BYPASS MARGINS, BASIN-RESTRICTED WEDGES, AND PLATFORM-TO-BASIN CORRELATION, UPPER DEVONIAN, CANADIAN ROCKY MOUNTAINS: IMPLICATIONS FOR SEQUENCE STRATIGRAPHY OF CARBONATE PLATFORM SYSTEMS

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ABSTRACT: **Carbonate platforms can commonly keep up with relative sea-level rise because of high rates of sediment accumulation and platform aggradation. Surrounding basinal environments are commonly starved but can receive variable extrabasinal siliciclastic input and episodically deposited carbonate sediment. If accumulation rates in basinal settings lag behind those of the platform, a bypass or erosional margin can develop. Under these circumstances platform and basin depositional sequences become physically detached and direct correlation of basinal and platform sequences is hindered.**

We report here the results of high-resolution stratigraphic analyses of two Upper Devonian isolated carbonate platforms in western Alberta that provide insight into the sequence stratigraphy of bypass margins and criteria for accurate correlation of platform and basinal sequences. The slope and basin sequences surrounding the Miette and Ancient Wall platforms consist of basin-restricted, onlapping wedges of fine-grained background sediment deposited dominantly from suspension and coarse-grained platform-derived sediment redeposited by a variety of gravity-flow mechanisms. Sequence boundaries are identified within the redeposited carbonate intervals. Identification of sequence boundaries and differentiation of highstand and lowstand slope and basinal facies was based on the geometry, mineralogy, and clast content of redeposited carbonate units. Highstand carbonates contain sheet-like debris flows and turbidites with abundant slope-derived clasts and background facies with high total carbonate content. Lowstand carbonates contain sheet-like and channelized debris flows and turbidites with abundant platform-derived clasts and background facies with low carbonate content and locally high amounts of organic carbon. Transgressive facies are dominated by initially carbonate-poor and organic-rich background sediments that display a progressive increase in carbonate content and decrease in organic carbon content. These patterns are interpreted to record abundant background carbonate sedimentation during late transgression and highstand when the carbonate factory was robust. Highstand redeposited carbonates record slope erosion due to oversteepening and slope readjustment processes. Lowstand redeposited carbonates indicate platform and platform-margin erosion and low background carbonate sedimentation when the platform was either exposed or under very shallow peritidal conditions. High siliciclastic and organic contents during lowstand and early transgression may partly be the result of reciprocal sedimentation but alternatively may represent continuous siliciclastic supply during times with little dilution by fine-grained carbonate sediment.

Successive stages of platform development at Miette and Ancient Wall were controlled by accommodation changes driven by relative sea-level fluctuations. Backstripping analyses of strata from both platforms confirm that significant differential subsidence was a major control on variations in platform thickness and patterns of slope development. Greater subsidence at Ancient Wall fostered the development of a steeper bypass margin and different slope evolution compared to Miette. Slope oversteepening also initiated a process of slope readjustment that eventually reduced the platform-to-basin gradient and facilitated regressive platform progradation.

In conventional siliciclastic sequence stratigraphy, basin-restricted wedges are interpreted as lowstand deposits on the basis of their geometry and position relative to an updip margin. Wedge-shaped basinal units along the Miette and Ancient Wall bypass margins contain both highstand and lowstand facies that straddle sequence boundaries. The results of this study provide objective criteria for differentiating systems tracts in carbonate slope and basin environments through mineralogic and compositional analyses providing more accurate correlation of detached platform and basin sequences. Interpretation of carbonate basin-restricted wedges as purely highstand or lowstand deposits may lead to erroneous conclusions regarding sequence stratigraphy, platform-to-basin correlation, and the volumetric partitioning of sediments deposited in different systems tracts.

INTRODUCTION

The pronounced differences between carbonate and siliciclastic depositional systems prompted Handford and Loucks (1993) to question the applicability of traditional sequence stratigraphic models to carbonate systems. Among the most important differences that affect the geometry of carbonate platform sequences is the ability of carbonate systems to aggrade or sometimes even prograde during all but the most rapid relative sea-level rises (Kendall and Schlager 1981; Schlager 1981). The margins of aggrading platforms can eventually oversteepen (Read 1985; Schlager and Camber 1986), resulting in sediment bypassing across a marginal escarpment and/or a steep gullied slope (McIlreath and James 1978; Mullins and Neumann 1979; Schlager and Chermak 1979). Sediments deposited seaward of bypass zones form onlapping wedges that pinch out against the steepened platform margin. Physical detachment of basin-restricted wedges and platform sequences renders direct correlation impossible and complicates platform-to-basin sequence stratigraphic interpretations.

In traditional sequence stratigraphy, predicated on analysis of siliciclastic passive continental margins, such basin-restricted wedges are interpreted as lowstand systems tracts on the basis of their geometry and position relative to an updip margin (Posamentier and Vail 1988; Van Wagoner et al. 1988). In carbonate systems with bypass margins, onlapping basin-restricted wedges can form under both highstand and lowstand conditions, as demonstrated along modern Bahamian platform margins (Mullins and Neumann 1979; Schlager and Chermak 1979; Grammer and Ginsburg 1992). Similar relationships were revealed in our high-resolution sequence stratigraphic analysis of two isolated Upper Devonian carbonate platforms (Miette and Ancient Wall) in the Canadian Rocky Mountains (Fig. 1; van Buchem et al. 1996; Whalen et al. 2000). In this study we apply high-resolution sequence stratigraphy and seismic-scale outcrop analysis to differentiate successive onlapping sequences, their systems tracts, and platform-margin geometries of the two coeval platforms. This study demonstrates how variations in platform-margin geometry and the relationship between platform

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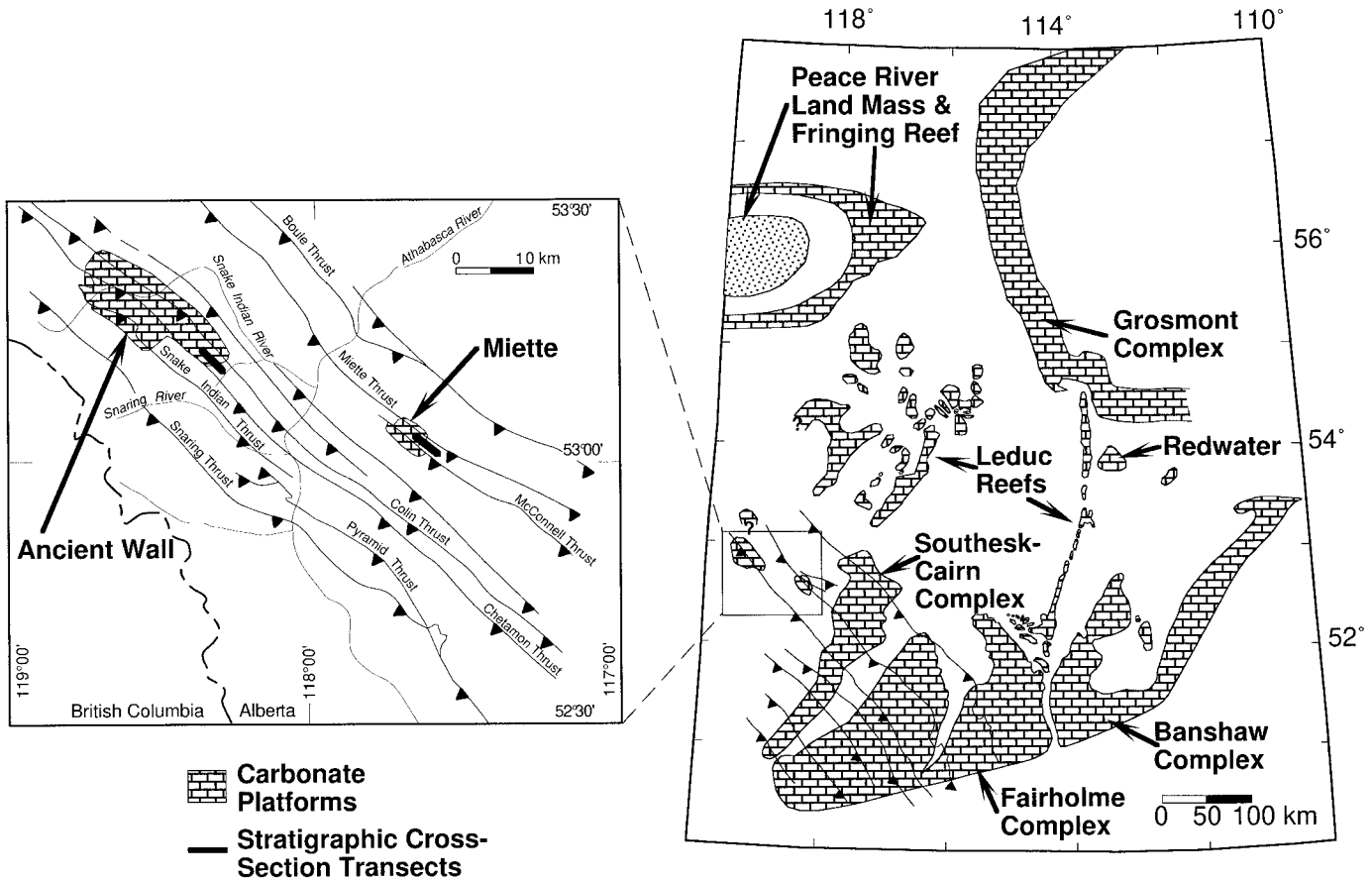


FIG. 1.—Location maps. **A)** Detailed location map of the overthrust belt in western Alberta illustrating the locations of the Miette and Ancient Wall platforms (after Mountjoy 1965). Thick black lines indicate the location of stratigraphic cross sections along the southeast margins of the two platforms. **B)** Map illustrating the location of isolated and attached carbonate platforms in the Alberta basin. Buildups located west of the barbed line, indicating the eastern limit of Laramide thrusting, are exposed in the Canadian Rocky Mountains (after Mountjoy 1980; Geldsetzer 1989; Switzer et al. 1994).

and slope/basin sequences are directly tied to patterns of platform development. We present a new technique to differentiate highstand, lowstand, and transgressive parts of the onlapping wedges through detailed analysis of the mineralogy and sediment composition of both fine-grained mixed carbonate–siliciclastic sediments and coarse-grained redeposited carbonates. This paper builds on earlier work that documented variations in the organic, carbonate, and siliciclastic basinal sediment flux surrounding the Miette platform (van Buchem et al. 1996) and the sedimentologic evolution of the Miette and Ancient Wall platforms (Whalen et al. 2000). Variations in rates of subsidence between the Miette and Ancient Wall platforms provided us with a natural experiment on the effects of such deviations on slope development, which are outlined below. The spectacularly exposed platform margins in the Canadian Rockies provide us with models to facilitate platform-to-basin correlation of other carbonate platforms with bypass margins.

Geologic Setting

Western Canada was located (Fig. 1) at near-equatorial latitudes, within the trade wind belt, along the meridionally oriented western margin of Late Devonian Laurentia (Witzke and Heckel 1988; Scotese and McKerrow 1990). A regionally extensive carbonate ramp (Figs. 2–4) first developed in the Alberta basin during the Middle to Late Devonian transgression across a widespread subaerial unconformity. A system of attached and isolated carbonate platforms developed atop the ramp during the Frasnian Age of the Late Devonian (Fig. 1; Andrichuk 1961; Mountjoy 1978, 1980; Moore 1989). Fine-grained siliciclastic sediment (Woodbend shales), interpreted to have been shed from the Ellesmerian Fold Belt in the Canadian Arctic Archipelago, mixed with platform-derived carbonates and was deposited around the platforms in the Alberta basin (Fig. 1; Oliver and Cowper 1963; Stoakes 1980; Switzer et al. 1994). Carbonate-platform growth kept up with a second-order sea-level rise (Fig. 5; Johnson et al. 1985; Johnson and Sandberg 1989) and outpaced basinal sedimentation during most of the Frasnian. The Frasnian–Famennian extinction event, which brought about the demise of many framework-building fauna, marks the end of Devonian reef development (McLaren 1982; Stearn 1987). Early Fammenian mixed carbonate–siliciclastic sediments (Mountjoy and Savoy 1995; Mountjoy and Becker 2000) filled the Alberta basin prior to widespread latest Devonian through Carboniferous carbonate ramp development (Poole and Sandberg 1991; Stoakes 1992).

Stratigraphy

Devonian rocks exposed in western Alberta range from latest Givetian or earliest Frasnian to Famennian in age, whereas those in the subsurface to the east range in age from latest Eifelian to Famennian (Fig. 2). Different formation names are given to basinal and platform lithologies, and an independent system of stratigraphic nomenclature was developed for the subsurface (Fig. 2). Major platform carbonate units in the Rocky Mountains are the Flume, Cairn, Southesk, and Palliser Formations (Fig. 2). These units are characterized by shallow-water platform and platform-margin facies (Klovan 1964; Mountjoy 1965, 1989; Geldsetzer 1989).

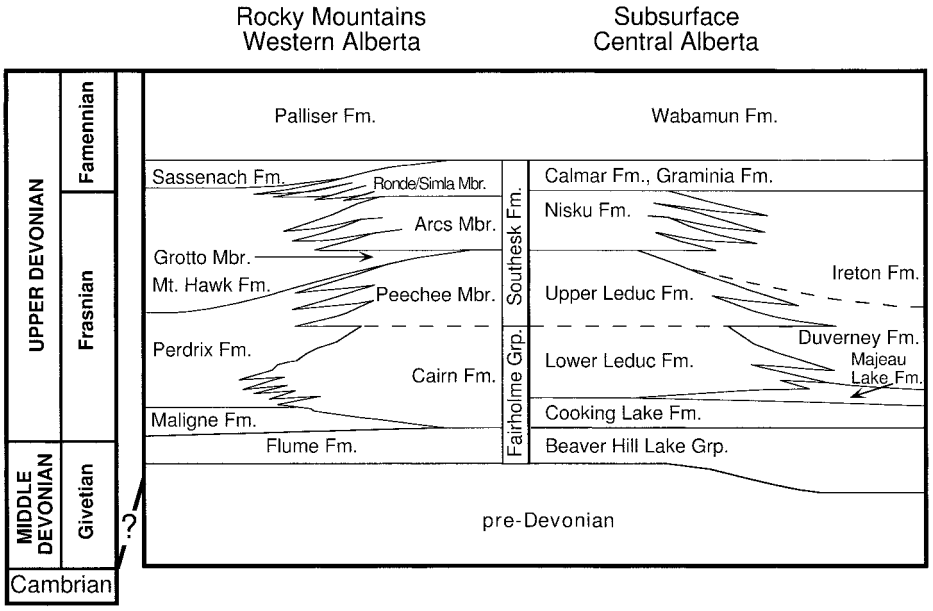


FIG. 2.—Upper Devonian stratigraphic nomenclature for the Rocky Mountains, western Alberta, and the central Alberta subsurface.

Major basinal units are the Maligne, Perdrix, Mount Hawk, and Sassenach Formations (Fig. 2). Basinal facies are dominantly fine-grained hemipelagic carbonate and siliciclastic sediments punctuated by coarse-grained carbonate sands, conglomerates, and breccias with platform-derived and slope-derived clasts (Cook et al. 1972; Hopkins 1972; Coppold 1976; Mountjoy and Jull 1978). Average siliciclastic content of these units increases upsection, but grains seldom exceed silt size until deposition of sand in the Fammenian Sassenach Formation. The only unequivocal stratigraphic evidence that demonstrates age equivalence of platform and basin units is distinct intertonguing. Biostratigraphy is seldom useful for correlation of platform and basinal units because of the lack of diagnostic conodont species in platform environments and the limited biostratigraphic resolution of other taxa such as stromatoporoids, rugose corals, or brachiopods (Mallamo and Geldsetzer 1991). Along the southeast margins of Miette and Ancient Wall, intercalation can be demonstrated only between the Maligne and lower part of the Upper Cairn Formation and the upper Mount Hawk Formation with the Arcs and Ronde Members of the Southesk Formation. Otherwise basinal formations onlap platform units, and we apply mineralogic and compositional criteria to refine correlations in onlapping units.

