Introduction

General Description

The middle Cenomanian (lowermost Upper Cretaceous) Dunvegan Formation is a lithostratigraphically defined unit that comprises an extensive, southwesterly thinning, sandy clastic wedge that departs from northwestern Alberta, northeastern British Columbia, and extending as far north as the Northwest Territories (Fig. 22.1). It presently covers an area of about 300,000 km². This includes undeformed and relatively flat-lying strata, which lie in the subsurface south of the Peace River, and which are exposed along the Peace River valley and farther north (Fig. 22.2). Where the Dunvegan is not structurally deformed, it dips gently to the southwest (Fig. 22.2). To the west, along the central and northern foothills, the Dunvegan Formation becomes incorporated into the tectonically deformed belts, where it is also exposed.

The Dunvegan Formation attains thicknesses of about 350 m, and consists of interbedded mudstone, sandstone, and conglomerate. The conglomeratic facies are confined to the outcrops in the far north (Fig. 22.1b). Thinner beds of coal and shelly limestone also are present in places. The Dunvegan cannot be mapped much farther south than the Athabasca River (Fig. 22.3), although in the subsurface, age-equivalent mudstones can be traced throughout the basin (Fig. 22.4). The Dunvegan Formation is overlain by shales of the Kaskapau Formation and underlain by the sandstones of the Shubenacadie Formation, although the relations are better described as interfingering, since both the upper and lower boundaries are highly diachronous (Fig. 22.6).

Hydrocarbon-bearing intervals are apparently confined to the Alberta subsurface, especially in the area between Twp. 50 and Twp. 70 in ranges west of the 5th meridian (Fig. 22.2). Further north, Dog Creek sandstones of the lower Kaskapau are also productive (Walcott-Dudley and Leckie, in press).

Tectono-Eustatic Framework

Stott (1984) interpreted the Dunvegan as having been derived from the actively rising Cordillera to the northwest during the waning phases of the Early to mid-Cretaceous Columbian Orogeny. Carr and Stockmal (1989) suggested that this may have related to accretion of the Cascadia terrane in the Western Cordillera in southern British Columbia. The wedge-shaped geometry of the Dunvegan shows that tectonic subsidence was the major control on shaping the foreland basin fill at this time. To the southwest, the Dunvegan was increasingly affected by Tertiary deformation of the Laramide Orogeny, resulting in deformation of the western edge of the Dunvegan depositional basin. The present-day southwest structural dip of the Dunvegan in subsurface (Fig. 22.3) also results from depression of the Alberta Foothills Basin as a consequence of tectonic loading.

The Dunvegan wedge built into the Cretaceous Western Interior Seaway, which is interpreted to have been open all the way to the south during the middle Cenomanian (Fig. 22.1a). Progradation was controlled, in part, by a third-order eustatic drop of sea level (Bhattacharya, 1988; Bhattacharya and Walker, 1991a), dated at 94 Ma on the global sea-level curves published by Haq et al. (1987; Fig. 22.5).

Previous Work

The Dunvegan Group was first used by Dawes (1881) to describe his "Lower Sandstones" which cropped out along the Peace River valley. The formation was named at the time by the Dunvegan Trading Post situated by the Peace River (Twp. 80 Rge. 3W), although only the upper, largely nonmarine portion of the Dunvegan is exposed there. McLean (1919) subsequently changed the Dunvegan from group to formation status.

Biostratigraphically oriented work, centered on the age and correlation of the Dunvegan, Kaskapau, and Shubenacadie formations, was completed by researchers at the Alberta Research Council and the University of Alberta (Stelick and Wall, 1955; Stelick et al., 1958) and has been summarized by Caldwell et al. (1978). More recent work by Singh (1983) details the palynological aspects of the Dunvegan and their implications for Cenomanian biostratigraphy. Stott (1982) completed a major study of the Dunvegan in outcrop and included a detailed historical summary of early work, including definition and nomenclature of the formation. In much of this previous work, the Dunvegan was interpreted as broadly deltaic, and the term "Dunvegan Delta" was applied to this rather complex sedimentary package. Stott's mapping and biostratiographic interpretations are incorporated into Figures 22.1, 22.2, and 22.3. More detailed sedimentological descriptions of selected Dunvegan outcrops, originally mapped by Stott (1982), have been published by Plint and Hart (1986). The only detailed petrological work that is published by Tait (1964), who examined sandstones in the type area of Dunvegan.

