Chapter 12

# Stratigraphy of the Upper Cretaceous Mancos Shale (Upper Part) and Mesaverde Group in the Southern Part of the Uinta and Piceance Basins, Utah and Colorado

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**Volume Title Page**

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Chapter 12 *of*

**Petroleum Systems and Geologic Assessment of Oil and Gas in the Uinta-Piceance Province, Utah and Colorado**

*By* USGS Uinta-Piceance Assessment Team

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## Introduction

Cross section *A–A′* was constructed in support of the oil and gas assessments of the Mesaverde and Mancos/Mowry Total Petroleum Systems in the Uinta and Piceance Basins of Utah and Colorado (fig. 1). The Mesaverde Total Petroleum System contains continuous gas derived primarily from carbonaceous shale and coal in the Mesaverde Group (Chapter 13 by Johnson and Roberts, this CD-ROM). The Mancos/Mowry Total Petroleum System contains continuous gas derived primarily from marine source rocks in the Mancos and Mowry Shales (Chapter 6 by Kirschbaum, this CD-ROM). Cross section *A–A′* illustrates the stratigraphy of these Upper Cretaceous rocks, emphasizing the fluvial, coal-bearing coastal plain, nearshore marine, and offshore marine strata. The cross section is presented as a printed copy in Hettinger and Kirschbaum (2002).

Cross section *A–A′* extends west-east about 200 mi from near the town of Price, Utah, to near the town of Redstone, Colo. (fig. 1). Correlations within the Uinta Basin are shown on plate 1, and correlations within the Piceance Basin are shown on plate 2. Drill holes and measured sections shown along the cross section are listed in table 1. The general orientation of the cross section is roughly perpendicular to the paleoshorelines of the Cretaceous Interior seaway; however, the more north-south segments of the cross section trend subparallel to the paleoshoreline. Orientations of the cross section with respect to the paleoshorelines are shown below the cross section on plates 1 and 2.

The cross section was located along the south flanks of the Uinta and Piceance Basins so that descriptions from nearby exposures could be used for depositional interpretations and more direct stratigraphic control. Correlations in the southern part of the Piceance Basin are based on outcrop investigations by Kirschbaum and Hettinger (1998) and Collins (1976), and subsurface investigations by Hettinger and others (2000). Correlations along the south flank of the Uinta Basin represent a synthesis of outcrop investigations by Balsley (1980), Clark (1928), Franczyk and others (1990), Kamola and Van Wagoner (1995), Kirschbaum and Hettinger (1998), Lawton (1983, 1986), McLaurin and Steel (2000), O'Byrne and Flint (1995), Pattison (1995), Taylor and Lovell (1995), Van Wagoner (1991a, b, c, 1995), Van Wagoner and others (1990), Yoshida and others (1996), and Young (1955, 1966). Selected measured sections from those investigators are shown on the cross section. Based on our field reconnaissance, we have changed the position of some formational contacts shown on measured sections by Franczyk and others (1990) and Lawton (1983); in each case, the original position of the contact is also shown.

### Depositional History

During the Late Cretaceous (approximately 95–67 million years ago) the region now occupied by the Uinta and Piceance Basins was located near the western shoreline of the Western Interior seaway and within the Cretaceous Rocky Mountain Foreland basin. Fluvial systems transported sediment eastward from the Sevier highlands to the coastal areas, and coal-forming wetlands occupied the coastal plains. Shorelines migrated during the Late Cretaceous owing to variations in relative sea level and sediment supply. The seaway attained its maximum extent during the Turonian (early Late Cretaceous) when its western shoreline was located in central Utah. It retreated slowly eastward between the Turonian and early Campanian and moved permanently from the region during the Maastrichtian (latest Cretaceous). During the late Campanian the shoreline moved repeatedly back and forth across the Uinta and Piceance Basins region, and its orientation varied from about N. 65° E. to N. 15° W. (Johnson, 1989a). Depositional systems of the Late Cretaceous were summarized in paleogeographic maps of North America by Roberts and Kirschbaum (1995), and the depositional history of the Campanian in the Uinta and Piceance Basin region was summarized by Fouch and others (1983) and Johnson (1989a).

Structural development of the Uinta and Piceance Basins began near the end of the Cretaceous and beginning of the Tertiary Periods, as the foreland basin segmented into smaller sedimentary basins (Johnson and Finn, 1986). As tectonic activity increased, coarse-grained sediment accumulated adjacent to highland areas, and finer grained sediment was deposited in the basin centers. By the middle Eocene, the Uinta and Piceance Basins were inundated by Lake Uinta, and

*Click on image below to bring up high-resolution image of plate 1.*

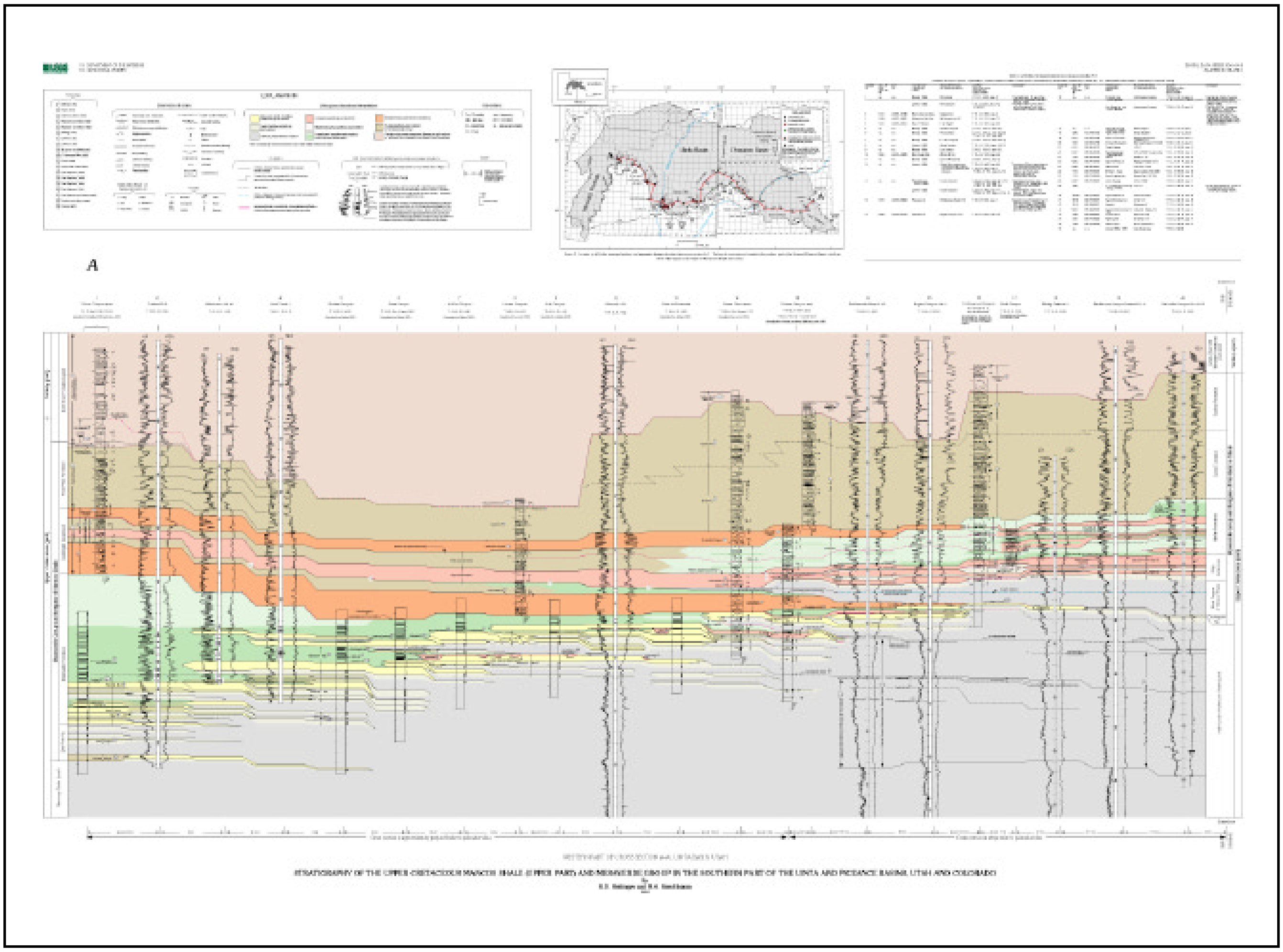

**Plate 1**. Western part of cross section *A–A′*.

*Click on image below to bring up high-resolution image of plate 2.*

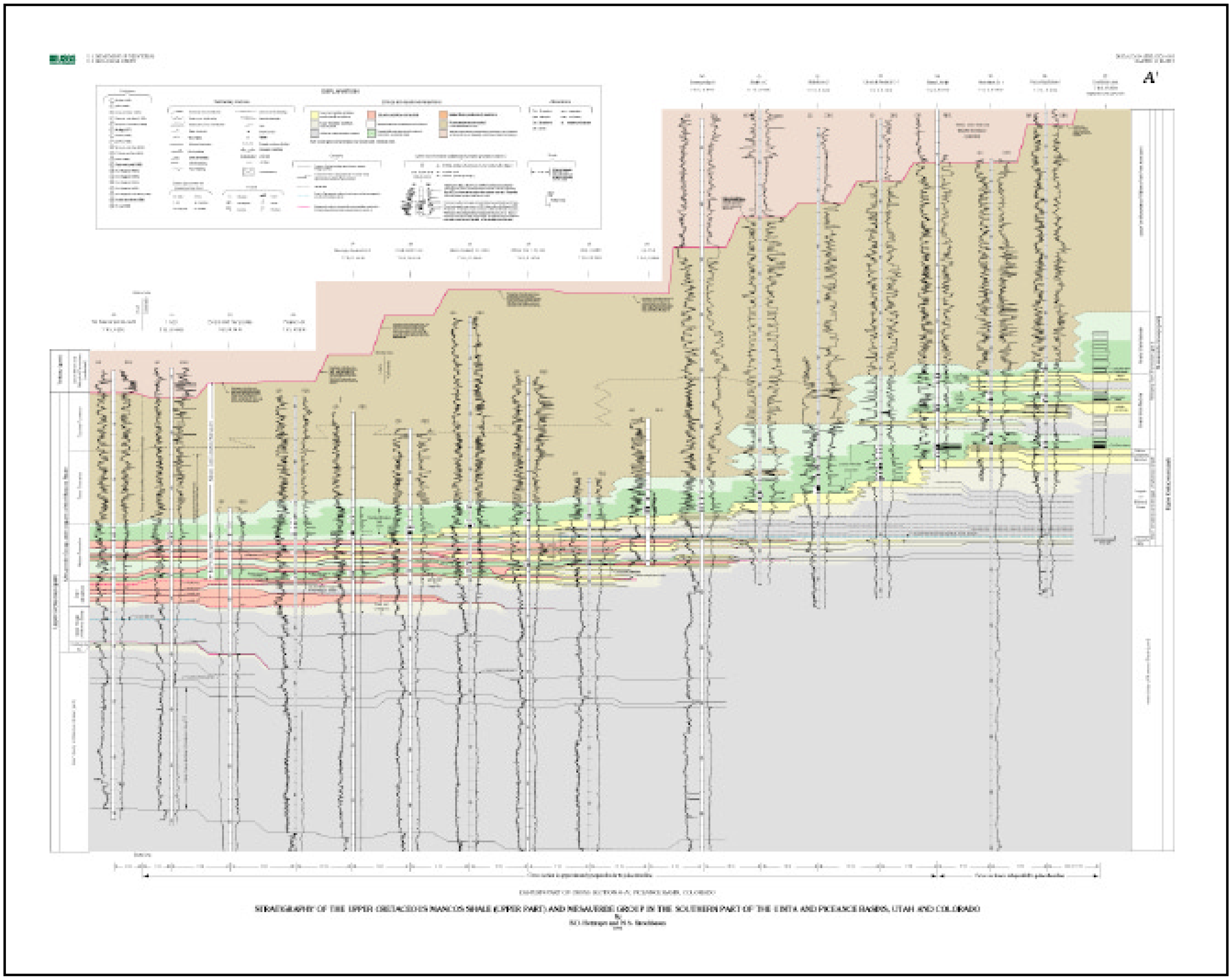

**Plate 2**. Eastern part of cross section *A–A′*.

sediment accumulated in lacustrine environments (Donnell, 1961; Roehler, 1974; Johnson, 1985). Later, during the late Eocene, Lake Uinta was filled in by locally derived sediment as well as volcaniclastic sediment from Wyoming to the north (Johnson, 1985).

