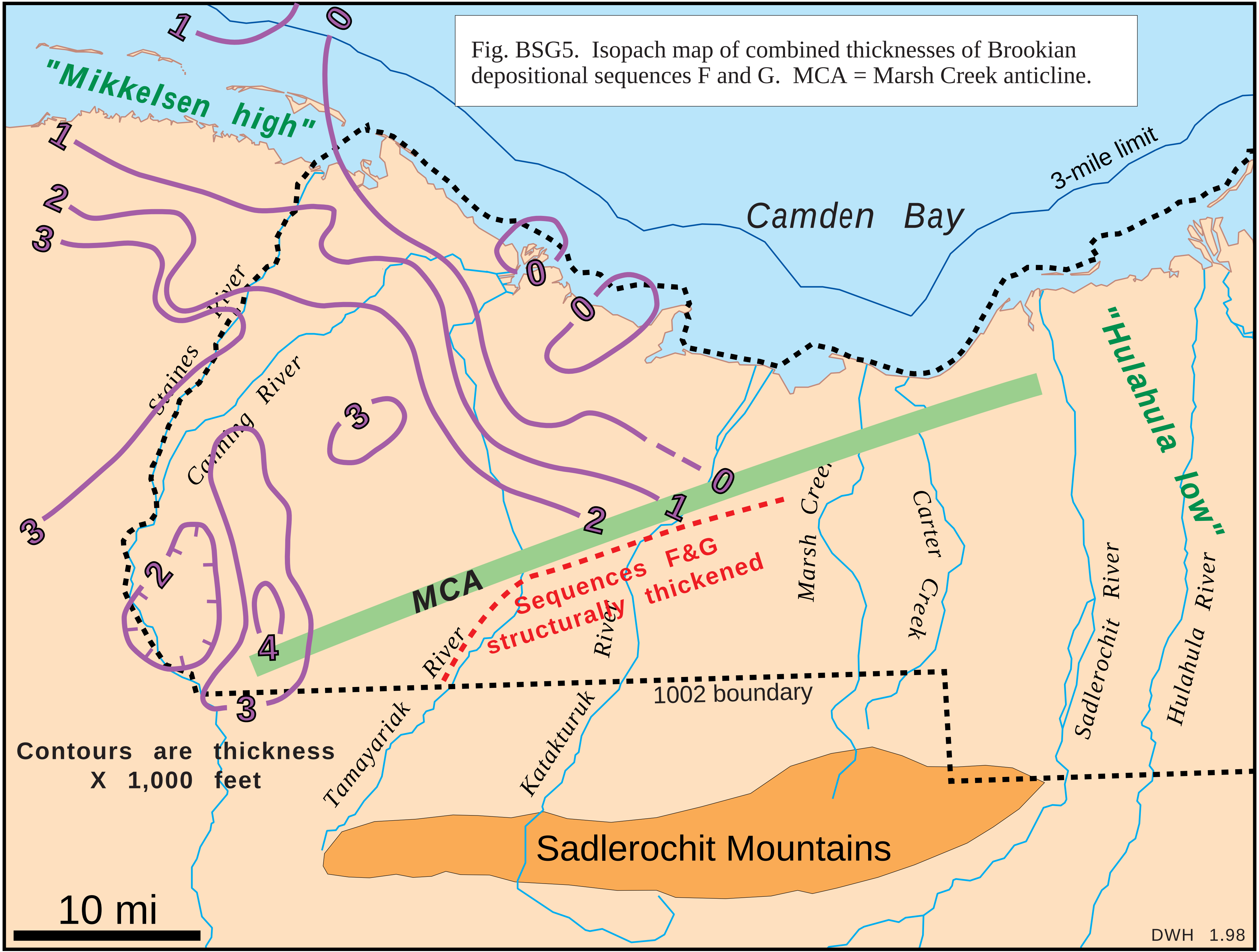
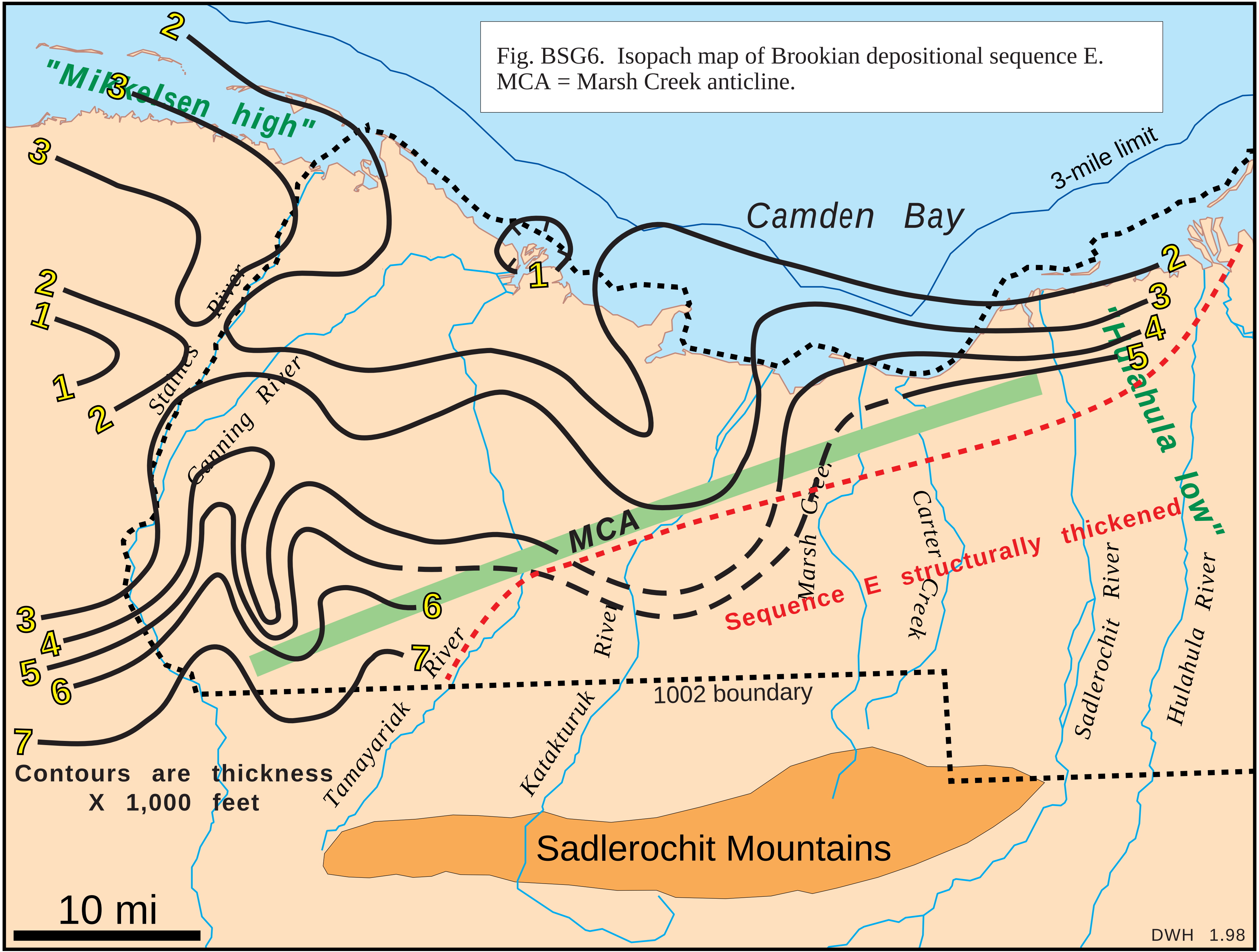


