Sentinel Hill Core Test 1: Facies Descriptions and Stratigraphic Reinterpretations of the Prince Creek and Schrader Bluff Formations, North Slope, Alaska

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U.S. Department of the Interior
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By Romeo M. Flores, Gary D. Stricker, Paul L. Decker, and Mark D. Myers

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Sentinel Hill Core Test 1: Facies Descriptions and Stratigraphic Reinterpretations of the Prince Creek and Schrader Bluff Formations, North Slope, Alaska

By Romeo M. Flores,[1] Gary D. Stricker,[1] Paul L. Decker,[2] and Mark D. Myers[1]

Abstract

The Sentinel Hill Core Test 1 well penetrated an intertonguing sequence of (1) the marine Schrader Bluff Formation in the depth intervals 950–1,180 ft and 690–751 ft, which consists of shoreface and offshore deposits that accumulated along a storm-dominated, barred shoreline; and (2) the nonmarine Prince Creek Formation in the depth intervals 751–950 ft and surface to 690 ft, which consists of fluvial channel, crevasse splay, backswamp, and ash fall deposits. The strata range in age from early Campanian to early Maastrichtian.

An erosional contact at a depth of 690 ft at the base of the upper unit of the Prince Creek Formation is interpreted as a major regional sequence boundary, and the overlying conglomeratic fluvial channel deposits are interpreted to have accumulated in a paleovalley. In its more proximal reaches along the Colville River, channels of this paleovalley cut down 75 ft into the lowermost Prince Creek Formation and the uppermost Schrader Bluff Formation. Farther offshore, the equivalent surface to the aforementioned paleovalley appears to be a subtle discontinuity between middle and lower Schrader Bluff Formation shelfal marine strata. Still farther offshore, the equivalent paleovalley surface is interpreted as a marine mass-wasting surface that locally cuts through the lowermost Schrader Bluff Formation and into the underlying Seabee Formation.

[1] U.S. Geological Survey.

[2] Alaska Division of Oil and Gas.

Introduction

The Sentinel Hill Core Test 1 well is one of many holes drilled by the U.S. Navy between 1944 and 1953 to evaluate petroleum potential in the Naval Petroleum Reserve No. 4 (now the National Petroleum Reserve in Alaska [NPRA]) on the Alaskan North Slope (Gryc, 1988) (fig. 1). This core hole was drilled primarily to ascertain the nature of the shallow subsurface formations on the Sentinel Hill anticline at the east edge of the NPRA. Drilled in 1947 to a total depth of 1,180 ft, the Sentinel Hill Core Test 1 well was positioned approximately 12 mi east and more than 1,000 ft structurally below the crest of the anticline, on an eastward-plunging subsurface structural nose (fig. 2); the well was subsequently abandoned as a dry hole. The well site is on a gravel bar on the west side of the Colville River at the base of 350-ft bluffs of the coal-bearing Upper Cretaceous Prince Creek Formation near the axis of a small surface syncline. The present study is in

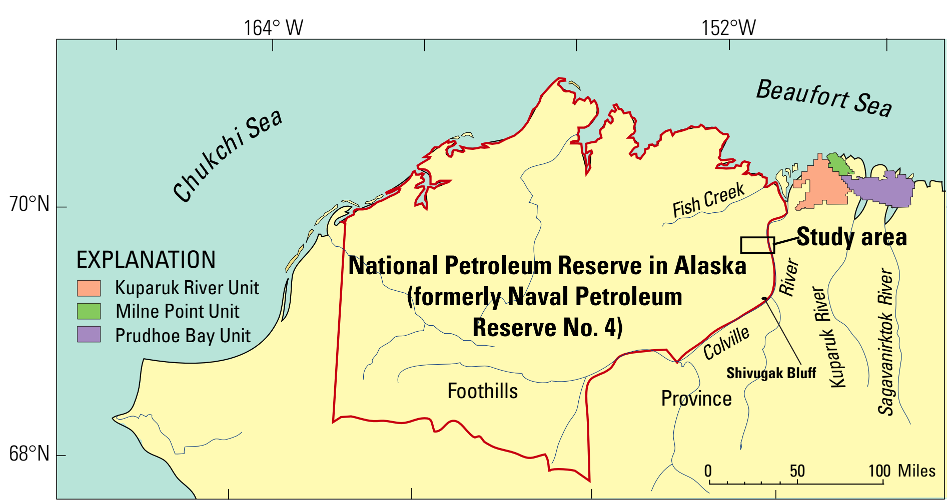


Figure 1. Map showing locations of National Petroleum Reserve in Alaska (formerly Naval Petroleum Reserve No. 4) and study area where Sentinel Hill Core Test 1 is located (see fig. 2).

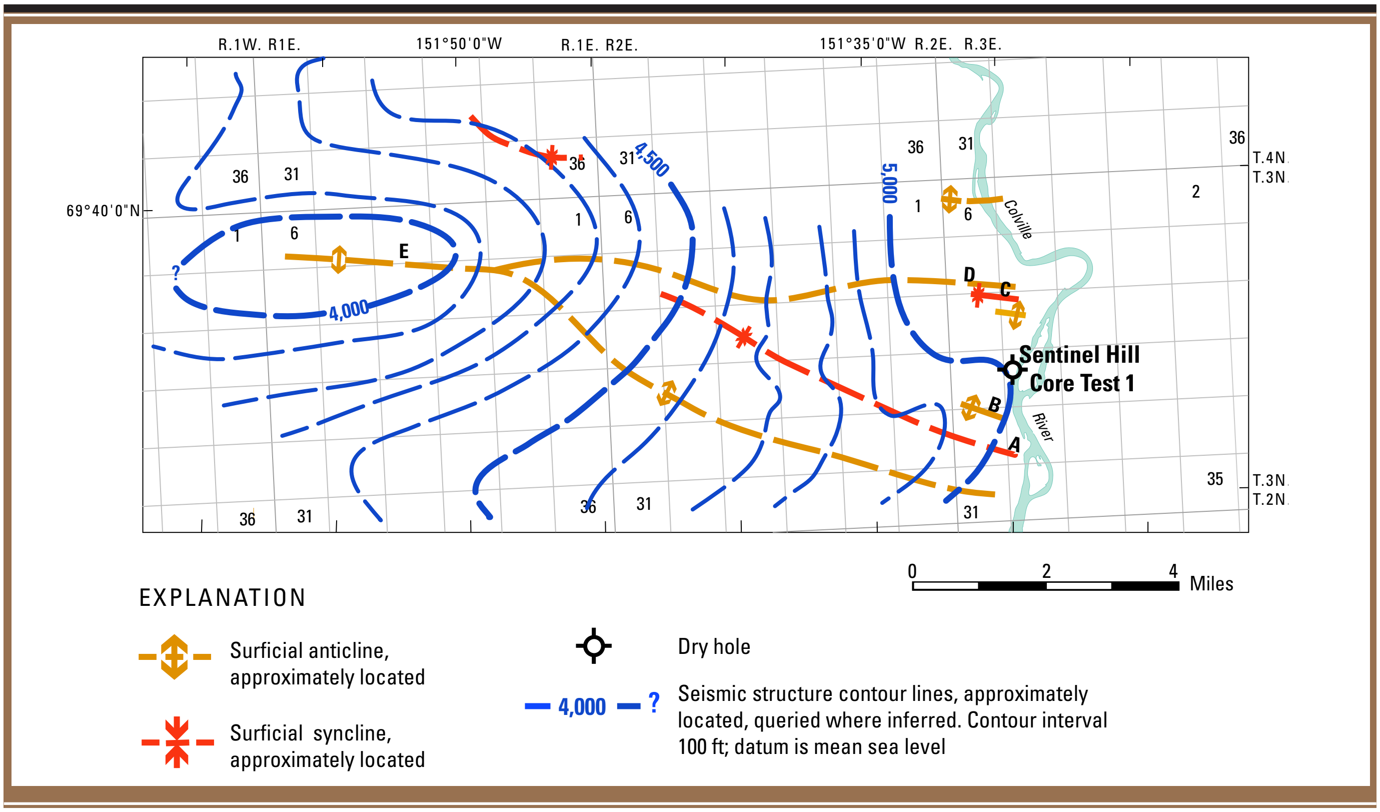


Figure 2. Map showing drill site for Sentinel Hill Core Test 1 at the base of the bluffs on the west bank of the Colville River, Alaska, in relation to seismically defined subsurface structure and surficial fold axes. Note that this core test was drilled more than 1,000 ft structurally below the crest of the anticline on an east-plunging subsurface nose. Letters A–E indicate the flexures recognized during field studies in 1945 (Robinson and Collins, 1959). Base map from 1:63,360-scale Umiat C-3 quadrangle, Alaska, 1955.

conjunction with recent outcrop studies conducted along the lower Colville River (Flores and others, 2007). Both studies describe and interpret the shallow subsurface stratigraphic relations differently than they were presented by Robinson and Collins (1959), because the present study and Flores and others (2007) are based on modern sequence stratigraphic principles and the revised stratigraphic nomenclature of Mull and others (2003).