## Acknowledgments

We thank Philip Nelson and Joyce Kibler (U.S. Geological Survey) for preparing the digital suite of geophysical logs shown on the cross section. Steve Roberts and Ron Johnson (U.S. Geological Survey) are acknowledged for their assistance regarding the stratigraphic location of some formational boundaries shown on the cross section. We thank Chris Schenk and Ron Johnson (U.S. Geological Survey) for their technical reviews of the manuscript and cross section. Alex Donatich and Katharine Varnes (U.S. Geological Survey) are also acknowledged for their editorial reviews.

# Nomenclature of Upper Cretaceous Rocks in the Southern Part of the Uinta and Piceance Basins

Upper Cretaceous rocks investigated in this report include (in ascending order) the middle and upper parts of the Mancos Shale, Mesaverde Group (Formation), and lower part of the North Horn Formation. Nomenclature for these rocks is complex and has been used inconsistently by previous investigators as shown in figure 2. Stratigraphic unit ages have been provided by Fouch and others (1983), Gill and Hail (1975), Johnson (1989a), and Molenaar and Cobban (1991). The Mancos was deposited during the Cenomanian through Campanian. The Mesaverde Group (Formation) was deposited during the Campanian, and also includes Maastrichtian strata in the Piceance Basin. A regional unconformity divides the Mesaverde Group (Formation) from overlying Maastrichtian and Tertiary strata. Strata above the unconformity have been assigned to the North Horn Formation (Maastrichtian to Eocene), and the intertonguing Wasatch (including the conglomerate beds at Dark Canyon), Colton, and Green River Formations (late Paleocene to Eocene).

Nomenclature used in this report is shown in figure 3. In the southern part of the Uinta Basin, the Mesaverde Group is divided (in ascending order) into the Star Point Sandstone, Blackhawk Formation, Castlegate Sandstone, Sego Sandstone, Neslen Formation, Price River Formation, Farrer Formation, and Tuscher Formation, following the terminology of Fouch and others (1983) (fig. 3). In the southern part of the Piceance Basin, the Mesaverde Group is divided into the Castlegate Sandstone, Sego Sandstone, Iles Formation, and Williams Fork Formation (fig. 3). As used in this report, the Iles Formation nomenclature has been extended from the Grand Hogback westward to the State line and includes those parts of the Mesaverde and Mount Garfield Formations that lie below the top of the Rollins Sandstone Member (fig. 2). The Iles Formation includes the Corcoran, Cozzette, and Rollins Sandstone Members (fig. 3). In this report, the Williams Fork Formation nomenclature has also been extended from the Grand Hogback westward to the State line. As such, the Williams Fork includes (1) the Bowie Shale and Paonia Shale Members and an undifferentiated member in the Grand Hogback and Grand Mesa areas, (2) the part of the Mount Garfield that lies above the Rollins Sandstone Member in the eastern Book Cliffs area, (3) the Hunter Canyon Formation in the eastern Book Cliffs area, and (4) all strata that are equivalent to the Ohio Creek Conglomerate (fig. 2).

# Descriptions of the Mancos Shale and Mesaverde Group along Cross Section *A–A′*

## Mancos Shale

The Mancos Shale is dominated by mudrock that accumulated in offshore and open-marine environments of the Cretaceous Interior seaway. It is 3,450–4,150 ft thick where exposed in the southern part of the Piceance and Uinta Basins (Fisher and others, 1960), and geophysical logs indicate the Mancos to be about 5,400 ft thick in the central part of the Uinta Basin (Chapter 6 by Kirschbaum, this CD-ROM). The upper part of the formation grades into and intertongues with the Mesaverde Group. The shale tongues typically have sharp basal contacts and gradational upper contacts. Named tongues include the Buck and the Anchor Mine Tongues.

An important hydrocarbon-producing unit in the middle part of the Mancos was referred to as the “Mancos B Formation” by Kellogg (1977). The Mancos B consists of thinly interbedded and interlaminated, very fine grained to fine-grained sandstone, siltstone, and claystone that was interpreted to have accumulated as north-prograding “fore slope” sets within an open-marine environment (Kellogg, 1977). Cole and others (1997) subsequently incorporated the Mancos B into a thicker stratigraphic unit that they identified as the Prairie Canyon Member of the Mancos. Their subsurface correlations showed that the Prairie Canyon was about 1,200 ft thick at the Rattlesnake State 2-12 drill hole (loc. 14). The north progradation of the fore slope is further documented by Johnson (Chapter 10, this CD-ROM), whose subsurface correlations indicate that the Mancos B of Kellogg occupies approximately the lower 800 ft of the Prairie Canyon at the Rattlesnake State 2-12 drill hole. Hampson and others (1999) interpreted the Prairie Canyon as having accumulated in tidally influenced fluvial channels, fluvial-dominated delta

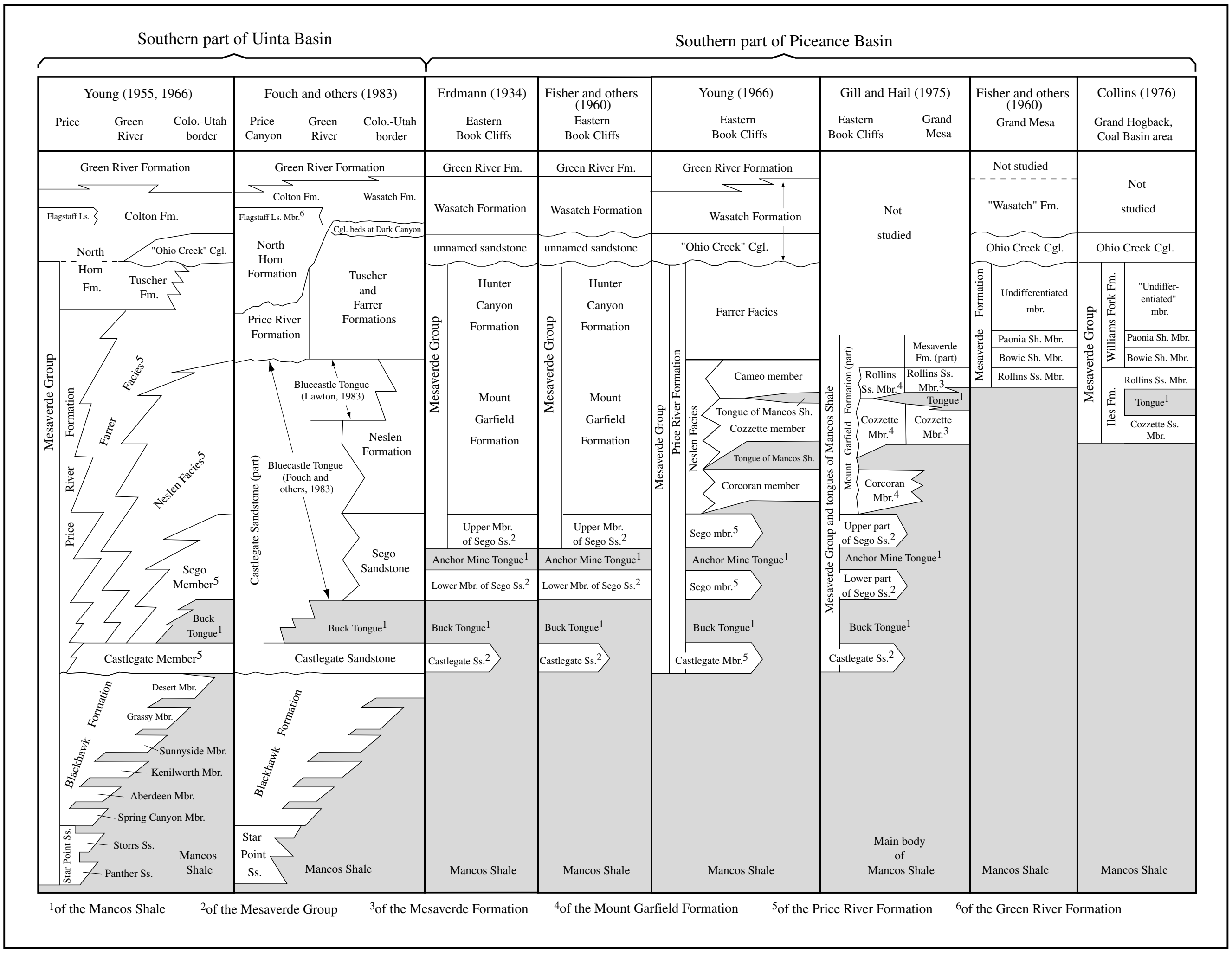


**Figure 2.** Nomenclature used by various authors for Upper Cretaceous and lower Tertiary rocks in the southern part of the Piceance and Uinta Basins. Abbrevations: Formation (Fm.), Member (Mbr., mbr.), Conglomerate (Cgl.), Limestone (Ls.), Sandstone (Ss.), Shale (Sh.).