Miette and Ancient Wall Reef Complexes

The Miette and Ancient Wall reef complexes, located in the western part of the Alberta basin, are 400–500 m thick (Figs. 1, 3, 4). Miette had an areal extent of about 165 km^2, and Ancient Wall was approximately 1200 km^2 (Geldsetzer 1989; Mountjoy 1989). In both platforms, the dominant organisms were tabular, bulbous, and domal stromatoporoids, *Amphipora*, and tabulate and rugose corals (Noble 1970; Kobluk 1975; Coppold 1976). Platform margins are locally characterized by a rim of stromatoporoid biostromes surrounding a typical back-reef interior with subtidal and peritidal meter-scale shoaling-upward cycles (Mountjoy 1965, 1989; Mountjoy and Mackenzie 1974; Kobluk 1975; Stearn 1975; McLean and Mountjoy 1994; Whalen et al. 2000).

Well-exposed platform margins along the southeast edge of both Miette and Ancient Wall provide the data for this study (Figs. 1, 3, 4). The Miette platform margin, where exposed, either interfingers with or is abruptly onlapped by slope facies. In the latter case the margin was interpreted as a submarine unconformity (Pray 1968; Hopkins 1977). At Ancient Wall, the buildup margin is better exposed and sheds more insight into the evolution of platform-margin geometries. A transition between interfingering and onlapping margins appears to be related to patterns of platform development and an increase in deposition of gravity-flow deposits. Slope facies deposited by turbidity currents, debris flows, and slumps extend several kilometers into the basin and punctuate fine-grained basinal sediments (Figs. 6–11; Cook et al. 1972; Coppold 1976; Hopkins 1977; Whalen et al. 2000).

METHODS

The sequence stratigraphic and lithofacies analysis of the Miette and Ancient Wall is on the basis of a high-resolution lithostratigraphic data base of 34 detailed measured sections (Miette, 19; Ancient Wall, 15) along the southeast margins of the two platforms (van Buchem et al. 1996; Whalen et al. 2000). Lithostratigraphic sections were placed in the geometrical framework observed in outcrop and in photographic panoramas in order to aid in correlation of platform and basin strata (Figs. 3, 4). Important sequence stratigraphic horizons representing sequence boundaries or systems-tract boundaries (e.g., ravinement, exposure, and flooding surfaces) were identified by their physical expression and associated lithofacies stacking patterns.

Samples for facies analysis were collected approximately every meter depending on lithologic heterogeneity. Lithofacies were defined on the basis of observations from outcrop, polished slabs (175 samples), and standard thin-section petrography (250 samples). Clast content of redeposited carbonate units was measured in outcrop by counting 300 clasts within a single bed and in thin section by counting 300 points per thin section. Measurement of total carbonate content and total organic carbon (TOC) were made using Rock Eval pyrolysis, outlined in more detail in van Buchem et al. (1996). Correlation between platforms hinges on biostratigraphy, and 8 to 10 kg conodont biostratigraphic samples were collected at significant stratigraphic horizons. Conodont age dating, using the Montagne Noire zonation based on graphic correlation (Klapper 1989; McLean and Klapper 1998), provides important tie points for correlation (Figs. 3, 4, 5). Traditional backstripping methods (Steckler and Watts 1978; Bond and Kominz 1984) were applied to stratigraphic data from the platform interior of both buildups to gain insight into tectonic subsidence history.

LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS

Subsurface Upper Devonian buildups in Alberta are important petroleum reservoirs that are directly associated with basinal petroleum source rocks

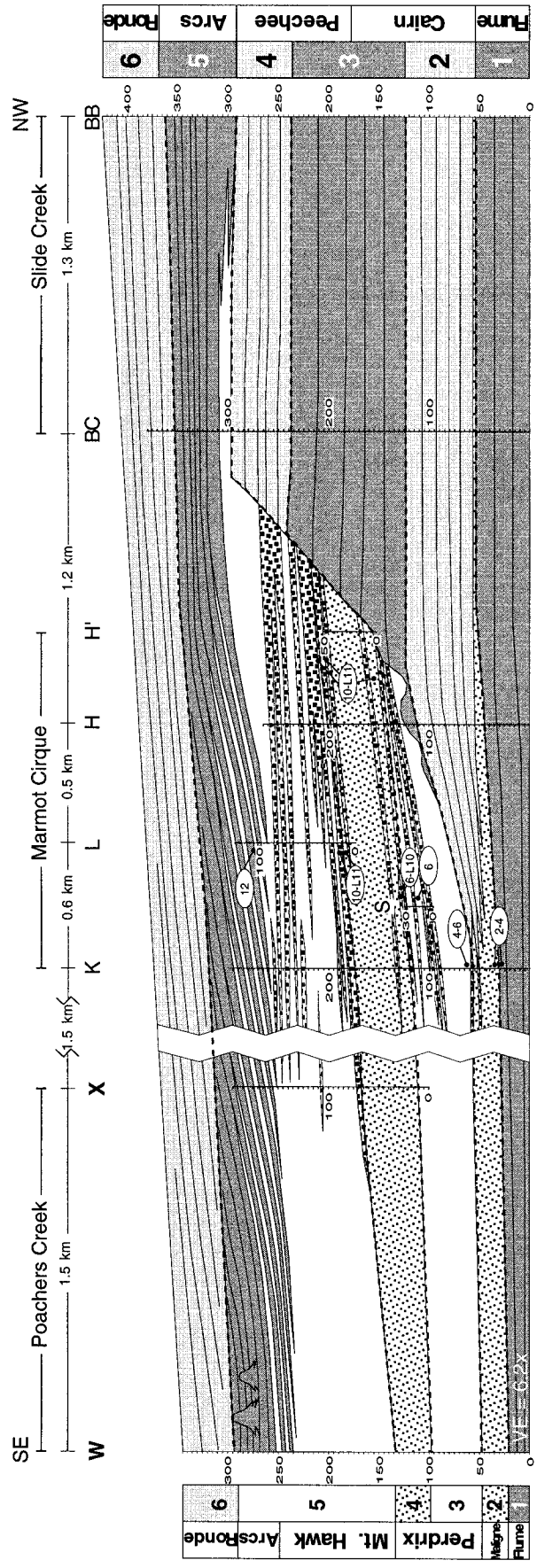


FIG. 3.—Cross section of the southeast margin of the Miette platform illustrating lithostratigraphy, the sequence stratigraphic subdivision, and general lithofacies. Locations of stratigraphic sections are indicated by letters and graduated lines. Conodont sample locations and Montagne Noire zones are shown within ovals next to measured sections. Platform sequences are indicated by alternating dark and light shades of gray. Slope and basin sequences are indicated by alternating white and stippled patterns. For the sake of simplicity, facies of the prograding Arcs and Ronde are lumped as platform facies. The stratigraphic positions of coarse-grained redeposited carbonates are indicated in basinal sequences. Thick dashed black lines indicate sequence boundaries. Thin black lines within platform sequences indicate parasequence boundaries.

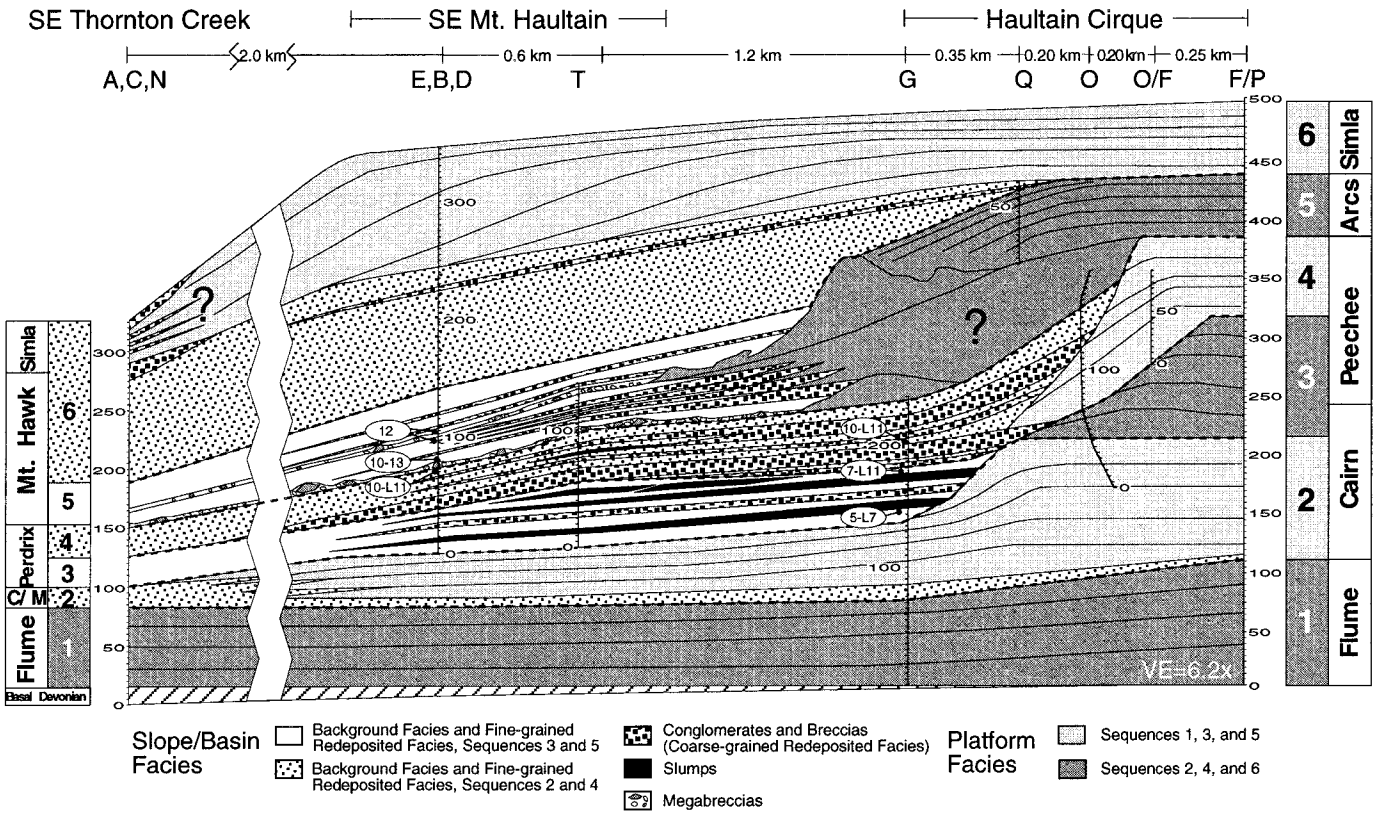


FIG. 4.—Cross section of the southeast margin of the Ancient Wall platform illustrating lithostratigraphy, the sequence stratigraphic subdivision, and general lithofacies. Locations of stratigraphic sections are indicated by letters and graduated lines. Conodont sample locations and Montagne Noire zones are shown within ovals next to measured sections. Platform sequences are indicated by alternating dark and light shades of gray. Slope and basin sequences are indicated by alternating white and stippled patterns. For the sake of simplicity, facies of the prograding Simla are lumped as platform facies. The stratigraphic positions of coarse-grained redeposited carbonates are indicated in basinal sequences by different patterns for slumps, megabreccias, and other coarse-grained facies. Thick dashed black lines indicate sequence boundaries. Thin black lines within platform sequences indicate parasequence boundaries. The abbreviation C/M in the lithostratigraphy column on the left stands for Cairn and Maligne Formations.

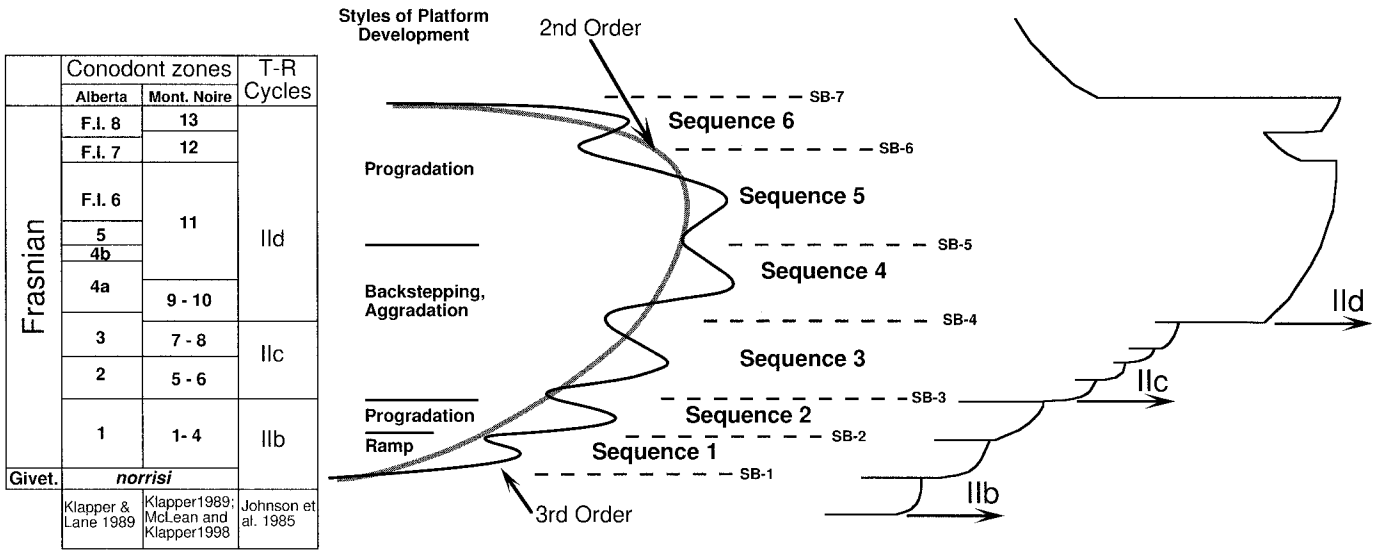


FIG. 5.—Sequence stratigraphy, patterns of platform development, and interpreted Upper Frasnian second- and third-order sea-level curves based on this study. Conodont zonations (Klapper and Lane 1989; McLean and Klapper 1998) and the sea-level curve of Johnson et al. (1985) are also illustrated.

(Chow et al. 1995; van Buchem et al. 1996), and petroleum exploration provided the impetus for much of the lithostratigraphic research on these platforms. Lithofacies analyses of specific buildups or reef complexes (Klovan 1964; Jenik and Lerbekmo 1968; Coppold 1976; Walls 1983; Theriault 1988; Wendte 1994) or regional and interregional syntheses (Krebs and Mountjoy 1972; Playford 1980; Burchette 1981; Hladil 1986; Wendte 1992; Machel and Hunter 1994) provide a wealth of information for depositional interpretations. A detailed analysis of facies from platform, slope, and basinal areas associated with the Miette and Ancient Wall buildups is presented in Whalen et al. (2000), and the reader is referred there for more detailed sedimentologic data. This paper focuses on facies deposited near the platform margin, including forereef, slope, and proximal basin environments (Table 1), with an emphasis on depositional style and its relationship to platform development. Coarse-grained facies are collectively referred to as conglomerates, but those with dominantly rounded clasts are classified as floatstones and rudstones (Embry and Klovan 1972) and those with angular clasts or clasts greater than 64 mm in diameter are referred to as breccias or megabreccias, respectively.

Forereef and Proximal Slope Facies Association

Facies on the forereef and slope were deposited either from suspension (background sediments) with *in situ* faunal components or as platform- or slope-derived material redeposited by various types of gravity-flow mechanisms (redeposited carbonates). Fauna and clasts indicative of platform environments include bulbous, branching, and thick tabular stromatoporoids, *Amphipora*, tabulate corals, colonial rugose corals, calcareous algae, oncoids, calcimicrobes like *Renalcis* and *Girvanella* (Klovan 1964; Playford 1980), light gray, subangular to subrounded limestones of variable textures, reddened or blackened limestone, and micritized bioclasts. Slope-derived fauna and grains include crinoids, solitary rugose corals, some tabulate corals, thin laminar stromatoporoids, most brachiopod species (Klovan 1964; Playford 1980) and dark gray, tabular to subangular limestone clasts.