Previous Lithostratigraphic Descriptions

The Sentinel Hill Core Test 1 well was continuously cored below a depth of 100 ft, a method that provided excellent stratigraphic information on the intertonguing nature of the Upper Cretaceous Schrader Bluff and Prince Creek Formations. Robinson and Collins (1959) identified the rock units as interbedded Kogosukruk Tongue of the Prince Creek Formation (nonmarine) and Sentinel Hill Member of the Schrader Bluff Formation (marine), both of which are parts of the Upper Cretaceous Colville Group (fig. 3), in the following ascending order: (1) Sentinel Hill Member of the Schrader Bluff Formation, thickness 231 ft; (2) Kogosukruk Tongue of the Prince Creek Formation, thickness 109 ft; (3) an upper Sentinel Hill Member, thickness 371 ft; and (4) an upper Kogosukruk Tongue, thickness 460 ft (fig. 3). These rock units were differentiated mainly on correlations with outcrops and on the presence of marine macrofossils and microfossils. The nomenclature for these and many other stratigraphic units of the Brookian sequence has been substantially revised (Mull and others, 2003) such that the names Kogosukruk Tongue and the Sentinel Hill Member, as well as the Colville Group, are now abandoned. Both this study and that by Flores and others (2007) continue to recognize the fundamental intertonguing nature of the Prince Creek and Schrader Bluff Formations in the Sentinel Hill Core Test 1, as described in Robinson and Collins (1959), but the placement and genetic significance of the intertonguing contact are reinterpreted as shown in figure 4 (see fig. 3 in Flores and others, 2007).

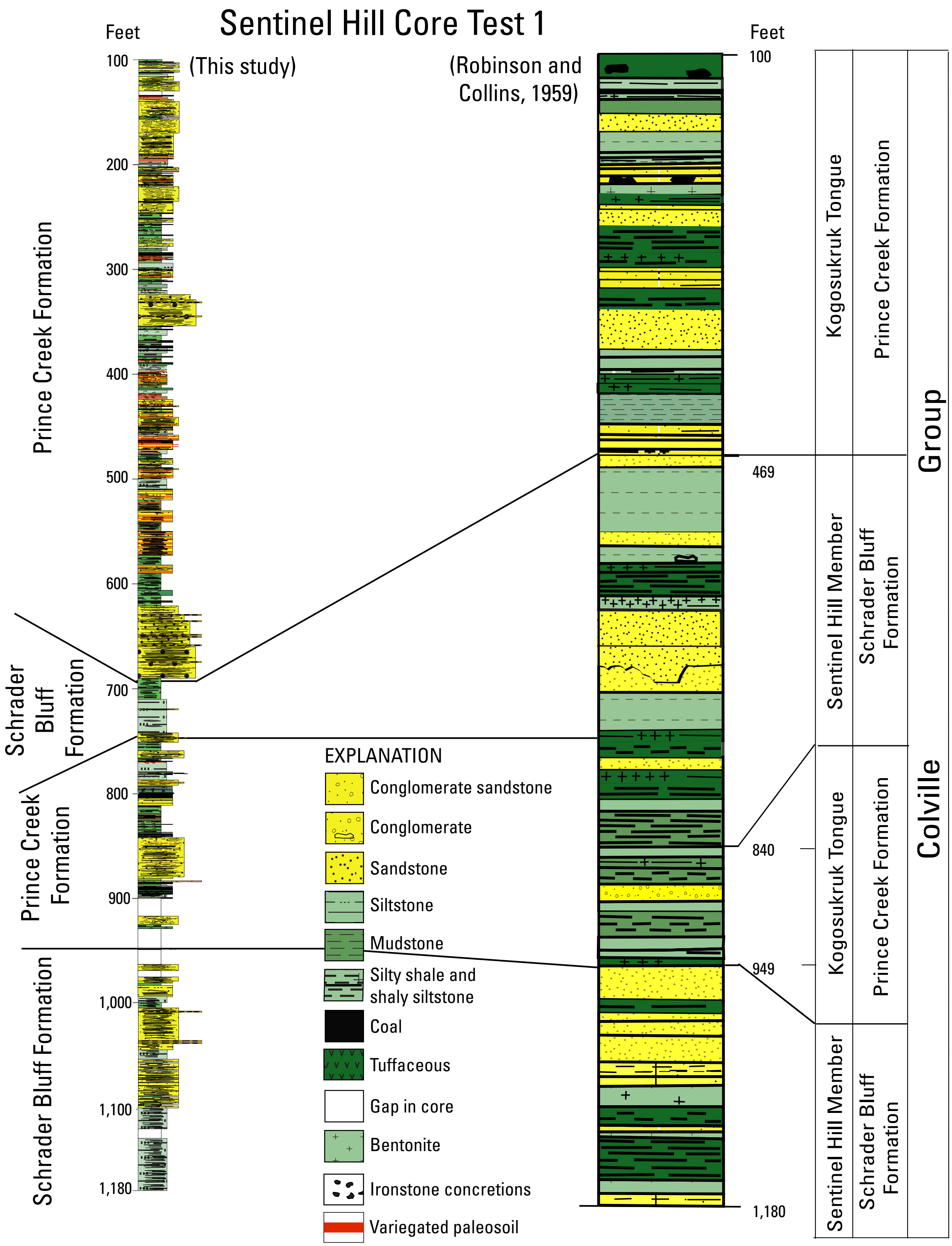


Figure 3. Stratigraphic section penetrated in the Sentinel Hill Core Test 1 showing detailed lithologies and comparison between correlations used in the present study and those used by Robinson and Collins (1959). For lithologic explanation, see figure 4.