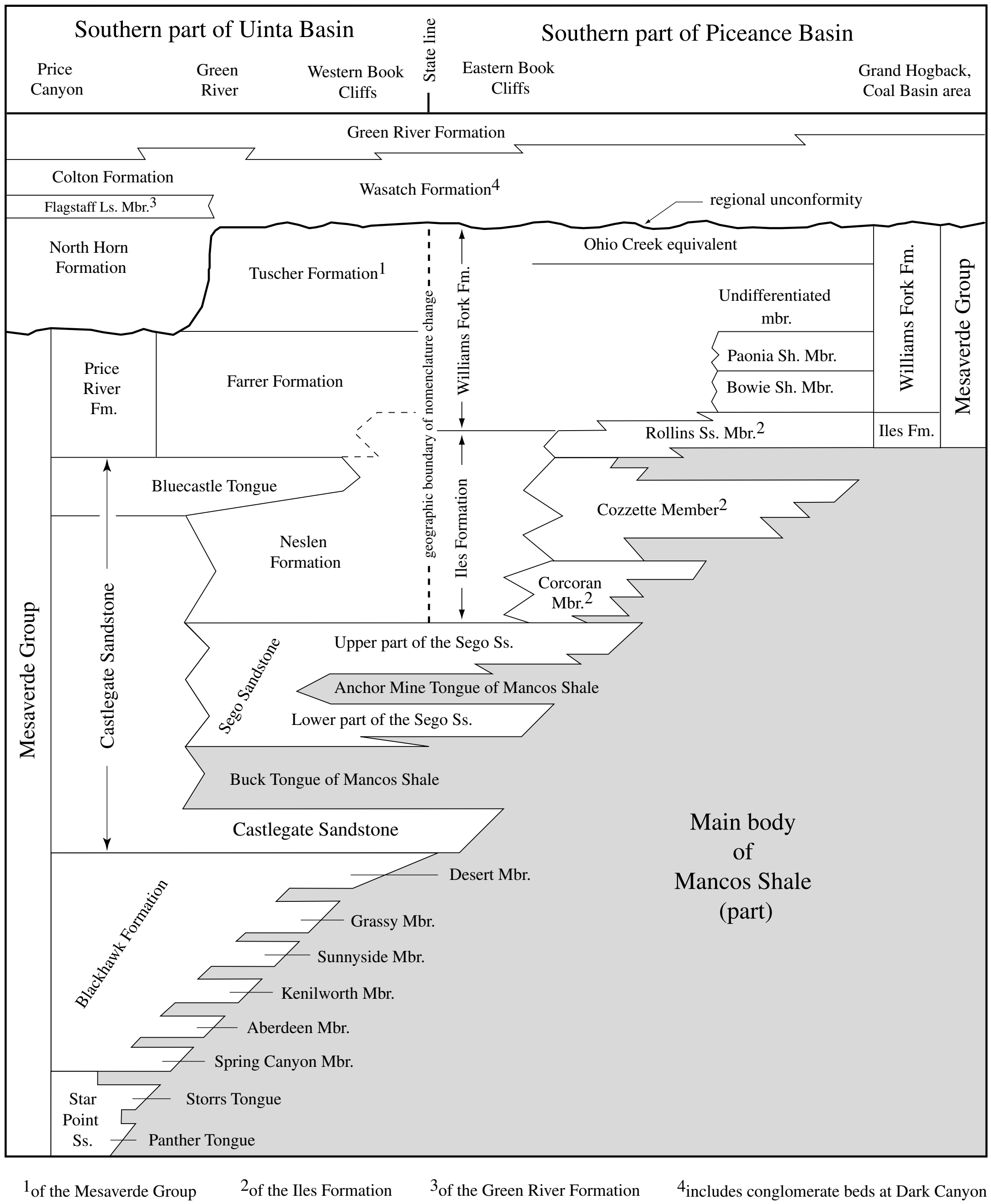


**Figure 3.** Nomenclature used in this report for Upper Cretaceous and lower Tertiary rocks in the southern part of the Uinta and Piceance Basins. Nomenclature for the Blackhawk Formation and Star Point Sandstone is from Young (1955) (fig. 2). Nomenclature for strata above the Blackhawk Formation in the southern part of the Uinta Basin is based on Fouch and others (1983) (fig. 2). The conglomerate beds at Dark Canyon are included with the Wasatch Formation based on Franczyk and others (1990). Use of the Bluecastle Tongue of the Castlegate Sandstone is based on modifications by Lawton (1983) (fig. 2). In this report, the Iles and Williams Fork nomenclature is extended from the Grand Hogback westward to the State line. As such, the Iles Formation includes the Rollins Sandstone and Cozzette Sandstone Members of Collins (1976) as well as the Rollins Sandstone, Cozzette, and Corcoran Members of the Mesaverde and Mount Garfield Formations of Gill and Hail (1975) (fig. 2). The Williams Fork Formation includes the Bowie Shale Member, Paonia Shale Member, and undifferentiated member used in the Grand Hogback area (Collins, 1976) and Grand Mesa area (Fisher and others, 1960), as well as the Hunter Canyon Formation and those parts of the Mount Garfield and Mesaverde Formations that lie above the Rollins Sandstone Member in the eastern Book Cliffs area (Erdmann, 1934; Fisher and others, 1960) (fig. 2). Inclusion of Ohio Creek equivalent strata in the Williams Fork is based on redefinition of the Ohio Creek as a member of the Hunter Canyon and Mesaverde Formation by Johnson and May (1980). Abbreviations: Formation (Fm.), Member (Mbr., mbr.), Limestone (Ls.), Sandstone (Ss.), Shale (Sh.).

fronts, and shoreface environments more than 30 mi seaward (eastward) of contemporaneous shorelines in the Blackhawk Formation. They identified and correlated several marker horizons (W, X, Y, and Z) in the middle part of the Prairie Canyon, with each marker horizon representing the contact between shoreface or valley-fill deposits and overlying open marine strata. The stratigraphic positions of the X, Y, and Z marker horizons were interpreted by Hampson and others (1999) at the Rattlesnake State 2-12 and Bogart Canyon 14-4 drill holes (locs. 14, 15).

Intertonguing between the Mancos Shale and Mesaverde Group occurs along the entire length of cross section *A–A′* (pls. 1, 2). The Prairie Canyon Member of Cole and others (1997) is identified at the Rattlesnake State 2-12 drill hole (loc. 14), and it is extended between localities 14 and 30 based on geophysical signatures. The Mancos B of Kellogg (1977) is also shown at the Rattlesnake State 2-12 drill hole based on Johnson (Chapter 11, this CD-ROM). The X, Y, and Z marker horizons are shown at the Rattlesnake State 2-12 and Bogart Canyon 14-4 drill holes (locs. 14, 15) based on Hampson and others (1999), and the W marker has been extended into the Bailey Federal 1 drill hole (loc. 18) based on correlations from nearby drill holes shown in Hampson and others (1999). Our correlations indicate that the base of the Prairie Canyon is approximately stratigraphically equivalent to the base of the Star Point Sandstone at Price Canyon (loc. 1). Our correlations also show that the top of the Prairie Canyon is approximately stratigraphically equivalent to the top of the Grassy Member of the Blackhawk Formation at Tusher Canyon (loc. 13).

## Star Point Sandstone

The Star Point Sandstone was named by Spieker and Reeside (1925) after a prominent headland of the Wasatch Plateau, Utah, and it was regarded as the basal formation of the Mesaverde Group by Spieker and Reeside (1925), Clark (1928), and Fisher and others (1960). In the western Book Cliffs of Utah, Young (1955) restricted the Star Point to strata between the base of the Panther Tongue and top of the Storrs Tongue. The formation spans a 350-ft stratigraphic interval at Price Canyon, Utah (fig. 1), but becomes finer grained eastward and grades into the Mancos Shale in the vicinity of the Price and Soldier Canyon areas (fig. 1). Young (1955) described the Star Point Sandstone as consisting of predominantly littoral marine and marine deposits. However, Balsley (1980) interpreted the Panther Tongue to be a distributary mouth bar deposit. The Star Point Sandstone was correlated between localities 1 and 5 on cross section *A–A′*, based on Balsley (1980) and Young (1955).

## Blackhawk Formation

The Blackhawk Formation, which contains the most important coal-bearing strata in the Uinta Basin, was named by Spieker and Reeside (1925) for exposures in Emery County, Utah. The formation is exposed along the south flank of the Uinta Basin west of Floy Canyon (called Saleratus Canyon by Fisher and others, 1960) (fig. 1) and is located stratigraphically between the Storrs Tongue of the Star Point Sandstone and the Castlegate Sandstone (Young, 1955). It conformably overlies a thin unnamed tongue of the Mancos Shale, and is unconformably overlain by the Castlegate Sandstone (Young, 1955; Van Wagoner, 1991b, c, d, 1995). The Blackhawk was measured to be about 800 ft thick at Price Canyon (Young, 1955), but thickens to 1,240 ft in the nearby Pacific Gas and Electric Federal 6-8 drill hole (loc. 2).

Outcrops of the Blackhawk Formation were investigated along the south margin of the Uinta Basin by Young (1955) and Balsley (1980). Young divided the Blackhawk into (in ascending order) the Spring Canyon, Aberdeen, Kenilworth, Sunnyside, Grassy, and Desert Members. Each member contains very fine grained to medium-grained sandstone, mudrock, carbonaceous shale, and coal that accumulated in coastal plain and shoreface environments. To the northwest, the members grade into coal-bearing coastal plain deposits of the undivided Blackhawk Formation, and to the southeast they intertongue with, and pinch out into, the Mancos Shale. Correlation diagrams by Young (1955) depict facies transitions and the stratigraphic rise of various facies within the Blackhawk. Balsley (1980) interpreted the strata to have been deposited within deltaic, nearshore, tidal, and coastal plain environments. His correlation diagrams generally followed those of Young but provided greater detail regarding facies variations and their lateral transitions.

More recently, sequence stratigraphic studies of the Blackhawk Formation were made from Book Cliffs exposures in Utah (fig. 1). Included are investigations of (1) the Spring Canyon Member by Kamola and Van Wagoner (1995), (2) the Kenilworth Member by Taylor and Lovell (1995) and Pattison (1995), (3) the Grassy Member by O'Byrne and Flint (1995) and Van Wagoner (1995), and (4) the Desert Member by Van Wagoner (1991b, 1995). Their collective investigations identified several unconformity-bound sequences and associated systems tracts and provided details regarding shoreface stacking patterns. Taylor and Lovell (1995) identified valley-fill deposits and an associated sequence boundary unconformity at the top of the Kenilworth Member. O'Byrne and Flint (1995) and Van Wagoner (1995) identified several valley-fill systems and associated unconformities within the Grassy Member; the unconformities were identified (in ascending order) as Grassy sequence boundaries 1, 2, and 3, respectively. Similarly, Van Wagoner (1991b, 1995) described a valley-fill system within the Desert Member and its basal unconformity was identified as the Desert sequence boundary.

The Blackhawk Formation was correlated on cross section *A–A′* between localities 1 and 13 (pl. 1), and the correlations follow those of Balsley (1980) and Young (1955). Stratigraphic control was provided from measured sections by Balsley (1980) (locs. 1, 5, 6, 7, 9, 11), and Lawton (1983) (locs. 12, 13), and interpretations by Van Wagoner and others (1990) of the Rattlesnake State 2-12 drill hole (loc. 14). Significant stratigraphic relations and correlations are described in the following:

1. Sequence boundaries shown in the Kenilworth, Grassy, and Desert Members are based on Taylor and Lovell (1995), O'Byrne and Flint (1995), and Van Wagoner (1991b, 1995).

2. Coal-bearing strata are in a thick interval of the undivided Blackhawk Formation near the Price Canyon area (locs. 1, 2). Approximately 63 ft of net coal was drilled at locality 2 where individual beds are between about 2 and 12 ft thick.

3. The coal-bearing strata pass eastward into the Spring Canyon, Aberdeen, Kenilworth, Sunnyside, and Desert Members, and the amount of net coal generally decreases to the southeast.

4. Principal coal beds shown on the cross section include: (1) the Spring Canyon coal group in the Spring Canyon Member, (2) the Castlegate "A" coal bed in the Aberdeen Member, (3) the Kenilworth, Gilson, Rock Canyon, Fish Creek, and Rock Creek coal beds in the Kenilworth Member, and (4) the Sunnyside coals in the Sunnyside Member (Balsley, 1980; Clark, 1928; Young, 1955).

## Castlegate Sandstone

The Castlegate Sandstone contains sheet-like sandstones that extend across large areas of the Uinta Basin. The formation is 623 ft thick at Price Canyon, Utah (fig. 1), where it lies unconformably between the Blackhawk and Price River Formations (Fouch and others, 1983; Lawton, 1983, 1986). To the east, it grades into the main body of the Mancos Formation, the Buck Tongue of the Mancos Formation, and the Sego and Neslen Formations (Fouch and others, 1983; Franczyk and others, 1990).