Fig. BSG6. Isopach map of Brookian depositional sequence E.
MCA = Marsh Creek anticline.



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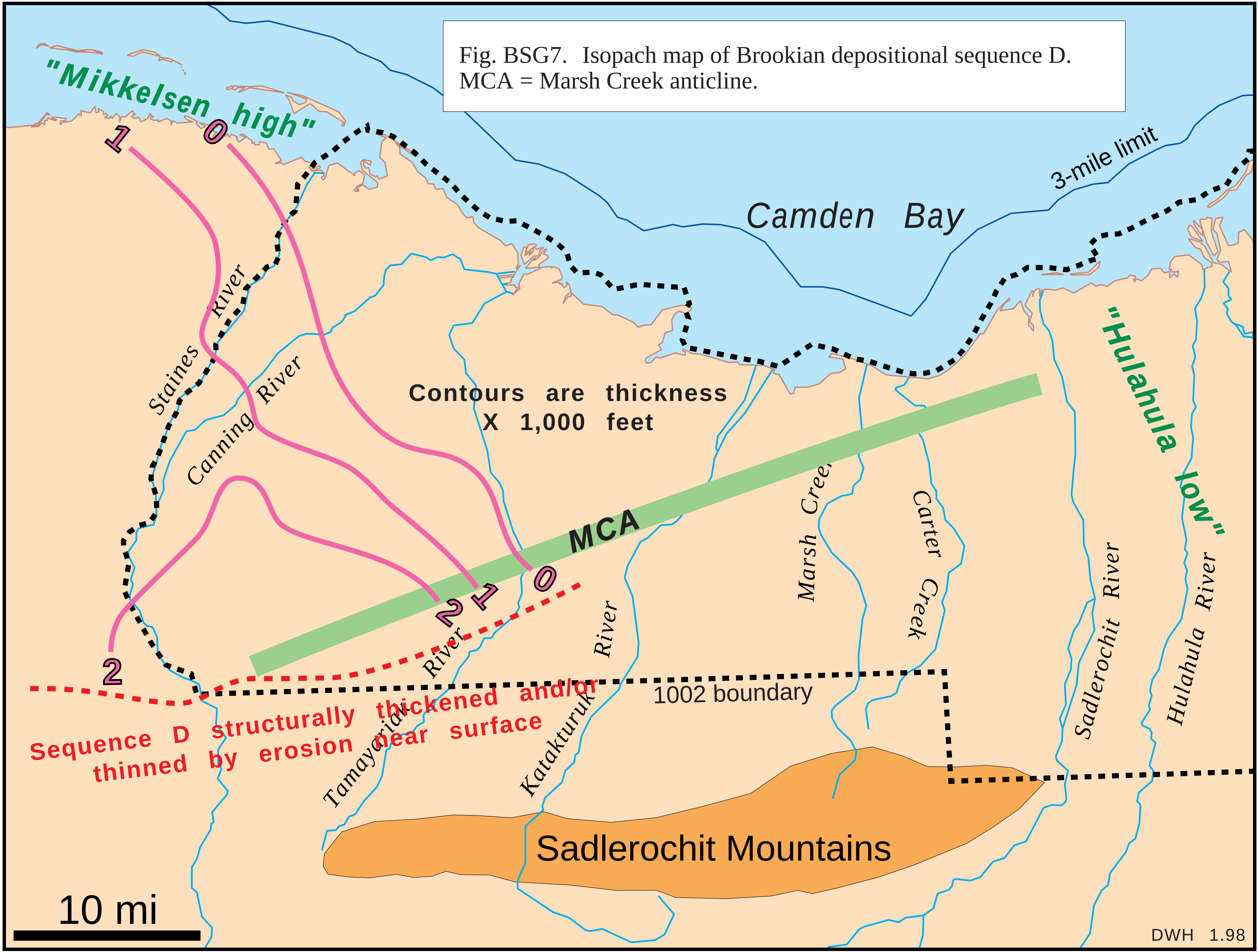

Fig. BSG7. Isopach map of Brookian depositional sequence D. MCA = Marsh Creek anticline.