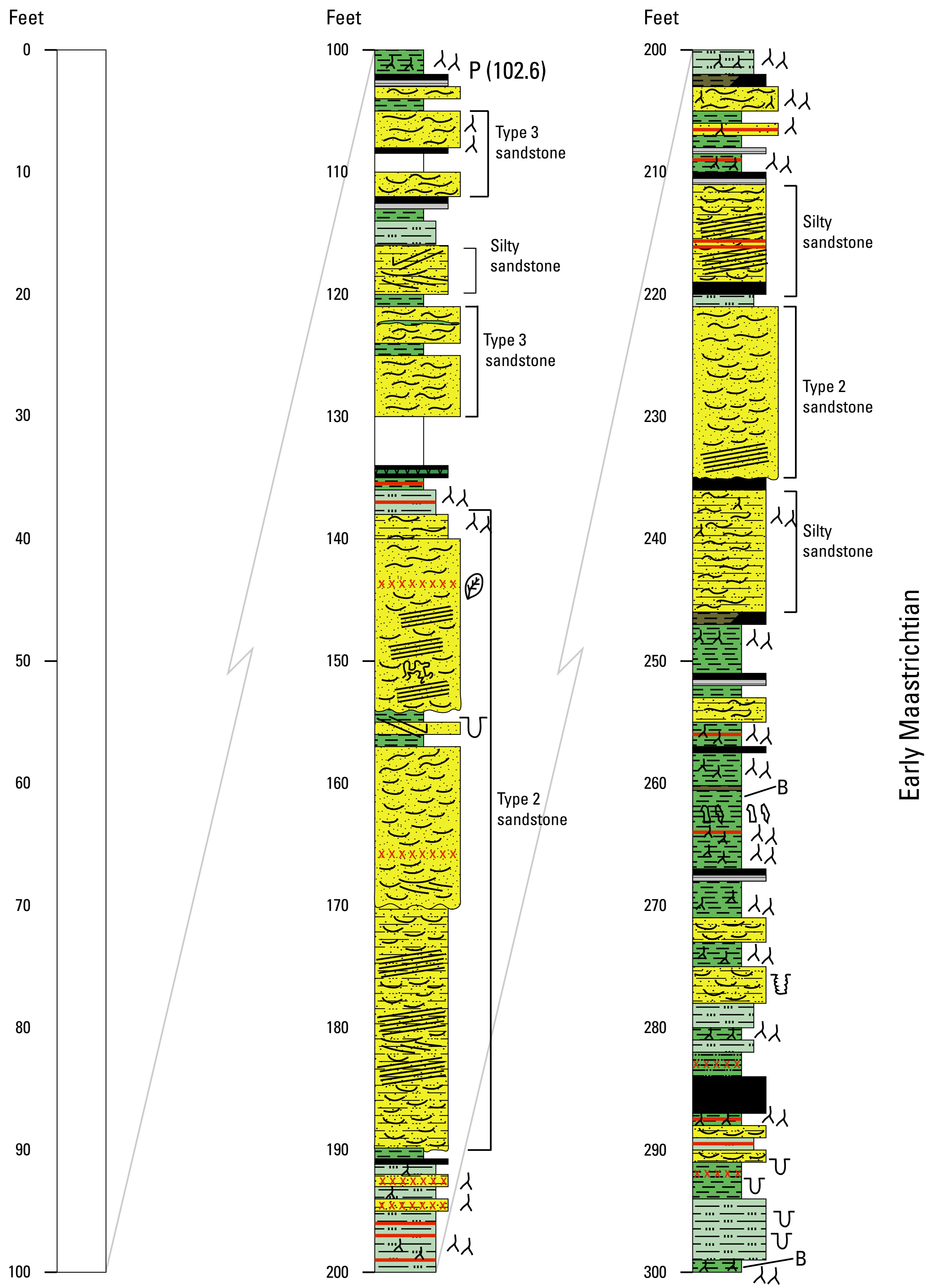
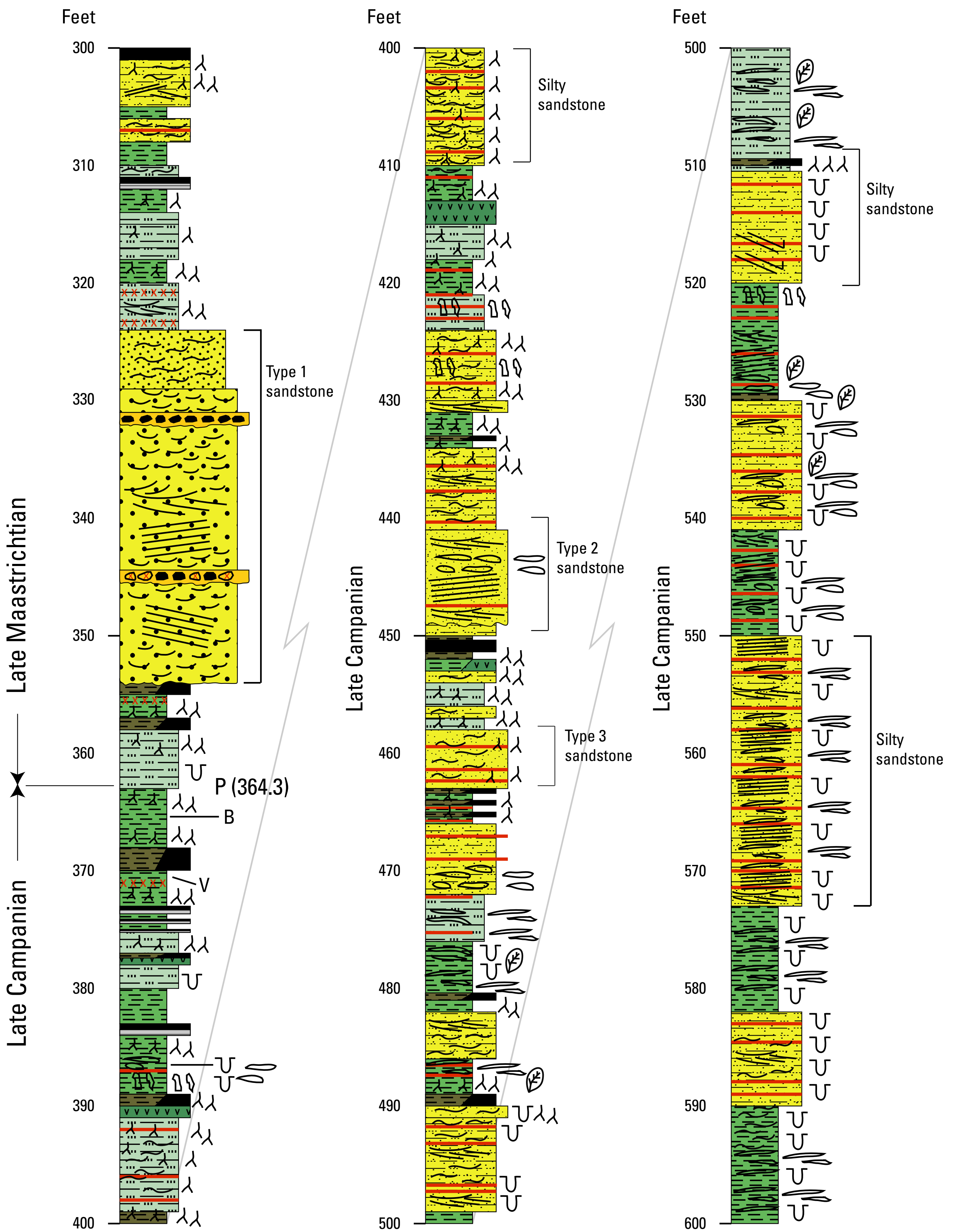
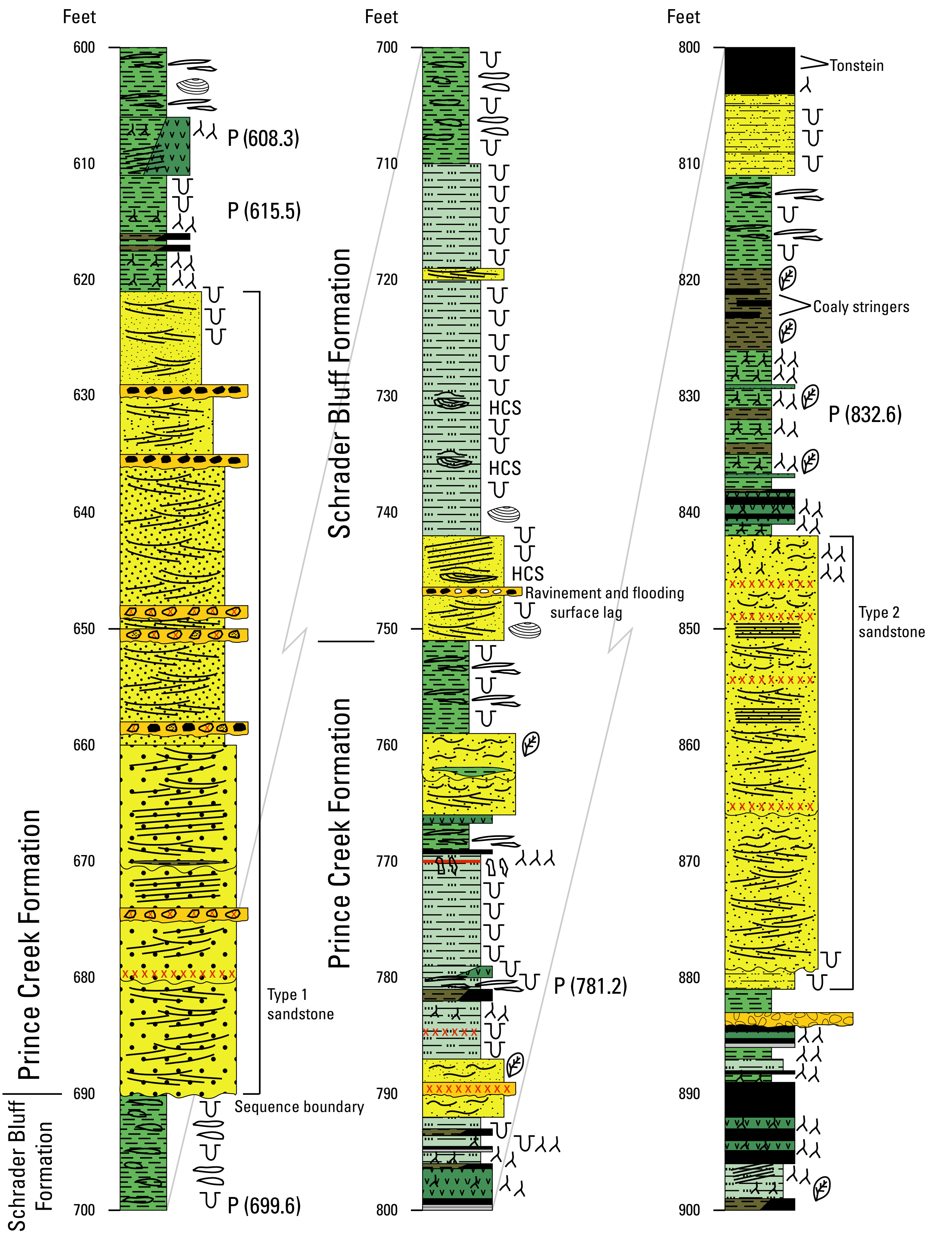
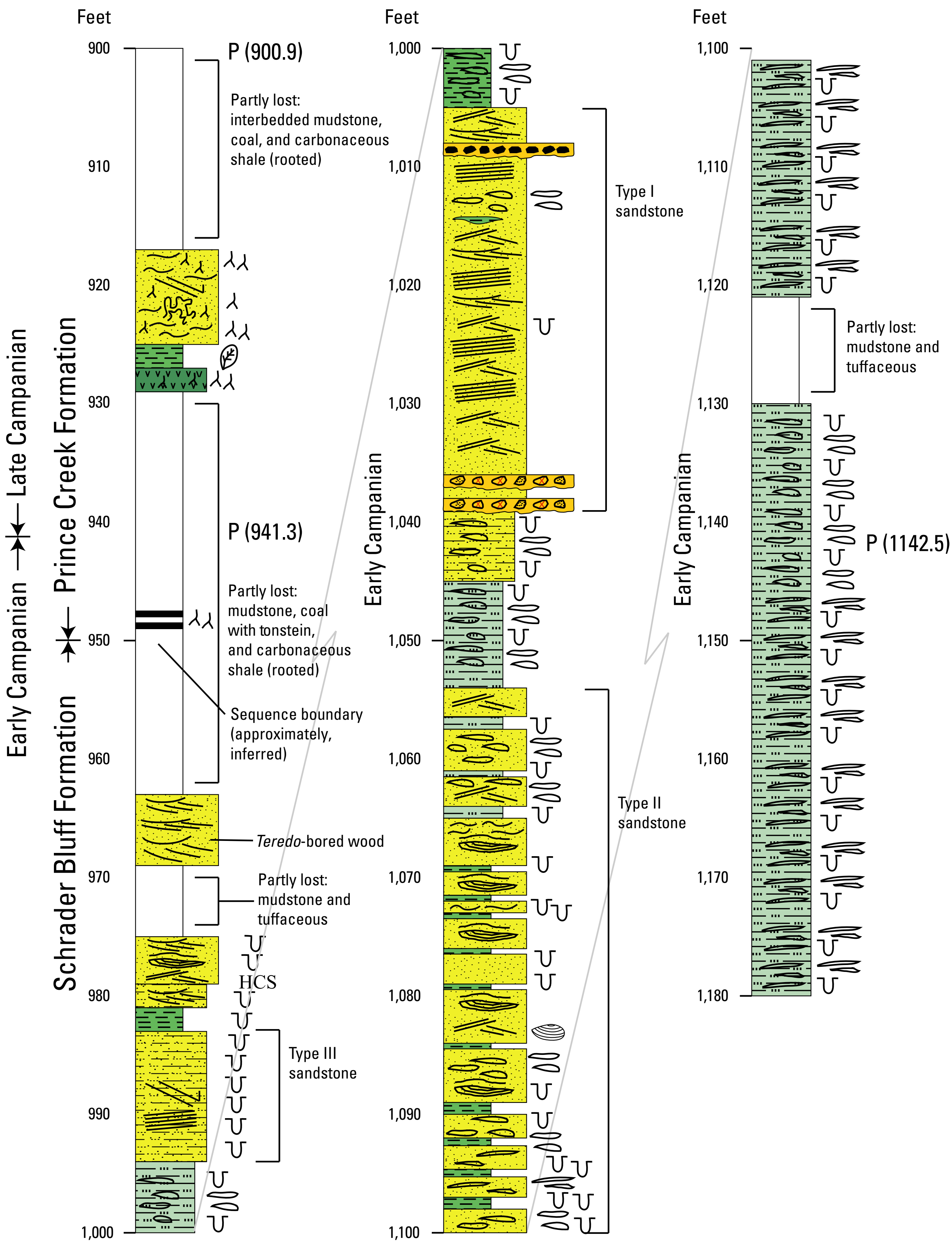