The Castlegate was divided into lower and upper units at Price Canyon (Lawton, 1986; Spieker, 1931); the units split to the east, and only the lower unit retains the name of Castlegate Sandstone. The lower unit of the Castlegate is about 295 ft thick and was described as a predominantly fine- to medium-grained massive sandstone that was deposited in a braided fluvial environment (Lawton, 1986). The lower unit thins and becomes finer grained to the southeast, and passes into the Mancos Shale near the Colorado border (Fisher and others, 1960; Gill and Hail, 1975). The upper unit of the Castlegate is about 330 ft thick in Price Canyon, where it is dominated by interbedded fine-grained sandstone and mudrock that were deposited in a meandering fluvial environment (Lawton, 1986). The uppermost 66–98 ft consists of coarse-grained and pebbly sandstone that was correlated with the Bluecastle Tongue (Lawton, 1983, 1986), a unit that pinches out into the Neslen Formation near Sego Canyon, Utah (fig.1) (Franczyk and others, 1990). The basal contact of the Bluecastle was interpreted to be unconformable and was referred to as the Bluecastle sequence boundary by Yoshida and others (1996).

Sequence stratigraphic studies by Van Wagoner (1991b, c, d, 1995) and Van Wagoner and others (1990) demonstrated that the lower unit of the Castlegate Sandstone was dominated by valley-fill braided fluvial and estuarine strata that passed eastward into shoreface strata near Cottonwood Canyon (fig. 1). The unconformable base of the valley-fill deposits extended eastward across the shoreface strata and was referred to as the Castlegate sequence boundary. The valley-fill deposits were interpreted to represent a lowstand systems tract associated with overlying transgressive and highstand deposits within the Buck Tongue of the Mancos Shale. Shoreface strata within the lower Castlegate were interpreted as highstand deposits associated with the Desert Member of the Blackhawk Formation (Van Wagoner, 1995).

Additional sequence stratigraphic studies by McLaurin and Steel (2000) and Yoshida and others (1996) described possible eastward facies transitions of the Castlegate Sandstone, as summarized in figure 4. Both groups interpreted the strata between the Castlegate and Bluecastle sequence boundaries to represent a third-order sequence (fig. 4). Finer grained strata between the lower unit of the Castlegate and the Bluecastle sequence boundary at Price Canyon were referred to as the mudstone member by Yoshida and others (1996), and as the middle member by McLaurin and Steel (2000) (fig. 4). Yoshida and others (1996) interpreted the mudstone member to pass eastward into five higher order sequences within the Sego and Neslen Formations, and the Buck Tongue to be truncated by an unconformity at the base of the Sego Sandstone (fig. 4). Contrasting interpretations were made by McLaurin and Steel (2000); they contended that (1) the middle member graded laterally into the Buck Tongue and Sego and Neslen Formations; (2) these combined strata were divided by five fourth-order sequence boundaries (fig. 4); and (3) the transgressive surface of erosion and maximum flooding surface of the third-order sequence extended from within the middle member eastward to the base of the Buck Tongue and Anchor Mine Tongue, respectively (fig. 4).

The Castlegate Sandstone was correlated eastward from Price Canyon (loc. 1) along cross section *A–A′* (pls. 1, 2). Stratigraphic control was provided by the measured sections of Balsley (1980) (locs. 5, 6, 7, 9, 11), Lawton (1983) (locs. 1, 8, 12, 13), and Van Wagoner and others (1990) (loc. 16), as well as interpretations by Van Wagoner and others (1990) of the Rattlesnake State 2-12 drill hole (loc. 14). Significant correlations and stratigraphic relations are described in the following:

1. The Castlegate Sandstone at Price Canyon (loc. 1) is divided into lower and upper units and the Bluecastle Tongue following the usage of Lawton (1983, 1986). The mudstone member of Yoshida and others (1996) and middle member of McLaurin and Steel (2000) are also shown.

2. The lower unit of the Castlegate is extended eastward through laterally continuous units of coarser grained strata as interpreted from geophysical logs and as described on measured sections of Balsley (1980) and Lawton (1983).

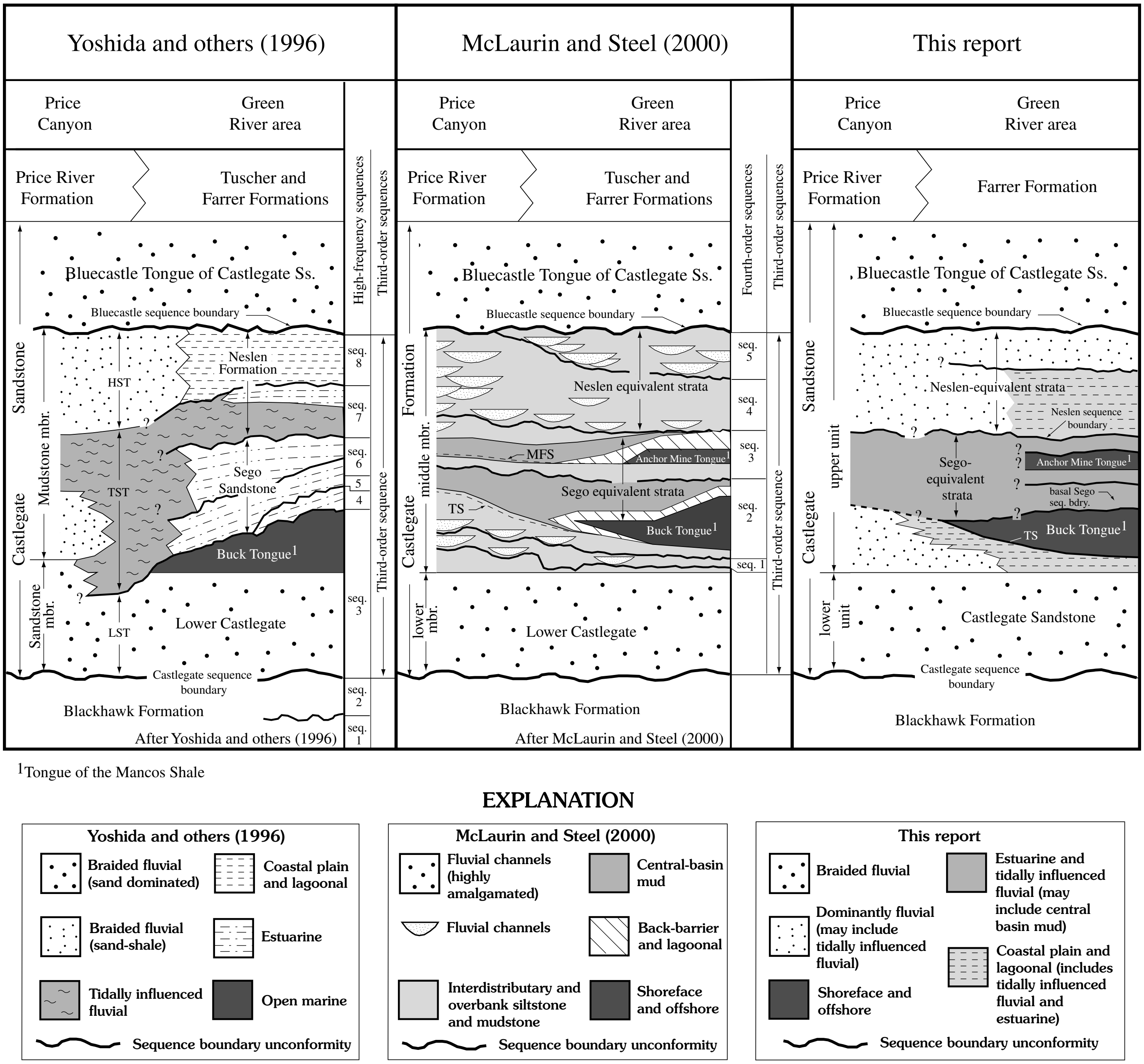


**Figure 4.** Interpretations of Yoshida and others (1996) and McLaurin and Steel (2000) regarding facies transition from the Castlegate Sandstone at Price Canyon eastward to the Buck Tongue of the Mancos Shale, Sego Sandstone, and Neslen Formation in the Green River area, Utah. The interpretations of Yoshida and others (1996) and McLaurin and Steel (2000) are compared to the more generalized interpretations made in this report. Abbreviations: Sandstone (Ss.), member (mbr.), sequence (seq.), boundary (bdry.), highstand systems tract (HST), lowstand systems tract (LST), transgressive systems tract (TST), transgressive surface (TS), maximum flooding surface (MFS).

Its facies transitions into shoreface strata (near Cottonwood Canyon, loc. 16) and the Mancos Shale (near locality 22) are based on Van Wagoner and others (1990). The Castlegate sequence boundary is correlated between localities 13 and 22 based on Van Wagoner (1991b, c, d, 1995) and Van Wagoner and others (1990), and it is extended westward along the unconformable base of the Castlegate Sandstone.

3. The Bluecastle Tongue is extended eastward through laterally continuous units of coarser grained strata based on interpretations of geophysical logs and descriptions of measured sections by Lawton (1983). It pinches out into the Neslen Formation several miles north of Sego Canyon near locality 15. The Bluecastle sequence boundary is extended along the unconformable base of the Bluecastle Tongue.

4. The transition of the middle part of the Castlegate into the Buck Tongue and Sego and Neslen Formations, as shown on the cross section, is described in following sections of this report. Figure 4 compares our synthesis of multiple reports with the interpretations of Yoshida and others (1996) and McLaurin and Steel (2000).

## Buck Tongue of the Mancos Shale

The Buck Tongue of the Mancos Shale, named for exposures in Buck Canyon (fig. 1), consists of offshore marine mudrock between the lower unit of the Castlegate Sandstone and the Sego Sandstone (Fisher and others, 1960). The Buck Tongue is about 350 ft thick where it grades into the main body of the Mancos Shale near the Colorado-Utah border (Gill and Hail, 1975), and it thins and pinches out to the west between the Green River and Horse Canyon, Utah (fig. 1) (Fisher and others, 1960). Its upper contact with the Sego is both conformable (Fisher and others, 1960) and locally unconformable (Van Wagoner and others, 1990). The basal contact with the Castlegate is erosional and was interpreted as a transgressive surface by Van Wagoner and others (1990). Lawton (1983, 1986) placed the basal contact at a red-weathering chert and mudstone horizon in the Green River and Tusher Canyon areas (fig. 1), and he interpreted the horizon to be a paleosol.

Van Wagoner and others (1990) interpreted the Buck Tongue as part of an unconformity-bounded sequence that extended between the Castlegate sequence boundary and the lowest sequence boundary in the Sego Sandstone. The lowstand systems tract was represented by fluvial and estuarine strata in the lower unit of the Castlegate Sandstone. The transgressive systems tract was represented by offshore mudrock in the Buck Tongue, and the maximum flooding surface was placed at the top of a retrogradational parasequence stack in the middle part of the Buck Tongue (Van Wagoner and others, 1990, figs. 28, 29, 31). The highstand systems tract was represented by offshore and shoreface strata in the basal part of the Sego Sandstone.