Background facies include bioturbated, nodular, bioclastic, and silty bioclastic wackestone and packstone, silty marl, and calcareous siltstone. These facies contain no evidence of traction transport or reworking by waves and currents and are dominantly hemipelagic. Fine-grained turbidites, however, are difficult to differentiate from hemipelagic facies, and we have opted to lump all facies that are dominantly finer-grained than fine sand as *background* sediments, to differentiate them from coarser-grained redeposited carbonates. Bioturbation and shelly fauna in many of these facies indicate that they were deposited in oxygenated environments. Background sediments locally exhibit soft-sediment deformation features on a variety of scales (Figs. 6, 7).

Redeposited facies include megabreccias, lithoclastic breccias, oncolitic, bioclastic and lithoclastic floatstone and rudstone, coarse- and fine-grained bioclastic–lithoclastic turbidites, and slumps. Redeposited carbonates exhibit a wide range of grain sizes and sedimentary structures indicative of deposition from turbidity currents, debris flows, and slumping (Whalen et al. 2000). Various redeposited slope facies at Miette and Ancient Wall provide insight into slope morphology and depositional processes. Facies described as breccias, floatstones, and rudstones most commonly contain chaotically oriented, poorly sorted clasts in sheet-like or lenticular beds with basal scours. Their chaotic structure indicates deposition of beds as individual debris sheets or channelized debris flows. Mud-supported gravity-flow deposits (floatstones) are indicative of downslope transport of unconsolidated sediment along shallow slopes whereas grain-supported facies indicate greater slope angles (Kenter 1990). Slumps are most common in the lower and middle Perdrix Formation at Ancient Wall (Fig. 7) and the Perdrix and Mount Hawk Formations at Miette (Whalen et al. 2000). They are similar to those from modern carbonate slopes of the Bahamas (Schlager et al. 1985) and Mesozoic slope deposits of the Swiss Alps (Eberli 1987). Kenter (1990) demonstrated that carbonate slump deposits are most common on mud-dominated slopes with relatively shallow slope angles ($< 10°$).

Megabreccias are the most spectacular deposits in the slope sequence. They occur at similar stratigraphic levels along the southeastern and western margins of the Ancient Wall platform (Figs. 4, 7–9; Cook et al. 1972; Mountjoy and Jull 1978; Geldsetzer 1989) but have not been observed around the Miette platform. These units have a sheet-like geometry, lack internal stratification, are commonly matrix supported and contain a heterogeneous mixture of poorly sorted angular to subangular clasts. Clast size is commonly greater than one meter and in some cases up to 25 m in diameter (Fig. 9C) with boulder-size clasts found several kilometers from the platform margin (Cook et al. 1972). These characteristics support a submarine-debris-flow transport mechanism and suggest catastrophic failure of the platform margin resulting in significant slope and platform-margin erosion (Cook et al. 1972; Hopkins 1972; Whalen et al. 2000).

Distal Slope and Basin Facies Association

Basin and lower slope facies include argillaceous mudstone and wackestone, calcareous shale (marl), and organic-rich mudstone and shale (Whalen et al. 2000). These facies are characterized by their fine grain size, thin internally laminated beds, and a dominantly hemipelagic fauna. Bedding surfaces are commonly iron stained and locally exhibit *Trypinites* borings (Fig. 9F). Various basin and lower slope facies provide insight into distal depositional processes. Argillaceous mudstones and wackestones, which may be bioturbated and/or nodular (Fig. 6H), and calcareous shales and marls contain autochthonous fauna (mainly crinoids and brachiopods) as well as pelagic biota (criccoconarids and calcispheres) that settled from suspension. Thin graded beds of wackestone and bedding-plane concentrations of bioclasts interbedded with finer-grained facies indicate that storm deposition or turbidity currents episodically interrupted background sedimentation (Whalen et al. 2000). Sedimentary boudinage, indicating sediment loading, is locally exhibited where thin-bedded shales are overlain by coarser-grained redeposited carbonates (Fig. 6D). Dark gray to black, laminated, organic-rich, carbonate-poor mudstones and shales have high TOC content (Figs. 8, 10; van Buchem et al. 1996). They commonly lack benthic fauna and bioturbation and contain small framboids, cubes, or nodules of pyrite (Whalen et al. 2000). Interbedding of these facies with nodular and bioturbated mud/wackestones indicate deposition under varying levels of oxygenation from dysaerobic or anaerobic to well oxygenated, respectively. The fine-grained texture and lack of sedimentary structures indicative of wave or current energy suggest hemipelagic deposition. Platform-derived material suspended by storms or tides can be transported along ocean surface layers or mid-level pycnoclines before gravitationally settling into basinal environments (Heath and Mullins 1984).

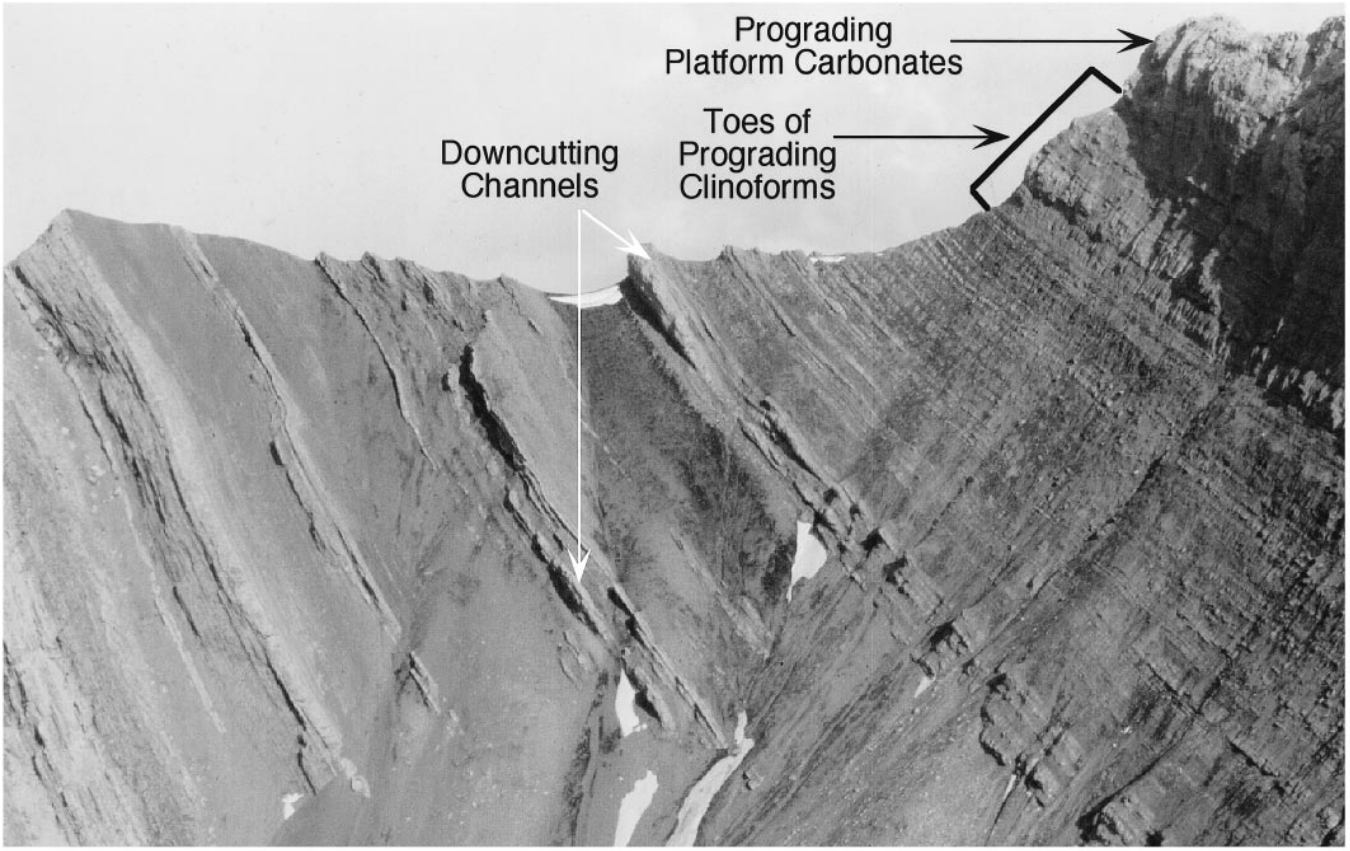
SEQUENCE STRATIGRAPHY: STAGES OF PLATFORM AND SLOPE DEVELOPMENT AND BASIN FILLING

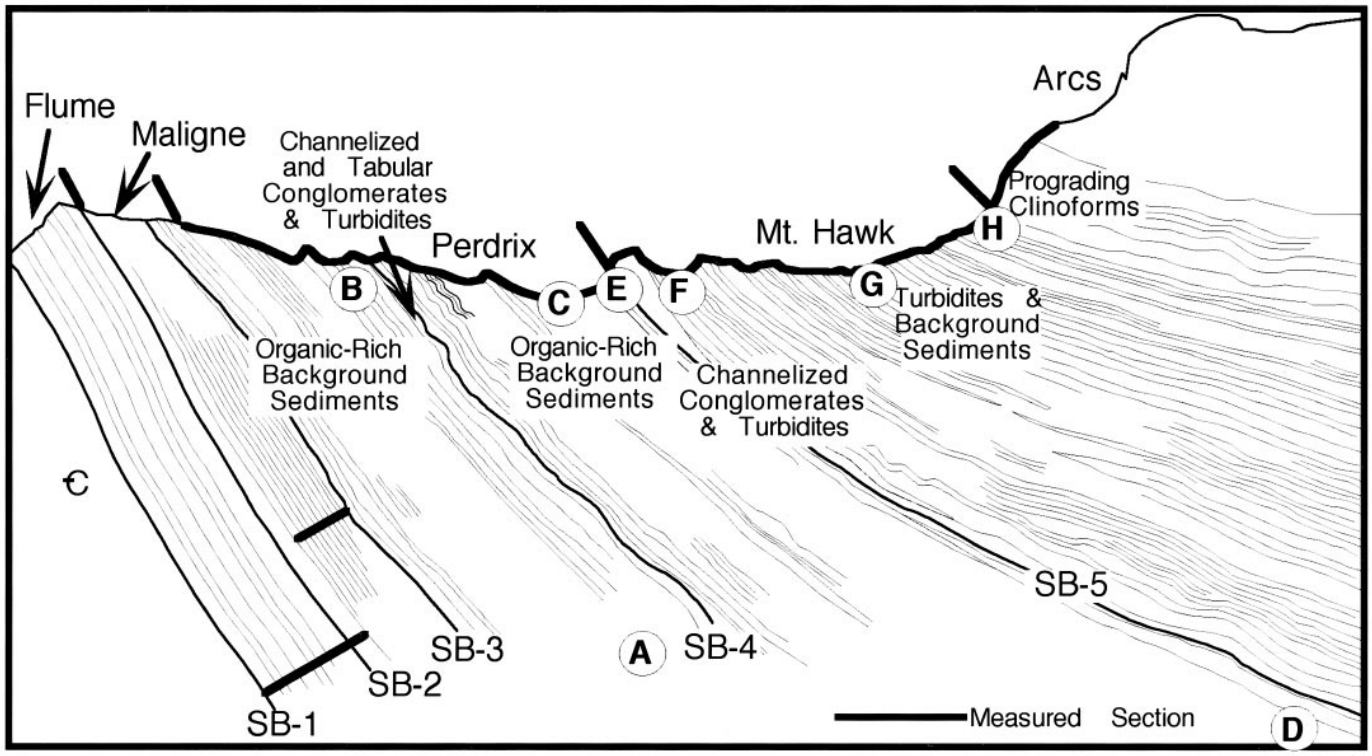
The Miette and Ancient Wall platforms were deposited as six genetic depositional sequences and four geomorphic phases of development (van Buchem et al. 1996; Whalen et al. 2000). Sequences were defined on the basis of their geometric expression, stratal stacking patterns, sediment composition, and identification of important platform and slope stratal horizons (van Buchem et al. 1996; Whalen et al. 2000). Stratal horizons interpreted as platform sequence boundaries are subaerial exposure surfaces or significant transgressive marine-flooding surfaces. We have interpreted thick coarse-grained slope packages to represent sequence-boundary intervals (discussed below). Stratal horizons in these coarse-grained slope units, that indicate downcutting, incision, and/or marine flooding, are interpreted as slope sequence boundaries. Systems tracts for each sequence are indicated by traditional sequence stratigraphic abbreviations followed by a subscript

TABLE 1.—*Slope and basin facies of the Miette and Ancient Wall platforms*

Facies	Back/ Redep.	Components and Matrix	Sedimentary Features	Water Energy	Environment of Deposition	Facies Association
Amphipora Floatstone, Rudstone	R	*Amphipora*, bulbous stromatoporoids, ±lime mud matrix	cm-m bedding, bioturbation	moderate agitation moderate turbulence	intertidal, subtidal lagoon, reef flat	fore-reef and upper slope
Stachyoides Floatstone, Rudstone	R	*Stachyoides* and other stromatoporoids, *Amphipora*, corals, ±lime mud matrix	dm-m bedding, imbricated or chaotic clasts, shelter pores	moderate-strong agitation, strong turbulence	reef flat, reef foreslope	fore-reef and upper slope
Bioclastic, Intraclastic Float/Rudstone	R	stromatoporoids, ±*Amphipora*, ±taulate corals, ±crinoids, intraclasts, ±lime mud matrix	cm-m bedding, shelter pores, burrows	moderate agitation strong turbulence	reef flat, shallow lagoon, reef foreslope	fore-reef and upper slope
Bioclastic, Intraclastic, Peloidal Pack/Grainstone	R	stromatoporoids, crinoids, brachiopods, rugose & tabulate corals, intraclasts, peloids, ±lime mud matrix	cm-dm bedding, bioturbation, wispy carbonaceous partings	slight agitation moderate turbulence	platform margin shoals, slope, basin	fore-reef and upper slope
Burrowed or Bioturbated Wacke/Packstone	B	peloids, crinoids, brachiopods, *Amphipora*, corals, lime mud matrix	dm-m bedding, burrows or bioturbation	intermittent agitation episodic turbulence	subtidal lagoon, upper slope	fore-reef and upper slope
Nodular Wacke/Packstone	B	peloids, brachiopods, crinoids, stromatoporoids, corals, *Amphipora*, lime mud matrix	cm-dm bedding, nodules, burrows, shaly or carbonaceous partings	intermittent agitation episodic turbulence	subtidal lagoon, upper slope	fore-reef and upper slope
Megabreccias	R	lithoclasts > 1 m in diameter, stromatopoids, tabulate and rugose corals, intraclasts, peloids, lime mud or wacke/packstone matrix	m bedding, chaotic clasts, largest clasts protrude above or below bed	slight agitation episodic strong turbulence	slope, basin	slope and basin
Lithoclastic Breccias	R	pebble to cobble size lithoclasts with few stromatoporoids, tabulate and rugose corals, lime mud/wackestone matrix	m bedding, chaotic clasts or crude graded bedding, scoured bases	slight agitation episodic strong turbulence	slope	slope and basin
Oncolitic, Bioclastic Float/Rudstone	R	oncoids, stromatoporoids, corals, crinoids, lime mud or wacke/packstone matrix	cm-dm, tabular or lenticular normal graded bedding	slight agitation episodic strong turbulence	slope, basin	slope and basin
Lithoclastic, Bioclastic Rudstone	R	variety of bioclasts and/or light or dark, angular or rounded limestone lithoclasts, lime mud or wacke/packstone matrix	dm-m, tabular or lenticular bedding, chaotic clasts	slight agitation episodic strong turbulence	slope	slope and basin
Lithoclastic, Bioclastic Floatstone (Pebbly Mudstone)	R	light or dark gray angular to rounded limestone lithoclasts, variety of bioclasts, lime mud/wackestone matrix	dm-m, tabular, crude graded bedding	intermittent agitation episodic strong turbulence	slope	slope and basin
Coarse-grained Bioclastic, Lithoclastic Turbidites	R	sand to cobble size bioclasts and lithoclasts in a wacke/packstone matrix	dm-m, tabular or lenticular, normal or coarsetail graded bedding	intermittent agitation episodic strong turbulence	slope	slope and basin
Fine-grained Bioclastic, Intraclastic, Peloidal Turbidites	R	sand to pebble size bioclasts and intraclasts and peloids in a mud/wackestone matrix	cm-dm tabular, normal or coarse-tail graded bedding	intermittent agitation episodic turbulence	slope, basin	slope and basin
Slumps	B	bed scale blocks of fine-grained slope facies	soft sediment folds, rotated beds, intraformational truncation surfaces	intermittent agitation episodic turbulence	slope	slope and basin
Crinoid Wacke/Packstone	B	lime mud matrix, crinoids, rugose corals, brachiopods	cm-dm bedding	intermittent agitation episodic turbulence	slope, basin	slope and basin
Silty Bioclastic Mud/Wackestone	B	lime mud, quartz silt, crinoids, brachiopods	laminations, cm-dm bedding, nodules	intermittent agitation episodic turbulence	slope, basin	slope and basin
Calcareous Siltstone, Silty Marl	B	lime mud, clay, quartz silt or sand, crinoids, brachiopods	laminations, cm-dm bedding, nodules	quiet water	slope, basin	slope and basin
Argillaceous Mud/Wackestone	B	lime mud, clay, crinoids, calcispheres, cricoconarids	laminations, cm bedding, nodules, burrows	quiet water	slope, basin	slope and basin
Calcareous Shale	B	lime mud, clay, crinoids, criccoconarids	laminations	quiet water	slope, basin	slope and basin
Organic-rich Shale/Mudstone	B	clay, lime mud, organics	laminations	quiet water	slope, basin	slope and basin

Columns from left to right indicate lithofacies (classified based on Dunham 1962 and Embry and Klovan 1972), whether facies are redeposited (R) or background (B) deposits, lithologic and biologic components and matrix, sedimentary features, relative water energy based on Embry and Klovan (1972), environment of deposition, and general facies association.