Figure 4. Stratigraphic section penetrated in the Sentinel Hill Core Test 1 showing facies types, facies succession, lithology, contacts, and ages of the Prince Creek and Schrader Bluff Formations. Locations of samples for palynomorph analyses are also shown. Numbers alongside columns indicate measured depth, in feet, below kelly bushing datum.


Feet
300
310
320
330
340
350
360
370
380
390
400
Late Maastrichtian
Late Campanian
Type 1
sandstone
P (364.3)
B
V
Feet
400
410
420
430
440
450
460
470
480
490
500
Late Campanian
Silty
sandstone
Type 2
sandstone
Type 3
sandstone
Feet
500
510
520
530
540
550
560
570
580
590
600
Late Campanian
Silty
sandstone
Silty
sandstone


Feet
600
610
620
630
640
650
660
670
680
690
700
P (608.3)
P (615.5)
Type 1
sandstone
Sequence boundary
P (699.6)
Prince Creek Formation
Schrader Bluff
Formation
Feet
700
710
720
730
740
750
760
770
780
790
800
HCS
HCS
HCS
Ravinement and flooding
surface lag
P (781.2)
Schrader Bluff Formation
Prince Creek Formation
Feet
800
810
820
830
840
850
860
870
880
890
900
Tonstein
Coaly stringers
P (832.6)
Type 2
sandstone


Feet
900
910
920
930
940
950
960
970
980
990
1,000
P (900.9)
Partly lost: interbedded mudstone, coal, and carbonaceous shale (rooted)
P (941.3)
Partly lost: mudstone, coal with tonstein, and carbonaceous shale (rooted)
Sequence boundary (approximately, inferred)
Teredo-bored wood
Partly lost: mudstone and tuffaceous
HCS
Type III sandstone
Late Campanian
Early Campanian
Prince Creek Formation
Schrader Bluff Formation
Feet
1,000
1,010
1,020
1,030
1,040
1,050
1,060
1,070
1,080
1,090
1,100
Type I sandstone
Type II sandstone
Early Campanian
Feet
1,100
1,110
1,120
1,130
1,140
1,150
1,160
1,170
1,180
Partly lost: mudstone and tuffaceous
P (1142.5)
Early Campanian

EXPLANATION

- Sandstone
- Silty sandstone
- Conglomerate
- Siltstone
- Mudstone (clay)
- Carbonaceous mudstone
- Carbonaceous shale
- Tuffaceous
- Coal
- Coal and carbonaceous mudstone
- Coal and carbonaceous shale
- Coal and tuff
- Clinker gravel
- Covered or lost
- P (102) Pollen sample depth (feet) (see table 1)

- Trough crossbeds
- Bidirectional crossbeds
- Planar crossbeds
- Cross laminations
- Ripple laminations
- Subparallel laminations
- Root marks
- Burrows
- *Ophiomorpha* burrows
- Hummocky cross stratification
- Convolution
- Dinosaur bones
- Mottles
- B Bentonitic
- V Tuffaceous
- XXXX Ironstone
- Variegated color (reds)
- Plant leaves
- Slump
- Lenticular lenses
- Wispy lenses
- Pelecypod shells

Grain size

- Mudstone
- Siltstone
- Silty sandstone
- Very fine sandstone
- Fine sandstone
- Medium sandstone
- Coarse sandstone
- Conglomerate sandstone

Prince Creek Formation

Robinson and Collins (1959) assigned two intervals of the core test hole to the Prince Creek Formation: an upper unit at depth interval 0–469 ft and a lower unit at depth interval 840–949 ft (fig. 3). They described these intervals as mostly sandstone, siltstone, and bentonitic, silty, carbonaceous, and calcareous claystone that is interbedded with, and grades into, clay ironstone. Sandstone and siltstone constitute only about 25 percent of the section they assigned to the Prince Creek Formation. The sandstone ranges from fine to medium grained and consists of about 50 percent quartz grains and lesser amounts of metamorphic rock fragments, chert, mica, and volcanic glass shards. The siltstone is similar in composition to the sandstone; both also contain plant fragments. Coal and carbonaceous shale constitute about 10 percent of the Prince Creek Formation strata as described by Robinson and Collins (1959); the coal is black and brittle and exhibits blocky fracture. Tuff or bentonite and limey mudstone are less common rock types, the former being mainly disseminated in the claystone but also occurring in white to yellowish gray units interbedded with other rock types. The limey mudstone is dense and sideritic and exhibits conchoidal fractures.

Schrader Bluff Formation

Robinson and Collins (1959) assigned two intervals of the core test hole to the Schrader Bluff Formation: an upper unit at depth interval 469–840 ft and a lower unit at depth interval 949–1,180 ft (fig. 3). They reported these units as being mostly sandstone, siltstone, clay shale, and claystone that is less calcareous and sideritic than strata in the Prince Creek Formation. Sandstone and siltstone constitute as much as 45 percent of the total rock thickness, with sandstone units reaching thicknesses of 100 ft. The sandstone is silty to medium grained and is composed of as much as 85 percent quartz with minor mica and rock fragments. The siltstone is composed of similar framework grains but is more calcareous and locally bentonitic. Overall, bentonite is as common in the Schrader Bluff Formation as it is in the Prince Creek Formation. Marine pelecypods and foraminifera are common fossils. The common presence of foraminifera microfossils in the Schrader Bluff Formation permitted identification of related rock units as zones of *Eoeponidella strombodes* (Tappan, 1951).

New Biostratigraphic Age Constraints

A total of 12 core samples from Sentinel Hill Core Test 1 were submitted for new biostratigraphic analysis by consultants of the irf group, inc. These consisted of 10 samples of organic-rich mudstone and carbonaceous shale that were examined for organic-walled palynomorphs from the depth interval 102.6–1,142.5 ft and 2 samples of probable marine mudstones that were examined for foraminifera from depths of 699.6-ft and 1,142.5 ft. The stratigraphic position of the core samples is shown in figure 4, and the assemblages and point counts for each genus are summarized in table 1. The results indicate that a majority of the palynomorphs are nonmarine along with a few nonmarine algae and fungal remains.

Ages of the samples submitted for biostratigraphic analysis range from early Campanian (sample at depth 1,142.5 ft) to early Maastrichtian (sample at depth 364.3 ft) to early Campanian (sample at depth 102.6 ft). The uppermost sample (at depth 102.6 ft) contains a relatively low-diversity terrestrial assemblage with few age-diagnostic taxa. The next sample down (at depth 359 ft), however, contains a rich and characteristically late Campanian assemblage including, in particular, numerous specimens of the important late Campanian indicator pollen species *Aquilapollenites trialatus*. Because of the absence of typical late Maastrichtian taxa from the uppermost sample, it is interpreted as being early Maastrichtian in age. The late Campanian assemblage persists throughout most of the rest of the core, down to 941.3 ft, and is characteristically nonmarine in nature. Of the two samples examined for foraminifera, the uppermost sample (at depth 699.6 ft) was barren, whereas the lowermost sample (at depth 1,142.5 ft) yielded 11 distinct types that are consistent with the early Campanian age, including the major marker marine dinoflagellate cysts of the species *Spongodinium delitiense* and *Chatangiella ditissima*.

These biostratigraphic results, particularly the palynomorph analyses, permitted a much improved and clearer resolution of the chronostratigraphy of the Sentinel Hill Core Test 1 than was reported by Robinson and Collins (1959). The new chronostratigraphy indicates that the interval from 100 to 359 ft, which includes the uppermost Prince Creek Formation, is early Maastrichtian in age and that the interval from 359 to 941.3 ft, which includes the upper and lower parts of the Prince Creek Formation and intervening tongue of the Schrader Bluff Formation, is late Campanian in age. The lower part of the Schrader Bluff Formation is interpreted as early Campanian in age on the basis of marine dinoflagellate cysts.

Table 1. Palynological ages of samples collected from the Sentinel Hill Core Test 1 well, North Slope of Alaska. See vertical stratigraphic section in figure 4 for position of palynology samples.