Previous subsurface work is that of Burk (1963). Burk (1963) presented a gross sandstone isochron map of the Dunvegan and established the overall southwest thinning in the subsurface although he did not make any attempt at further stratigraphic subdivision.

Bhattacharya (1998, 1989a,b and 1991) and Bhattacharya and Walker (1991a,b) completed a major study of the Dunvegan in the Alberta subsurface (Fig. 22.1b). Their work involved the application of sequence stratigraphic principles, as outlined by Van Wagner et al. (1990). In designing the stratigraphic subdivisions they used allostratigraphy (North American Commission on Stratigraphic Nomenclature, 1983). An allostratigraphic unit is defined on the basis of its bounding discontinuities, rather than on gradational facies boundaries. Throughout this chapter, sequence stratigraphic terminology is indicated in brackets as it relates to the interpretations presented.

Maps

Structure

The southwest structural dip of the Dunvegan top (Fig. 22.2) is subparallel to the present-day structural strike in the Cordillera. This map is based on the contact between the Kaskapau and Dunvegan which, as shown in the cross section (Fig. 22.4), is disconformable and rises steadily to the northwest as the Dunvegan gets thicker. No physically continuous surface actually corresponds to this structure map, although at the scale of the entire basin, physical surfaces and time lines within the Dunvegan probably approximate the trend indicated. Along the left-hand side of the map the contour swing around counter-clockwise and indicate a dip to the south. This apparent dip change probably results from increased thickening of the Dunvegan rather than an actual change in the dip of surfaces within the Dunvegan.

Thickness and Lithology

Figure 22.3 shows an isopach of the sediments between the Fish Scales marker in the Shubenacadie Formation, and the top of the Dunvegan Formation, and emphasizes the wedge-shaped geometry that thins to the southwest. The isopach values range from 480 m in the northwest to 80 m around the Athabasca River. The Fish Scales marker is interpreted as being close to a time line, although the diachronous nature of the top-Dunvegan introduces an element of distortion.

The summary paleogeographic map (Fig. 22.1b) shows that conglomerates (as mapped by Stott, 1982) are predominant to the far northeast. The southeastern limit of Dunvegan shoreline sandstones (mapped by the author) is also indicated. This map is shown in greater detail in Figure 17.10 (Smith, this volume, Chapter 17).

The superimposed lithological domains (Fig. 22.3) represent a statistically derived summary of the lithologies between the top of the Dunvegan and the Base of Fish Scales. The map thus includes both Dunvegan sandstone and upper Shubenacadie shale, although data are available only over a restricted area relative to total Dunvegan distribution. The map indicates some interesting north-south trends, although an interpretation of these in terms of mapped depositional systems is not clear.
DUNVEGAN STRUCTURE

Generalized structure contours for the top Dunvegan; and prominent oil and gas fields in the Dunvegan and Doe Creek

Contour Interval = 100 metres

- Control well
- Dunvegan outcrop (commodity beneath Quaternary cover)
- Oil fields (see table 22.2a)
- Gas fields (see table 22.2b)

scale: 1:5,000,000

Table 22.2a Dunvegan oil fields.

<table>
<thead>
<tr>
<th>Field</th>
<th>Formation</th>
<th>No. of Wells</th>
<th>Initial Entrapment Reserves</th>
<th>Recoverable Volume</th>
<th>Cumulative Production</th>
<th>Recovery Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valhalla</td>
<td>Doe Creek</td>
<td>4</td>
<td>70</td>
<td>254</td>
<td>12</td>
<td>20</td>
</tr>
</tbody>
</table>

There are no Dunvegan oil fields with significant Entrapment Reserves at this time. Further study of the Valhalla field may yield additional oil formations.

