STACKED LATE DEVONIAN LOWSTAND SHORELINES AND THEIR RELATION TO TECTONIC SUBSIDENCE AT THE CORDILLERAN HINGELINE, WESTERN UTAH

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ABSTRACT: **The Upper Devonian (lower Famennian) Cove Fort Quartzite and associated strata of western Utah comprise three stratigraphic sequences, each containing a thick (as much as 65 m) lowstand systems tract. Coarse-grained shoreface quartz arenite and lagoonal dolomicrite of the lowstand systems tracts display the following features characteristic of forced regression: (1) they contain coarse-grained proximal shoreline deposits that overlie an erosional surface (sequence-bounding unconformity) cut into fine-grained distal-marine carbonate facies; (2) they lie seaward of a zone of sediment bypass, and are spatially detached and separated from the previous highstand shoreface; (3) they are confined geographically to a relatively narrow zone less than 30 km wide; (4) they are onlapped and overlain by transgressive systems tract deposits consisting of deep subtidal carbonates (West Range Limestone); and (5) landward of the lowstand shoreline pinch-out, the sequence-bounding unconformity beneath them merges with a transgressive surface of erosion above them.**

A thick wedge of siliciclastic forced-regression deposits is present at the base of each depositional sequence. The stratigraphic position of each wedge above the basal sequence boundary was controlled by eustatic sea-level fall. The forced-regression deposits are geographically restricted to a narrow strike belt along the eastern margin of the Pilot basin, which coincides with the trace of the Cordilleran Hingeline, a zone of crustal discontinuity. The geographic confinement and unusual stratal thickness of barrier-bar complexes in the lowstand systems tract, as well as the stratigraphic stacking of the forced-regression deposits, were controlled by flexurally induced high subsidence rates focused at the Cordilleran Hingeline.

INTRODUCTION

The Upper Devonian Cove Fort Quartzite of western Utah locally comprises a succession of exceptionally thick (as much as 65 m) shoreface sandstone bodies encased in deep subtidal carbonate facies and apparently detached from a time-equivalent coastal plain. The sandstone bodies are vertically stacked in a narrow belt of thick sand-rich facies deposited along the eastern margin of the Pilot basin (Fig. 1). The eastern margin of the Pilot basin coincides with the western side of the Cordilleran Hingeline. The Cordilleran Hingeline is an axis of persistent eastward stratigraphic thinning that trends north–northeast through west-central Utah and corresponds to a crustal discontinuity associated with the Late Precambrian rift margin (Kay 1951; Stokes 1976; Picha and Gibson 1985)

In this paper we apply sequence stratigraphy to the Cove Fort Quartzite and associated formations in order to provide a basis of correlation between seemingly disparate lithologic successions exposed in Basin and Range uplifts that are loosely correlated on the basis of biostratigraphy. We also propose a tectonic mechanism to explain the presence of stacked barrier-bar complexes in the lowstand systems tract, and their consequent exceptional thickness and narrow distribution within the Cordillera.

Shoreline-detached shelf sand bodies are important hydrocarbon reservoir targets housing million-barrel oil fields. Outcrop analog studies such as this provide keys to the depositional character of these facies and thus provide a predictive guide to porosity and permeability trends. Conclusions from our study may offer insight into exploration and exploitation of this type of deposit found along the margins of other tectonically active basins.

Geologic Setting of the Upper Devonian Strata in Western Utah

Upper Devonian strata of western Utah are exposed in north–south-trending mountain ranges of the Basin and Range Province (Fig. 1). Upper Devonian formations of interest in this study include the Cove Fort Quartzite, Pinyon Peak Limestone, West Range Limestone, and Pilot Shale (Fig. 2). Conodont and brachiopod biostratigraphy indicates a latest Frasnian to early Famennian age for the limestone units (Kellogg 1963; Johnson et al. 1969; Sandberg and Poole 1977; Bocko 1997) and provides the basis for general correlation across the study area. These strata were deposited along the southeastern margin of the Upper Devonian Pilot basin, which was spatially and temporally associated with Antler orogenesis in central Nevada (Johnson 1971; Poole 1974; Gutschick and Rodriguez 1979; Sandberg et al. 1989; Giles 1994).