[indet, indeterminant]

Depth, in feet	102.6	364.3	608.3	615.5	699.6	781.2	832.6	900.9	941.3	1,142.5
Formation	Prince Creek	Prince Creek	Prince Creek	Prince Creek	Schrader Bluff	Prince Creek	Prince Creek	Prince Creek	Prince Creek	Schrader Bluff
Taxon										
Bisaccate gymnosperm pollen indet.	33	32	42	20	101	23	10	58	27	104
Stereisporites spp. indet.	132	36		3	2	2		46	20	2
Deltoidospora spp. indet.	5	29	7	145	4	4		6	94	25
Osmundacidites wellmanii	9	23	33	9	29	27	6	45	2	30
Laevigatosporites spp. indet.	4	2	62	2	45	4		3		7
Retitriletes spp.indet.	7	17	16	5	4	3	1	2		3
Tsugaepollenites sp. indet., small	1						2	29	1	2
Gleicheniidites senonicus	1								25	
cf. *Converrucosisporites* sp. small, pale, vague	2	3	1					1		
Stereigranisporis regius	3									
cf. *Anacolosidites* sp. indet.	1									
Betulaceoipollenites/Carpinuspollenites group	1									
Camarozonosporites sp. indet., small	1									
Selagosporis sp. 1		1		1					1	
Taxodiaceaepollenites hiatus		29	14			22	2	2		
Aquilapollenites trialatus		24				11		5		
Mancicorpus pseudosenonicus		1				2				
Aquilapollenites cf. *fusiformis*		1		1		1				
Erdmannipollis procumbentiformis		1	2							
Tricolporopollenites sp. indet., small, prolate		1								
Aquilapollenites spp. - indet.			17	6	1	2		1		2
Polycingulatisporites cf. *reduncus* - vague			1		5					
Echinatisporis spp. indet.					1	1				
Sigmopollis carbonis			2	1		1				
Linear septate fungal hypha			2			3				
Fibulapollis scabratus			1	1						
Hannisporis scollardensis										
Expressipollis cf. *accuratus*				2		20				5
Verrucosisporites sp. indet., small					1					
Cibotiumspora juncta				1						
Lobatia involucrata				1						
cf. *Divisisporites* sp. indet.				1						
Undulatisporites sp. indet.										
Ovoidites arcticus				1						
Cicatricosisporites sp. 1					3				5	2
Trilites sp. indet.					1					2
Podocarpidites sp. indet.					1					
cf. *Perinopollenites* sp. indet.					2					
Cicatricosisporites sp. 2						1				1
cf. *Loranthacites* sp. indet.						2				
Anacolosidites/Expressipollis striatus						69	177			
Cranwellia subtilis						1	1			
Aquilapollenites amygdaloides						1				
Ovoidites parvus							1			
Sequoiapollenites polyformosus										

EXPLANATION

Nonmarine, pollen/spores

Nonmarine, algae

Fungal

33 Number of taxa per sample

Sequence Stratigraphy and Depositional Setting

The contacts of the Prince Creek and Schrader Bluff Formations in the Sentinel Hill Core Test 1 well as originally defined by Robinson and Collins (1959) were based primarily on the presence or absence of coals and marine beds. Although some of the contacts have now been revised (Flores and others, 2007), these traditional criteria demonstrate the intertonguing of terrestrial and marine deposits that result from regressive and transgressive shifts of the paleoshoreline, respectively.

In sequence stratigraphic terms, a regressive (seaward) retreat of the shoreline occurs during relative sea-level fall and results in a regional erosion surface that is recorded as a sequence boundary. Transgressive (landward) advance of the shoreline occurs during relative sea-level rise and generates a transgressive surface of erosion (ravinement surface) that is cut by wave energy. The sharp or erosional contacts between the Prince Creek and Schrader Bluff Formations in the core test include both types of sequence stratigraphic surfaces.

In the Sentinel Hill Core Test 1, the contact juxtaposing the upper Prince Creek Formation interval (above) and the upper Schrader Bluff Formation interval (below) is at a depth of 690 ft and is a clear sequence boundary (Mid-Campanian unconformity [MCU] of Decker [2007]; see fig. 4 of Flores and others [2007]). This erosional boundary is at the base of a conglomeratic, fine- to coarse-grained multiscoured sandstone, which contains vertical burrows in the uppermost part. Outcrop evidence links this sequence boundary to an incised paleovalley that was eroded during a falling sea level and then was filled with sediment during the subsequent sea-level rise.

Flores and others (2007) suggest that this sequence boundary is present in outcrops along the Colville River Bluffs as a widespread, channelized surface with erosional relief from 25 to 75 ft. At Shivugak Bluff (fig. 1), the sequence boundary forms a paleovalley that scoured out 100 ft or more of stratigraphic thickness, thereby incising through lowermost Prince Creek strata and into uppermost shoreface sandstones of the Schrader Bluff Formation (Flores and others, 2007). In the Sentinel Hill Core Test 1, the same sequence boundary is incised into a lower shoreface or offshore mudstone. If the upper shoreface sandstone below the contact at Shivugak Bluff and the lower shoreface to offshore mudstone at Sentinel Hill Core Test 1 are parts of the same parasequence, then the depth of incision at the sequence boundary would appear to be greater at the core hole than at Shivugak Bluff. Alternatively, Decker (2007) correlated the Schrader Bluff Formation strata beneath the contact at Shivugak Bluff with the lower part of the Schrader Bluff Formation in Sentinel Hill Core Test 1 (depth interval 950–1,180 ft). In that model, erosion on the sequence boundary would be greatest at Shivugak Bluff, where all strata equivalent to the upper Schrader Bluff Formation interval in Sentinel Hill Core Test 1 were erosionally removed and where the deepest part of the paleovalley was incised even through the lower part of the Prince Creek Formation.

The contact between the upper Schrader Bluff Formation interval and the underlying lower Prince Creek Formation interval is now placed at the base of the conglomeratic lag at 751 ft (fig. 4) (Flores and others, 2007). This contact is interpreted as a ravinement surface (also known as a transgressive surface of erosion), and the lag conglomerate—which consists of tuff, coal, and rock fragments—represents older terrestrial deposits reworked during the landward advance of the paleoshoreline (during sea-level rise). The thin nature of the ravinement lag conglomerate suggests rapid transgression. The ravinement lag conglomerate is in the middle of a hummocky cross-stratified, storm-related upper shoreface sandstone. The contact between the lower Prince Creek Formation interval and the underlying lower Schrader Bluff Formation interval is estimated to be at the 950-ft depth (the contact is within an interval of lost core, so the sequence boundary predicted at this relatively abrupt facies change could not be directly observed).

Recognition of key sequence stratigraphic surfaces (two sequence boundaries and one ravinement surface) has resulted in a reinterpretation of the positions of the contacts between the Prince Creek and Schrader Bluff Formations previously identified by Robinson and Collins (1959). In the reinterpretation, the following revisions were made: (1) the contact (sequence boundary) between the upper Prince Creek Formation and upper Schrader Bluff Formation is placed much lower (from 469 to 690 ft), resulting in a thicker Prince Creek nonmarine section; and (2) the contact (transgressive surface of erosion) between the upper Schrader Bluff Formation and lower Prince Creek Formation is placed higher (from 747 to 777 ft), resulting in a thinner Schrader Bluff marine section.

The Schrader Bluff and Prince Creek Formations in the Sentinel Hill Core Test 1 represent an overall progradational succession of genetically linked, cyclic marine and nonmarine depositional environments. The transition grades from entirely marine at the bottom to entirely nonmarine at the top, but it was interrupted by one significant transgressive pulse and punctuated by sequence boundaries. The upper Schrader Bluff Formation marine interbed is substantially thinner than the Schrader Bluff Formation sections observed in outcrops nearby to the south, which represent more proximal depositional settings. It is likely that this marine interbed is absent from the lower accommodation settings further south either because of nondeposition or erosional removal at the upper sequence boundary described above. The Schrader Bluff Formation rock record preserved in the core test consists mainly of lower shoreface environments. The overlying Prince Creek Formation was deposited in a variety of settings landward of similar shoreface deposits. Initial sediment infill in the paleovalley, represented by the conglomeratic sandstone in the lowermost part of the upper Prince Creek interbed, reflects bedload sedimentation by aggrading rivers concomitant with the rise of sea level. Subsequent filling of the paleovalley occurred in a tidal-estuarine-influenced coastal and alluvial environment.

Facies Descriptions and Interpretations

Facies of the Prince Creek and Schrader Bluff Formations in the Sentinel Hill Core Test 1 represent coastal and alluvial depositional environments. They are best described as they are below on the basis of lithology, color, nature of contact, grain size, sedimentary structures, megafossils, trace fossils, and vertical facies associations of the rocks (fig. 4). The descriptions are followed by discussions of interpreted depositional environments. The continental Prince Creek Formation sandstones (Types 1–3) are differentiated from the marine Schrader Bluff Formation sandstones (Types I–III) by the use of arabic and roman numerals, respectively.

Prince Creek Facies

Descriptions

The Prince Creek Formation, in the depth intervals 100–690 ft and 751–950 ft, consists of three general facies that are distinguished on the basis of grain size and organic content: a coarser grained facies, a finer grained facies, and an organic-rich facies.