Table 22.2b Dunvegan gas fields.

<table>
<thead>
<tr>
<th>Field</th>
<th>Formation</th>
<th>No. of Wells</th>
<th>Initial Entrapment Reserves</th>
<th>Recoverable Volume</th>
<th>Cumulative Production</th>
<th>Recovery Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valhalla</td>
<td>Doe Creek</td>
<td>4</td>
<td>620</td>
<td>580</td>
<td>157</td>
<td>30</td>
</tr>
</tbody>
</table>

Dunvegan gas fields are not economically viable at this time.

Figure 22.2 Structure map on the top of the Dunvegan, showing the overall dip to the southwest. At the scale of the map, the overall trend approximates the dip of time lines surfaces within the Dunvegan, although the map does not coincide with any real physical surface. Structure geology is taken from Scott (1982) and Green (1972). Dunvegan and Doe Creek oil and gas fields, and the accompanying summary tables, are derived from Hay (this volume, Chapter 12).
DUNVEGAN TO BASE OF FISH SCALES
ISOPACH AND LITHOFACIES

Generalized thickness contours - top Dunvegan to base of Fish Scales, and generalized lithology

Contour interval = 20 meters

- Control well
- Well with Correlate coverage

Dunvegan outcrop (commonly beneath Quaternary cover)

Factor 1
Shale, gray, silt, grading upward to gray sandstone, fine grained, wall sorted, channelized, slightly to strongly cross-bedded.

Factor 2
Shale, gray, with interbedded silts; overlain by sandstones, fine grained, medium to well sorted, minor laminae.

Factor 3
Shale, gray, slightly silt, overlain by gray slightly silty sandstones, fine grained, medium to well sorted, minor laminae.

Factor 4
Shale, gray, with interbedded silts; grading upward to gray silty sandstones, fine grained, medium to well sorted.

Factor 5
Shale, gray, silt, grading upward to fine silty sandstones, fine-grained, medium to well sorted.

Figure 22.3 Isopach map of the interval from the top of the Dunvegan to the base of Fish Scales marker, showing the overall shape of the Dunvegan clastic wedge, thinning to the southeast. The top of the Dunvegan represents a disconformity and interfingered lacustrine change, whereas the base of Fish Scales approximates a time line. This isochronous nature of the top of the Dunvegan highlights some distortion of the shape, although at the scale of the map, it is probably not extreme. A more detailed isopach is shown in Figure 22.10. Lithofacies designations are based on standard Atlas methodologies, as described in Mossop and Sheehan (this volume, Chapter 1).

Figure 22.4 Regional cross section H-H' through the Dunvegan and related strata of Alberta. The northeastern end of H-H' is in the Peace River valley where the Dunvegan is exposed. The cross section illustrates the wedge-shaped nature of the Dunvegan and its discontinuous boundaries, and shows the interfingerings relative to the Shaheen and Kakepak formations. The Dunvegan prograded to the southeast and downslopes onto the FSU and Fish Scales markers, producing a prominent condensed section in the east and south. This is also indicated by the loss of lower Campanian strata further southeast. The Dunvegan comprises shoreline-related sandstones (yellow) and heterolithic, non-marine facies to the northeast (orange-pink). Silty, progradational marine mudstones (green) are distinguished from dominantly transgressive, horizontal to slightly mound-like mudrocks (gray). This section is based on correlations in cross section H-H' in Chapter 20 (Locke et al., this volume). All correlation lines are interpreted as representing chronostatigraphically significant surfaces. Facies changes are indicated with a jagged line. Designation of lettered allochthons in the Dunvegan is based on correlations shown in Figures 22.7 and 22.8. Location of the cross section is shown in Figure 22.10.
Stratigraphy
Regional Correlation
Figure 22.4 shows the regional lithostratigraphic and allostratigraphic relations of the Dunvegan Formation and related strata, with relevant biostratigraphic units also shown. The time-stratigraphic interpretation of this cross section is shown in Figure 22.5.