The Antler orogeny began in Late Devonian time and continued through mid-Mississippian time (Smith and Ketner 1968; Johnson and Pendergast 1981; Speed and Sleep 1982). The exact tectonic setting of the Antler orogeny is poorly understood but is generally interpreted as a collision of the former North American passive margin with an arc system (Moores 1970; Johnson 1971; Speed and Sleep 1982; Burchfiel and Royden 1991). Contraction along the margin generated a stack of east-vergent thrust sheets collectively termed the Roberts Mountains allochthon (Poole 1974). Under the structural load of the Roberts Mountains allochthon, the lithosphere east of the Antler orogenic belt and west of the cratonic platform formed two parallel, flexurally subsiding basins (Poole 1974; Harbaugh and Dickinson 1981; Speed and Sleep 1982; Giles and Dickinson 1995). The basin adjacent to the allochthon is termed a foredeep basin (Fig. 3) and the distal basin is termed a back-bulge basin (Goebel 1991; Giles 1994; DeCelles and Giles 1996). The basins are separated by a zone of flexural upwarping termed the forebulge. The locus of subsidence associated with these basins migrates through time in response to migration of the thrust load. The Pilot basin represents the flexurally subsiding back-bulge basin that formed during the initial phase of Antler orogenesis (Giles 1994; Giles and Dickinson 1995).

Passive-margin sedimentation along a west-facing continental shelf (Stewart 1972; Speed and Sleep 1982; Sheehan and Boucot 1991) characterized central Nevada eastward to central Utah prior to the onset of Antler orogenesis. Passive-margin deposition produced mainly carbonate-ramp and platform-margin facies (Cook et al. 1983; Tucker and Wright 1990). The Upper Devonian (Frasnian) Guilmette Limestone, which directly underlies the Cove Fort Quartzite (Fig. 2), represents the last period of passive-margin deposition. The Guilmette Limestone comprises shallow to deep subtidal carbonate facies deposited during continent-wide transgression (Taghanic onlap of Johnson 1970).

The Cove Fort Quartzite and associated facies in western Utah represent deposition during a major regression following the culmination of the Taghanic onlap and also record initiation of thrusting in the Antler orogenic belt (Poole 1974; Sandberg and Poole 1977). These synorogenic strata were deposited along the distal southeast side of the Pilot basin and began with shoreface deposition of the Cove Fort Quartzite (Crosby 1959; Johnson et al. 1991). The Cove Fort Quartzite is abruptly overlain and locally intercalated with the West Range and lower Pinyon Peak limestones (Fig. 2).

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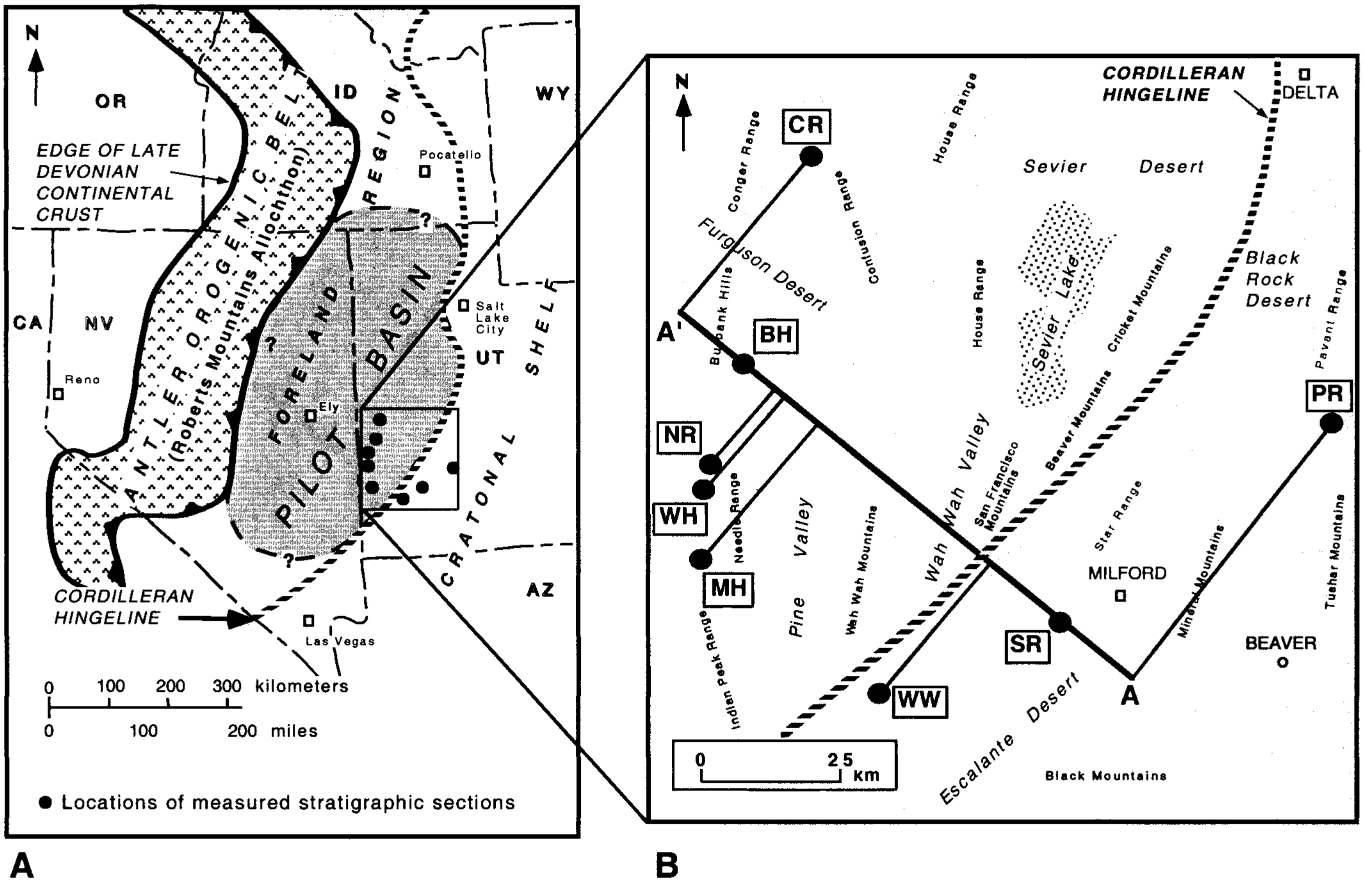