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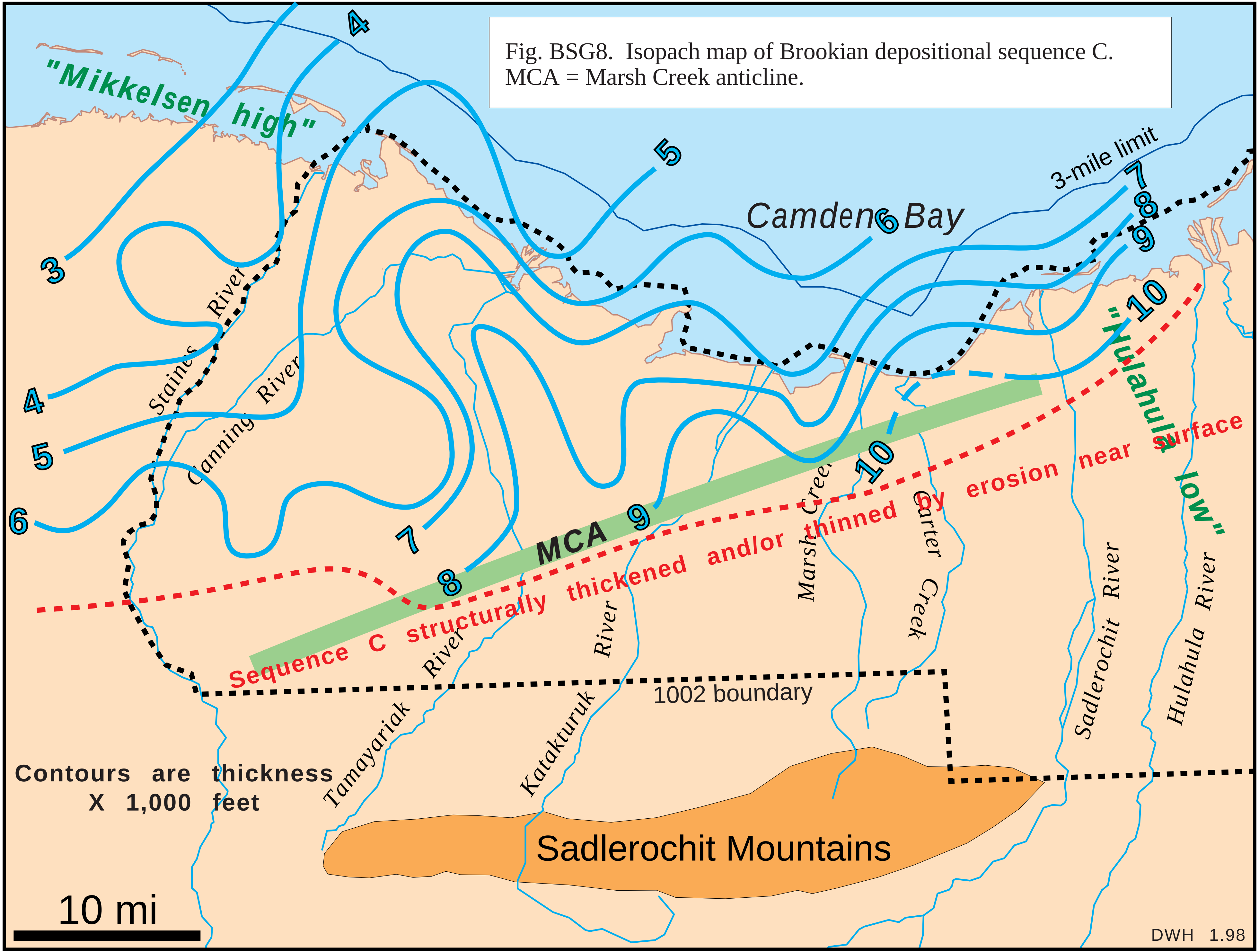

Fig. BSG8. Isopach map of Brookian depositional sequence C.
MCA = Marsh Creek anticline.

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Fig. BSG9. Isopach map of Brookian depositional sequence B. MCA = Marsh Creek anticline.

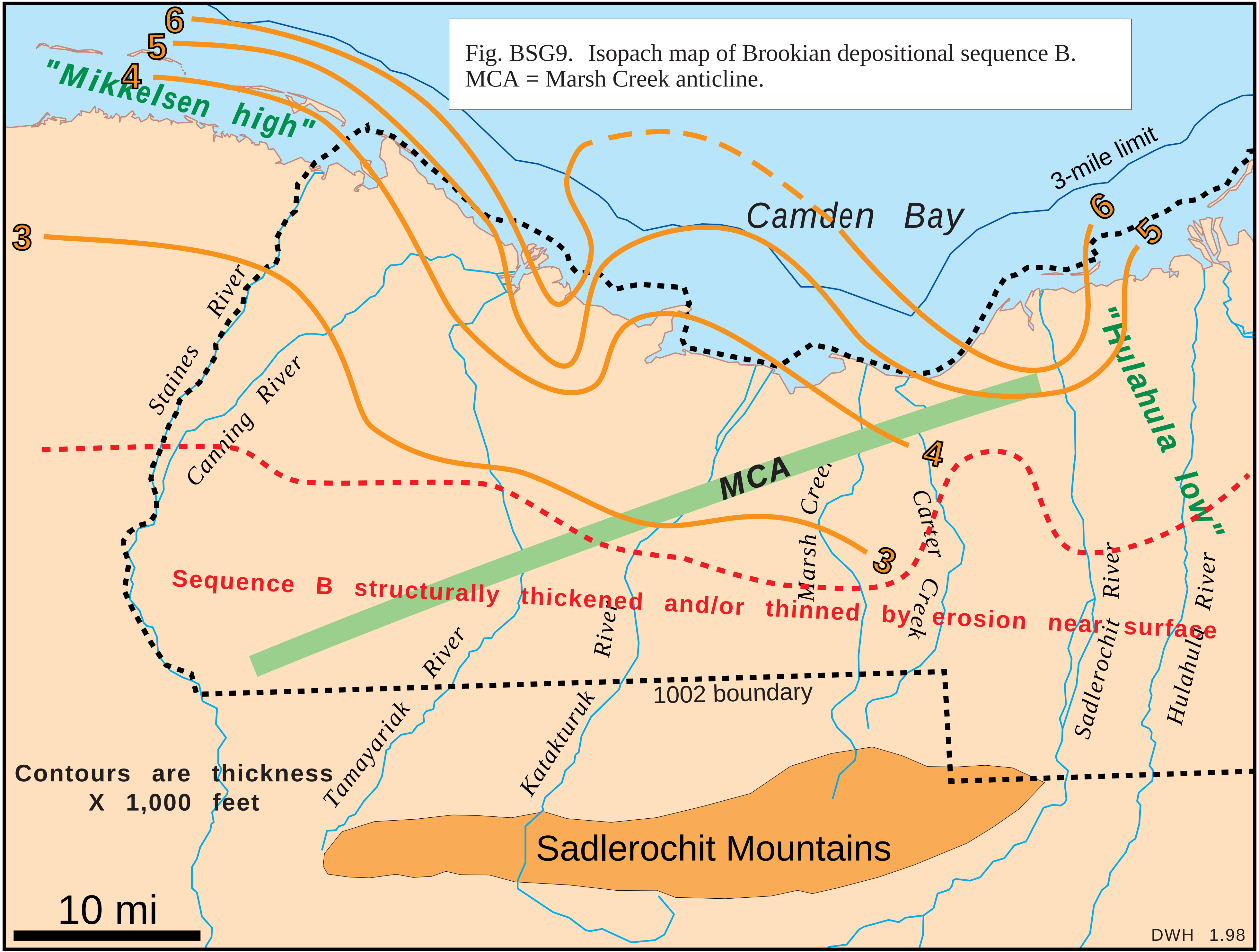

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Fig. BSG10. Isopach map of Brookian depositional sequence A. MCA = Marsh Creek anticline.