The Dunvegan Formation correlates eastward with shales of the La Biche Formation and to the south with shales of the Sundaby Member of the Blackstone Formation. In the Alberta and Saskatchewan subsurface, it correlates with the silty shales that lie between the Second White Specks and the Fish Scales. It broadly correlates with the upper Ashville in Manitoba and with the upper portion of the Big River Formation in Saskatchewan. In the Western Interior of the U.S.A., the Dunvegan correlates with the Belle Fourche shale (Rice, 1984), portions of the Pierre and Dakota formations, and is generally equivalent to Woodbine strata in Texas.

Shaftesbury/Dunvegan
Regional cross section 11-11 (Fig. 22.6) indicates that strata in the lower part of the Dunvegan downlap to the southeast. The downlap surface is represented by a prominent marker designated as the FSU (Fish Scales Upper). The FSU lies within the upper Shaftesbury, above the Fish Scales, although it merges with the Fish Scales to the southeast. Core across the FSU marker shows a dramatic lithological change (Fig. 22.6). Dark, greenish-black, fish-scale-bearing bentonitic shales, lacking burrows, underlie the FSU marker and are interpreted as representing deposition in deepwater, below wave base. Above, the strata consist of siltstone, ripple, and silty mudstones without fish scales, and indicate deposition in shallower water, probably above storm wave base. This abrupt transition is interpreted as marking the change from deepwater marine conditions into the shallower water brackish conditions caused by progradation of deltaic depositional systems of the Dunvegan. Thus, the strata above the FSU marker are genetically related to Dunvegan progradation, whereas the shales below are unrelated to Dunvegan progradation and represent deposition during an earlier time of peak transgression (Bhattacharya and Walker, 1991a). This interpretation is also shown in a detailed cross section highlighting the allostratigraphic relations (Fig. 22.7). It shows that all members in the lower portion of the Dunvegan pass seaward (southeastward) into equivalent shales of the upper Shaftesbury Formation above the FSU marker. Bentonites just below this horizon also provide important time markers for local correlation (Fig. 22.6).

The allostratigraphic relations also help to explain the loss of several bioclines at the Fish Scales to the southeast (Figs. 22.4, 22.5). The Fish Scales is a major, basin-wide marker horizon that has been interpreted as representing a condensed section deposited during a long period of very slow sedimentation (Leece et al., 1992), an interpretation supported by the downlapping nature of overlying units documented here (Figs. 22.4, 22.5). It has been used to subdivide stratigraphically the Shaftesbury Formation into upper and lower units, and also has been interpreted as marking the contact between the Upper and Lower Cretaceous (Albian/Cenomanian boundary, Caldwell et al., 1978; Singh, 1988).

A detailed foraminiferal biostratigraphy has been developed for these strata in the Peace River area to the northwest, although several of the zones are absent farther south and east (Caldwell et al., 1978). To the northwest, where the stratigraphic section is thickest, the Dunvegan includes fauna of the Ventronus perplexus and Tentaculites alaminus zones (Figs. 22.4, 22.5). In addition, the Hu-
The allomembers broadly represent progradational cycles beginning with marine mudstones at the base and passing upward through transitional interbedded mudstones, siltstones, and sandstones into shallow marine, shoreline sandstones. These are overlain by heterolithic nonmarine facies, including coals and palaeosols, which are thickest in allomembers D and E (Figs. 22.6, 22.8). The non-marine facies increase in thickness and proportion to the northwest (Fig. 22.7).