Coarser Grained Facies

The coarser grained facies, constituting about 60 percent of the Prince Creek Formation strata, includes sandstones and conglomerates. Silty sandstones are the main rock type, constituting 40 percent of the Prince Creek Formation. Individual units, as much as 27 ft thick, are typically sharp based and rarely erosional based. Internal sedimentary structures vary from abundant ripple laminations to commonly alternating, fining-upward lenticular, trough, and subparallel laminations (depth intervals 400–410 ft and 550–573 ft) (fig. 5). Trace fossils include *Ophiomorpha*-like and nondescript vertical burrows, and root marks and mottled structures are pervasive throughout this facies type (fig. 6). The mottled structures are commonly formed by vertically alternating red and gray horizons (fig. 7). Slumped structures are common (for example, see depth intervals 116–120 ft and 510–520 ft, fig. 4).

Sandstones range from very fine to coarse grained with gradational, sharp, or erosional bases. Three sandstone facies types are recognized on the bases of the nature of their basal surfaces, vertical grain size variations, sedimentary structures, and facies associations.

The Type 1 sandstone facies, in units as much as 69 ft thick, is characterized by vertically stacked multierosional surfaces or multiscours, upward fining, and trough-, subparallel-, and ripple-bedded deposits (see depth intervals 324–354 ft and 621–690 ft in fig. 4 and photograph in fig. 8). The upper part of this sandstone type shows mud drapes, syneresis or mud cracks, and root traces (fig. 9). The Type 2 sandstone facies, as much as 20 ft thick, is characterized by a single erosional basal surface; mainly uniform grain size from base to top; and trough-, subparallel-, ripple-, and lenticular-bedded deposits (see depth intervals 221–235 ft and 441–449 ft in fig. 4 and photograph in fig. 10). This sandstone facies may be stacked, as shown in the depth interval 138–170 ft (see fig. 4). Types 1 and 2 sandstone facies are either capped by root traces or by vertical burrows (fig. 11). Type 3 sandstone facies, as much as 9 ft thick, is characterized by a sharp base and mainly ripple-bedded sandstones (see depth intervals 121–130 ft and 458–463 ft in fig. 4 and photograph in fig. 12).

Figure 5. Lenticular bedding and burrows in silty sandstone of the Prince Creek Formation. Photograph is of a core surface.

Figure 6. Mottled and root-marked silty sandstone facies type of the Prince Creek Formation. Photograph is of slabbed surfaces.

Figure 7. Alternating red and gray variegated, mottled mudstone of the Prince Creek Formation. Left side of photograph is of a core surface, and right side of photograph is of a slabbed surface.

Figure 8. Trough crossbeds in Type 1 sandstone of the Prince Creek Formation. Photograph is of a core surface.

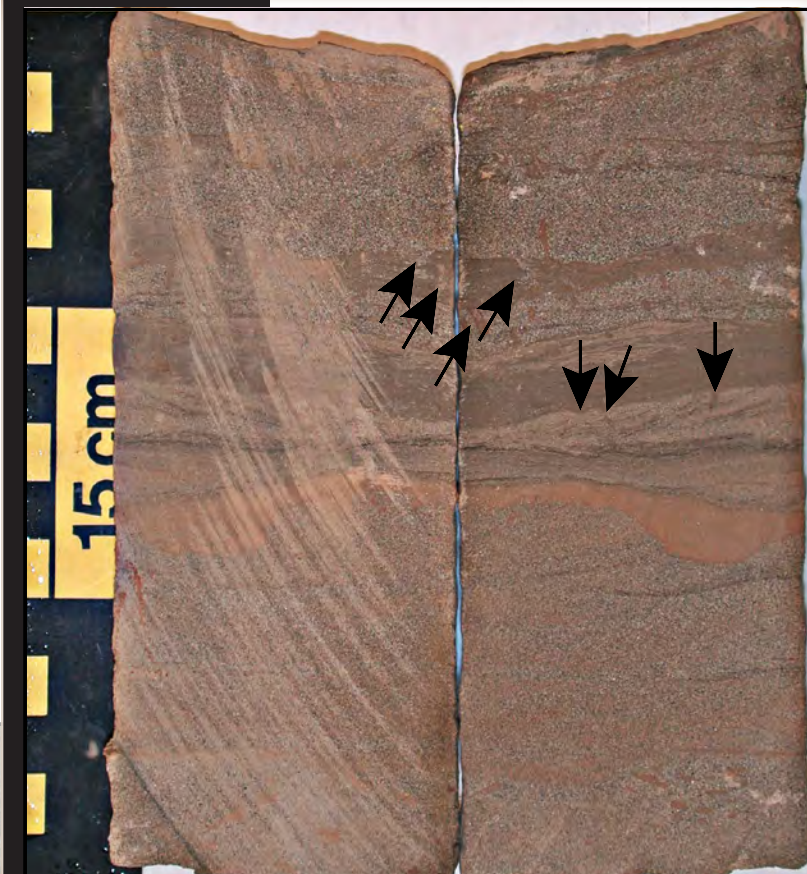


Figure 9. Mud drapes, root marks, and syneresis or mud cracks (all indicated by arrows) in the upper part of Type 1 sandstone of the Prince Creek Formation. Photograph is of slabbed surfaces.

Figure 10. Subparallel laminations in Type 2 sandstone of the Prince Creek Formation. Photograph is of a core surface.

Figure 11. Rooted (indicated by arrows) and burrowed upper part of Types 1 and 2 sandstones of the Prince Creek Formation. Photograph is of a core surface.

Figure 12. Ripple laminations in Type 3 sandstone facies of the Prince Creek Formation. Photograph is of slabbed surfaces.

Conglomerate beds, which are 0.5–1.5 ft thick, exhibit erosional bases and contain rounded to subrounded pebbles and cobbles of sandstone, ironstone, chert, coal spar, mudstone, and carbonaceous shale. The fragments are matrix to grain supported, and there is some crude imbrication (fig. 13). The conglomerates mainly lie above erosional surfaces within the Type 1 sandstone facies (see depth intervals 324–355 ft and 621–690 ft in fig. 4).

Finer Grained Facies

Siltstone, mudstone, and tuffaceous beds compose the finer grained facies (fig. 14) and constitute 12–40 percent of the Prince Creek Formation (fig. 4). The siltstone beds are gray, have gradational to sharp contacts, and are as much as 12 ft thick (depth interval 769–781 ft, fig. 4). The mudstone beds are light to dark gray, have sharp to gradational contacts, and are as much as 32 ft thick (depth interval 590–622 ft, fig. 4). The finer grained facies is mainly lenticular bedded, burrowed, rooted, and mottled and contains abundant plant fragments. Ironstone and variegated layers are abundant and commonly interbedded with mudstones (depth intervals 195–202 ft and 392–398 ft, fig. 4) and silty sandstones (depth intervals 510–520 ft and 530–540 ft, fig. 4); these beds are typically associated with plant-rich horizons and are the result of oxidation.

The tuff or bentonite beds are a minor part (1 percent) of the finer grained facies (fig. 14). They form vitreous (glassy) white layers that vary from a few inches to as much as 6 ft thick (depth interval 606–612 ft, fig. 4) and contain root traces and plant fragments. The tuffaceous beds mostly either are interbedded with (depth interval 889–896 ft, fig. 4) or underlie (depth interval 797–799 ft, fig. 4) coal and carbonaceous shale beds. Tuffaceous beds are interbedded with mudstone beds (fig. 14).

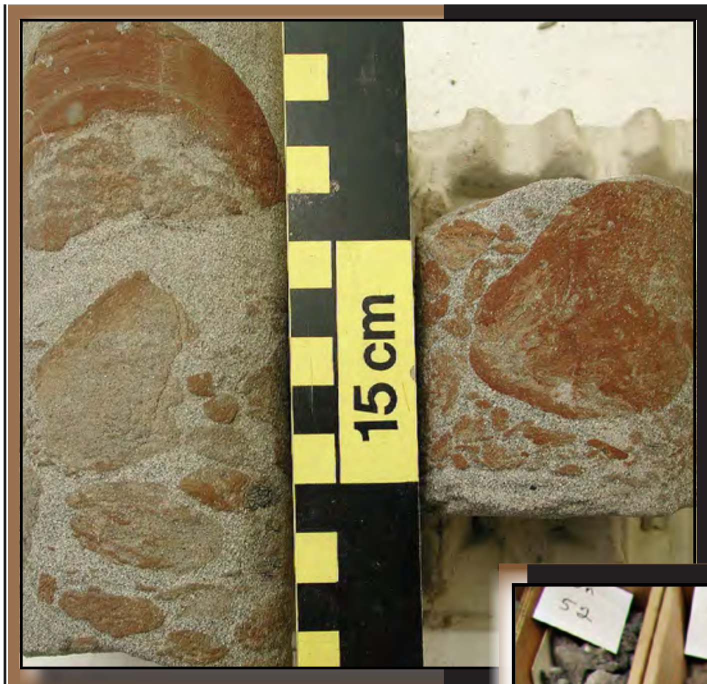


Figure 13. Matrix- and grain-supported sandstone conglomerate in Type 1 sandstone facies of the Prince Creek Formation. Photograph is of core surfaces.

Figure 14. Interbedded tuffaceous (or bentonitic) mudstone, siltstone, and carbonaceous mudstone of the finer grained facies of the Prince Creek Formation.

Organic-Rich Facies

The organic-rich facies includes coal and carbonaceous shale beds (fig. 15), which constitute approximately 2 percent of the Prince Creek Formation. Coal is in relatively pure seams that are as much as 4 ft thick (depth interval 800–884 ft, fig. 4) or in beds as much as 7 ft thick with tuffaceous partings that are as much 1.5 ft thick (depth 889–896 ft, fig. 4). The coal is composed mainly of bright banded units interbedded with dull, nonbanded units. The bright banded units contain vitrain macerals (mainly woody plant fragments), and the dull, nonbanded units consist of macerals that are mainly degraded cellular plant remains.