Prograding
Platform Carbonates
Toes of
Prograding
Clinoforms
Downcutting
Channels


Flume
Maligne
Channelized
and Tabular
Conglomerates
& Turbidites
Perdrix
Mt. Hawk
Arcs
Prograding
Clinoforms
B
C
E
F
G
H
Organic-Rich
Background
Sediments
Organic-Rich
Background
Sediments
Channelized
Conglomerates
& Turbidites
Turbidites &
Background
Sediments
SB-1
SB-2
SB-3
SB-4
SB-5
A
Measured Section
D

indicating the sequence with which they are associated (e.g. TST_2 = transgressive systems tract, Sequence 2).

Mountjoy (1965) and Mountjoy and Mackenzie (1974) were the first to note the successive stages of development and the long-term transgressive–regressive trend of the Miette and Ancient Wall buildups. The platforms are characterized by a lower biostromal phase (Sequences 1–3) and an upper sandy, peritidal phase (Sequences 4–6) (Mountjoy 1965; Mountjoy and Mackenzie 1974). The first three sequences record construction of a rimmed platform and infill of a subtidal to peritidal lagoon, and the last three sequences indicate deposition on a relatively flat-topped peritidal platform (Whalen et al. 2000). The four phases of platform development vary both lithologically and in the geometry of platform and basin units (Figs. 3, 4; van Buchem et al. 1996; Whalen et al. 2000). They include: a regionally extensive, aggrading carbonate ramp (Sequence 1), an isolated prograding platform (Sequence 2), a backstepping and aggrading isolated platform (Sequences 3 and 4), and a second ramp-like phase (Sequences 5 and 6) that prograded across basin fill (van Buchem et al. 1996; Whalen et al. 2000). The entire succession was deposited during a second-order transgressive–regressive cycle (Fig. 5; Johnson et al. 1985). Patterns of platform and slope development at Miette and Ancient Wall were relatively similar during much of the Frasnian but differ markedly during the deposition of Sequence 5.

Aggrading Ramp (Sequence 1)

The initial ramp phase (Flume Formation) displays a relatively tabular to slightly wedge-shaped geometry (Figs. 3, 4). The base of the sequence is a regional angular unconformity that developed during early Paleozoic exposure of the west Alberta ridge. In the field area, Upper Devonian carbonates directly overlie Cambrian age rocks, but to the east and west Devonian rocks overlie progressively younger lower Paleozoic rocks (Pugh 1973). The Flume Formation records three aggrading parasequence sets at Miette and four at Ancient Wall that contain both subtidal- and peritidal-dominated cycles (McLean and Mountjoy 1994; Whalen et al. 2000). The outer ramp is dominated by broad, domal to spherical stromatoporoid framestones (0.5 to 1.0 km wide; Cook 1972; Whalen et al. 2000). Evidence of subaerial exposure is not present at the top of Sequence 1, but a marine flooding surface and associated ravinement produced erosionally truncated stromatoporoid framestones that clearly mark the sequence boundary.

Prograding Platform 1 (Sequence 2)

The first prograding platform phase (lower Cairn Formation and most of the laterally equivalent Maligne Formation) is wedge-shaped and characterized by five parasequences of basinward-tapering, low-angle, sigmoidal clinoforms (Figs. 3, 4). This sequence marks the initiation of isolated platform development atop the underlying Flume ramp (Figs. 1, 3, 4). The platform margin was dominated by stromatoporoid biostromes similar to those in Sequence 1. The uppermost parasequences at Ancient Wall backstep approximately 2 km from the farthest extent of platform progradation (Fig. 4). In outcrop, physical continuity was observed between platform and slope facies, but a clear distinction in depositional style developed between the two during Sequence 2. Carbonate-rich background sediments characterize most of the Maligne Formation (Fig. 10), although coarse-grained redeposited carbonates in the uppermost Maligne signal the onset of gravity-flow deposition (Fig. 3). The carbonate and clast content of Maligne facies also provides clues to the sequence stratigraphic development. The progressive decrease in carbonate content throughout the lower part of the Maligne Formation (Fig. 10) is interpreted to indicate transgression and incipient drowning of the platform. Reinitiation of abundant carbonate production during late transgression and highstand permitted platform progradation (Figs. 3, 4) and is indicated by the increase in carbonate content in the upper Maligne Formation (Fig. 10). Slope-derived clasts within the first upper Maligne gravity-flow deposits are interpreted to represent platform-margin steepening and slope erosion during late highstand progradation (HST_2). In platform-interior settings, lithofacies at the top of Sequence 2 contain laminated fenestral wackestones indicating either very shallow peritidal conditions or subaerial exposure (Whalen et al. 2000).

Backstepping to Aggrading Platform (Sequences 3 and 4)

Backstepping and aggradation mark the initiation of bypass-margin development and detachment of slope/basin sequences from platform facies. The uppermost Maligne Formation at Miette (Figs. 3, 10) and lowermost Perdrix Formation at Ancient Wall (Figs. 4, 8) contain channelized bio-lithoclastic conglomerates interpreted as LST_3, on the basis of downcutting and channel geometry and their stratigraphic position near the top of a coarsening-upward package. Platform-derived clasts in uppermost Malinge conglomerates lend support to the interpretation of platform erosion during a relative sea-level lowstand. LST_3 forms a very thin onlapping wedge that pinches out against the HST_2 platform margin (Figs. 3, 4, 11). During deposition of LST_3, the platform was either subaerially exposed or under very shallow peritidal conditions with little accommodation space and low carbonate production. The sequence boundary on the platform top occurs where fenestral wackestones of uppermost Sequence 2 are overlain by a thin lag containing reworked blackened limestone clasts that are interpreted to represent early transgression of Sequence 3.

Abruptly overlying LST_3 and the updip transgressive lag are slope and basin facies of the lower Perdrix Formation. Lower Perdrix facies contain lens-shaped units that are dominated by interbedded organic-rich calcareous shales, nodular mud/wackestones (Figs. 8, 10), minor bio-lithoclastic conglomerates, and at Ancient Wall, large-scale slump structures up to several meters thick (Figs. 7, 8). These facies indicate marine flooding atop the underlying Cairn and uppermost Maligne Formation and represent TST_3. Transgressive facies are stacked in meter-scale cycles that generally display an upward increase in total carbonate content. Although individual cycles record an increase in carbonate content, overall the lower Perdrix Formation displays a net decrease in average carbonate content (Figs. 8, 10). We interpret this mineralogic trend to represent lower carbonate input during incipient platform drowning and deposition of TST_3.

Backstepping and aggrading platform phases (Sequences 3 and 4, uppermost Cairn Formation and Peechee Member, Southesk Formation) are characterized by layer-cake stratal packages and a relatively steep-sided erosional or bypass margin (Figs. 3, 4, 11). TST_3 records minor backstepping (0.5–1.0 km) during deposition of the first two parasequences of sequence 3 (Figs 3, 4, 11). The platform margin of HST_3 records a series of three aggrading parasequences bounded by thin brachiopod-rich nodular and argillaceous mudstones and wackestones that indicate episodes of minor marine flooding (Figs. 3, 4; Whalen et al. 2000). An aggradational style of platform development continued during deposition of Sequence 4 (Figs. 3, 4, 11), but systems tracts are difficult to differentiate because intense dolomitization has obscured primary fabrics. Aggrading platform-margin facies are laterally restricted (hundreds of meters) when compared to those

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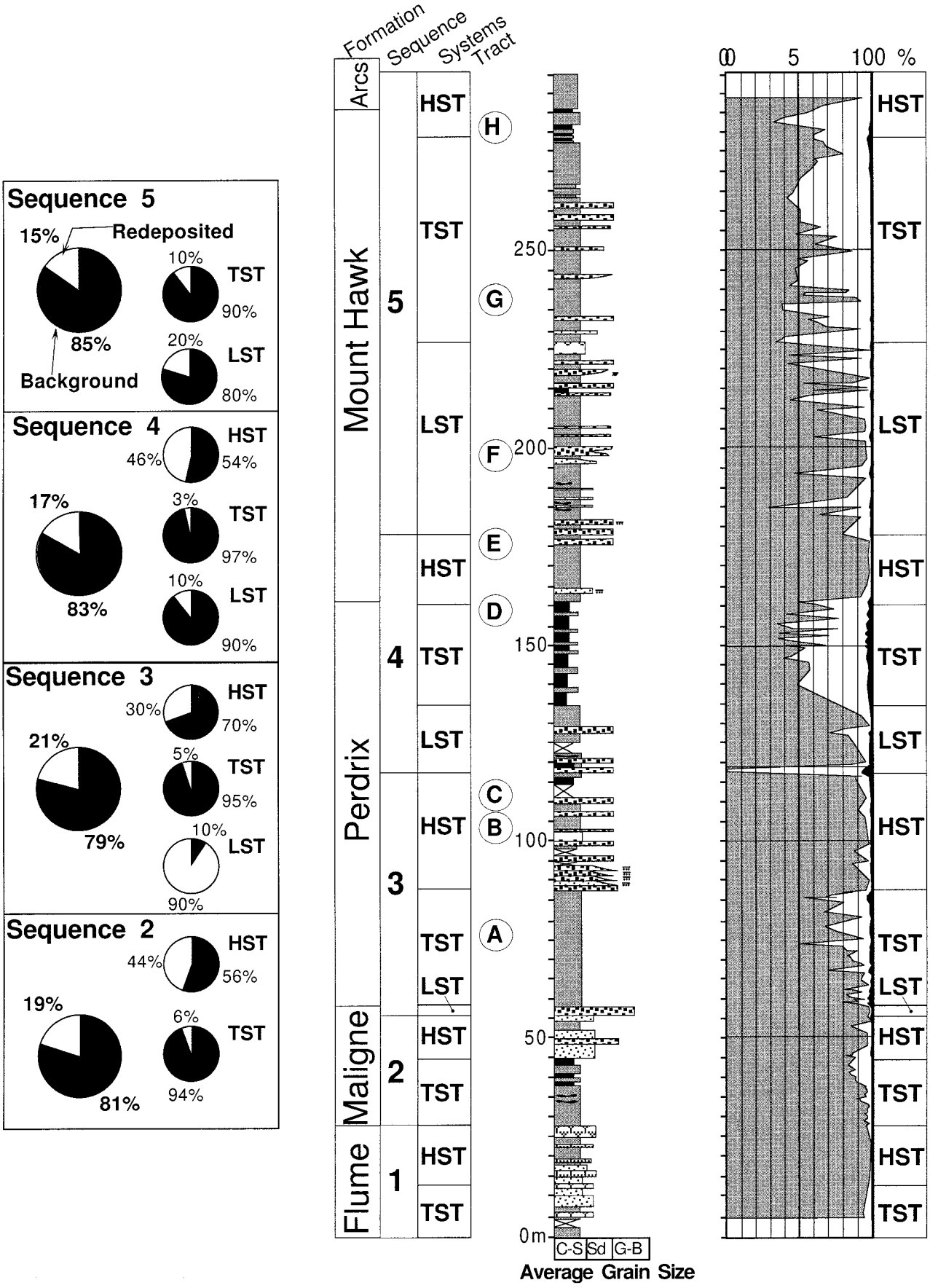
FIG. 6.—Outcrop photo and line drawing interpretation of the slope and basin section along the southeast margin of the Miette platform (section K). The line drawing illustrates the location of measured sections, lithostratigraphic units, sequence boundaries, and the location of photographs (circled letters) in Figure 8. Note the two intervals with downcutting channels at the base of Sequences 3 and 4, the prograding clinoforms in the upper Mount Hawk Formation, and the massive prograding carbonates in the Arcs Member of the Southesk Formation.


Sequence 5
15%
Redeposited
85%
Background
10%
TST
90%
20%
LST
80%
Sequence 4
46%
HST
54%
17%
83%
3%
TST
97%
10%
LST
90%
Sequence 3
30%
HST
70%
21%
79%
5%
TST
95%
10%
LST
90%
Sequence 2
44%
HST
56%
19%
81%
6%
TST
94%
Formation
Sequence
Systems Tract
Arcs
Mount Hawk
Perdrix
Maligne
Flume
5
4
3
2
1
HST
TST
LST
HST
TST
LST
HST
TST
LST
HST
TST
HST
TST
H
G
F
E
D
C
B
A
250
200
150
100
50
0m
C-S
Sd
G-B
Average Grain Size
0
5
100 %
HST
TST
LST
HST
TST
LST
HST
TST
LST
HST
TST
HST
TST

of Sequences 1 and 2 (Figs. 3, 4). The top of Sequence 3 on the platform is a subaerial exposure horizon that was karsted and underwent minor soil development (Whalen et al. 2000). The top of Sequence 4 is a significant marine flooding surface but displays no evidence of subaerial exposure (Whalen et al. 2000).

The lower middle Perdrix Formation is wedge-shaped, onlaps the platform margin, and is made up of bioclastic packstones, slumped wacke/packstones, lithoclastic breccias, and bio-lithoclastic conglomerates (Figs. 8, 10). Conglomerates occur in sheet-like bodies that extend at least 2 km from the platform margin (Figs. 3, 4, 11). Clasts within coarse-grained facies are dominated by slope-derived intraclasts and faunal elements. Facies within this unit have high overall carbonate contents in both background and redeposited carbonate facies (Figs. 8, 10). On the basis of the mineralogy, clast content of redeposited carbonate facies, and stratigraphic position, the lower Middle Perdrix Formation is interpreted as an onlapping wedge deposited during HST_3 (Figs. 3, 4, 11).

The upper middle Perdrix Formation is wedge-shaped and thins mainly toward the platform margin, where it onlaps and pinches out. This unit is dominated by channelized or sheet-like bio-lithoclastic floatstone and rudstone debris flows interbedded with turbidites, slumps, and background wackestones, mudstones, and shales (Figs. 8, 10). Interbedded background sediments have very low to moderate carbonate contents (0–70%) indicating low rates of fine-grained carbonate input (Figs. 8, 10). Platform erosion during subaerial exposure at the top of Sequence 3 provided coarser-grained bioclastic and lithoclastic sediment to this onlapping package. Debris flows with downcutting channels and platform-derived clasts and the relatively low carbonate content of background sediments supports an interpretation of upper middle Perdrix strata as a lowstand wedge (LST_4; Figs. 3, 4, 11).