FIG. 1.—**A)** Major paleogeographic and tectonic elements associated with the Antler orogeny. The outline of the Antler orogenic belt represents the present distribution of rocks included in the Roberts Mountains allochthon. Lightly stippled area denotes area of the Antler foreland region. Darkly stippled area denotes area of the Pilot basin within the Antler foreland region. Diagram adapted from Bocko (1997). **B)** Study area in southeastern Utah showing modern mountain ranges, locations of measured sections, and trend of cross section A to A′. PR = Pavant Range, SR = Star Range, WW = Wah Wah Range, MH = Mountain Home Range, WH = Wild Horse Draw, NR = Needle Range, BH = Burbank Hills, and CR = Confusion Range.

The West Range Limestone comprises wavy, thin- to medium-bedded, nodular, argillaceous and fossiliferous, deep to shallow subtidal limestone (Kellogg 1963; Johnson et al. 1969; Bocko 1997). The lower Pinyon Peak Limestone comprises dolomitized, intercalated, algal-laminated mudstone and thick-bedded, peloidal wackestone–packstone interpreted to represent shallow subtidal to supratidal environments (Sandberg and Poole 1977; Bocko 1997). Correlative strata of the Pilot Shale to the west are fine-grained basinal deposits that consist of laminated siltstone and shale with local sandstone turbidites, debris flows, and slump deposits interpreted to have accumulated in a submarine-fan environment (Sandberg and Poole 1977; Gutschick and Rodriguez 1979; Jones 1990). The Upper Devonian strata are unconformably overlain by shallow subtidal carbonates of the Joana and Gardison limestones deposited on a regionally extensive, westward-sloping ramp (Giles 1996).

SEDIMENTOLOGIC AND STRATIGRAPHIC ANALYSIS

In western Utah a series of eight stratigraphic sections on a northwest-trending, shelf-to-basin transect across the southeastern margin of the Pilot basin (Figs. 1, 3, 4) were measured and described (Sandberg and Poole 1977; Gutschick and Rodriguez 1979; Bocko 1997). Each section was measured from the contact of the Guilmette Limestone (Frasnian) with overlying Upper Devonian (Famennian) strata to the base of the lower Mississippian Joana or Gardison Limestone (see Bocko 1997 for details of measured-section sites). Lower Famennian strata encompass the Cove Fort Quartzite and West Range Limestone, and include the lower parts of the Pilot Shale and Pinyon Peak Limestone (Fig. 2). Our stratigraphic studies show that units mapped as Cove Fort Quartzite locally are interbedded with West Range Limestone (Fig. 2). For our sequence-stratigraphic analysis, we have subdivided the lower Famennian strata into 10 lithofacies and interpreted each lithofacies with regard to depositional setting. The attributes and depositional interpretation of each lithofacies are summarized in Table 1 and Figure 5. The lithofacies represent both carbonate and siliciclastic depositional settings that range from shoreline and tidal-flat complexes to deep marine basinal facies (Fig. 5).