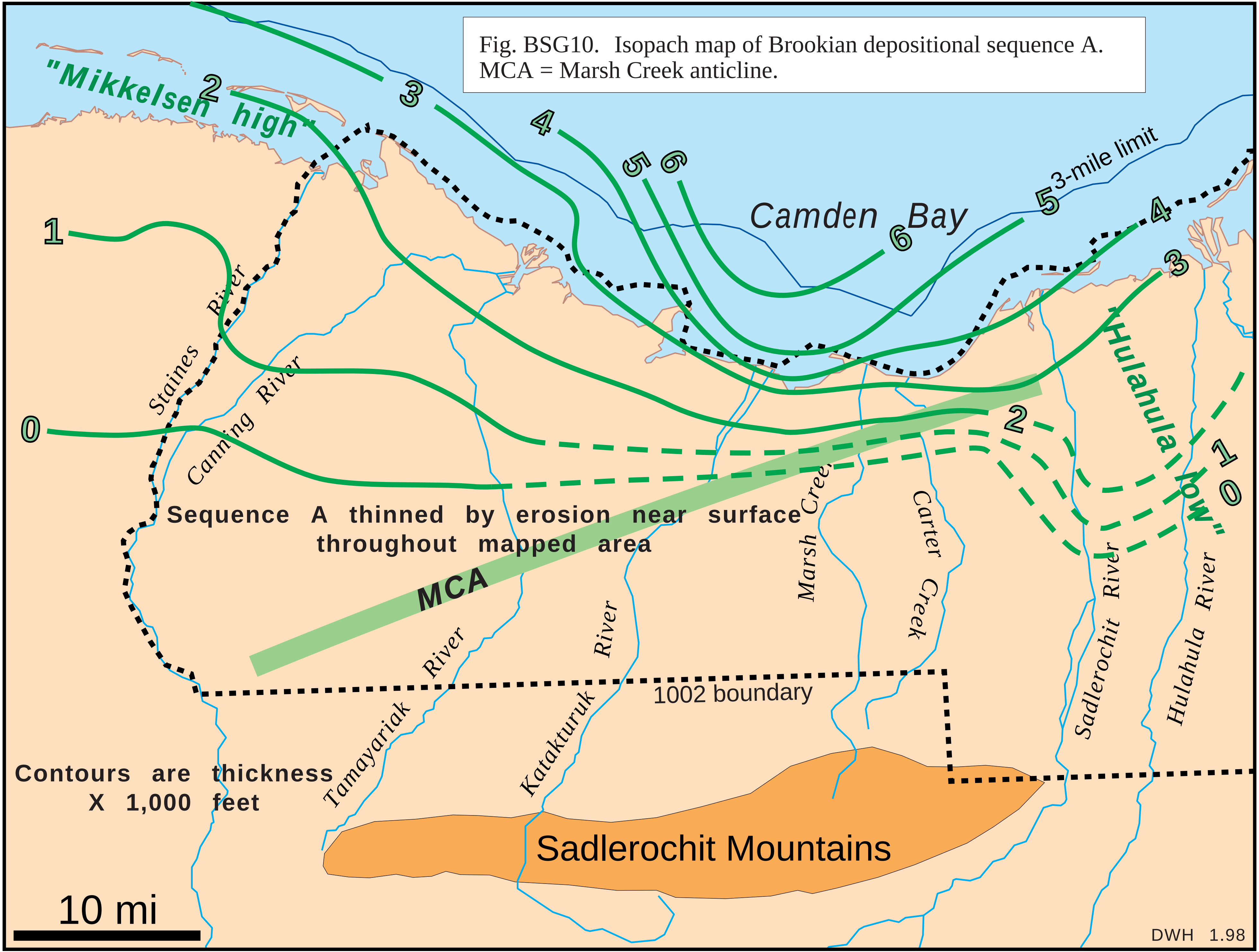

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Fig. BSG11. Map showing location of five shelf edges mapped within Brookian depositional sequences. In all cases, shelf edges faced east or northeast (i.e., deeper, open ocean to east - northeast). MCA = Marsh Creek anticline.