Carbonaceous shale beds are black sheeted mudstone (at depths 211, 252, 267, 312, 374–276, 384, 799, and 886 ft, fig. 4) that contain abundant macerated plant leaf and stem fragments and coal stringers. These beds either are interbedded with or underlie the coal beds, are commonly rooted with vertical root traces as large as 0.20 inch in diameter and 1 ft in length, and typically are mottled and variegated (see figs. 6 and 7) where there are high concentrations of plant fragments.

Interpretations

The coarser grained facies is interpreted as fluvial channel deposits on the basis of erosional basal contacts; fining-upward profiles; the vertical succession of internal sedimentary structures; and multiple stacked, internal erosional contacts and beds. The Type 1 sandstone facies, distinguished by multiple stacked, fining-upward beds—each of which is underlain by an erosional base and contains basal conglomerate beds—probably was deposited in bedload fluvial channels. The fining-upward profiles indicate that this facies infilled waning flow fluvial channels. The Type 1 sandstone facies is typified by the lower part of the upper tongue of the Prince Creek Formation (depth interval 622–690 ft, fig. 4), which consists of a thick, fining-upward sequence characterized by a succession of thinner, fining-upward sandstone beds, each of which is underlain by an erosional base marked by imbricated, matrix- to framework-supported, pebble-cobble conglomerates. This sandstone succession probably indicates vertical aggradation of the fluvial channels. Investigations of the Prince Creek Formation in outcrops along the Colville River by Flores and others (2007), which shows similar vertical facies variations, suggest that Type 1 sandstones were deposited in sandy braided streams. The conglomerates of the Sentinel Hill Core Test 1 are bottom channel lag or armor deposits bypassed by sands that formed longitudinal dunes and bars. The rippled and small-scale crossbedded sandstones in the uppermost part of the succession indicate deposition during waning flow and lateral aggradation of the braided streams in chute bars and flood plains. The presence of mud drapes, syneresis or mud cracks, and root marks suggests point bar accretion during the lateral aggradation (Flores and others, 2007).

The Type 2 sandstone facies is interpreted as a linear fluvial channel deposit on the basis of the single erosional basal surface; largely uniform grain size from base to top; and trough-, subparallel-, ripple-, and lenticular-bedding styles.

Figure 15. Interbedded coal, carbonaceous shale, and tuffaceous beds of the organic-rich facies of the Prince Creek Formation.

These sandstones probably represent vertically aggrading channels that were cut and filled by migrating sand dunes and small-scale ripples. Their sharp bases and dominant rippled bedding indicate that Type 3 sandstones were probably deposited in crevasse channels that aggraded laterally into the flood plain. The silty sandstone facies probably represents the crevasse splay environment at the mouth of crevasse channels.

The finer grained facies—consisting mainly of rooted, mottled, rippled, burrowed siltstone and mudstone—represents vertically aggraded flood plain detritus deposited by rivers that overtopped channel levees or by crevasse channels cut into the levees. The rooted, mottled, and variegated horizons reflect diverse paleosols formed during alternating lowering and rising of groundwater tables during dry and wet paleoclimatic periods (Flores, 2003). The variegated horizons interbedded with mudstones that formed in distal flood plains reflect more mature paleosols than do the variegated horizons interbedded with silty sandstones that formed in well drained, proximal flood plains resulting from wet and dry paleoclimatic changes. According to Buurman (1975), mottling is characteristic of gley soils in which movement of reducing pore waters is sluggish. The tuffaceous or bentonitic layers interbedded with the fine-grained detritus represent deposition of volcanic ash falls. Eruption of volcanic ash must have been intense, as indicated by the thick tuffaceous layers. These layers are dominant in the flood plain environments rather than in the fluvial channels because of the higher preservation potential in the vertically aggrading flood plain compared to laterally aggrading and erosional fluvial channels.

The organic-rich facies, which consists of coal and carbonaceous shale, represents flood plain swamp deposits. The woody vitrain bands of the coal beds indicate that the swamps were likely vegetated by trees. That the swamps were low lying and topogeneous is indicated by the interbedded carbonaceous shale composed of mixed organic matter and mud. The mud probably resulted from flood deposition into the low-lying, flat swamps. Like the detrital flood plain areas, the swamps were also episodically covered with airborne volcanic ash, which was preserved as interbedded tuffaceous layers. The ash falls probably caused intermittent suffocation of swamp vegetation.

Schrader Bluff Facies

Descriptions

The Schrader Bluff Formation (depth intervals 690–751 ft and 950–1,180 ft) consists of about 40 percent silty to coarse-grained sandstone and conglomerate beds and about 60 percent siltstone and mudstone beds. The strata are assigned to two principal facies mainly on the basis of grain size—a coarser grained facies and a finer grained facies.

Coarser Grained Facies

The coarser grained facies includes sandstone and conglomerate beds. Two types of sandstone are recognized on the basis of the nature of their basal surfaces (sharp to erosional), vertical grain size variations, very fine to coarse-grained textures, sedimentary structures, and facies associations. Intervals of Type I sandstone beds are characterized by uniform grain size throughout, bidirectional crossbedding, subparallel laminations, lenticular bedding, and burrowing (see depth interval 1,005–1,038 ft in fig. 4 and photograph in fig. 16). Framework-supported conglomerates with basal erosional contacts are common at or near the base and top of Type I sandstone beds, a presence which reflects a vertically multiscoured sandstone body in which each scouring event is marked by a basal conglomerate. The conglomerates consist mainly of subrounded pebbles and cobbles of sandstone, coal spar, chert, volcanic, and metamorphic rocks (see depth interval 746.2–747.0 ft in fig. 4 and photograph in fig. 17).

Figure 16. Bidirectional crossbeds in Type I sandstone facies of the Schrader Bluff Formation. Photograph is of a core surface.

Figure 17. Pebble lag conglomerate in the Schrader Bluff Formation. On the left and right are core surfaces, and in the middle is an interior surface parallel to bedding plane.

Intervals of Type II sandstone are marked by a sharp basal surface; largely uniform grain size from base to top; and bidirectional, hummocky cross-stratified (fig. 18), and lenticular bedding. In the depth interval 1,054–1,100 ft (fig. 4), this facies is commonly interbedded with burrowed mudstone; also the sandstone is commonly reworked by vertical and lateral burrows of the trace fossils *Bergaueria*, *Conichnus*, *Phycosiphon incertum*, *Schaubcylindrinus*, *Teichichnus*, *Zoophycus*, and *Thalassinoides* (figs. 19–25). In addition, the Type II sandstone is locally interbedded with erosional-based conglomerates consisting of chert, volcanics, and bivalve shell fragments (fig. 26).

Type III sandstones have sharp bases, are commonly heavily burrowed to bioturbated with rarely preserved trough-like shapes, and exhibit subparallel laminations and slumped stratification (see depth interval 963–994 ft in fig. 4 and photograph in fig. 27).

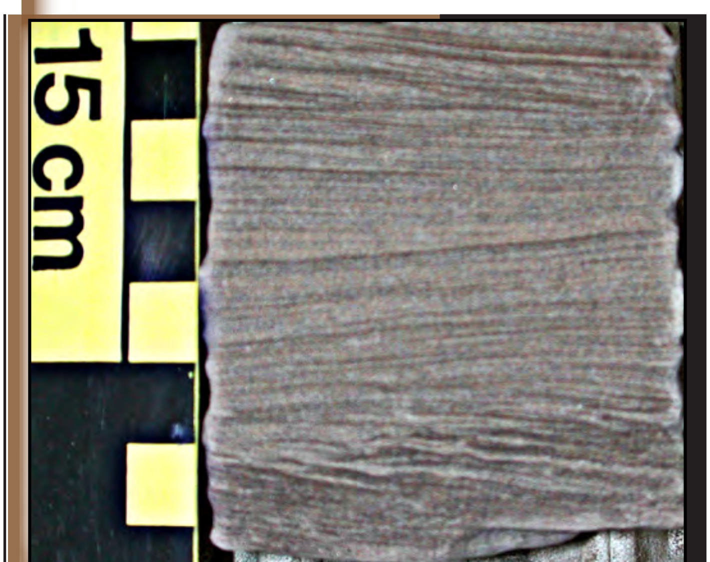


Figure 18. Hummocky cross stratification in Type II sandstone facies in the Schrader Bluff Formation. Photograph is of a slabbed surface.

Figure 19. Probable *Bergaueria* trace fossil (indicated by arrow) in Type II sandstone of the Schrader Bluff Formation.

Figure 20. Probable *Conichnus* trace fossil (indicated by arrow) in Type II sandstone of the Schrader Bluff Formation.

Figure 21. *Phycosiphon incertum* trace fossil (indicated by arrows) in Type II sandstone of the Schrader Bluff Formation.

Figure 22. Trace fossil *Schaubcylindrinus* (indicated by arrows) in Type II sandstone of the Schrader Bluff Formation.