Erosional surfaces in the middle portion of the Dunvegan are indicated by channelized units in allomembers E, D, and C, and correlate with nonmarine intervals in interlobe areas (Figs. 22.7, 22.9). These channels have also been recognized in outcrop (Plint and Bhattacharya, 1991) and show paleocurrent flows dominantly to the southeast (Plint and Hart, 1988). The channels tend to be filled with sandstone that has been referred to as "the arkosic member." In outcrops described by previous workers (Stelck et al., 1985), the channel fills in Figure 22.9 are dominated by fine-to medium-grained sandstone. Previous workers have also speculated that the Dunvegan contains a significant unconformity, indicated by the deeply incised nature of the "arkosic member" in outcrop (Stelck et al., 1985). The cross-sectional relations documented in Figure 22.9 show that there were several phases of channeling causing erosional surfaces at several different levels. In any given outcrop section, however, usually only one channel is observed (Fig. 22.9). The portion of the Dunvegan containing channels is interpreted as being broadly correlative with the time of maximum progradation of the Dunvegan (corresponding to allomembers C, D, and E) and may correlate with the conglomerate facies mapped by Stott (1982) in northern British Columbia (Figs. 22.16). Channels are found in the older allomembers in the northwest portion of the map area and in places lie directly on upper Shaffersbury shales. Sediments of allomember C extend farther into the basin (i.e., southeast) than any other formally defined allomember (Fig. 22.4).

Several of the marine flooding surfaces defined by Bhattacharya (1988) have been traced to the northwest (Plint, pers. comm.). Including those capping allomembers E, F, and G. The correlations to the north (Fig. 22.4) also indicate the additional presence of several older progradational units that probably represent older allomembers.

The upper allomembers in the Dunvegan (allomembers A, B) lie unconformably on the substratum and are the subject of detailed mapping of depositional dip. As in the publication (Bhattacharya and Walker, 1991b; Bhattacharya, 1991), the Dunvegan is diachronous, and becomes progressively younger in a landward position (i.e., to the northwest). In the Foothills outcrop along the Pine River (in B.C.), Stucker (1982) described the upper part of the Dunvegan Formation as the Suakinka Member. Stelck and Wall (1955) indicated that the Suakinka Member correlates with the base Kaskapau farther to the east, although Stott (1982) suggested that this was not so, and that beds of the Suakinka dipped below the Kaskapau farther eastward. Direct correlations of the Suakinka Member in the Pine River section to the subsurface have not yet been attempted.

**Doe Creek/Touchoue Coupe**

Among the sand units in the lower part of the Kaskapau Formation are the Doe Creek, Touchoue, and Howard Creek sandstones (Figs. 22.4, 22.6). Wallace-Dudley and Leckie (in press) have shown that the Doe Creek/Touche Coupe sandstones comprise a series of backstepping sandy units (i.e., paraconglomerates) culminating in highly radioactive sands of the Second White Specks, which probably represent another condensed section, similar to others documented in the Caribou of Western Canada (Leckie et al., 1990). The Touchoue Coupe represents the most landward sandy tongue recognized (Wallace-Dudley and Leckie, in press). It thins to the southeast and ultimately disappears completely, although it is not clear whether the Touchoue Coupe interval has been eroded or was never deposited farther east and south. The younger Howard Creek is a thin, sandy unit that lies a little farther east into the basin than the Touchoue Coupe.

Two radioactive markers correlate with the top of the Howard Creek and the top of the Touchoue Coupe intervals, respectively (Fig. 22.6). The lower marker coincides with the top of the Doe Creek farther south and east, where the Touchoue Coupe is missing (Fig. 22.6). These markers identify the Imperial Spirit River well (Wallace-Dudley and Leckie, in press) and allow correlation with the detailed faromolecular biotratigraphy developed for that area (Stelck and Wall, 1955). The upper marker coincides with the base of the Fadileamnites gulae (zone) of the Fadileamnites gulae (zone). The lower marker coincides with the contact between the Verrucalesiotes perples and Fadileamnites gulae (zone).

The section between the top of the Dunvegan and the base of the Second White Specks has been divided into four zones (Fig. 22.11b). The fourth zone is the uppermost Dunvegan (Fig. 22.11b). This zone is characterized by the presence of the Fadileamnites gulae (zone). The lower marker coincides with the base of the Fadileamnites gulae (zone) of the Fadileamnites gulae (zone). The lower marker coincides with the contact between the Verrucalesiotes perples and Fadileamnites gulae (zone).
Reference Wells

Two reference wells highlight the depositional facies, degree of cyclicity, and the major well-log markers.