Nodular wackestones and organic-rich shales of the upper Perdrix Formation abruptly overlie coarse-grained facies of the middle Perdrix. This juxtaposition is interpreted as signaling the onset of transgression and deposition of TST_4. The generally decreasing carbonate content through the lower upper Perdrix Formation is similar to the pattern seen in the lower Maligne and lower Perdrix strata (Fig. 8) and is interpreted to represent another cycle of incipient platform drowning during transgression. The increase in carbonate content through the uppermost Perdrix Formation signals the reinitiation of carbonate production on the platform during late transgression. The lowermost Mount Hawk Formation consists of bioclastic and lithoclastic turbidites and debris flows with slope-derived clasts and fossils. The mineralogic and lithologic trends are interpreted to indicate abundant carbonate input and slope erosion due to oversteepening during deposition of HST_4. In the basin, Sequence 4 forms a wedge that thins and onlaps the upper slope below the platform margin (Figs. 3, 4, 11).

Prograding Platform 2 (Sequences 5 and 6)

The most profound variations in platform-margin and slope development between Miette and Ancient Wall occur within Sequence 5. At Miette, the slope and basinal HST_4 is overlain by a series of incised channels filled with chaotic slope-derived conglomerates interbedded with carbonate-poor background sediments of the lower Mount Hawk Formation (Figs. 3, 10, 12). At Ancient Wall, this interval is characterized by two megabreccia units that bracket a package of prograding, redeposited conglomerates, packstones, and grainstones interbedded with carbonate-poor nodular wackestones and shales (Figs. 4, 7, 8). The first megabreccia contains the widest range of clast sizes including platform-derived blocks over 25 m in diameter in a matrix of lime mud and fine-grained carbonate peloids and intraclasts (Figs. 7, 9C; Cook et al. 1972). The second megabreccia is similar in composition but the maximum clast size is less than 5 m. Platform-margin collapse resulting in megabreccia deposition appears to have rearranged the platform-margin geometry and facilitated the development of a lowstand carbonate factory atop the submerged part of the collapsed margin. Updip of the megabreccias, small-scale reefal mounds prograded about 2.5 km basinward of the former platform margin (Figs. 4, 11). The prograding redeposited facies are interpreted to be turbidites and debris flows that were fed by carbonates produced in the downslope mounds. These intervals form wedge-shaped units that onlap below the platform margin of Sequence 4 (Figs. 3, 4, 11). Their stratal position, geometry, clast content, and mineralogy are interpreted to indicate deposition as LST_5. Megabreccias can potentially form within any systems tract, but a recent review of their genesis implicates collapse due to relief of overpressure as fluids drain from discrete platform-margin horizons during sea-level lowstands (Spence and Tucker 1997). The stratigraphic position of the megabreccia-bounded unit at Ancient Wall and its relationship with carbonate-poor background sediments suggests that it was dominantly deposited during lowstand, which is consistent with the model of Spence and Tucker (1997). Oversteepening of the platform margin during aggradation, however, could also have initiated megabreccia deposition during late highstand.

The Mount Hawk Formation, above LST_5 at Miette, contains carbonate-poor background sediments interbedded with carbonate-rich, redeposited, chaotic conglomerates and graded packstones (Fig. 10). The upward decrease in carbonate content is similar to that seen in sequences 2, 3, and 4 (Fig. 10) and is here similarly interpreted to represent transgressive deposition (TST_5) and incipient drowning of the platform. In contrast to previous sequences, TOC content is relatively low except for a thin organic-rich interval in the upper Mount Hawk Formation that is interpreted as the maximum flooding surface (Fig. 10). These units onlap the margin and platform top of Sequence 4 and infill the platform-to-basin relief to a distance approximately 1 km seaward of the former platform margin of Miette (Fig. 3). Interbedded carbonate-rich, redeposited facies represent the distal toes of prograding HST_5 clinoforms (Arcs Member, Southesk Formation), which downlap along the maximum flooding surface (Figs. 3, 11). Along the southeast margin of Miette, the rest of HST_5 consists of sigmoid to sigmoid–oblique clinoforms (Arcs Member) that prograde approximately 5 km basinward from the former platform margin (Figs. 3, 11, 12). Downlapping clinoforms containing redeposited conglomerates sometimes served as nucleation sites for aggrading mudmounds that were able to keep up with relative sea-level rise (Fig. 3).

Atop the second megabreccia at Ancient Wall is a series of mud mounds containing laminar to tabular stromatoporoids, rugose corals, and abundant interskeletal algae and *Renalcis*. These mounds display a distinctive backstepping pattern (Mountjoy and Jull 1978) and commonly include bored and iron-stained omission surfaces and are interpreted to indicate deposition during transgression (TST_5; Fig. 11). It appears that the Arcs platform at

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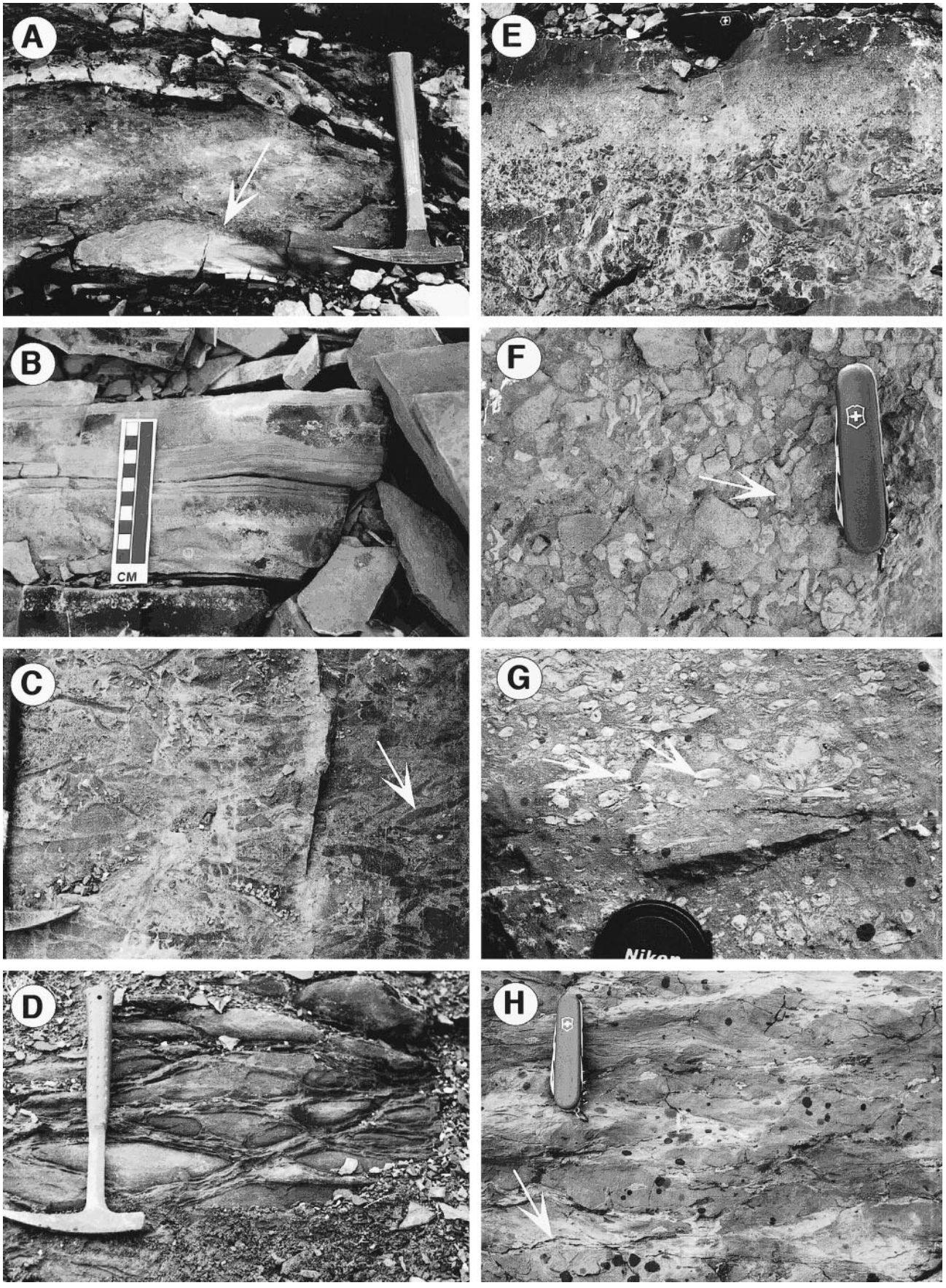
FIG. 7.—Stratigraphic, compositional, and mineralogic data from section K along the southeast margin of the Miette platform. Pie diagrams on left illustrate the percentage of redeposited and background sediments in sequences and systems tracts. The center column illustrates lithostratigraphy, sequence stratigraphy, and systems tracts. Abbreviations for average grain size at the base of the lithostratigraphic column stand for: C-S, silt–clay; Sd, sand, G-B, gravel–boulder. Circled letters indicate the stratigraphic position of photographs illustrated in Figure 8. The column on the right illustrates the percentage of total carbonate (gray shaded area), siliciclastics (white area), and total organic carbon (TOC; solid black area) through the stratigraphic section. Note the high TOC values associated with lowstand and transgressive intervals (Sequences 3 and 4) and increasing fine-grained siliciclastic influx in Sequence 5. Also note the occurrence of conglomerate-rich intervals in both lowstand and highstand deposits on either side of most sequence boundaries. See Figure 10 for keys to lithofacies and mineralogic curve. See text for further discussion of variations in carbonate content in different systems tracts.


A
B
CM
C
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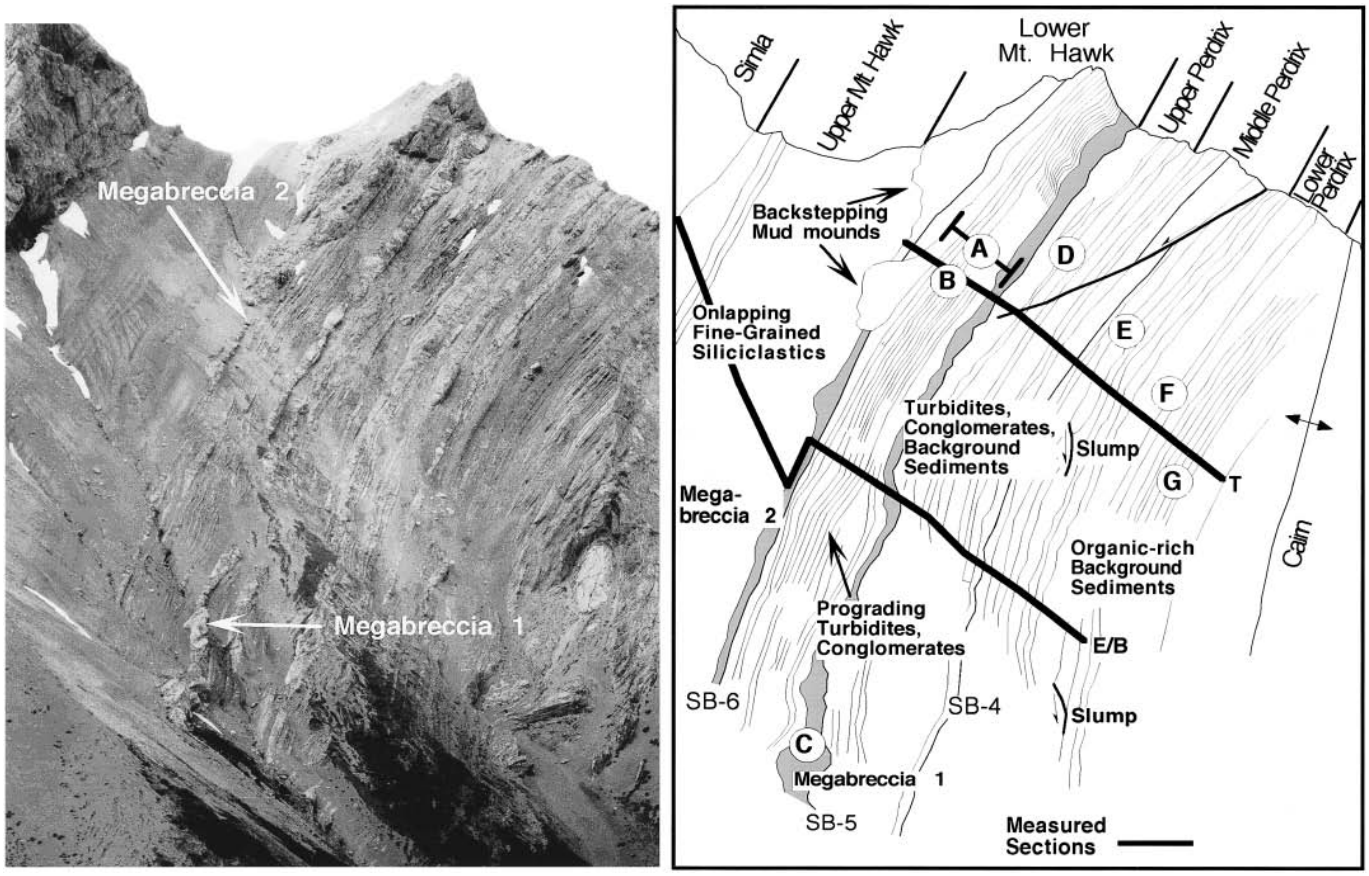

FIG. 9.—Outcrop photo and line-drawing interpretation of the slope and basin section along the southeast margin of the Ancient Wall platform (sections E/B and T). The line drawing illustrates the locations of measured sections, lithostratigraphic units, sequence boundaries, and photographs (circled letters) in Figure 11. Note the locations of slumps with intraformational truncation surfaces in the lower and middle Perdrix Formation and the two megabreccia units in the lower Mount Hawk Formation. Also note the backstepping mud mounds and onlapping siliciclastic-rich facies in the Mount Hawk Formation.

Ancient Wall remained subaerially exposed or only shallowly submerged until late transgression, when renewed carbonate production on the platform sourced a series of prograding deposits. Prograding facies ultimately filled residual accommodation space updip of the marginal mounds and were associated with aggradation on the Arcs platform top during deposition of HST_5 (Figs. 4, 11). The top of the Arcs Member at both Miette and Ancient Wall records subaerial exposure (Sequence 5; Whalen et al. 2000), which was also documented in other nearby coeval platforms (Fejer and Narbonne 1992; McLean and Mountjoy 1993).

Sequence 6 on the Miette and Ancient Wall platforms is represented by the Ronde and Simla Members of the Southesk Formation, respectively, whereas coeval strata of the uppermost Mount Hawk Formation comprise equivalent slope and basin facies. Facies of the Lower Ronde and Simla and uppermost Mount Hawk Formation include carbonate-poor argillaceous and silty facies. At Ancient Wall these facies are interbedded with distal carbonate conglomerates of the basal Simla Member deposited about 4.5 km basinward of the terminal platform margin of Sequence 5 (Fig. 4). At Miette, karst breccias within the basal Ronde Member occur atop downslope Arcs mounds. The siliciclastic content and karsting are interpreted as indicating deposition during LST_6. Subsequent flooding initiated the final stage of Frasnian platform progradation, which is most readily observed in the sigmoidal clinoforms of the Simla Member at Ancient Wall, during TST and HST_6 (Figs. 3, 4, 11).