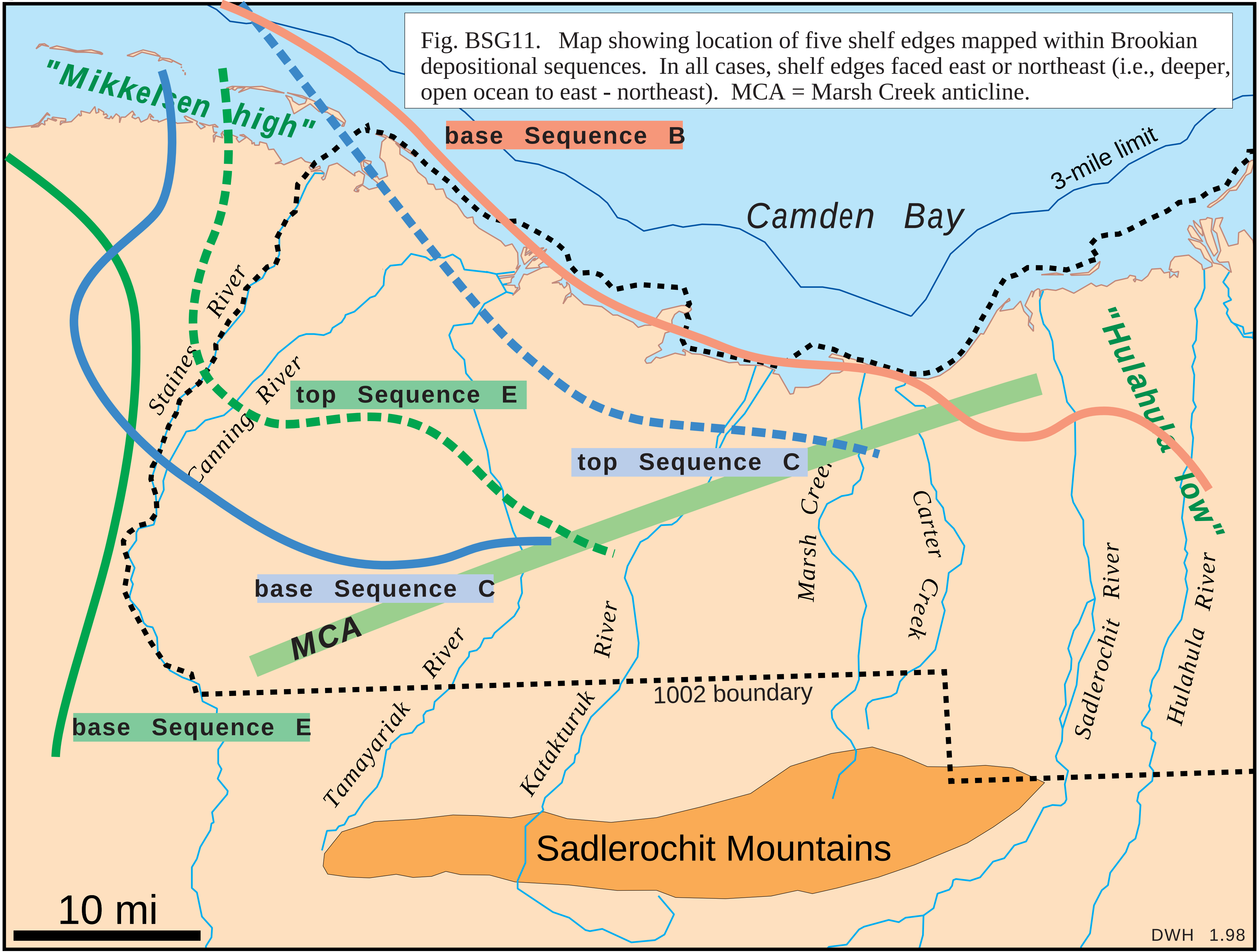

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Fig. BSP1 Outcrop photo of Late Cretaceous turbidites within ANWR 1002 Area. Outcrop located on east fork of Tamayariak River; view to the northeast. White rectangle shows location of photo in Figure BSP2.

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Fig. BSP2 Closer view of thin bedded turbidite sandstones in outcrop shown in Figure BSP1.

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Fig. BSP3 Outcrop photo of sandstone inferred to represent incised turbidite channel deposit. The sandstone is an amalgamation of individual beds that average about three feet thick, each of which displays an erosive base and an abruptly finer grained top. Top of one such bed located at man’s right knee. Outcrop located on Canning River.

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Fig. BSP4 Outcrop photo of silty mudtones and thin bedded sandstones inferred to represent marine slope deposits. Note broad truncation surface (indicated by white arrows labeled “t”), which may imply slumping of underlying slope deposits or erosive channeling of slope facies. Man inside white circle for scale. Outcrop located on Canning River.

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Fig. BSP5 Outcrop photo of interbedded sandstones and mudstones inferred to represent marine shelf deposits. All sandstone beds display sharp, erosive bases and hummocky stratification. Thick sandstone at left end of exposure is heavily oil stained. Outcrop located on Canning River.

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Fig. BSP6 Outcrop photo of hummocky bedded sandstone just down section from interval shown in Figure BSP5. Well exposed hummocky bedding visible between red arrows. Hammer inside red circle for scale.

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Fig. BSP7 Outcrop photo of sandstone displaying erosive base (white line near river level) and accretionary bedding (pairs of white arrows), suggesting deposition in a meandering channel. Outcrop located on Canning River.