Imperial Spirit River #1, 12-26-79-6W6, (Fig. 22.6) includes core from the Fish Scales through the Second White Specks and is the only well known to have cored through the FSU marker. The Dunvegan is here about 170 m thick and contains several coarsening- and fining-upward facies successions capped by marine flooding surfaces. This well is north of the area used by Bhattacharya and Walker (1991a) to define their seven allomembers, and the exact correlation of their stratigraphy into this well is uncertain. The positions of the allomembers are tentatively indicated.

Two 30 m thick interpreted channelized sands are present at 1150 and 1350 ft. Two non-marine, rooted horizons are also present in the upper half of the Dunvegan at 1190 and 1220 ft. The detailed biostratigraphy of Steidt and Wall (1995), discussed above, is also shown. Foraminiferal recovery from the upper Shattesbury in the lower part of the well was sparse, although Milionides was found below the Fish Scales (Wall, pers. comm.).

Figure 22.9 Well log cross section K-K', oriented along depositional strike, illustrating a number of channel fills. Successive channels in allomembers E, D, and C are offset from each other. Shingles E1 and D1 are represented by channels. The associated deltaic systems lie in a seaward position and are indicated in Figure 22.7. Location of cross section is shown in Figure 22.10. Figure from Bhattacharya and Walker (1991a).

The upper part of the Spirit River well was originally logged by Halliburton, with the final re-logging of the entire well completed by Schlumberger. The Halliburton log is shown here, although the stratigraphic picks are about 10 ft higher than in the Schlumberger log.

The Triad Pan Am Big Mountain Creek well, 3-26-66-7W6 (Fig. 22.8), is in the northwestern part of the area studied in detail by Bhattacharya and Walker (1991a;b, Fig. 22.1b). It contains a fairly complete core through the lower and middle part of the Dunvegan, from allomembers G, F, E, D, and C. Here the Dunvegan is about 100 m thick and also consists of a series of coarsening-upward successions capped by marine flooding surfaces. The facies in allomembers E, D, and C include nonmarine strata, and are broadly interpreted as representing progradational deltaic shoreline sediments. The well also shows the characteristic gamma and resistivity log response through the Dunvegan, Shattesbury and Kaskapau. This includes the radioactive marker horizon associated with the Fish Scales, FSU, Doe Creek and Howard Creek. A silty, bioturbated horizon in the lower Kaskapau (designated as the K1 marker) was used as a datum for mapping and correlation. No Pouce Coupe-equivalent strata are interpreted as existing in this well.

Figure 22.10 Isopach of K1 to FSU marker in area studied by Bhattacharya (1986a), showing overall seaward thinning of the Dunvegan clastic wedge. The geometry is similar to that in Figure 22.3. Dots indicate data points. Dots on lines of cross sections indicate well logs only; squares indicate cored wells. Figure from Bhattacharya and Walker (1991a). Indicated cross sections are shown in Figures 22.7 (J-J') and 22.9 (K-K').
Paleogeography and Depositional History

Bhattacharya (1989a) completed a detailed study of the allostratigraphic, facies, and depositional systems of the Dunvegan Formation in the Alberta subsurface. His study area ranged from Twp. 56 to Twp. 67 and from Rge. 10W3 to the deformed belt in the west (Figs. 22.1b, 22.10). The study incorporated data from about 500 well logs and 130 cores. Individual isopach and sand isolith maps and detailed facies interpretations of the Dunvegan alloclasts and shingles are presented in Bhattacharya (1989a, 1991), and Bhattacharya and Walker (1991a, b).

As a result of this work, a range of distinct depositional systems was interpreted in the Dunvegan Formation, from highly river-dominated deltas in alloclast E to transgressive sheet sands in alloclast C (Bhattacharya and Walker, 1991b). The paleogeographic reconstructions presented here are based on sand body geometries and facies relations documented in Bhattacharya (1989a). The most generalized paleogeography for the Dunvegan indicates shorelines trending northeast-southwest fed by south-east-flowing rivers (Fig. 22.1b).