MINERALOGIC AND COMPOSITIONAL VARIATIONS AND FACIES PARTITIONING WITHIN THE SEQUENCE STRATIGRAPHIC FRAMEWORK

The average carbonate content of platform interior facies is 87% at Ancient Wall and 95% at Miette (Whalen et al. 2000). Platform sequence-boundary intervals are indicated by lower than average total carbonate content associated either with soil development (1–3% carbonate) on subaerial exposure horizons or transgressive onlap of argillaceous facies (56–85%

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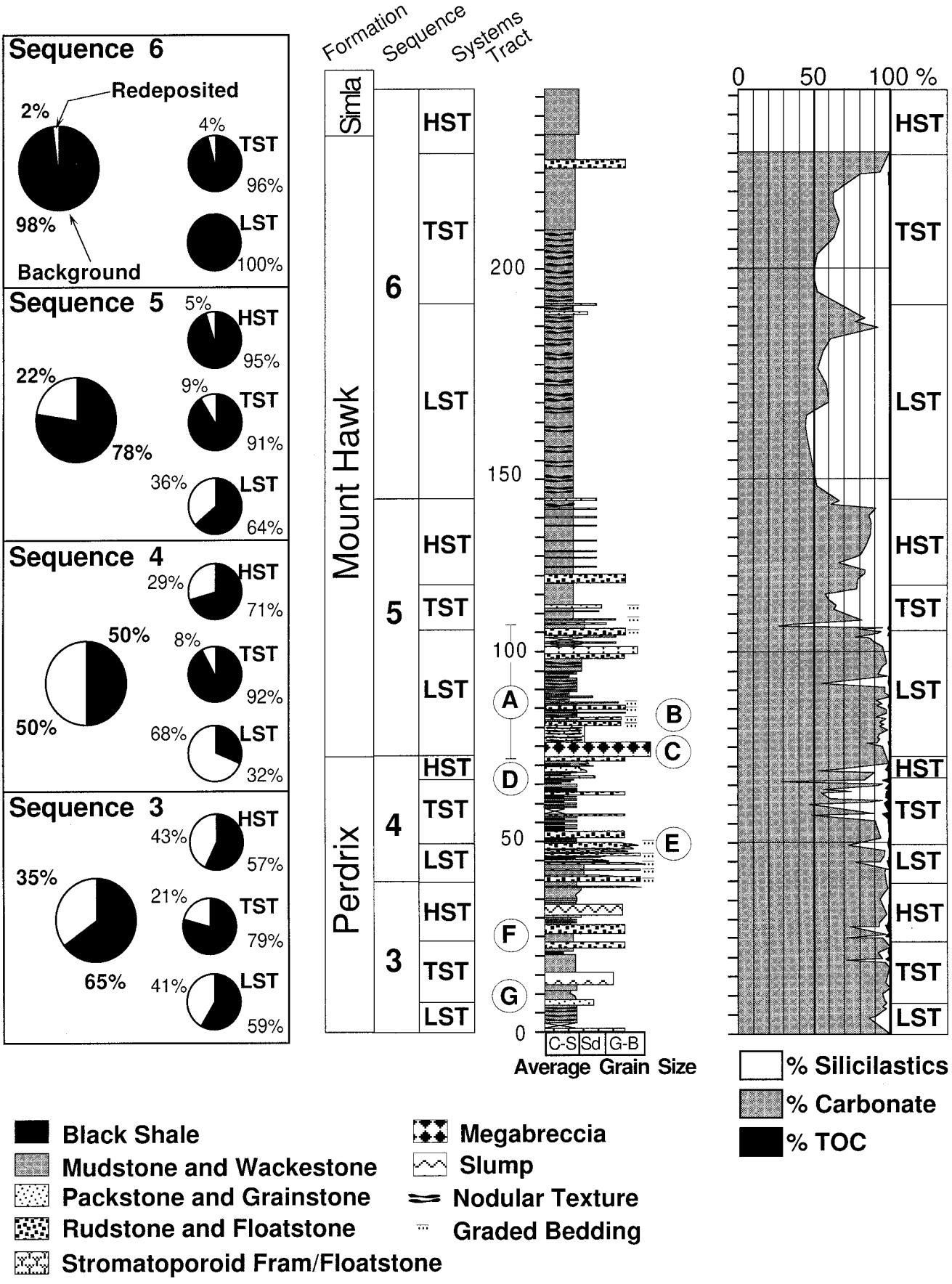
FIG. 8.—Photographs illustrating important slope and basin facies from the Miette platform. **A)** Soft-sediment fold in organic-rich facies of the lower Perdrix Formation (TST_3). Core of fold (arrow) directly overlies a detachment surface along which the fold moved downslope. **B)** Thin-bedded to laminated carbonate-rich mudstone–wackestone background facies of the middle Perdrix Formation (HST_3). **C)** Lithoclastic breccia with tabular (arrow) and angular dark-gray, slope-derived lithoclasts from the middle Perdrix Formation (HST_3). **D)** Sedimentary boudinage in organic-rich, carbonate-poor background facies of the upper Perdrix Formation (TST_4). **E)** Graded lithoclastic–bioclastic floatstone with subangular dark-gray, slope-derived lithoclasts and bioclasts from the upper Perdrix Formation (HST_4). **F)** Chaotic lithoclastic–bioclastic rudstone containing light gray, platform-derived lithoclasts and bioclasts in the lower Mount Hawk Formation (LST_5). Bioclasts include thamnoporid corals (arrow) and stromatoporoids. **G)** Carbonate-poor, argillaceous mudstone–wackestone with abundant burrows (arrows) from the upper Mount Hawk Formation (TST_5). **H)** Nodular, carbonate-rich, silty bioclastic wackestone from the upper Mount Hawk Formation (HST_5). Nodules are commonly bounded by wispy argillaceous laminae (arrow).


Sequence 6
Redeposited
2%
98%
Background
4%
TST
96%
LST
100%
Sequence 5
5%
HST
95%
22%
78%
9%
TST
91%
36%
LST
64%
Sequence 4
29%
HST
71%
50%
50%
8%
TST
92%
68%
LST
32%
Sequence 3
43%
HST
57%
35%
65%
21%
TST
79%
41%
LST
59%
Formation
Sequence
Systems Tract
Simla
Mount Hawk
Perdrix
6
5
4
3
HST
TST
LST
200
150
100
50
0
A
B
C
D
E
F
G
C-S
Sd
G-B
Average Grain Size
0
50
100 %
% Silicilastics
% Carbonate
% TOC
Black Shale
Mudstone and Wackestone
Packstone and Grainstone
Rudstone and Floatstone
Stromatoporoid Fram/Floatstone
Megabreccia
Slump
Nodular Texture
Graded Bedding

carbonate; Whalen et al. 2000). Because of subaerial exposure or very shallow peritidal conditions, lowstand systems tracts are either poorly developed or were not deposited on the platform top (Whalen et al. 2000). Transgressive and highstand systems on the platform are characterized by relatively pure carbonate facies except for early transgressive argillaceous units (Whalen et al. 2000).

In basinal successions, sedimentation was more continuous across sequence boundaries, but variations in organic content, the lithologic makeup of coarse-grained carbonate conglomerates, and changes in carbonate content appear to have sequence stratigraphic significance (Figs. 8, 10). The carbonate content of basinal facies generally ranges from 40 to 96% (Figs. 8, 10). Low carbonate contents in slope and basin facies are most common during lowstand and early transgression, when subaerial exposure or shallow peritidal conditions permitted only minimal carbonate production (Figs. 8, 10). Carbonate-rich LST facies (e.g., LST_4 and LST_5 at Ancient Wall; Fig. 8) appear to indicate abundant transport of platform-derived redeposited carbonates. Offbank transport of voluminous carbonate sediment is most likely when the platforms are flooded and there is highstand shedding from a robust carbonate factory (Schlager et al. 1994). Data from this study confirm this notion, with slope and basin HSTs generally displaying the highest average carbonate content (Figs. 8, 10). However, the upper parts of TSTs are also commonly carbonate rich, indicating that high rates of carbonate production and shedding began during late transgression (Figs. 8, 10).

Significant accumulation of organic matter, of predominantly marine origin (Chow et al. 1995), was observed in the lowstand and transgressive systems tracts of Sequences 3 and 4 (van Buchem et al. 1996). Inverse linear trends on carbonate–TOC crossplots imply that background organic matter and clay were episodically diluted by abundant carbonate input (van Buchem et al. 1996). This is consistent with the interpretation that the highest TOC values in basinal facies (e.g., LST/TST_3 and LST/TST_4; Figs. 8, 10) are related to times of platform exposure or shallow flooding and little offbank transport of fine-grained carbonate (van Buchem et al. 1996).

The lithologic makeup of coarse-grained carbonate conglomerates records variations that have sequence stratigraphic significance. Outcrop clast counts and thin-section point counts were used to differentiate the relative input of platform-derived and slope-derived material. Although many clasts and fossil types provide definitive source information not all skeletal and nonskeletal grains counted could unequivocally be identified as platform-derived or slope-derived. Therefore, total percentages of platform-derived and slope-derived elements from clast and point-count data (Fig. 13 and below) may not add up to 100%.

Outcrop clast counts in coarse-grained slope facies reveal deviations in clast content that vary depending on systems tract (Fig. 13). Although clast counts do not provide definitive criteria for systems-tract identification, they provide information pertinent to interpreting depositional processes in slope environments. Outcrop clast counts from facies on the distal slope (Fig. 13A) reveal some overlap between samples interpreted to be lowstand and highstand facies. Generally, lowstand conglomerates contain between 45 and 65% platform-derived clasts, presumably eroded from the platform top or margin, and between 35 and 55% slope-derived clasts. Highstand facies vary more broadly in clast composition, but most samples fall within a relatively tight cluster of points (Fig. 13) with platform-clast content between 0 and 22% and slope-clast content between 30 and 100%. The dichotomy in clast content between highstand and lowstand facies appears to diminish with proximity to the platform. Thin-section point counts that included clasts, cement, and carbonate mud from the proximal slope and forereef document an even wider range of variation in clast content (Fig. 13B). In all cases, facies contain less than 25% slope clasts because of the proximity of these samples to the platform margin.

Pie diagrams depicting the percentage of redeposited and background sediments within the sequence stratigraphic framework (Figs. 8, 10) and the percent stratigraphic thickness of different systems tracts (Fig. 14) reveal consistent patterns governed by variation of the dominant depositional processes. During deposition of the aggrading ramp and the first prograding platform phase (Sequences 1 and 2), transgressive and highstand systems dominate and lowstand sedimentation is nonexistent or negligible (Fig. 14). In general, transgressive and highstand systems are dominated by background deposition. As platform aggradation ensued (Sequences 3 and 4), the percentage of lowstand sediments steadily increased (Fig. 14) and the percentage of redeposited carbonates was predictably high because of self-erosion and bypassing of platform sediments (Figs. 8, 10).

The process of slope readjustment tends to decrease oversteepened slope gradients until a new equilibrium profile is attained (Dailly 1983; Ross et al. 1994). Deposition of both background and redeposited sediments contributed to the slope readjustment process. Establishment of a new equilibrium profile and renewal of platform progradation appears to coincide with the progressive increase in the amount of fine-grained siliciclastic sediment that is mixed with platform-derived carbonate sediment (Figs. 8, 10, 11). This increase is documented in the broad carbonate minima and siliciclastic maxima during deposition of Sequence 5 at Miette and Sequence 6 at Ancient Wall (Figs. 8, 10). The differential timing of siliciclastic influx suggests a progressive east-to-west infilling of the Alberta basin as previously documented in the subsurface of central Alberta (Oliver and Cowper 1963; Stoakes 1980).

BYPASS-MARGIN RELIEF AND SLOPE GRADIENT

Measurements of platform-margin relief and slope gradient were calculated for Miette and Ancient Wall by comparing the thickness of sequences in platform-interior sections with those from slope sections located approximately three kilometers from the platform margin (Table 2). Stratigraphic sections used for these calculations were separated by 2.8 km at Ancient Wall and 3.6 km at Miette. Stratigraphic data were projected to a point 3.0 km basinward of the platform interior sections, and this distance was used in calculations for both platforms to permit direct comparisons. The slope gradient was calculated by using the inverse tangent of the acute angle of a right-angle triangle with the hypotenuse representing the slope, the vertical leg representing the maximum relief, and the horizontal leg representing the distance between platform and slope sections. The horizontal leg is a projection of a platform sequence boundary, and the vertical leg terminates at the equivalent sequence boundary on the slope. These calculations are meant to approximate the relief and gradient between the platform top and the proximal slope. Because slope packages thin basinward, the total relief would increase while the declivity would decrease away from the platform margin. Sources of error for these types of cal-

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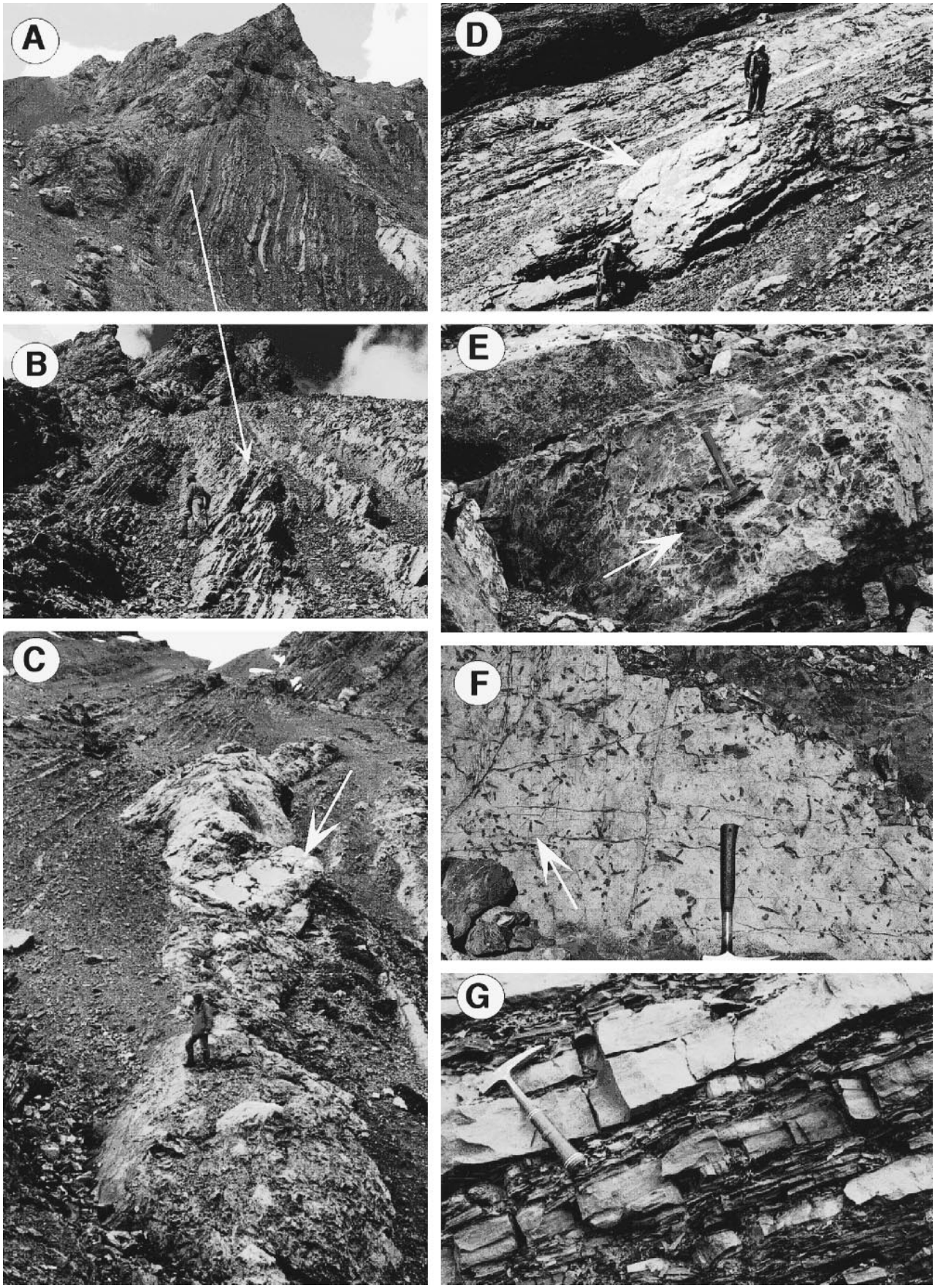
FIG. 10.—Stratigraphic and mineralogic data from section E/B along the southeast margin of the Ancient Wall platform. Pie diagrams on the left illustrate the percentage of redeposited and background sediments in sequences and systems tracts. The center column illustrates lithostratigraphy, sequence stratigraphy, and systems tracts. Abbreviations for average grain size at base of lithostratigraphic column stand for: C-S, silt–clay; Sd, sand; G-B, gravel–boulder. Circled letters indicate the stratigraphic position of photographs illustrated in Figure 11. The column on the right illustrates the percentage of total carbonate, siliciclastics, and total organic carbon (TOC) through the stratigraphic section. Note the high TOC values associated with lowstand and transgressive intervals (Sequences 3 and 4) and the decrease in carbonate content, signaling increasing fine-grained siliciclastic deposition, in Sequence 5. Also note the occurrence of conglomerate-rich intervals in both lowstand and highstand deposits. See text for further discussion of variations in carbonate content in different systems tracts.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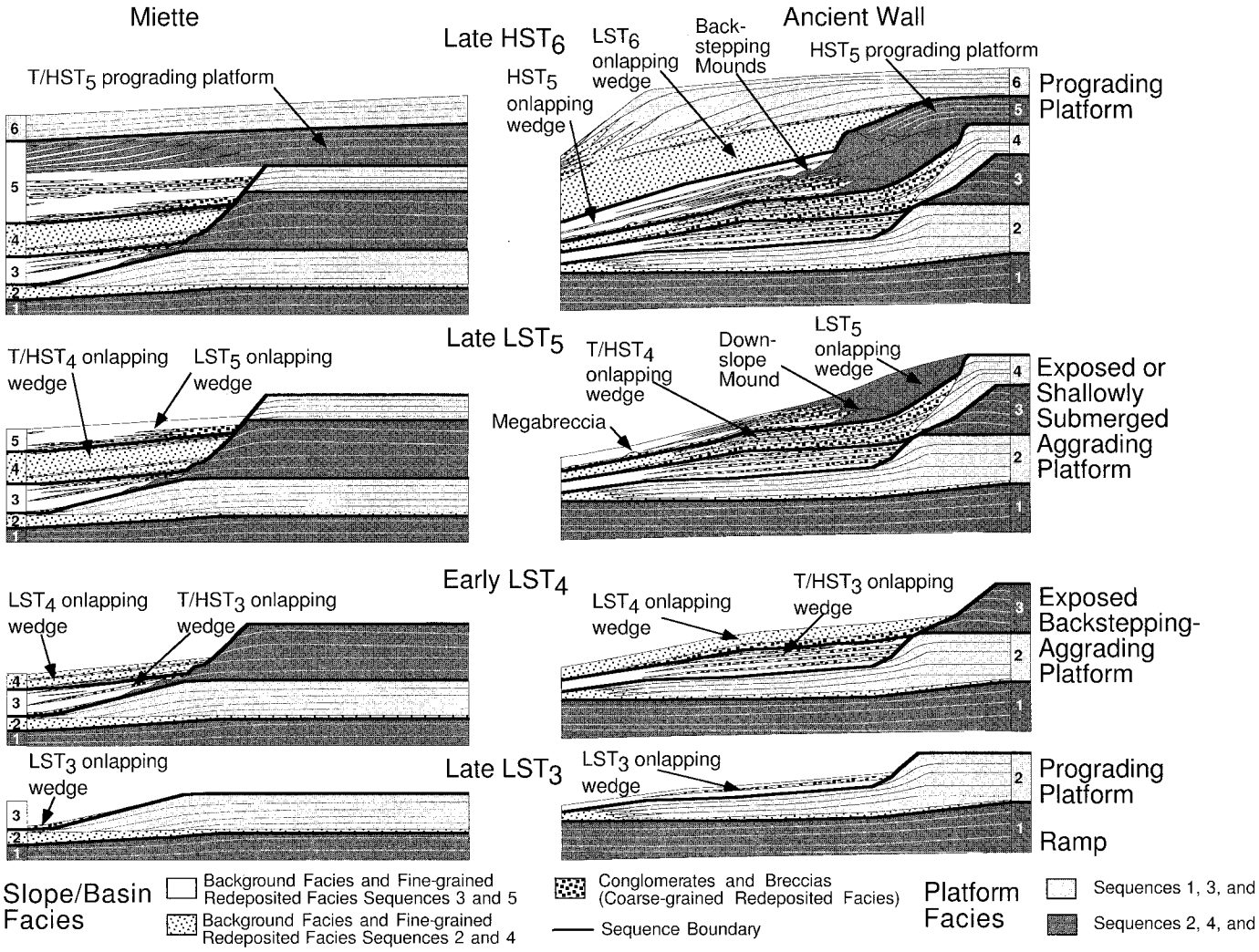