Parasequence Types

The lithofacies are assembled into progradational facies successions ranging in thickness from 0.5 to 25 m and bounded above and below by flooding surfaces, which define parasequences. Four types of parasequences were delineated on the basis of dominant lithofacies and inferred depositional setting (Fig. 6). The parasequence types are: (1) shoreface siliciclastic, (2) peritidal carbonate, (3) shallow subtidal carbonate, and (4) deep subtidal carbonate.

Shoreface Siliciclastic Parasequences.—Shoreface siliciclastic parasequences are mapped as Cove Fort Quartzite in the study area. The lower parts of these parasequences consist of laminated, fine-grained, moderately to well sorted quartz arenite containing hummocky cross-stratification, wave ripples, and burrow mottling. The fine-grained quartz arenite grades

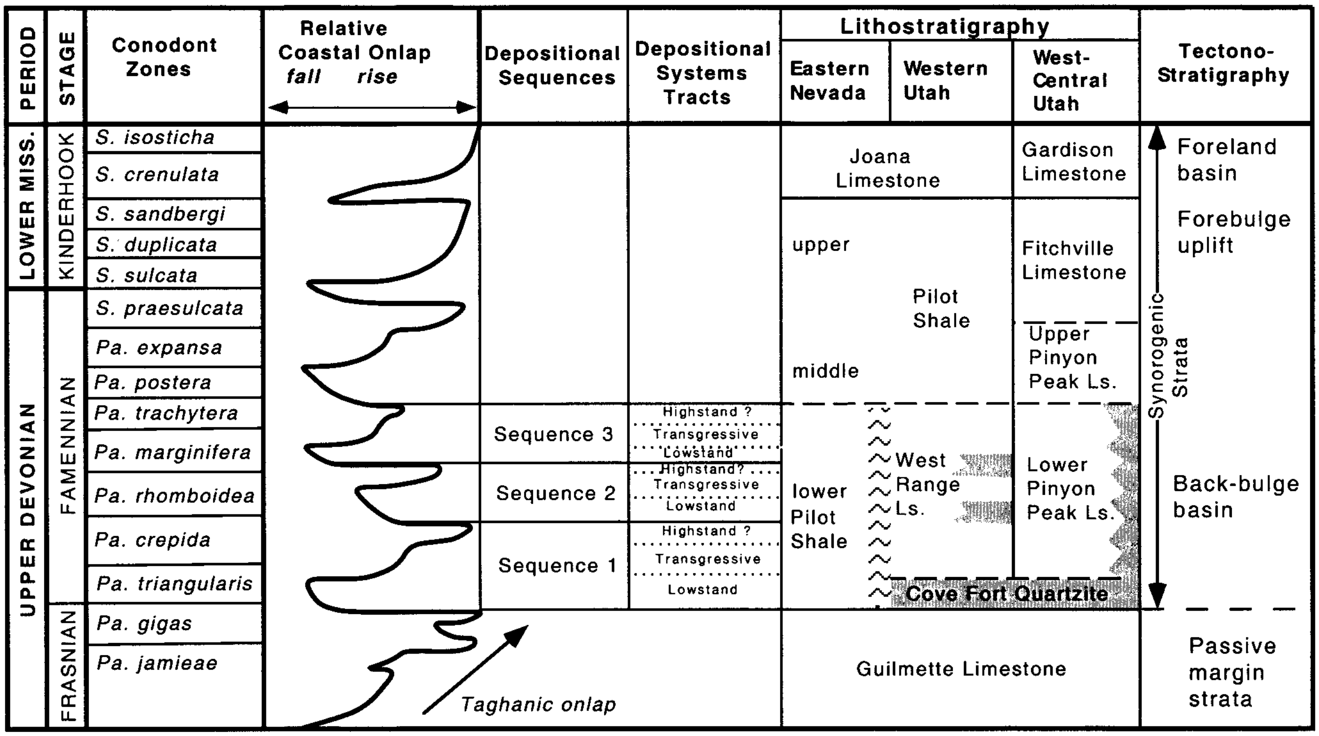


FIG. 2.—Generalized Upper Devonian through lower Mississippian stratigraphic column for eastern Nevada and central Utah showing major formational names, depositional sequences and systems tracts defined for this study, conodont zonation, and the coastal-onlap curve indicating third-order eustatic sea-level changes during the Late Devonian and earliest Mississippian. Coastal onlap for the Late Devonian was derived from Johnson et al. (1991), and from Ross and Ross (1987) for the lower Mississippian. Conodont zonation is derived from Sandberg et al. (1980), Sandberg et al. (1989), Johnson et al. (1991), and Poole and Sandberg (1991).