Sandstones in the five shingles of alloclast G (Fig. 22.7) were collectively mapped and indicate a series of overlapping lobate sand bodies interpreted as representing deltas (Fig. 22.1la). The presence of wave ripples and hummocky cross-stratification in the core delta front sandstone indicates a wave-influenced depositional setting. Isopach values of alloclast C reach up to 80 m in the west where the deltas are confined. Deposition of alloclast G was terminated by a widespread transgression with succeeding marine shales blanketing the area (Fig. 22.1lb), although these are not very thick.

Alloclast F contains two overlapping shingles (Fig. 22.7). Mapping of shingle F2 indicates a prograding delta consisting of three sub-lakes (Fig. 22.11e). The sand body geometries and core facies indicate fluvial-dominated deltas. Associated feeder channels are seen in well-log cross sections farther north west. Shingle F1 is only partly preserved and is interpreted as having been largely reworked into linear shelf sands. It is truncated to the northwest by the transgression that terminates alloclast F (Fig. 22.11d) and is blanketed by thin transgressive mudstones (Fig. 22.11e) that have been traced farther north (Plint, pers. commun.).

Alloclast E has been subdivided into four prograding shingles that extend successively farther seaward (Fig. 22.7). These are shown in Figures 22.11a to 22.11i, and are interpreted as deltaic. Shingle E4 is interpreted as an elongate, river-dominated delta with two main lobes (Fig. 22.11f). The presence of wave ripples and hummocky cross-stratification in the core delta front sandstone indicates some wave influence. Shingles E3, E2, and E1 (Figs. 22.11g, h) also consist of rather elongate sand bodies, but the general shape and lack of wave-produced sedimentary structures in core indicates that they are highly river-dominated (Bhattacharya, 1991). Shingle E3 (Fig. 22.11g) comprises three main feeder channels with associated lobes that also have an elongate geometry. Shingle E2 (Fig. 22.11h) has three main lobes that have an elongate to birdfoot shape. The northwest part of the map is a zone of nondeposition and sedimentary bypass.

Figure 22.11 Summary paleogeographic facies maps of area studied in detail by Bhattacharya (1989a). Maps are based on sand isolith maps and facies relations documented in Bhattacharya (1989a, b, 1991) and Bhattacharya and Walker (1991a, b). Discussion of maps is in the text. Location of study area shown in Figure 22.1b.
Each of shingles E4, E3, and E2 contain several channels and associated lobes (Fig. 22.11a). Shingle E1, in contrast, seems to have been associated with a single major river that fed a larger and less spread out delta complex (Fig. 22.11b). There also is a marked basinward shift in the general shoreline position. The entrenchment of the fluvial systems and abrupt seaward shift in facies has been interpreted as possibly representing an erosional unconformity (i.e., type I sequence boundary) resulting from a eustatic drop of sea level at 94 Ma (Bhattacharya and Walker, 1991a). E1 progrades farther seaward than any other shingle in allomember E and may represent a lowstand delta. It is abruptly overlain by blanketlike marine mudstones representing another major transgression (Fig. 22.11c). This is followed by progradation of allomember D.

Allomember D contains three offlapping shingles (Fig. 22.7), although the lowest shingle (D3) is rather poorly exposed. The sand isilith maps and facies successions in shale D2 show a linear, shore-parallel sand body interpreted as a wave-dominated prograding barrier/lagoon system (Fig. 22.11d), quite different from the more river-dominated systems in allomember E. Although they were not originally mapped separately (Bhattacharya, 1991b); cross-sectional relations indicate that shingle D1 incises into the older D2 barrier (Fig. 22.9). The depth of erosion shown in Figure 22.9 indicates a major valley system with a possible associated lowstand delta developed (shown on Fig. 22.11e). The sand isilith maps and facies successions in the lowstand delta indicate that it was wave dominated. During the initial stages of transgression, following the deposition of the D1 delta, the associated feeder channels and incised valleys were filled with marine sediments and transformed into estuaries (Bhattacharya, 1991b). These are distinctly different from the predominantly fluvially-dominated channel fills associated with allomember E, as documented by Bhattacharya and Walker (1991b). Allomember D is blackened by transgressive marine shales (Fig. 22.11f).