The Buck Tongue–Castlegate transition was investigated by Yoshida and others (1996) and McLaurin and Steel (2000). Yoshida and others (1996) concluded that the westward pinch out of the Buck Tongue resulted from erosional scour at the base of the Sego Sandstone, whereas McLaurin and Steel (2000) concluded that the Buck Tongue changed facies into the middle member of the Castlegate (fig. 4). McLaurin and Steel also contended that landward expressions of the Buck Tongue's basal transgressive surface were represented by the red-weathering chert and mudstone horizon described by Lawton (1986) in the Green River area, as well as a bone bed at the base of a bayhead-delta and tidal flat complex in the middle member of the Castlegate at Price Canyon.

The Buck Tongue is correlated between localities 12 and 22 along cross section *A–A′* (pls. 1, 2). Stratigraphic control was provided from measured sections of Lawton (1983) (locs. 12, 13) and Franczyk and others (1990) (loc. 16) and well-log interpretations by Van Wagoner and others (1990) (loc. 14). Figure 4 compares our synthesis of multiple reports to the interpretations of Yoshida and others (1996) and McLaurin and Steel (2000). Significant stratigraphic relations along cross section *A–A′* are described in the following:

1. The top of the transgressive systems tract in the Buck Tongue is labeled at the Rattlesnake State 2-12 drill hole (loc. 14) following Van Wagoner and others (1990); it is correlated eastward to locality 28 and is used as a local datum between localities 13 and 21.

2. The transgressive surface at the base of the Buck Tongue is interpreted to climb stratigraphically to the west and pass over the coal-bearing strata described by Lawton (1983) at Horse Canyon (loc. 8). Following McLaurin and Steel (2000), and based on our own field observations, the red chert and mudstone horizons described by Lawton (1983) at the Green River and Tusher Canyon areas (locs. 12, 13) are interpreted as a ravinement lag associated with the transgressive surface of erosion.

3. The Buck Tongue is tentatively interpreted to have been truncated by the lowest sequence boundary in the Sego Sandstone, following Yoshida and others (1996), based on the possibility that the upward transition from offshore marine mudrock (Buck Tongue) into tidally influenced strata (Sego Sandstone) represents a facies dislocation. However, it is also possible that the offshore deposits are overlain conformably by strata that accumulated along a tidally influenced muddy shoreline.

## Sego Sandstone

The Sego Sandstone was defined by Fisher (1936) near Sego Canyon, Utah (fig. 1), where it consists of about 180 ft of fine- to medium-grained sandstone and mudrock between the Buck Tongue and Neslen Formation (Franczyk and others, 1990). Farther to the east in Colorado, the Sego is overlain by the Corcoran Member of the Mount Garfield Formation (the name Iles Formation is used in this report) (Gill and Hail, 1975). The Sego passes into the Castlegate Sandstone to the west, and into the Mancos Shale to the east. The formation is divided into lower and upper parts by a westward-thinning wedge of marine mudrock named the Anchor Mine Tongue of the Mancos Shale (Gill and Hail, 1975). The Anchor Mine Tongue is about 230 ft thick where it merges with the main body of the Mancos Shale near Hunter Canyon, Colo. (fig. 1) (Gill and Hail, 1975). The lower and upper parts of the Sego are each about 100 ft thick near the Utah-Colorado State line; the lower part passes into the Mancos near Hunter Canyon and the upper part passes into the Mancos near the Farmers Mine (fig. 1) (Gill and Hail, 1975).

Van Wagoner and others (1990) and Van Wagoner (1991a) conducted detailed sequence stratigraphic investigations of the Sego Sandstone and Anchor Mine Tongue along exposures between Thompson Canyon, Utah and West Salt Creek, Colo. (fig. 1). They demonstrated that the interval containing the Sego Sandstone and Anchor Mine Tongue was deposited within eight unconformity-bounded sequences consisting of estuarine and shoreface strata. Sequence boundaries were interpreted along regionally scoured surfaces that juxtaposed estuarine strata over shoreface strata. Van Wagoner and others (1990) identified the sequence boundaries on geophysical logs from the Rattlesnake State 2-12 drill hole (loc. 14); the boundaries were subsequently renamed (in ascending order) 1 through 9 by Van Wagoner (1991a). They considered sequence boundary 9 to be a major unconformity beneath which the entire upper part of the Sego Sandstone was locally removed. Van Wagoner (1991a) also referred to sequence boundary 9 as the Neslen sequence boundary because overlying strata were considered to be within the Neslen Formation. Estuarine complexes in sequences 8 and 9 were also identified farther eastward in Colorado by Kirschbaum and Hettinger (1998). The lower complex pinched out into the Mancos Shale near East Salt Creek, and the upper complex pinched out along the Sego's upper contact near the Grasso Mine (fig. 1) (Kirschbaum and Hettinger, 1998).

The Sego-Castlegate transition was investigated by McLaurin and Steel (2000) and Yoshida and others (1996). Yoshida and others extended the Sego sequence boundaries of Van Wagoner and others (1990) westward to Horse Canyon, Utah (fig. 1), and interpreted that the Sego merged with tidal and fluvial deposits in the lower and middle parts of the Castlegate Sandstone at Price Canyon (fig. 4). McLaurin and Steel (2000) interpreted that the Sego Sandstone and Anchor Mine Tongue were within three unconformity-bounded sequences that extended westward into the middle member of the Castlegate Sandstone at Price Canyon (fig. 4). They contended that Sego-equivalent strata were represented by central basin and interdistributary mudrock in exposures between Green River and Price Canyon, Utah (fig. 4). McLaurin and Steel (2000) also interpreted that the top of the Anchor Mine Tongue represented a third-order maximum flooding surface that correlated to a zone of brackish-water trace fossils in the Price Canyon area (fig. 4).

The Sego Sandstone and Anchor Mine Tongue are correlated between localities 12 and 28 along cross section *A–A′* (pls. 1, 2). Stratigraphic control is provided from measured sections by Lawton (1983) (locs. 12, 13) and Van Wagoner (1991a) (loc. 16), and geophysical log interpretations by Van Wagoner and others (1990) (loc. 14). Additional stratigraphic control is also provided from nearby exposures described by Kirschbaum and Hettinger (1998), Van Wagoner (1991a), and Van Wagoner and others (1990). Charts in figure 4 compare our interpretations of the Sego-Castlegate transition with those of Yoshida and others (1996) and McLaurin and Steel (2000). Significant stratigraphic relations along cross section *A–A′* are described in the following:

1. The lower and upper parts of the Sego Sandstone, the Anchor Mine Tongue, and associated sequence boundaries are labeled at localities 14 and 16 (pl. 1), following Van Wagoner and others (1990, fig. 28) and Van Wagoner (1991a). Sequence boundaries at locality 14 are named 1, 6, 8, and 9 to match the revised nomenclature of Van Wagoner (1991a). The stratigraphic contacts and sequence boundaries are extended eastward to the USA 1 8 MR drill hole (loc. 28, pl. 2) and westward to Tusher Canyon (loc. 13, pl. 1). Correlations between localities 13 and 28 closely follow outcrop studies by Kirschbaum and Hettinger (1998), Van Wagoner (1991a), and Van Wagoner and others (1990).

2. Signatures on the geophysical logs indicate that the Sego passes into a finer grained facies that extends from Tusher Canyon westward to Price Canyon, where it becomes the middle part of the Castlegate Sandstone. This finer grained unit is interpreted to consist of tidally influenced strata based on descriptions of the middle member and mudstone member of the Castlegate Sandstone by McLaurin and Steel (2000) and Yoshida and others (1996) (fig. 4).

3. Our correlations suggest that the Buck Tongue was truncated by the basal Sego sequence boundary of Van Wagoner (1991a) (see previous section regarding the Buck Tongue of the Mancos Shale). This tentative interpretation is made because the juxtaposition of tidally influenced strata over marine mudrock in the Green River area (loc. 12) may reflect a facies dislocation. Alternatively, the upward transition from marine mudrock into tidally influenced strata may represent a conformable facies transition related to a muddy, rather than sandy, shoreline.

## Neslen Formation

The Neslen Formation was defined and named in Neslen Canyon, Utah (T. 20 S., R. 20 E.), where it lies between the Sego Sandstone and Farrer Formation (Fisher and others, 1960). The Neslen consists of about 320 ft of very fine grained to medium-grained sandstone, siltstone, mudstone, carbonaceous shale, and coal as described in nearby Sego Canyon (fig. 1) (Franczyk and others, 1990). Franczyk and others (1990) interpreted the Neslen to have been deposited along a coastal plain and lower alluvial plain, and that its fluvial deposits were within tidally influenced meandering rivers.

The contacts of the Neslen Formation have not been precisely defined by previous investigators. The Neslen grades into the overlying Farrer Formation (Franczyk and others, 1990), and its contact with the Bluecastle Tongue of the Castlegate Sandstone was considered to be unconformable (Yoshida and others, 1996; McLaurin and Steel, 2000). Fisher (1936) apparently mapped the base of the Neslen along a change in topography; cliff-forming sandstone was associated with the underlying Sego Sandstone and slope-forming strata were associated with the Neslen Formation. However, these criteria are not wholly satisfactory because both formations contain slope-forming strata that are in contact locally. Lawton (1983, 1986) considered the Neslen-Sego contact to be gradational, and arbitrarily placed the base of the Neslen at the top of the lower unit of the Castlegate Sandstone where the Sego was not present. Van Wagoner (1991a) placed the base of the Neslen at the Neslen sequence boundary, even though Fisher and others (1960) previously considered some of the overlying strata to be associated with the Sego Sandstone.

Neslen coal beds were mapped within (in ascending order) the Palisade, Ballard, Chesterfield, and Carbonera(?) coal zones by Fisher (1936), who also identified and mapped two clean and well-sorted sandstone marker beds between the Ballard and Chesterfield coal zones. The marker beds were referred to as the Thompson Canyon sandstone bed and Sulphur Canyon sandstone bed by Fisher (1936) and Fisher and others (1960). The Thompson Canyon sandstone bed extends between Tusher Canyon and Buck Canyon, and the Sulphur Canyon sandstone bed extends from Buck Canyon eastward to the Colorado border (fig. 1). Neslen coal beds were measured at about 270 localities in the northeastern and north-central parts (T. 7 S., Rs. 104, 105 W.; Ts. 15, 16, 17, 18 S., Rs. 22, 23, 24, 25, 26 E.) of the Westwater 30’ x 60’ quadrangle (Gualtieri, 1991a, b). Within that area: (1) the Palisade coal zone (lower zone of Gualtieri) is less than 60 ft thick and contains one to nine coal beds that range from 1 in. to 4 ft thick; (2) the Ballard coal zone is as much as 30 ft thick and contains one to four coal beds that are 1 in. to 4 ft thick; (3) the Chesterfield coal zone is as much as 40 ft thick and contains one to six coal beds that are 1 in. to 7 ft thick; and (4) the Carbonera coal zone has a maximum thickness of 29 ft and contains one to six coal beds that range from 1 in. to 6 ft thick (Gualtieri, 1991a, b).