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PLATE BS1

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Plate BS1

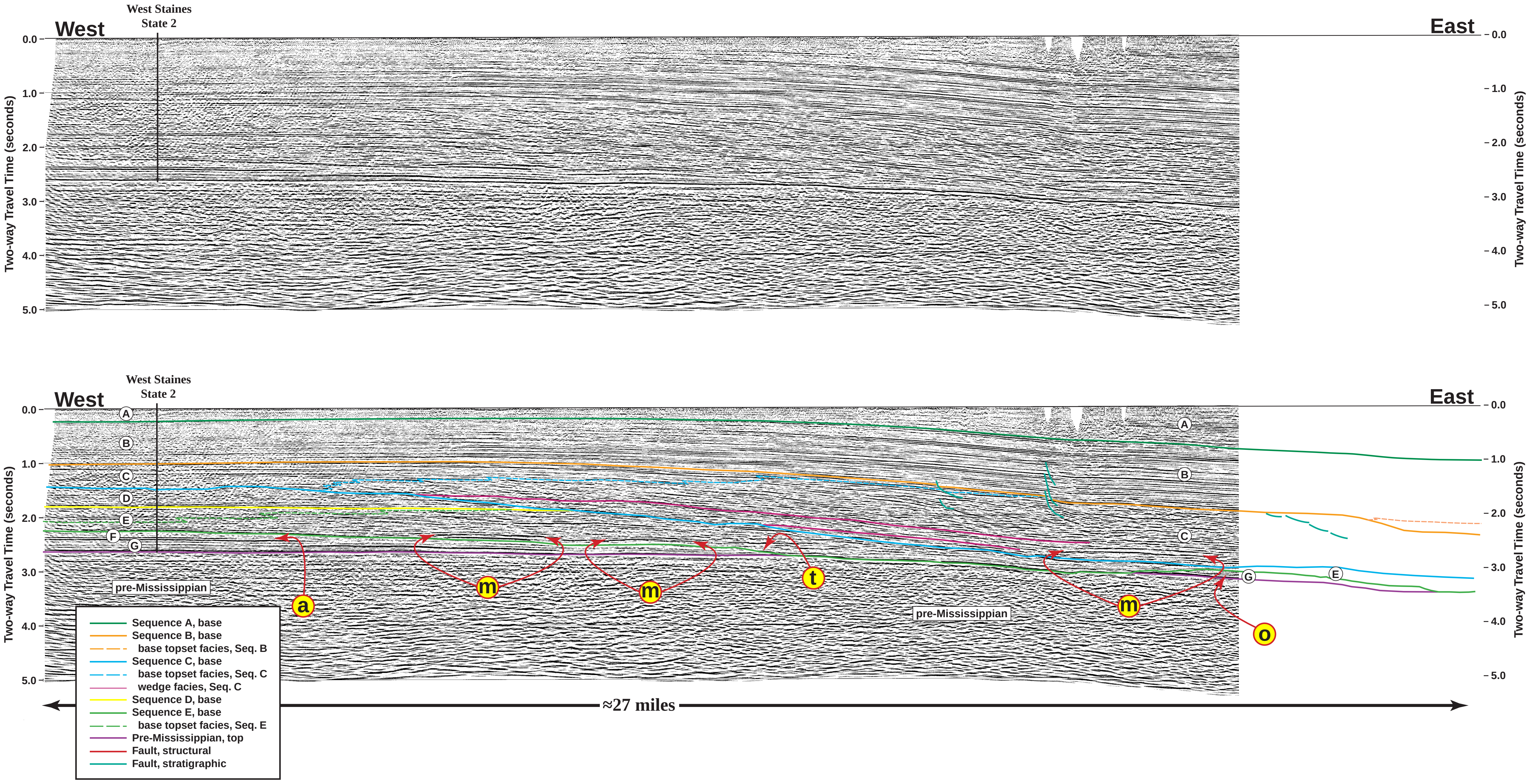

Plate BS1. Seismic line AN84-1 illustrating inferred sequence boundaries within Brookian strata. Sequence interpretations were extended eastward using seismic line ANV84-1, which cannot be shown because of proprietary status. Sequences defined in text are identified by capital letters in white circles. Yellow circles identify the following features: a = seismic expression of boundary between sequences G and F; m = mounded features that may represent submarine fan mounds; o = inferred "outlier" of sequence G; t = apparent truncation of sequence G by erosion or slumping at base of sequence E.

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PLATE BS2

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Plate BS2

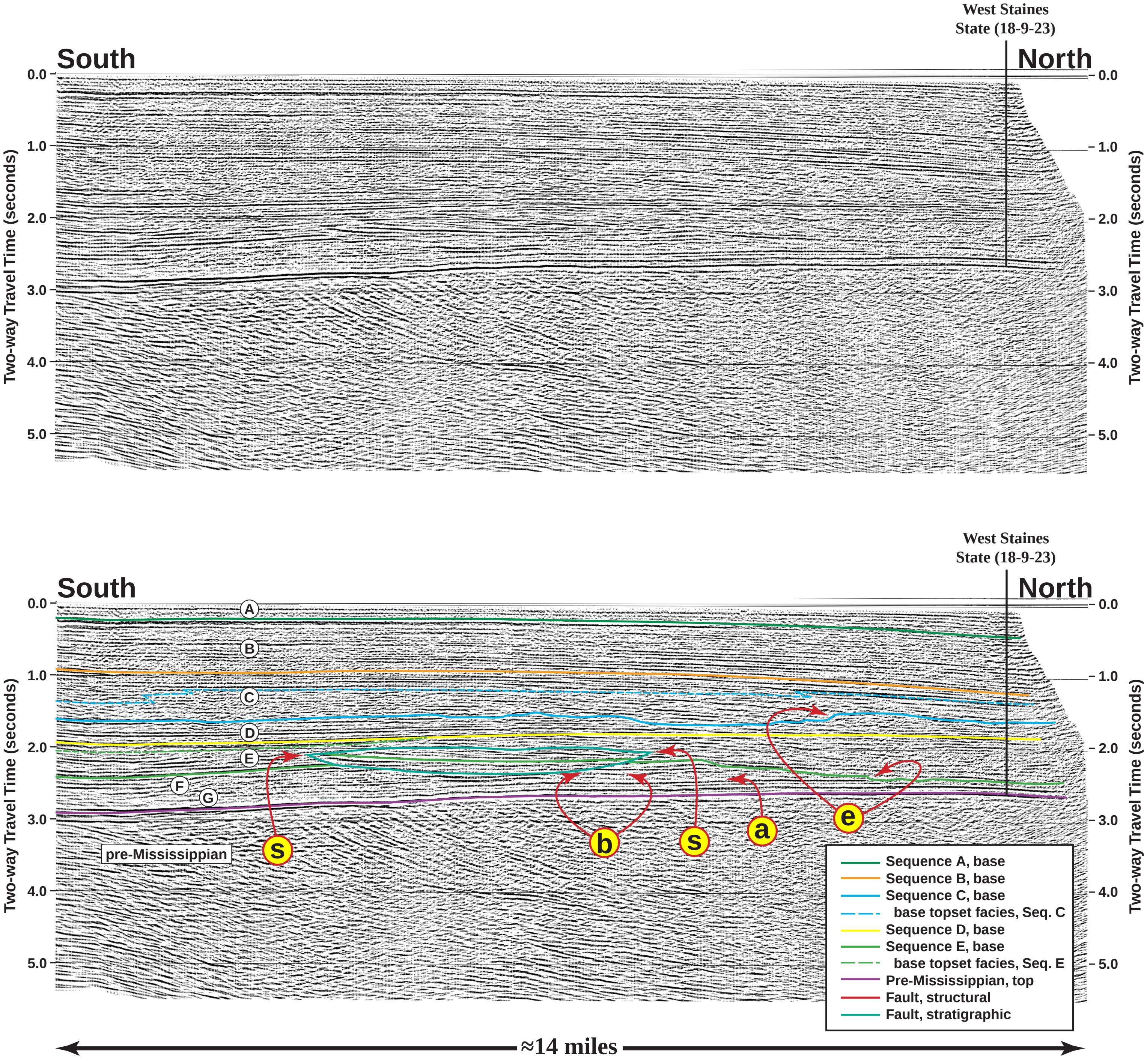

Plate BS2. Seismic line AN85-2 illustrating inferred sequence boundaries within Brookian strata. Sequences defined in text are identified by capital letters in white circles. Yellow circles identify the following features: a = seismic expression of boundary between sequences G and F; b = subtle mounded feature within sequence F that may represent submarine fan mound; e = apparent erosion at bases of sequences E and C; s = boundary of inferred slump involving slope and bottomset facies within sequences E and F.