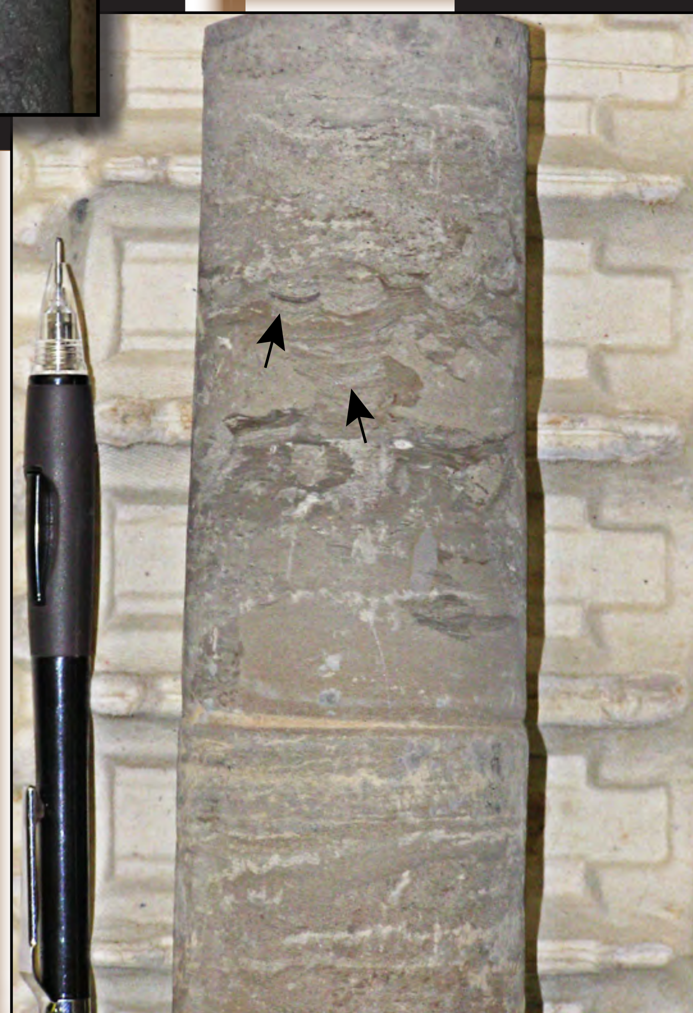


Figure 23. Trace fossil *Teichichnus* (indicated by arrows) in Type II sandstone of the Schrader Bluff Formation.

Figure 24. Trace fossil *Zoophycus* (indicated by arrows) in Type II sandstone of the Schrader Bluff Formation.

Figure 25. Trace fossil *Thalassinoides* (indicated by arrows) in Type II sandstone of the Schrader Bluff Formation.

Figure 26. Articulated pelecypod body fossil in Type II sandstone of the Schrader Bluff Formation.

Figure 27. Slumped structures in Type III sandstone of the Schrader Bluff Formation.

Finer Grained Facies

Beds of siltstone and mudstone (fig. 28) compose 60 percent of the Schrader Bluff Formation (fig. 4). Siltstone beds are gray, have gradational to sharp contacts, and are as much as 78 ft thick (depth interval 1,102–1,180 ft in fig. 4). Mudstone beds are dark gray, have sharp to gradational contacts, and are as much as 20 ft thick (see depth interval 690–710 ft in fig. 4 and photograph in fig. 28). The siltstone-mudstone facies is mainly lenticular bedded and contains a trace fossil assemblage closely similar to that observed in the sandstones. These burrows are filled either with sand from overlying beds or by reworked siltstone and mudstone (fig. 28). The dark-colored mudstone contains finely comminuted plant fragments.

Figure 28. Siltstone and mudstone in the finer grained facies of the Schrader Bluff Formation. Note burrows (indicated by arrows).

Interpretations

The coarser grained and finer grained facies in the 1,005–1,100-ft depth interval (fig. 4) are interpreted as shoreface deposits on the basis of their sharp to erosional basal contacts, uniform grain size, vertical succession of internal sedimentary structures, and the amalgamation of beds across multiple stacked, internal erosional contacts. The Type I sandstone facies in the upper part of the sequence (depth interval 1,005–1,038 ft in fig. 4) is a composite of three depositional cycles, each marked by an erosional base, a basal lag conglomerate about 1 ft thick, an upper sandstone of uniform grain size, and a highly variable preserved thickness. This interval commences with a 2-ft-thick lower package; a 28-ft-thick middle package dominated by a crossbedded and subparallel laminated, sparsely burrowed sandstone; and an upper package with trough crossbedded sandstone. These amalgamated conglomerate-sandstone cycles are interpreted as upper shoreface to foreshore (beach) facies (Reading, 1986). The remainder of the succession between 1,038 ft and 1,100 ft (fig. 4) is composed dominantly of Type II sandstone and of lesser amounts of Type III sandstone that are sharp based and separated by thin mudstones and siltstones. The Type II sandstones are replete with hummocky cross stratification and bioturbation and are only partially amalgamated, which is consistent with their origin as storm-influenced middle to lower shoreface deposits. Between 1,090 ft and 1,100 ft (fig. 4), hummocky cross stratification is absent from the bioturbated, lenticular, slightly thinner sandstone beds, which is consistent with deposition either in lower shoreface to offshore transitional settings or during weaker storm events. The lenticular bedded, heavily bioturbated, silty sandstones common to most of the Type III sandstones represent a depositional setting still further offshore.

The sandstones are interbedded with lenticular-bedded, bioturbated mudstones and siltstones. The finer grained facies either alternates with Type II sandstone facies or underlies both Types II and III sandstone facies. The alternating coarser and finer grained facies indicate multicycle, coarsening-upward sequences of parasequence sets. The lowermost parasequence set is in the depth interval 1,054–1,180 ft (fig. 4) and consists mainly of amalgamated Type II sandstone and finer grained facies that are indicative of a progradational shoreline. The uppermost parasequence set, depth interval 1,005–1,054 ft (fig. 4), includes the coarsening-upward sequence of finer grained facies overlain by Type III sandstone facies, which in turn is overlain by erosional-based Type I sandstone facies. The Type I sandstone facies is interpreted as the first-stage filling of a paleovalley incised into lower shoreface deposits in response to a lowering of sea level.

The coarser grained and finer grained facies of the Schrader Bluff Formation, between the depths of 690 ft and 751 ft (fig. 4), are interpreted as a transgressive succession consisting of a basal shoreface sandstone overlain by offshore transitional siltstones and mudstones. The sandstone in the lower part of this fining-upward unit is interpreted as a shoreface deposit on the basis of sharp to erosional basal contacts, uniform grain size, and vertical succession of internal sedimentary structures. Siltstones and mudstones dominate the upper part, which is interpreted as offshore transitional deposits. The thinness of the sequence probably reflects a slow rate of sea-level rise (low accommodation potential) and minimal sediment supply during transgression. The onset of transgression is believed to coincide with the conglomerate at the 747-ft depth (fig. 4), which is interbedded with the Type II sandstone facies. This conglomeratic deposit is interpreted as a ravinement lag reworked from older deposits, the erosional base of which marks a transgressive surface of erosion.

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Summary

The Sentinel Hill Core Test 1 well penetrates intertonguing deposits of the nonmarine Prince Creek Formation and the marine Schrader Bluff Formation, which range in age from early Campanian to early Maastrichtian. Strata in the depth interval 751–1,180 ft (fig. 4), which range in age from early to late Campanian, represent a regressive succession that began with shoreface units being deposited along a storm-dominated, barred shoreline and then was succeeded by deposition of fluvial channel, crevasse splay, and backswamp deposits. These deposits were overprinted by volcanic ash falls, which may have suffocated swamp vegetation.

The Schrader Bluff Formation in depth interval 690–751 ft (fig. 4), which is late Campanian in age, represents a relatively condensed transgressive succession of shoreface and offshore deposits, which in turn was succeeded by regressive fluvial channel, crevasse splay, and backswamp deposits. The upper interval of the Prince Creek Formation, extending from the surface to the 690-ft depth (fig. 4), is late Campanian to early Maastrichtian in age and is mainly composed of fluvial, crevasse, and backswamp deposits. The erosional contact at the base of the upper intertongue of the Prince Creek Formation (depth 690 ft) occurs at the base of the fluvial channel deposits and is interpreted as a sequence boundary.

The sequence boundary at the base of the upper tongue of the Prince Creek Formation may be a regionally significant surface. Decker (2007) tentatively traces this sequence boundary from Shivugak Bluff to Sentinel Hill Core Test 1 on the Colville River and farther northeast through the subsurface toward the Milne Point field on the coast of the Beaufort Sea. The character of the boundary changes along the depositional dip toward the north. In its more proximal reaches along the Colville River, the boundary is an incised, nonmarine erosion surface within the Prince Creek and Schrader Bluff stratigraphic interval, whereas farther offshore it appears to be a subtle discontinuity between middle and lower Schrader Bluff Formation shelfal marine sediments. Still farther offshore, the boundary is interpreted as a marine mass-wasting surface that locally cuts through the lowermost Schrader Bluff Formation and into the underlying Seabee Formation.

Correlations of this mid-Campanian sequence boundary and other Brookian horizons above and below it (Decker, 2007) indicate that Schrader Bluff strata at the Sentinel Hill Core Test 1 well and in nearby Colville River outcrops are probably at least as old as, if not older than, the isolated Tabasco sandstone near the bottom of the formation in the Kuparuk River Unit. If the Schrader Bluff Formation strata at the Sentinel Hill Core Test 1 well are as old as suggested by Decker (2007), then the producing Schrader Bluff, West Zak, Aurora, and Borealis oil pools in the Milne Point, Kuparuk River, and Prudhoe Bay Units of the central North Slope are in significantly younger reservoirs than (although possibly in a similar facies to) the time-transgressive deposits of the Schrader Bluff and Prince Creek Formations at and near the Sentinel Hill Core Test 1well.

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