The Neslen Formation merges westward with the middle part of the Castlegate Sandstone near the Green River, and eastward with the lower part of the Mount Garfield Formation (Iles Formation in this report) at the Colorado border. The Neslen-Castlegate transition was studied by Yoshida and others (1996) and McLaurin and Steel (2000) along exposures between Thompson and Price Canyons. Both groups interpreted that the Neslen was deposited within two unconformity-bounded sequences (fig. 4). Yoshida and others (1996) described tidally influenced strata in the lower sequence, and coastal plain and lagoonal strata in the upper sequence (fig. 4). The lower and upper sequences were considered to pass, respectively, into transgressive and highstand systems tracts of a larger third-order sequence west of Horse Canyon (fig. 1). Tidally influenced fluvial strata in the transgressive systems tract were considered to be overlain conformably by braided fluvial strata in the highstand systems tract (fig. 4). McLaurin and Steel (2000) interpreted that both sequences in the Neslen Formation consisted of interdistributary, overbank, and fluvial deposits (fig. 4). The basal unconformity of each sequence was overlain by thick channel belt sand bodies (fig. 4) McLaurin and Steel (2000) correlated the lower Neslen sequence from Thompson Canyon westward to the upper part of the middle member of the Castlegate Sandstone at Price Canyon, and they correlated the upper Neslen sequence westward from Thompson Canyon to near Soldier Creek where it was truncated by the Bluecastle sequence boundary (fig. 4).

The eastward transition of the Neslen Formation into the Mount Garfield Formation was studied by Kirschbaum and Hettinger (1998) in exposures along the Book Cliffs (fig. 1). They identified coal-bearing coastal plain and tidally influenced deposits in the Neslen, and traced a large discontinuous estuarine complex from Floy Canyon (fig. 1) westward to the lower part of the Cozzette Member of the Mount Garfield Formation (see following discussion of the Cozzette Member). The estuarine complex was capped by several forward-stepping sandstones identified as the Thompson and Sulphur Canyon sandstone beds by Fisher (1936). The Thompson and Sulphur Canyon beds were interpreted as beach or tidal flat deposits that accumulated along the edge of a large estuary (Kirschbaum and Hettinger, 1998).

The Neslen Formation is correlated along the western part of cross section *A–A′* (pl. 1) from the Colorado-Utah State line (near loc. 20) westward to the Green River area (near loc. 12), and Neslen-equivalent strata are correlated from the Green River area westward into the middle part of the Castlegate Sandstone at Price Canyon (loc. 1). Stratigraphic control was provided by sections measured by Franczyk and others (1990) (loc. 16), Lawton (1983) (locs. 1, 8, 12, 13), and Kirschbaum and Hettinger (1998) (loc. 17). Figure 4 contrasts our synthesis of previous interpretations regarding the Castlegate-Neslen transition with those of McLaurin and Steel (2000) and Yoshida and others (1996). Significant stratigraphic relations are described in the following:

1. The Neslen Formation is interpreted to be dominated by coal-bearing coastal plain deposits and estuarine complexes based on Franczyk and others (1990), Lawton (1983), and Kirschbaum and Hettinger (1998). Neslen-equivalent strata west of the Green River area are interpreted as fluvial, overbank, and interdistributary deposits based on McLaurin and Steel (2000) and Yoshida and others (1996).

2. In this report, the Neslen is shown to lie unconformably between the Sego Sandstone and Bluecastle Tongue in the region between the Green River and Cottonwood Canyon (loc. 16); the unconformable contacts are the Neslen and Bluecastle sequence boundaries. Eastward

from Cottonwood Canyon, the Neslen lies conformably between the Sego Sandstone and Farrer Formation as defined by Fisher (1936).

3. The stratigraphic position of the Neslen sequence boundary as drawn at Buck Canyon (loc. 17), Cottonwood Canyon (loc. 16), and the Rattlesnake State 2-12 drill hole (loc. 14) is based on Van Wagoner and others (1990, figs. 28 and 31) (see previous discussion of the Sego Sandstone). The sequence boundary is extended tentatively from locality 14 westward beneath coarser grained fluvial rocks that are in sharp contact with underlying finer grained Sego-equivalent strata. The increase of grain size is recognized on measured sections at Green River (loc. 12), Horse Canyon (loc. 8), and Price Canyon (loc. 1), and is interpreted from well logs at localities 2, 3, 4, and 10 (pl. 1).

4. During our field studies in the Green River and Tusher Canyon areas (locs. 12, 13), we recognized a laterally persistent channel sandstone complex 150–200 ft below the Bluecastle Tongue of the Castlegate Sandstone. We have correlated this sandstone complex with other sandstones at similar stratigraphic positions at localities 8, 10, and 14 through 20 on the cross section. Sandstones within the complex are typically coarser grained than the underlying strata, and the contact is interpreted to represent the sequence boundary described in the upper part of the Neslen Formation by McLaurin and Steel (2000).

5. Neslen coal beds are shown within the Palisade coal zone as defined by Fisher (1936), and in the Chesterfield coal zone. Also shown are the Ballard coal zone at Buck Canyon (loc. 17) and the Cameo-Wheeler coal zone at locality 20. The Palisade coal zone, which overlies the Sego Sandstone and extends from the Bogart Canyon 14-4 drill hole (loc. 15) eastward to the State line, contains one to three coal beds that are about 2–4 ft thick. As correlated on the cross section, the Palisade coal zone of Fisher (1936) is correlated with the Anchor coal zone as redefined in Colorado by Young (1955) (see discussion of the Corcoran Member of the Iles Formation). The Chesterfield coal zone extends from Cottonwood Canyon (loc. 16) eastward to locality 24, about 25 mi east of the State line; it contains one to three coal beds that are about 1–4 ft thick. The Cameo-Wheeler coal zone is present throughout the southern part of the Piceance Basin and pinches out in the Neslen Formation a few miles west of the Colorado-Utah border; it contains three to four coal beds at locality 20, where the beds are about 2–6 ft thick. Erdmann (1934) mapped these coal beds within the Cameo and Carbonera coal zones just east of the State line.

## Iles Formation

In this report the name Iles Formation was extended from the Grand Hogback south to the Crested Butte area, and west to the Colorado border. As such, it includes strata below the top of the Rollins Sandstone Member in the Mount Garfield and Mesaverde Formations, and its members are referred to simply as the Corcoran, Cozzette, and Rollins Sandstone Members (fig. 3) (see previous discussion of Upper Cretaceous strata in the southern part of the Uinta and Piceance Basins). These members were deposited during several regressive marine cycles (Johnson, 1989a). The members are divided by tongues of Mancos Shale; the basal part of each shale tongue represents the transgressive phase of each marine cycle.

### Corcoran Member

The Corcoran Member was designated by Young (1955) near the old abandoned Corcoran Mine, which is located about 1.5 mi northwest of the Grasso Mine (fig. 1). Young considered it to be a member of the Price River Formation, but more recent publications include these rocks with the Iles, Mount Garfield, and Mesaverde Formations (Collins, 1976; Gill and Hail, 1975; Johnson, 1989a). North of Palisade, the Corcoran is about 100 ft thick and consists of very fine grained to fine-grained sandstone, siltstone, shale, and coal. Young (1955) interpreted sandstone in the lower part of the Corcoran to have been deposited in littoral marine environments. Thin tongues of Mancos Shale separate the Corcoran from the underlying Sego Sandstone and overlying Cozzette Member (Young, 1955; Gill and Hail, 1975). Its contact with the underlying shale tongue is gradational, and its contact with the overlying shale tongue is sharp. The Corcoran Member was traced eastward from Big Salt Wash, Colo. (fig. 1), to where it pinches out into the Mancos Shale several miles southeast of the town of Palisade (Young, 1955; Gill and Hail, 1975).

The Corcoran Member and laterally equivalent strata in the Mount Garfield Formation (fig. 2) contain coal-bearing strata that were assigned to the Anchor and Palisade coal zones by Erdmann (1934). The Palisade coal zone was designated by Erdmann near the town of Palisade, Colo. (fig. 1), and it was extended westward into Utah and mapped at the base of the Neslen Formation by Fisher (1936). The Anchor and Palisade coal zones of Erdmann (1934) were subsequently redefined by Young (1955, p. 190). Young restricted the Palisade zone to coal-bearing strata in the upper part of the Corcoran Member, and the Anchor zone to coal-bearing strata that immediately overlie the Sego Sandstone between the State line and Hunter Canyon, Colo. (fig. 1). As redefined, the Anchor coal zone correlates with the Palisade coal zone that Fisher (1936) mapped in Utah. The Palisade coal zone of Young (1955) is generally less than 40 ft thick and contains one to four coal beds that are 1–6 ft thick; net-coal accumulations vary from 2 to 10 ft (Hettinger and others, 2000). The Anchor coal zone of Young (1955) is generally less than 60 ft thick; it contains one coal bed that is as much as 5 ft thick locally, and several additional coal beds that are less than 2 ft thick (Hettinger and others, 2000).

Stratigraphic investigations by Kirschbaum and Hettinger (1998) demonstrated that the Corcoran Member contains several progradational and forward-stepping shoreface sandstones that were eroded locally and replaced by two estuarine complexes: (1) an upper one, within the Palisade coal zone, that extends at least 12 mi between the Grasso and Farmers Mines (fig. 1), and (2) a lower one, located between the Palisade and Anchor coal zones, that extends about 15 mi between the Grasso Mine and Big Salt Wash (fig. 1).

The Corcoran Member was correlated between localities 26 and 30 (pl. 2) on cross section *A–A′*. Stratigraphic control was provided from nearby outcrop investigations by Gill and Hail (1975) and Kirschbaum and Hettinger (1998), as well as descriptions of core from the CA-77-2 drill hole (loc. 29). Several lines of cross section were constructed between the outcrops and cross section *A–A′* in order to provide stratigraphic control. Significant stratigraphic relations are described in the following:

1. Progradational shoreface deposits were correlated between localities 26 and 30. The shoreface deposits merge westward with coastal plain strata of the Iles Formation, and eastward into offshore marine deposits of the Mancos Shale. Their offshore equivalent strata were traced eastward to locality 36 near Coal Basin.

2. An estuarine complex extends unconformably over shoreface strata in the Corcoran Member and westward across the Anchor-Palisade coal zone. Its basal contact was interpreted to represent a sequence boundary that extends between localities 18 and 32 in Colorado. The complex pinches out in the Neslen Formation in Utah between localities 19 and 20. The estuarine complex is probably the lower of the two complexes described by Kirschbaum and Hettinger (1998).

3. The Palisade coal zone, as redefined by Young (1955), extends between localities 24 and 29 and contains one to four beds of coal 1–5 ft thick. Net coal ranges from 2 to 12 ft.

4. The Anchor coal zone, as redefined by Young (1955), extends between localities 21 and 26 and contains one to three beds of coal 1–6 ft thick. Net coal ranges from 2 to 10 ft. To the west in Utah, the Anchor coal zone becomes the Palisade coal zone as mapped by Fisher (1936).

## Cozzette Member

The Cozzette Member was defined by Young (1955) near the old abandoned Cozzette Mine north of Palisade, Colo. (fig. 1). Young described the Cozzette as consisting of littoral marine sandstone and associated coal-bearing strata that overlie the Corcoran Member. He considered the Cozzette to be part of the Price River Formation, but it has been generally regarded as a member of the Iles, Mount Garfield, and Mesaverde Formations (Collins, 1976; Gill and Hail, 1975; Johnson, 1989a). The Cozzette is as much as 230 ft thick and consists of very fine grained to fine-grained sandstone, siltstone, shale, and coal. The Cozzette is separated from the Corcoran and Rollins Members by tongues of Mancos Shale (Young, 1955; Gill and Hail, 1975; Johnson, 1989a); its contact with the underlying shale is gradational and its contact with the overlying shale is sharp. The overlying shale pinches out on outcrops about 4 mi northwest of Hunter Canyon (fig. 1), and the upper contact of the Cozzette is difficult to identify beyond the shale pinch out. The Cozzette passes eastwardly into the Mancos Shale less than 10 mi west of the town of Paonia, Colo. (fig. 1) (Dunrud, 1989a, b), and it passes westwardly into nonmarine rocks of the Mount Garfield Formation (Iles Formation in this report) near Big Salt Wash (fig. 1) (Gill and Hail, 1975).