upward to slightly coarser-grained quartz arenite with planar lamination, trough cross-sets, and local burrow mottling. The siliciclastic units are abruptly overlain by laminated to slightly burrow-mottled, unfossiliferous, sandy dolomicrite.

The siliciclastic parasequences are interpreted as shoreface deposits formed between fair-weather wave base and the swash zone. Fine-grained arenite with hummocky cross-stratification and burrowing represents lower-shoreface deposition; medium- to coarse-grained arenite with trough foresets and horizontal lamination represents upper-shoreface deposition (Clifton et al. 1971, Van Wagoner et al. 1990, Hettinger et al. 1993); and overlying sandy dolomicrite represents subaqueous restricted conditions, perhaps in a lagoon (Sonnenfeld 1996) or sabkha (Shinn 1973). There is no evidence of subaerial exposure of these strata, with the exception of rare mudcracked horizons in the upper-shoreface sandstones. Facies progradation and progressive restriction of units in the parasequences are indicated by: (1) upward coarsening in sandstone overlain by carbonate mud that records increasing wave energy on a siliciclastic shoreface or barrier bar that fronted a quiet lagoon or sabhka; (2) upward increase in iron mineralization and dolomitization indicating progressively more reducing and restricted marine conditions (Sonnenfeld 1996); (3) lack of normal marine fauna in parasequence; and (4) low-energy grain types, such as pellets in dolomicrite overlying high-energy coarse-grained quartz.

Siliciclastic shoreface parasequences form thick, progradational parasequence sets within the basal parts of sections located directly west or basinward of the Cordilleran Hingeline (Fig. 4; Mountain Home, West Horse, and Needle Range sections). Progradation is indicated by an increased proportion of restricted lagoonal facies in higher parasequences, coupled with an upsection decrease in parasequence thickness. Directly east of the Cordilleran Hingeline, shoreface siliciclastic parasequences are absent, except in the easternmost section (Cove Fort Quartzite type section, Pavant Range), where they are significantly thinner with fewer sandstone bodies.

Peritidal Carbonate Parasequences.—The bases of these parasequences (Fig. 6) comprise planar-laminated, intraclast, peloidal wackestone to grainstone, and burrowed, fossiliferous wackestone to packstone that become progressively more mud-rich upward. These strata are abruptly overlain by algal-laminated mudstone.

The basal facies mosaic of the peritidal carbonate parasequences are interpreted to represent shallow subtidal to intertidal channel complexes on a tidal flat, and the overlying algal-laminated mudstone represents high intertidal deposition. Evidence for upward shallowing within each parasequence includes: (1) upward increase of carbonate mud and biogenically produced sedimentary structures, such as algal laminae; (2) upward increase in nonskeletal grains, such as pellets, peloids, and intraclasts derived from desiccation polygons; (3) upward disappearance of normal marine fauna; (4) upward appearance of fenestral fabric; and (5) upward decrease in grain size and high-energy grain types such as shoreface quartz sand and ooids.

Peritidal carbonate parasequence sets display progradational stacking patterns with progressive upward increase in proportion of restricted intertidal algal laminite facies within parasequences coincident with an overall decrease in parasequence thickness. Carbonate peritidal parasequences are present only directly to the east of the Cordilleran Hingeline, and are not present as far east as the Pavant Range (Fig. 4).

Shallow Subtidal Carbonate Parasequences.—Shallow subtidal carbonate parasequences consist of a basal horizon of wavy-bedded and burrowed skeletal wackestone–packstone (locally argillaceous and hummocky cross-stratified). The basal unit grades upward into trough cross-bedded skeletal packstone–grainstone facies.