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PLATE BS3

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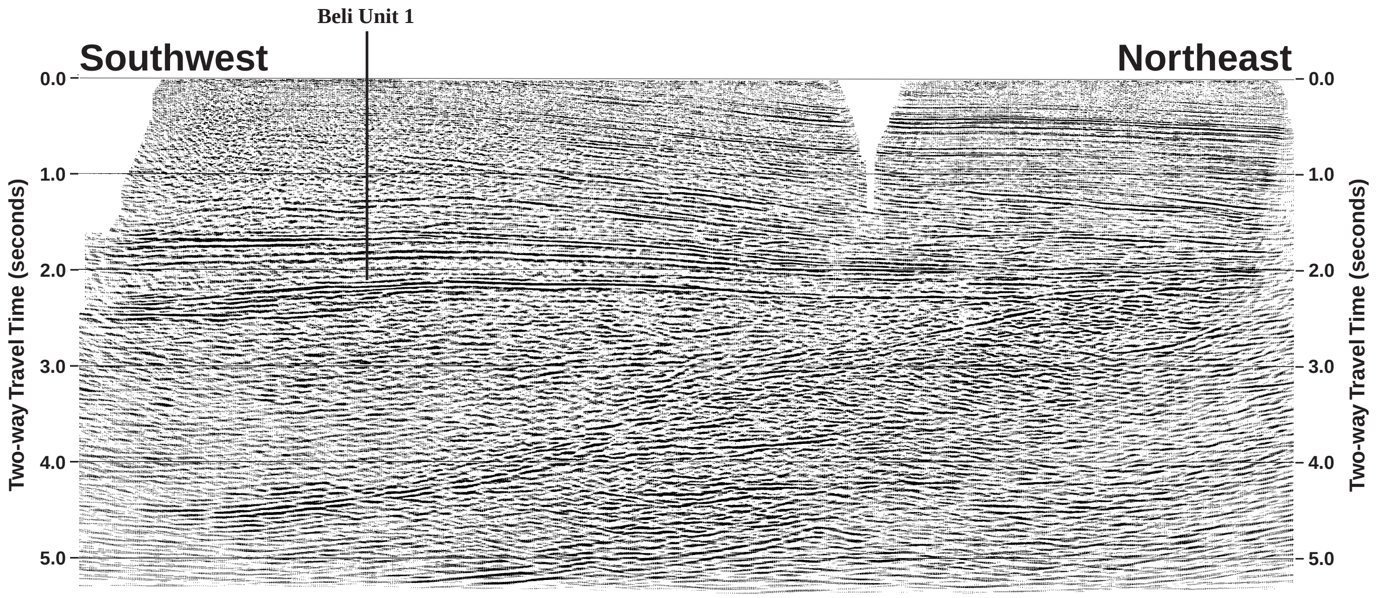
Plate BS3



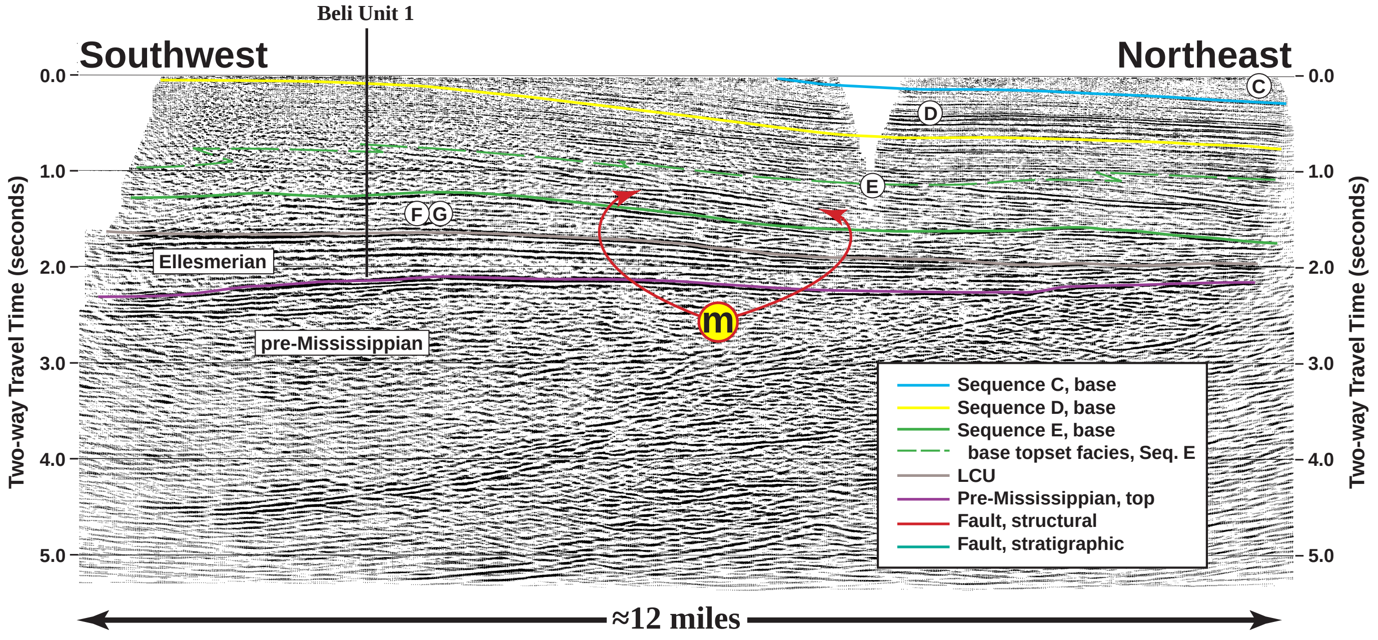


Plate BS3. Seismic line AN84-5 illustrating inferred sequence boundaries within Brookian strata and truncation of Ellesmerian strata beneath the Lower Cretaceous Unconformity (LCU). Sequences defined in text are identified by capital letters in white circles. Yellow circles identify the following feature: m = mounded features inferred to represent submarine fan mounds.