Kirschbaum and Hettinger (1998) described offshore, shoreface, estuarine, and coastal-plain strata within the Cozzette Member, and correlated those facies from the Farmers Mine westward to East Salt Creek, Colo. (fig. 1). They described a thin tongue of marine shale that divided the Cozzette into two parts. Both contained shoreface strata that were scoured and replaced by laterally extensive estuarine complexes; two in the lower part and one in the upper part. The lowermost estuarine complex was correlated from East Salt Creek westward to Floy Canyon, Utah (fig. 1). In Utah, the lower estuarine complex was capped by the Sulphur Canyon and Thompson Canyon beds of the Neslen Formation and it was overlain by the Chesterfield coal zone (see previous section regarding the Neslen Formation).

The Cozzette Member is correlated between localities 21 and 31 (pl. 2) along cross section *A–A′*. It merges with the Neslen Formation west of the State line, and its offshore-equivalent strata are traced eastward to locality 36 near Coal Basin. The upper contact is not well defined northwest of locality 26 owing to the pinch out of the overlying tongue of Mancos Shale. Our facies identifications and correlations are influenced strongly by those observed on nearby outcrops by Gill and Hail (1975) and Kirschbaum and Hettinger (1998). We have constructed several lines of cross section between the outcrops and cross section *A–A′* in order to provide stratigraphic control, and additional control is also provided by studies of core from the CA-77-2 drill hole (loc. 29). Significant stratigraphic relations are described in the following:

1. The Cozzette Member is divided into two parts by a thin tongue of marine shale that extends eastward from locality 24. The upper and lower parts are labeled on the cross section near locality 27.

2. The lower part of the Cozzette contains progradational sets of shoreface strata between localities 20 and 30. These strata have been partially eroded and replaced by two estuarine complexes that extend westward to Buck Canyon, Utah (loc. 17). The erosional base of each complex is interpreted as a sequence boundary. The upper sequence boundary has cut into shoreface strata between localities 25 and 29 and extends westward over the Chesterfield coal zone. The lower sequence boundary, about 20–60 ft below the Chesterfield coal zone, has removed shoreface strata between localities 20 and 24. At locality 25, the lower sequence boundary was eroded by the overlying sequence boundary, it then reemerged between localities 25 and 26, and passed beneath shoreface deposits at the base of the Cozzette Member. These sequence boundary

interpretations are based on field observations made along outcrops between Hunter Canyon and Coal Gulch (fig. 1) by Kirschbaum and Hettinger (1998). The stratigraphic relations indicate that shoreface strata west of locality 25 are within a sequence that is older than shoreface strata east of locality 25.

3. The upper part of the Cozzette is interpreted to contain progradational shoreface deposits between localities 24 and 31. They pass into coastal plain strata to the west and the Mancos Shale to the east. An estuarine complex is extended over the shoreface strata and westward to Buck Canyon, Utah (loc. 17). Its basal contact is interpreted as a sequence boundary, and is tentatively correlated to the Bluecastle sequence boundary in the Uinta Basin.

4. Uppermost strata in the Cozzette are interpreted as retrogradational shoreface deposits; they converge with the Rollins Sandstone Member near locality 25 and grade into offshore mudrock east of locality 30. The retrogradational strata are interpreted to have been deposited along a transgressive shoreline, and to represent the landward limit of the Rollins Sandstone Member at locality 25.

### Rollins Sandstone Member

The Rollins Sandstone Member was named by Lee (1909) for a prominent sandstone at the top of the Mancos Shale near Grand Junction, Colo. (fig. 1). The unit was mapped along the south flank of the Piceance Basin by Lee (1912) but it was miscorrelated in the Book Cliffs area. Revisions were made by Erdmann (1934) and more precise correlations were made by Gill and Hail (1975) and Kirschbaum and Hettinger (1998). Warner (1964) correlated the Rollins Sandstone Member with the Trout Creek Sandstone Member of the Iles Formation near the town of New Castle, Colo. (fig. 1).

The Rollins Sandstone Member is 0–200 ft thick and consists of very fine grained to coarse-grained, cliff-forming sandstone that accumulated in a regressive nearshore marine environment. The western terminus of the Rollins was found along the south flank of the Piceance Basin near Layton Wash, Colo. (fig. 1) (Gill and Hail,1975; Kirschbaum and Hettinger, 1998) and it trends approximately N. 30° E. through the basin's subsurface (Johnson, 1989a). The seaward limit was mapped in the vicinity of Crested Butte (fig. 1) by Gaskill and others (1986). At its landward terminus, the Rollins lies directly on the Cozzette Member, but farther southeast the two are separated by a tongue of Mancos Shale and the Rollins-Mancos contact is gradational (Gill and Hail, 1975). The shale tongue of the Mancos thickens to the southeast, owing to stratigraphic rise of the Rollins Sandstone, and is as much as 430 ft thick 12 mi west of the town of Paonia (fig. 1) (Gill and Hail, 1975). Collins (1976) reported the shale tongue to be about 800–1,000 ft thick at the Coal Basin area (fig. 1). Southeast of the Paonia and Coal Basin areas, the Rollins grades downward into the main body of the Mancos Shale owing to the seaward pinch out of the Cozzette Member.

On cross section *A–A'* (pl. 2), the Rollins Sandstone Member is correlated from the Coal Gulch 15-9 drill hole (loc. 25) eastward to the Coal Basin area (loc. 37). Stratigraphic control is provided by Gill and Hail (1975), Kirschbaum and Hettinger (1998), and a measured section by Collins (1976) at Coal Basin. Significant stratigraphic relations along *A–A'* are described in the following:

1. A maximum flooding surface extends from locality 25 eastward across the top of the Cozzette Member, and is used as a datum for demonstrating the stratigraphic rise of the Rollins Sandstone Member.

2. The Rollins Sandstone Member rises 800 ft stratigraphically eastward across a distance of 70 mi.

3. Forward-stepping shoreface deposits in the Rollins intertongue westward with coal-bearing coastal plain strata in the overlying Williams Fork Formation, and grade laterally into marine mudrock in the eastward-thickening tongue of Mancos Shale.

4. Marker beds can be correlated from the shoreface deposits into the offshore mudrock; correlations were made using conductivity logs (not shown). The marker beds downlap slightly toward the maximum flooding surface and pass eastward into the Mancos Shale.

## Williams Fork Formation and Equivalent Strata

Cretaceous rocks above the Iles Formation and its westward-equivalent strata were deposited mostly in coastal plain and fluvial environments. The continental deposits are within the Price River, Farrer, and Tuscher Formations of the Uinta Basin, and the Williams Fork Formation in the southern part of the Piceance Basin (fig. 3). The fluvial and coastal plain strata intertongue with marine deposits in the Bowie Shale Member of the Williams Fork Formation in the vicinity of the Grand Hogback and Crested Butte areas (fig. 1). In this report, the Williams Fork Formation was extended from the Grand Hogback south to the Crested Butte area, and westward to the Colorado border, and it includes all Cretaceous strata above the Rollins Sandstone Member of the Iles Formation (fig. 3). As such, it includes the Hunter Canyon Formation as well as the upper parts of the Mount Garfield and Mesaverde Formations (fig. 2).

### Price River Formation

The Price River Formation was named by Spieker and Reeside (1925) for exposures in Price River Canyon, and originally included all Cretaceous rocks above the Blackhawk Formation. The formation was restricted by Fouch and others (1983) and Lawton (1983, 1986) to about 620 ft of strata between the Castlegate Sandstone and North Horn Formation at Price River Canyon. It consists mostly of poorly sorted, fine- to medium-grained sandstone and siltstone deposited in northeast-flowing sinuous to meandering fluvial systems

(Lawton, 1983, 1986). The contact with the underlying Bluecastle Tongue of the Castlegate Sandstone is probably conformable, and the contact with the overlying North Horn Formation is disconformable (Lawton, 1986).

At Price Canyon, the unconformable contact between the Price River (Campanian) and North Horn (Maastrichtian to Paleocene) Formations was thought to be marked by a paleosol situated between a coarse-grained, pebbly, sheet sandstone and an overlying unit of lacustrine mudrock (Lawton, 1983, 1986) that was dated as Maastrichtian in age (Fouch and others, 1983, 1987). However, Olsen (1995) and Olsen and others (1995) considered the unconformity to be represented by a scoured surface at the base of the sheet sandstone rather than the overlying soil horizon. Olsen and others (1995) referred to the coarse-grained sheet sandstone as the Sulphur Creek Member of the Price River Formation, and the overlying lacustrine mudrock as the Ford Ridge Member of the North Horn Formation. The lacustrine interval is unconformably overlain by amalgamated fluvial bodies that mark a distinctive change to sand-dominated deposition (Franczyk and others, 1992; Olsen and others, 1995) and which are considered to be of Paleocene age (Fouch and others, 1987; Franczyk and others, 1992).

## Farrer Formation

The Farrer Formation was named by Fisher (1936) for exposures in Coal Canyon, Utah (T. 20 S., R. 17 E.). It consists of very fine grained to medium-grained sandstone and interbedded mudrock deposited along channels and floodplains of east- and northeast-flowing meandering fluvial systems (Lawton, 1986). The Farrer extends from the Colorado border westward to Solider Canyon, Utah (fig. 1), and it grades westward into the lower part of the Price River Formation (Lawton, 1986). Laterally equivalent strata in Colorado are represented by the upper part of the Mount Garfield Formation and possibly the lower part of the Hunter Canyon Formation (Fisher and others, 1960). The Farrer Formation overlies the Bluecastle Tongue of the Castlegate Sandstone and the Neslen Formation; its contact with the Bluecastle was considered to be disconformable (Lawton, 1986), and its contact with the Neslen was considered to be gradational (Franczyk and others, 1990). The Farrer is overlain unconformably by the North Horn Formation west of the Green River, and is overlain conformably by the Tuscher Formation east of the Green River (fig. 1) (Lawton, 1983, 1986). Its contact with the Tuscher was vaguely defined and previously considered to be disconformable by Fisher and others (1960). The Farrer was reported to be 130 ft thick at Soldier Canyon (Lawton, 1986) and 800 ft thick at Tusher Canyon (fig. 1) (Franczyk and others, 1990).

## Tuscher Formation

The Tuscher Formation was named by Fisher (1936) for exposures that lie between the Farrer Formation and Wasatch Formation in Tusher Canyon, Utah (fig. 1) (Fisher and others, 1960). It contains thick and laterally discontinuous units of sandstone that are separated by thinner beds of shale, and is distinguished from the underlying Farrer Formation by its lighter color and increased sandstone content. Sandstone is very fine grained to medium grained in the lower part, and coarser grained and pebbly in the upper part of the Tuscher (Lawton, 1983, 1986). The Tuscher was interpreted to have been deposited within northeast-flowing meandering and braided fluvial systems (Lawton, 1986). The formation extends along outcrops from Green River, Utah, eastward to the Colorado border, where it passes into the Hunter Canyon Formation (fig. 2) (Fisher and others, 1960, p. 18, pl. 10). Its contact with the overlying North Horn and Wasatch Formations is unconformable (Lawton, 1986; Franczyk and others, 1990); the Tuscher has been completely removed by erosion along the unconformity west of the Green River (Lawton, 1983). Its contact with the underlying Farrer Formation was vaguely defined by Fisher (1936) and has therefore been placed at various stratigraphic horizons by subsequent investigators (Franczyk and others, 1990). As a result, reported thicknesses of the Tuscher vary considerably. Spieker (1946) reported it to be about 215 ft thick near the Green River, and as much as 600 ft thick east of the Green River. Lawton (1983, 1986) placed the basal contact of the formation below where the sandstone content exceeded 50 percent and reported its thickness to be about 980 ft at Tusher Canyon. In contrast, Franczyk and others (1990) tried to use Fisher's original description and reported the Tuscher to be about 250 ft at Tusher Canyon.