FIG. 12.—Sequential sequence stratigraphic diagrams illustrating the development of the southeast margins of the Miette and Ancient Wall platforms. The diagram illustrates the four major phases of platform development and their associated basinal facies. Platform progradation and backstepping during sequences 2 and 3 resulted in isolated platform development. The first coarse-grained redeposited carbonates were deposited during LST_3. Onlapping, basin-restricted wedges developed during deposition of sequences 3, 4, and 5. Note the thick onlapping wedge with downslope mud mounds deposited as LST_5 at Ancient Wall. The major stage of basin filling at Miette occurred during LST_5 and TST_5, followed by sigmoid oblique platform progradation (HST_5). Basin filling at Ancient Wall is during LST_6 and TST_6, followed by sigmoid oblique platform progradation (HST_6).

culations, including postdepositional compaction and horizontality of the datum used for determining vertical changes in stratigraphic thickness, were noted by Bachtel and Dorobek (1998). We have assumed that sequence boundaries in the platform interior represent a horizontal datum, but this could also be a source of error if the platform top was inclined. Postdepositional compaction was probably a factor only for fine-grained slope facies, because platform facies and many coarse-grained slope facies underwent early cementation and probably compacted little (Mountjoy and Riding 1981; Melim et al. 2000; Whalen et al. 2000). The wide range of lithologies in slope sections complicates accurate assessment of decompaction, and calculations without decompaction thus represent a maximum estimate of relief and average slope gradient. Although these calculations provide estimates of the average slope gradient, they do not permit an estimate of the declivity of the actual bypass margins. In most situations lack of exposure of this critical interface prevented direct outcrop measurements. At Ancient Wall, however, outcrop exposures of the platform

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FIG. 11.—Photographs illustrating important slope and basin facies from the Ancient Wall platform. **A)** Lowstand prograding wedge deposited between two megabreccias (LST_5). **B)** Close-up of coarsening-upward packages of turbidites and debris flows of LST_5. **C)** Large platform-derived clasts in Megabreccia 1. Person is standing on a clast measuring approximately 25 m in diameter. Also note the light-gray angular block (arrow) farther upslope. **D)** Two-meter-diameter platform-derived clast (arrow) in a middle Perdrix Formation debris flow (LST_4). **E)** Lithoclastic–bioclastic rudstone in the upper Perdrix Formation (HST_4). Dark-colored, subangular to rounded slope-derived lithoclasts (arrow) are the dominant clast type. **F)** Iron-stained and *Trypinites* (arrow) bored hardground developed atop a lithoclastic-bioclastic rudstone in the lower Perdrix Formation (TST_3). **G)** Background sediments including laminated calcareous shale, argillaceous mudstone–wackestone, and crinoid wackestone–packstone in the lower Perdrix Formation (LST_3).

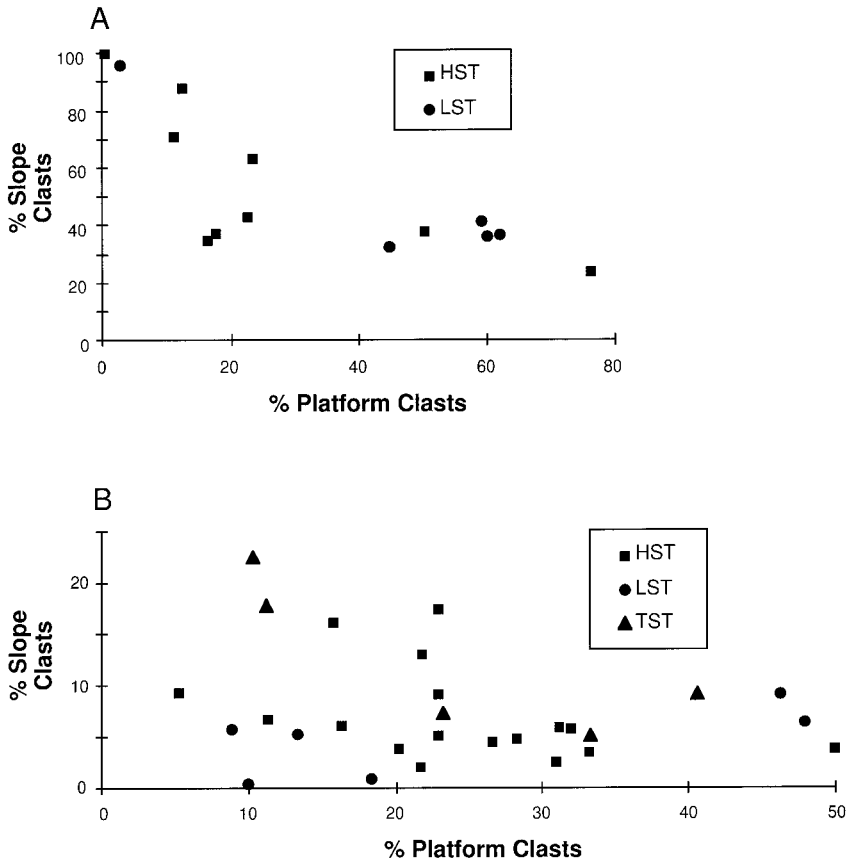

FIG. 13.—Percentage of slope-derived and platform-derived clasts plotted by systems tract. Only those clasts definitively linked to platform or slope environments were included in these plots. A) Outcrop clast counts of slope-derived and platform-derived clasts in coarse-grained redeposited carbonates from the distal slope of the southeast margin of the Miette platform (sections K, S, and L). Note the relatively tight cluster of HST facies with a high percentage of slope-derived clasts and low percentage of platform-derived clasts. Also note that most LST facies have a relatively high percentage of platform-derived clasts and a low percentage of slope-derived clasts. B) Point counts of slope-derived and platform-derived clasts in thin sections from the proximal slope and forereef of the southeast margin of the Miette platform (section H and H′). Note the generally low percentages of slope-derived clasts and the lack of correlation between systems tracts and clast content due to the proximal slope setting.

margin of Sequences 2, 3, and 4 provide estimates of the bypass margin gradient, which increases from less than 5° to approximately 15° in this interval (Fig. 15).

Platform-to-basin relief and slope gradient increased from Sequence 1 to 3 in both platforms (Table 2; Figs. 11, 15), with Ancient Wall attaining higher values. Relief and gradient continued to increase during deposition of Sequence 4 at Ancient Wall, but Miette saw a slight decrease in total relief and gradient over that developed during Sequence 3. This appears to signal the onset of basin filling in the eastern part of the basin. During deposition of Sequence 5, the variations in platform-margin relief and slope gradient between the two platforms became tangible (Table 2; Fig. 11). Ancient Wall maintained a similar platform-to-basin gradient during Sequences 4 and 5, whereas Miette displays a drastic decrease in relief and slope gradient by the end of Sequence 5. At the end of deposition of Sequence 6, the slope gradient at Miette was negligible, while at Ancient Wall the slope maintained a considerable gradient (Table 2).

BACKSTRIPPING AND SUBSIDENCE HISTORY

The Miette and Ancient Wall platforms developed along a subsiding continental margin with greater rates of differential subsidence to the west (McLean and Mountjoy 1993). Backstripping analyses were performed on platform-interior strata to quantify variations in tectonic subsidence (Fig. 16). Backstripping permits estimates of tectonically driven subsidence by calculating and subtracting the isostatic subsidence of the basement resulting from sediment loading (Steckler and Watts 1978; Bond and Kominz 1984). Backstripping was calculated using the six depositional sequences as sedimentary units. The temporal duration of each sequence was estimated on the basis of conodont biostratigraphic data (McLean and Klapper 1998; Whalen et al. 2000). Maximum and minimum amounts of basement subsidence, indicated by error bars (Fig. 16), were calculated using values of delithification based on burial and compaction of carbonate lithologies that were either uncemented or underwent early cementation, respectively (Bond and Kominz 1984). Calculation of backstripped basement subsidence was performed without correction for the weight of overlying water because carbonate-platform interiors were probably never submerged more than about 20 m.

Backstripping supports and quantifies the east-to-west increase in tectonic subsidence along the Devonian continental margin. Initial rates of tectonic subsidence were considerably higher at Ancient Wall than at Miette (Fig. 16). During deposition of Sequences 1 and 2, Ancient Wall displays approximately double the rate of subsidence of the Miette platform (Fig. 16). Subsidence nearly equilibrated during deposition of Sequences 3 and 4, as demonstrated by the nearly parallel basement subsidence curves (Fig. 16). During deposition of Sequence 5, however, Miette apparently experienced slightly greater subsidence than Ancient Wall, while Sequence 6 records a return to similar rates of subsidence.

DISCUSSION

Basin-Restricted Wedges, Highstand Shedding, and Slope Readjustment

In traditional sequence stratigraphic models, basin-restricted wedges are interpreted to be the result of lowstand sediments bypassing exposed continental shelves (Posamentier and Vail 1988; Van Wagoner et al. 1988). Bypassing of sediment along carbonate platform margins can occur whenever the slope gradient exceeds the angle of repose, regardless of sea level. Bypass margins and escarpments of carbonate platforms separate platform and basin sedimentation, resulting in detached sequences (Fig. 11). Sequence stratigraphic interpretations of detached sequences, consisting of aggrading or backstepping platform units and onlapping basinal wedges, are problematic, but our detailed analyses of variations in sediment com-

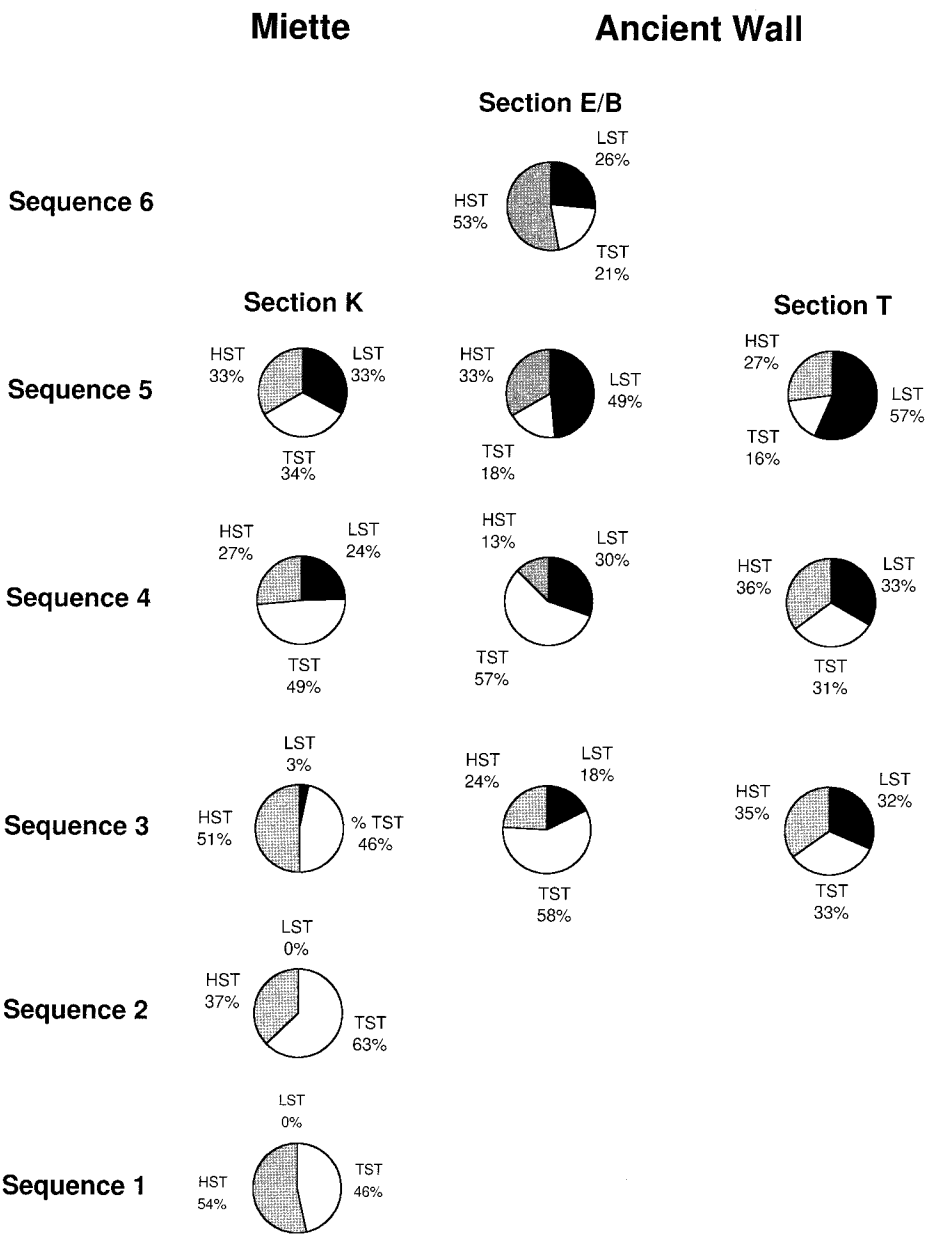

FIG. 14.—Pie diagrams depicting the percent stratigraphic thickness represented by different systems tracts along the southeast margins of the Miette (section K) and Ancient Wall (sections E, B, and T) platforms. Note that LSTs are nonexistent in sequences 1 and 2 and progressively increase in percent stratigraphic thickness from sequences 3 to 5.

position and carbonate content of the onlapping wedges were instrumental in differentiating the systems tracts (Figs. 8, 10, 13). Conglomerates in the lower parts of coarse-grained packages on the distal slope contain abundant slope-derived lithoclasts and faunal elements (Fig. 13A) within carbonate-rich background deposits (Fig. 8). The upper parts of these conglomerate packages contain more platform-derived lithoclasts and faunal elements (Fig. 13A) and carbonate-poor intercalated sediments (Figs. 8, 10). These lithologic and mineralogic trends are interpreted to reflect variations in platform sediment production and delivery to slope and basinal settings related to relative sea-level change.