Allomember C progrades farther seaward than any other allomembers and shingles of the Duvenegian never prograded as far basinward as allomember D. This resulted in the backstepping pattern shown in Figures 22.4 and 22.7. Allomember B is relatively limited in extent and associated sandy facies are extensively reworked and burrowed, indicating a transgressive depositional environment (Fig. 22.11g).

A phase of channel incision is indicated in shingle A2 of allomember A (Fig. 22.11h). The channels were filled estuaries, and sandy deltaic deposits are not observed seaward of the channel mouths. The upper portions of allomember A (shingle A1, Fig. 22.11i) are extensively reworked, also indicating transgressive modification, similar to that in allomember B. This style of sedimentation appears to be continued in the overlying Doce Creek sandstones (Wallace-Dudley and Leckie, in press).

Additional sedimentological details of the units discussed in this section are presented in Bhattacharya (1989a, 1991) and Bhattacharya and Walker (1991b).
General Geological History and Discussion

The geological history of the Dunvegan Formation can be viewed overall as a regressive-transgressive cycle. The initial regression began in the middle Ceramian, as shallow-marine deltaic facies of the lower Dunvegan (members C, G, and older) were deposited over the deeper marine transgressive shales of the upper Shutforsen (i.e., the shales below the FSU marker). This regression resulted in downlapping over the surface represented by the FSU marker and shows that shales of the upper Shutforsen above the FSU marker are genetically related to Dunvegan progradation. Peak regression occurred during deposition of members B, D, and C, as indicated by a pronounced seaward shift in the position of fluvial, channelized facies and their associated deltaic. This seaward shift may have been driven by a third-order eustatic drop of sea level at 94 Ma (Fig. 22, J. Bhattacharya, 1991a). Indication of subsequent Kaskapau transgression is first indicated by a transgressive surface of erosion at the top of member C, which may correlate with a rapid global rise of sea level at 93.5 Ma (Fig. 22). Dunvegan deltaic deposition never recovered from this transgression, and the facies show evolution of progressive deepening, culminating in the deep-water, calcareous shales of the Second White Specks (Vinny Member of the Blackstone) deposited in the early Turonian. These calcareous shales correlate with the transgressive Greenhorn Limestones farther south in the Western Interior of the United States (Rice, 1984) and coincide with a time of globally high sea level (Hag et al., 1987). Dunvegan deposition is interpreted as being broadly correlated with a third-order eustatic cycle of sea level.

Dunvegan progradation was interrupted by several transgressive events. One occurred in at least seven marine transgressions within the Dunvegan. These are interpreted as resulting from tectonically induced subsidence during periods of renewed thrusting in the Cordilleran (Bhattacharya, 1988 1990a; Bhattacharya and Walker, 1991a), although no attempt has yet been made to correlate the flooding events with specific tectonic episodes. These seven events are beyond the limits of stratigraphic resolution in terms of absolute time and are inferred to have been relatively rapid (a hundred thousand years or so). In general, the overall wedge shape of the Dunvegan and related shales indicates a tectonically formed basin. The nature of the basin fill, however, is interpreted as recording a combination of tectonic and eustatic effects. Autocyclic processes were probably responsible for producing some of the deltaic cycles seen in the various Dunvegan shingles within the members.

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References

Frontispiece 23.9 Cardium Formation. Conglomeratic shoreline to distal channel deposits exposed near Baytree, west of Deaseon-Cassie, northeastern British Columbia. The Turonian to Coniacian Cardium Formation is a prolific oil producer in the Alberta subsurface. Photograph by D.A. Lackie.