Correlations of the Price River, Farrer, and Tuscher Formations are shown along cross section *A–A′* between localities 1 and 20 (pl. 1). Stratigraphic control was from measured sections by Lawton (1983) (locs. 1, 8, 12) and Franczyk and others (1990) (locs. 13, 16). Stratigraphic relations along cross section *A–A′* are described in the following:

1. Coeval strata in the Price River and Farrer Formations extend over the Bluecastle Tongue of the Castlegate Sandstone and the Neslen Formation between Price Canyon (loc. 1) and the Colorado-Utah border (near loc. 20). Correlations are based on the measured sections of Lawton (1983) and Franczyk and others (1990).

2. The Tuscher Formation overlies the Farrer Formation between localities 10 and 20. Its contact with the Farrer is based on Lawton (1983) at locality 12, and Franczyk and others (1990) at localities 13 and 16. Its basal contact is considered to be gradational, and it is inferred to be at the base

of a thick sandstone dominated unit in drill holes. Tuscher-equivalent strata are extended eastward into the Piceance Basin as shown on plate 2.

3. Fluvial interpretations of the Price River, Farrer, and Tuscher Formations are based on Fouch and others (1983), Lawton (1983), and Franczyk and others (1990).

4. The Sulphur Creek Member of the Price River Formation and the Ford Ridge Member of the North Horn Formation, as defined by Olsen and others (1995), are shown at locality 1. Unconformities interpreted by Olsen and others (1995) at the bases of the Sulphur Creek and Ford Ridge Members are also shown at locality 1 and are shown to merge near locality 3 based on geophysical log interpretations from several intervening drill holes.

5. The Price River, Farrer, and Tuscher Formations were eroded beneath a regional unconformity that developed during the latest part of the Campanian or in early Maastrichtian time (Fouch and others, 1983). The erosional surface extends from locality 3 eastward into the southern part of the Piceance Basin, where strata in the upper part of the Williams Fork Formation were also removed. The erosional surface is represented on the cross section where unconformable upper contacts of the Price River, Farrer, and Tuscher Formations were described by Olsen (1995) at locality 1, Lawton (1983) at localities 8 and 12, and Franczyk and others (1990) at localities 13 and 16. In drill holes, the position of the unconformity is based on geophysical log interpretations by R.C. Johnson (U.S. Geological Survey, written commun., 2001). Correlations by Lawton (1983) indicated that as much as 700 ft of strata in the Tuscher and Farrer Formations were removed, or never deposited, along the unconformity west of locality 10.

## Williams Fork Formation

The Williams Fork Formation was named by Hancock (1925) for exposures along the Williams Fork River near its junction with the Yampa River in Moffat County, Colo. Collins (1976, 1977) traced the formation south along the Grand Hogback (fig. 1) where it includes about 3,600–5,155 ft of strata between the Iles and Wasatch Formations. The Williams Fork thins to the west and is about 1,200 ft thick near the Colorado-Utah State line (Fisher and others, 1960, pl. 10). The westward thinning was originally attributed to erosional scour along a regional unconformity that separates white kaolinized sandstone in the upper part of the Upper Cretaceous Williams Fork Formation from variegated beds in the lower Tertiary Wasatch Formation (Johnson and May, 1980). However, more recent investigations by Johnson (Chapter 10, this CD-ROM) suggest that the thinning might also be attributed to variations in subsidence rates across the basin.

The Williams Fork Formation in the Grand Hogback area was divided (in ascending order) into the Bowie Shale Member, Paonia Shale Member, and an “undifferentiated” upper part (fig. 2) (Collins, 1976, 1977). The Bowie Shale Member is 680–1,000 ft thick and consists of two superposed units of coal-bearing coastal plain strata overlain by marine shale and marginal marine sandstone. The marginal marine sandstones were referred to by Collins as the middle sandstone and upper sandstone, respectively. The Paonia Shale Member is 560 ft thick and consists of coal-bearing coastal plain deposits. The upper “undifferentiated” part of the Williams Fork Formation is about 2,000–4,000 ft thick, and is dominated by fluvial deposits of sandstone, conglomeratic sandstone, conglomerate, siltstone, and shale. The uppermost 50–400 ft is dominated by kaolinite-rich beds of sandstone, conglomeratic sandstone, and conglomerate of fluvial origin, which are equivalent to the Ohio Creek Member of the Hunter Canyon and Mesaverde Formations as designated by Johnson and May (1980).

The Williams Fork Formation and equivalent strata contain significant deposits of coal in the Cameo-Fairfield coal zone (Johnson, 1989a) that underlie the entire basin and crop out along its margin. The coal has been mined extensively and is also an important source for natural gas (Johnson, 1989a). Scott and others (1996) estimated that the deepest part of the Piceance Basin has a gas-in-place coalbed methane resource that exceeds 60 billion cubic feet of gas per square mile, with most of that resource in the Cameo-Fairfield coal zone. The coal zone was referred to as the Cameo-Fairfield coal group in a coal assessment of the southern part of the Piceance Basin (Hettinger and others, 2000). The coal group, as much as 1,400 ft thick with as much as 140 ft of net coal, is distributed in the Cameo-Wheeler, South Canyon, and Coal Ridge coal zones as defined by Hettinger and others (2000). The upper part of the Williams Fork Formation also contains several thin beds of coal in the Keystone coal group near the town of New Castle (fig. 1) (Gale, 1910). Coal beds in the Keystone group were not considered to be economical to mine according to Collins (1976).

### *Cameo-Wheeler Coal Zone*

The Cameo-Wheeler overlies and intertongues with the Rollins Sandstone Member of the Iles Formation, and it extends westward from the Grand Hogback to near the Colorado-Utah State line. The coal zone was designated by Hettinger and others (2000), and includes coal mapped in the Cameo and Carbonera coal zones (Erdmann, 1934), Fairfield coal zone (Collins, 1976), and the Wheeler coal zone (Fender and Murray, 1978; Ellis and others, 1988). The Cameo-Wheeler coal zone is about 50–450 ft thick, and it pinches out to the south beneath the West Elk Mountains (fig. 1) and to the west near the Colorado border (Hettinger and others, 2000). The Cameo-Wheeler contains as much as 87 ft of net coal in 1–21 beds that are 1–44 ft thick (Hettinger and others, 2000).

### *South Canyon Coal Zone*

The South Canyon overlies and intertongues with the middle sandstone of the Bowie Shale Member and laterally equivalent strata. It was named by Ellis and others (1988) for South Canyon Creek near the town of New Castle (fig. 1) where the coals are best developed; it includes coals previously described in the South Canyon coal group (Collins, 1976) or middle coal zone (Donnell, 1959, 1962; Kent and Arndt, 1980a, b). The South Canyon zone was traced from the Grand Hogback westward into the subsurface where it pinches out along a line that extends about N. 20° W. from T. 13 S., R. 92 W. (Hettinger and others, 2000). It is as much as 330 ft thick and contains as much as 48 ft of net coal in 1–11 beds that are 1–29 ft thick (Hettinger and others, 2000).

### *Coal Ridge Coal Zone*

The Coal Ridge coal zone overlies and intertongues with the upper sandstone in the Bowie Shale Member. It was named by Ellis and others (1988) for Coal Ridge near New Castle, and it includes coals previously described in the Coal Ridge coal group (Collins, 1976) or upper coal zone (Donnell, 1959, 1962; Kent and Arndt, 1980a, b). The coal zone underlies approximately the same part of the southern Piceance Basin as the South Canyon zone. The Coal Ridge is 200–500 ft thick along the Grand Hogback and Coal Basin area, and thins to less than 100 ft thick throughout its western half. Its thickness varies considerably due to the lenticular nature of the coal beds. The Coal Ridge zone contains as much as 44 ft of net coal in 1–14 beds that are 1–23 ft thick (Hettinger and others, 2000).

The Williams Fork Formation is correlated along cross section *A–A′* between localities 21 and 37 (pl. 2). Stratigraphic control is provided by a measured section at Coal Basin (loc. 37) by Collins (1976), and additional control was provided by subsurface correlations of several hundred drill holes in the southern part of the Piceance Basin by Ellis and others (1998) and Hettinger and others (2000). Significant stratigraphic correlations and relations are described in the following:

1. The Williams Fork Formation overlies and intertongues with the Iles Formation from the Colorado border (near loc. 21) eastward to Coal Basin (loc. 37). The Bowie Shale Member, Paonia Shale Member, and upper "undifferentiated" part of the formation are labeled at the measured section at Coal Basin, following Collins (1976). The middle and upper sandstones in the Bowie Shale Member are also labeled according to Collins (1976). The upper "undifferentiated" part of the Williams Fork Formation might be partially equivalent to the Tuscher Formation in the Uinta Basin.

2. Depositional interpretations of shoreface, offshore, and coal-bearing coastal plain strata in the Bowie Shale Member and Paonia Shale Member are based on descriptions by Collins (1976, 1977). The interpretation of fluvial origin for strata in the "undifferentiated" part of the Williams Fork Formation is also based on Collins (1976).

3. The Cameo-Wheeler coal zone extends from Coal Basin westward to the Rat Hole Canyon 23-14-25 drill hole (loc. 20), which is located about 2 mi west of the Colorado border. In Utah, the Cameo-Wheeler coal zone is in the uppermost part of the Neslen Formation. As viewed along the cross section, the Cameo-Wheeler coal zone contains about 8–81 ft of net coal in 3–10 beds that are 1–41 ft thick.

4. The South Canyon coal zone intertongues with, and overlies, the middle sandstone and extends between localities 34 and 37. As viewed along the cross section, the South Canyon coal zone contains about 20 ft of net coal in three to five beds that are 1–15 ft thick.

5. The Coal Ridge Coal zone intertongues with, and overlies, the upper sandstone and extends between localities 34 and 37. As viewed along the cross section, the Coal Ridge coal zone contains about 5–17 ft of net coal in two to four beds that are 2–8 ft thick.

6. The unconformable contact between the Williams Fork and Wasatch Formations is correlated from Coal Basin westward to the State line, and it extends westward across the Tuscher, Farrer, and Price River Formations in the southern part of the Uinta Basin (pl. 1).

7. The stratigraphic position of the unconformity between the Williams Fork and Wasatch Formations is based on well-log interpretations made by R.C. Johnson (U.S. Geological Survey, written commun., 2001), who placed the contact at the top of a zone that contains thick bodies of white, kaolinite-rich sandstone. The thick sandstone bodies are considered to be equivalent to the Ohio Creek Member of the Hunter Canyon and Mesaverde Formations. Johnson's interpretations are based on nearby outcrop descriptions by Johnson and May (1980) and well cuttings described by the American Stratigraphic Company from drill holes near the cross section. Overlying sandstone and mudrock is considered to be within the Wasatch Formation based on outcrop descriptions by Johnson and May (1980).

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