Highstand shedding is a well documented depositional process in Quaternary carbonate platforms and is interpreted to have operated in the geologic past, although the process is most pronounced on rimmed platforms (Everts 1991; Reijmer et al. 1992; Schlager et al. 1994; Vecsei and Sanders 1997). The major controls on highstand shedding appear to be related to the areal increase in the carbonate factory during highstand and the rapid lithification of highstand carbonate platform sediments due to lowering of wave base or exposure to fresh water during lowstands (Schlager et al. 1994). Our analyses demonstrate that slope-derived clasts and fauna and carbonate-rich, hemipelagic deposits represent slope erosion due to oversteepening and abundant shedding of fine-grained, platform-derived material during highstands (Figs. 8, 10, 13). Platform-derived clasts and fauna indicate platform erosion, and carbonate-poor, hemipelagic deposits imply reduced shedding of fine-grained carbonate material during platform exposure and a resultant relative enrichment in fine-grained siliciclastic and organic sediment during sea-level lowstand (Figs. 8, 10, 13). Transgressive facies are generally found to be carbonate-poor but locally increase in carbonate content during late transgression, indicating renewed platform carbonate production (Figs. 8, 10).

Grain-composition logs were recently used as a correlation tool along the margin of the Vercors platform in southeastern France (Everts et al. 1999). Slope facies of the unrimmed Vercors platform record an increase in open-sea biota interpreted to indicate initial platform flooding whereas a high proportion of platform-derived clasts indicated highstand sedimen-

TABLE 2.—*Platform-to-basin relief and slope gradient of the Miette and Ancient Wall platforms*

Miette

Sequence	Platform Sequence Thickness	Cumulative Platform Sequence Thickness	Cumulative Slope Sequence Thickness	Max. Relief	Max. Gradient
6	56.5	429	~415	~14	0.27°
5	81.2	372.5	~355.5	~17	0.32°
4	55.6	291.3	177.8	113.5	2.2°
3	100.1	235.7	118.5	117.2	2.2°
2	80.2	135.6	56.6	79.0	1.5°
1	55	55.4	28	27.4	0.52°

Ancient Wall

Sequence	Platform Sequence Thickness	Cumulative Platform Sequence Thickness	Cumulative Slope Sequence Thickness	Max. Relief	Max. Gradient
6	57	495	445.8	49.2	0.94°
5	63	438	255.7	182.3	3.5°
4	58	370	187.3	182.7	3.5°
3	100.7	312	154.5	157.5	3.0°
2	105.6	211.3	~115	~96	1.8°
1	105.7	105.7	~69	~37	0.71°

See text for details on calculation of maximum relief and slope gradient.

tation (Everts et al. 1999). Our observations denote a higher proportion of slope-derived fauna (comparable to the open-sea biota of Everts et al. 1999) during highstand and more platform-derived fauna during lowstand. The different response of these Devonian platforms in comparison to the Vercors is probably related to bypass-margin development and sequestering of platform fauna and clasts behind the platform margin during highstand. Our mineralogic data, especially from fine-grained, hemipelagic facies, supports the notion that production and delivery of fine-grained carbonate sediment to the slope is most pronounced during sea-level highstand.

Patterns of slope development similar to those documented above have been observed in both carbonate and siliciclastic systems (Ross et al. 1994; Bachtel and Dorobek 1998). Carbonate sediments can maintain much steeper slopes than siliciclastics and are therefore more prone to self-erosion (Schlager and Camber 1986). The slope-readjustment model of Ross et al. (1994) implies that progressive steepening of the platform-to-basin gradient initiates a slope grading process that eventually reestablishes an equilibrium profile. Sediment fabric is a major control on carbonate slope angle (Kenter 1990), and the style of platform-margin development influences the character of platform-derived slope sediments (Read 1985). The sediment fabric and thus the dominant depositional processes at Miette and Ancient Wall co-varied with changes in style of platform development. As the average slope gradient steepened from less than 1° to about 3°, a greater proportion of the basinal stratigraphic succession comprises redeposited carbonates (Table 2; Figs. 8, 10, 11). Both slope erosion and bypassing result in deposition of onlapping basinal wedges, which must reestablish a low-gradient profile before progradation can resume (Eberli and Ginsburg 1989; Ross et al. 1994). Steepening of slope profiles can result from rapid relative sea-level rise, tectonics, or alternation of carbonate and siliciclastic systems with carbonate margins maintaining a much steeper profile (Ross et al. 1994). We have demonstrated that carbonate-platform aggradation, margin backstepping, and self erosion resulting in gravity flows were the main controls on slope steepening and that these mechanisms are most likely related to rapid pulses of relative sea-level rise. Lowstand deposition became more important in the slope-grading process with increasing slope gradient (Sequences 3 and 4) and the onset of regressive platform progradation (Sequences 5 and 6; Fig 14). During the transgressive phase of platform progradation, when the slope gradient was relatively low, there was little or no gravity-flow deposition or self-erosion, but as slope declivity increases, both processes become increasingly important (Table 2; Figs. 11, 15).

Subsidence and Sequence Development

Variations in sequence thickness, slope gradient, and platform-to-basin relief are readily explained by differential subsidence between the two platforms (Table 2; Figs. 11, 16). Significant overlap in estimates of maximum and minimum amounts of basement subsidence (Fig. 16) may imply that there is little variation between the two platforms after deposition of Sequence 3. Variations in platform-interior sequence thickness (Table 2), however, could indicate that a change in the subsidence regime occurred sometime during deposition of Sequence 3. Sequence thicknesses and rates of subsidence were initially greater at Ancient Wall (Sequences 1 and 2). As relative rates of subsidence reversed, sequence thicknesses first equilibrated (Sequences 3 and 4) and then switched between the two platforms (Sequence 5; Fig. 16; Table 2). While Miette was experiencing increased siliciclastic influx and reduction of slope gradient (Sequence 5) the gradient at Ancient Wall remained high because of lower rates of siliciclastic input (Table 2; Figs. 8, 10, 11). The higher gradient maintained at Ancient Wall comes as no surprise, given the ability of carbonate platforms to keep up with accommodation created by differential subsidence. During deposition of Sequence 6, a significant reduction in slope gradient at Ancient Wall was facilitated by increased siliciclastic influx (Table 2; Figs. 8, 11). Variations in platform-margin gradient and rates of basinal sedimentation were the ultimate control on successive slope sequence geometries. Similar patterns of slope development were noted along the margins of a Mississippian carbonate ramp in south-central New Mexico, where steeper depositional profiles were progressively diminished by onlapping basinal wedges prior to platform progradation (Bachtel and Dorobek 1998). The deposition of basin-restricted wedges and the process of slope readjustment (Daily 1983; Ross et al. 1994) are integral to understanding slope development along the Miette and Ancient Wall platform margins.

CONCLUSIONS

The main controls on slope and basin sedimentation at Miette and Ancient Wall include variations in platform-margin development ultimately controlled by relative sea-level change. The successive stages of platform development and variations between Miette and Ancient Wall were dictated by accommodation created partly by subsidence that generally increased towards the west. Overall, Ancient Wall experienced greater differential subsidence but was able to keep up with the rise in relative sea level.

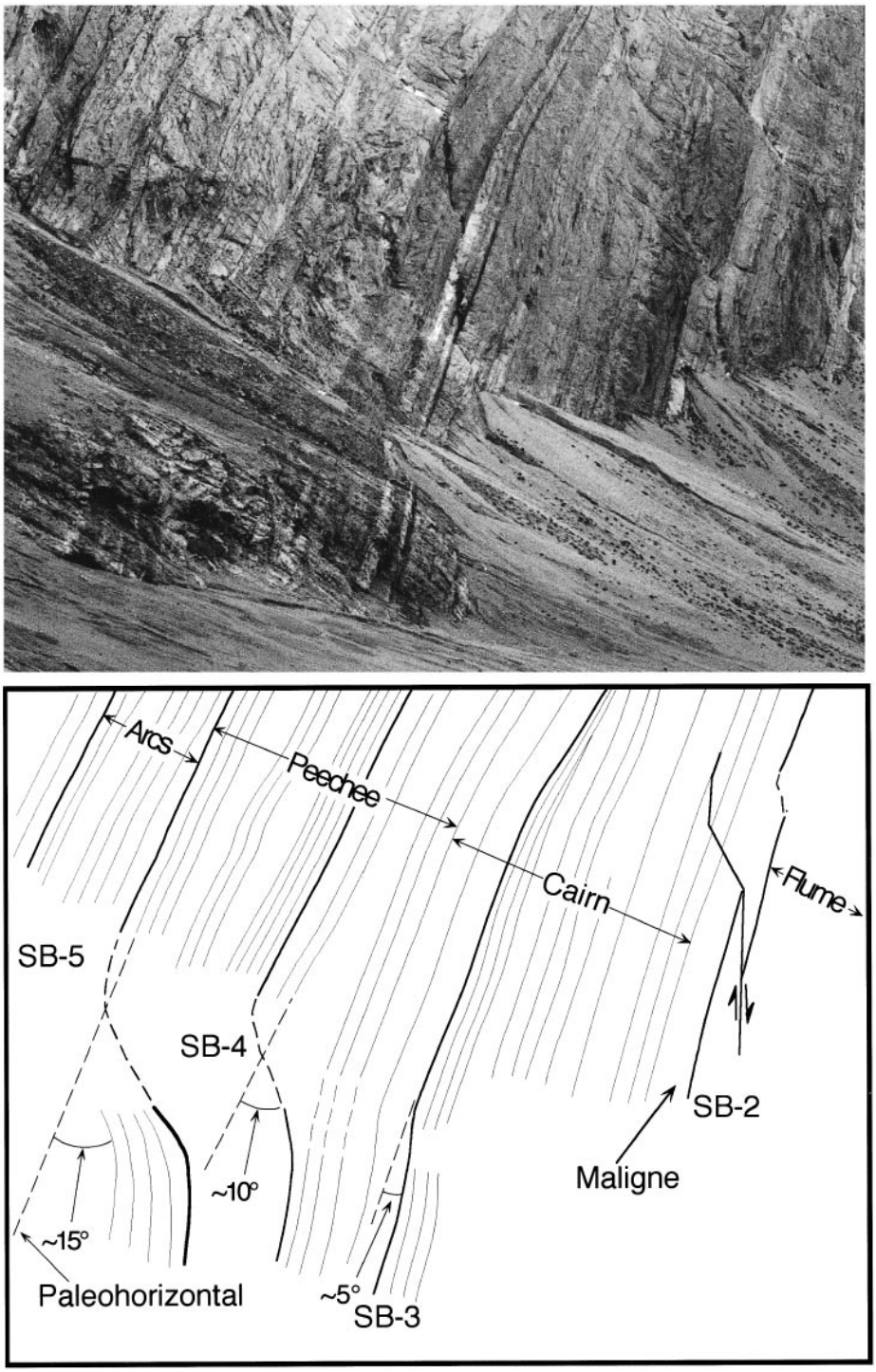

FIG. 15.—Determination of paleoslope gradient from outcrop measurement of onlap angle of Perdrix Formation facies along the southeast margin of the Ancient Wall platform, Haultain Cirque. Note the progressive increase in slope gradient from Sequence 2 through Sequence 4.

Variations in the subsidence regime between Miette and Ancient Wall might be related either to tectonism or to patterns of sediment loading, but further data from other nearby platforms is needed to evaluate the ultimate control. Increasing rates of second-order sea-level rise (Fig. 5) facilitated the transgressive transition from a regionally extensive ramp, to low-angle prograding platforms, to backstepping and aggrading platforms (Figs. 3, 4, 11). Platform backstepping and aggradation resulted in relatively steep-sided platforms, sediment bypassing, and self-erosion due to oversteepening. The increasing platform-to-basin gradient facilitated a process of slope readjustment which included the deposition of background sediments and redeposited carbonates in a series of basin-restricted wedges that onlapped the bypass margin. Infilling of antecedent topography by basin-restricted wedges eventually permitted regressive platform progradation during the latest Frasnian.

In traditional siliciclastic sequence stratigraphy basin-restricted wedges are interpreted as lowstand deposits on the basis of their geometry and position relative to an updip margin (Posamentier and Vail 1988; Van Wagoner et al. 1988). Wedge-shaped basinal units along the Miette and Ancient

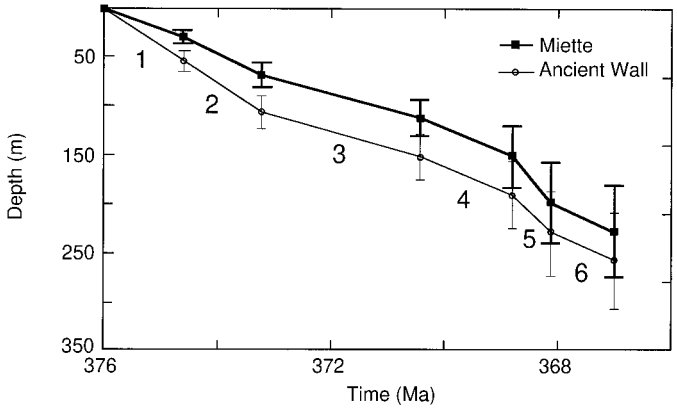

FIG. 16.—Basement subsidence beneath the Miette and Ancient Wall platforms based on backstripping analysis of platform interior sections (BB at Miette, F/P at Ancient Wall, Figs. 3 and 4). Error bars indicate the variations in subsidence based on estimates of minimum delithification if facies underwent early cementation and little compaction and maximum delithification for facies that remained uncemented prior to compaction. Note the overall greater differential subsidence experienced by the Ancient Wall platform, which exerts a major control on platform aggradation and slope gradient. Also note that the rate of subsidence was greater at Ancient Wall during deposition of Sequences 1 and 2, was similar to the rate of subsidence at Miette during deposition of Sequences 3, 4 and 6, but experienced a slightly lower rate of subsidence than Miette during deposition of Sequence 5.

Wall bypass margins contain conglomerate packages of highstand and lowstand origin that straddle the sequence boundary. The clast composition of redeposited carbonates and the carbonate content of background sediments provides criteria to identify sequence boundaries in slope and basin sequences that are detached from correlative platform sequences. Highstand facies consist of carbonate-rich background sediments and conglomerates with abundant slope-derived clasts. Lowstand facies consist of carbonate-poor background sediments and conglomerates with abundant platform-derived material. These patterns are not unequivocal, as demonstrated by the clast content of highstand and lowstand facies proximal to the platform margin (Fig. 13B) and the development of a downslope lowstand carbonate factory that produced carbonate-rich background sediments during LST_5 at Ancient Wall (Figs. 8, 10, 11). However, interpreting basin-restricted wedges in carbonate systems as purely highstand or lowstand deposits may lead to erroneous conclusions regarding sequence stratigraphy and the volumetric partitioning of sediments during the deposition of different systems tracts.

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