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PLATE BS4

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Plate BS4

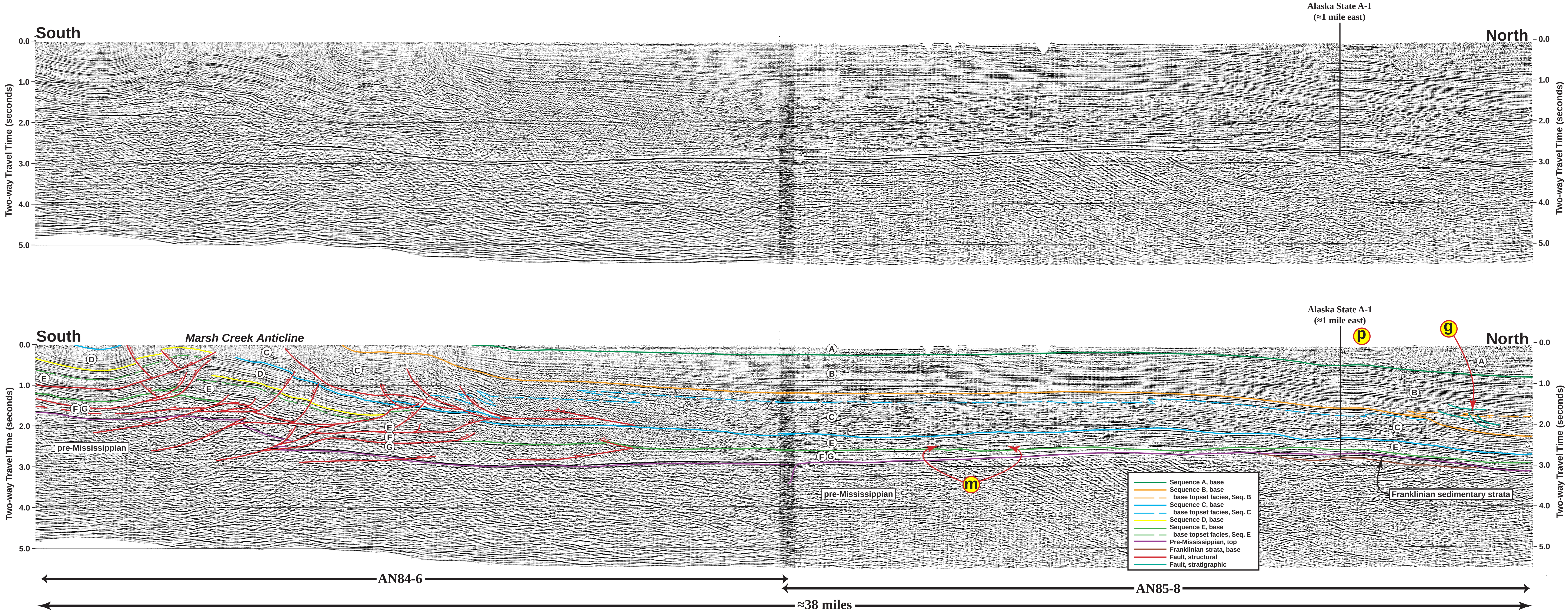

Plate BS4. Seismic lines AN84-6 and AN85-8 illustrating inferred sequence boundaries within Brookian strata. Note that some sequence boundaries could not be extended through structural complexities associated with the Marsh Creek Anticline. Sequences defined in text are identified by capital letters in white circles. Yellow circles identify the following features: g = inferred shelf-edge growth faults; m = mounded features that may represent submarine fan mounds; p = seismic pull-up associated with Flaxman Island permafrost. Note seismic expression of Franklinian sedimentary strata near north end of line.

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PLATE BS5

Houseknecht and Schenk
Plate BS5

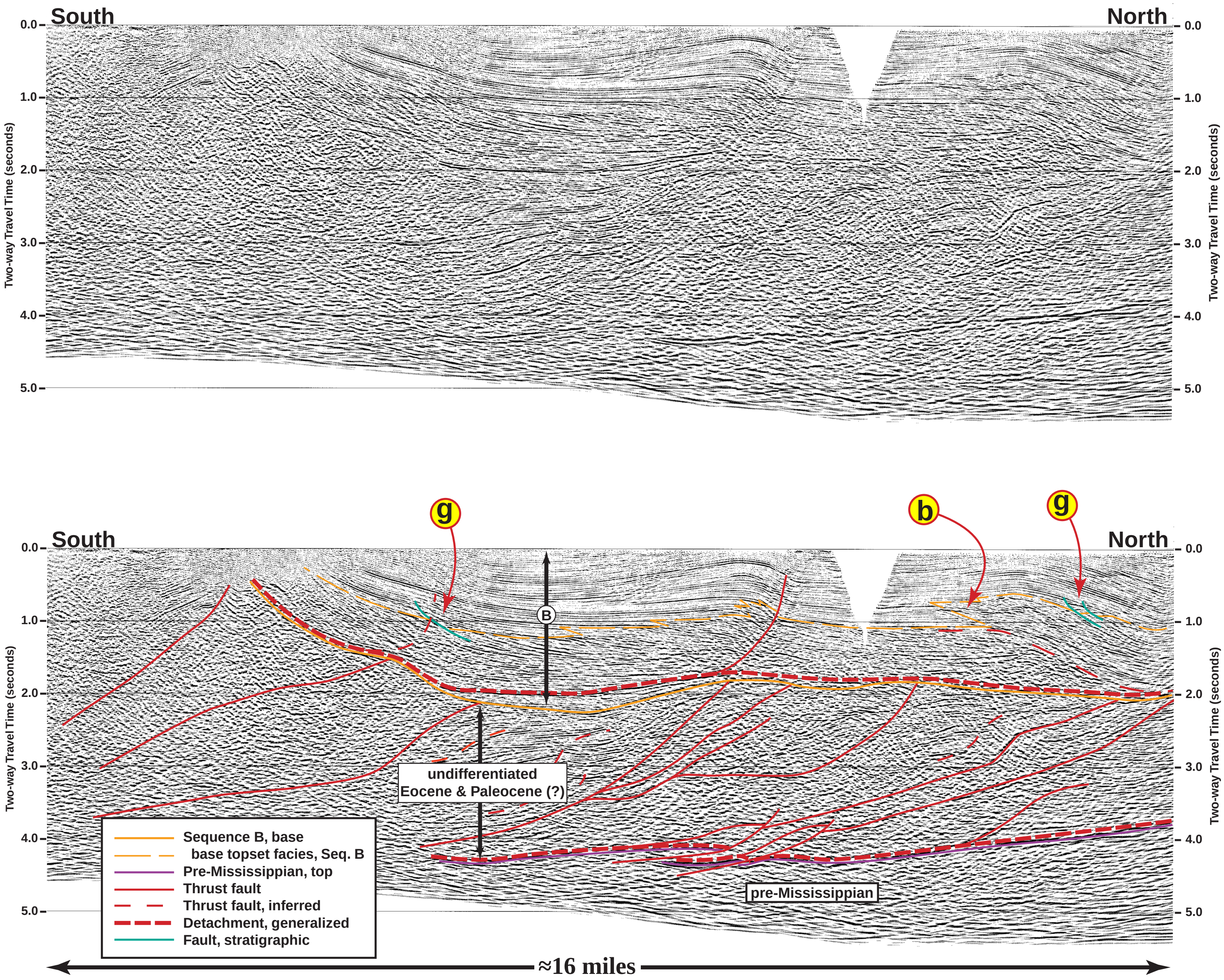

Plate BS5. Northern part of seismic line AN84-20 illustrating structural and stratigraphic relationships within Brookian strata in the eastern part of the 1002 Area. Undifferentiated Eocene and Paleocene(?) strata appear to be severely deformed by north-verging thrust faults. Overlying sequence B (Oligocene) appears to rest unconformably on severly deformed Eocene strata. Sequence B also is folded and thrust faulted, although not as severely as underlying Eocene strata. Yellow circles identify the following features: g = inferred shelf-edge growth faults; b = dramatic shelf-edge back-step that can be mapped across large part of study area.