The shallow subtidal carbonate parasequences are interpreted to represent subtidal, open marine deposition above storm wave base, shallowing into fair-weather wave base where the packstone–grainstone caps likely formed by migration of skeletal sand shoals across the open marine facies (e.g., Osleger 1991). Evidence for shallowing within shallow subtidal levels in-

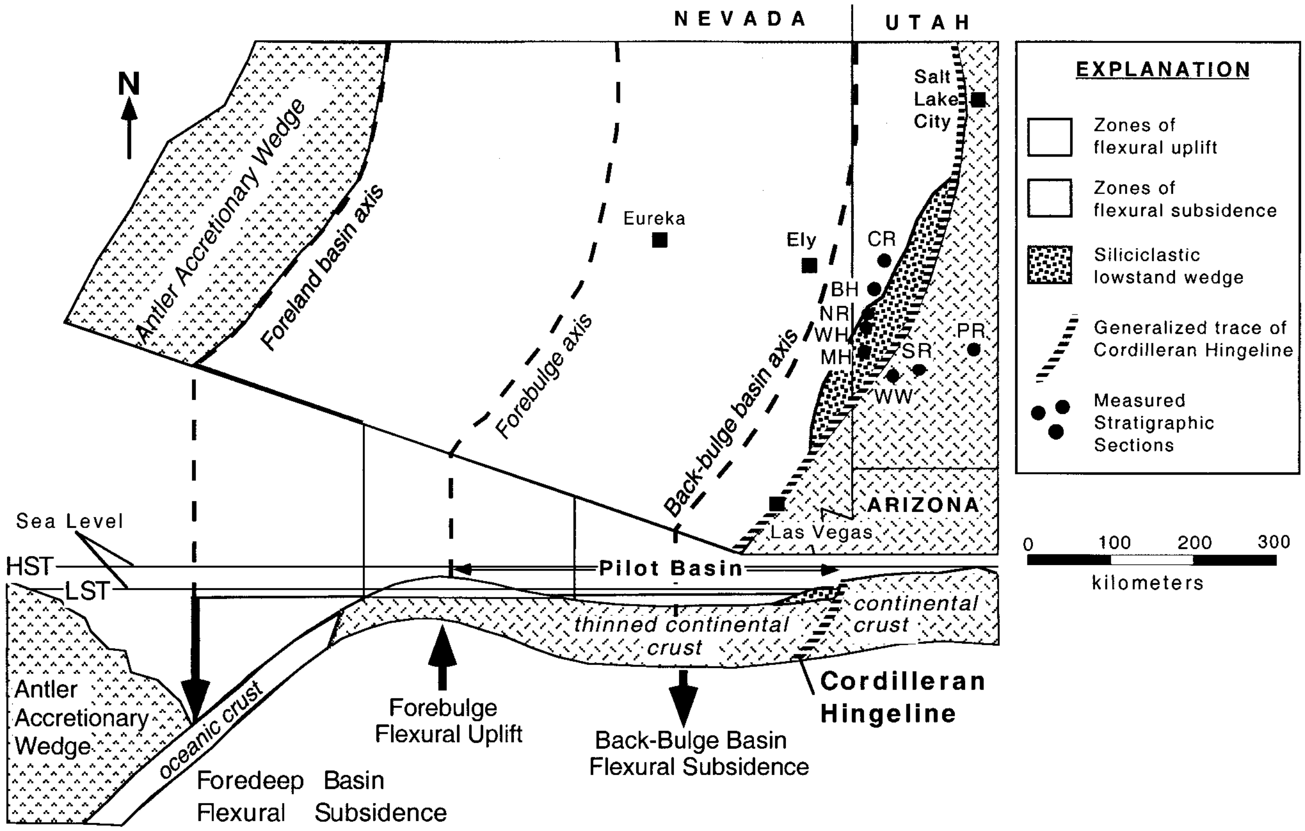


FIG. 3.—Diagram of interpreted position of the Pilot basin and Cordilleran Hingeline with respect to Late Devonian flexural features of the Antler foreland region in eastern Nevada and western Utah. The presence of oceanic crust is inferred from boundary $^{87}Sr/^{86}Sr$. (Diagram adapted from Giles 1994). Positions of stratigraphic sections are marked by black dots and are indicated as follows: SR = Star Range, WW = Wah Wah Range, IP = Indian Peak, MH = Mountain Home, WH = West Horse, NR = Needle Range, BH = Burbank Hills, and CR = Confusion Range.

clude: (1) upward increase in abundance of skeletal grains associated with an upward decrease in faunal diversity; (2) upward decrease in carbonate mud associated with a shift from highly burrowed facies to cross-stratified and current-laminated facies; (3) upward increase in bed thickness; and (4) upward increase in grain size. The shallow subtidal and peritidal carbonate parasequences constitute a unit mapped as the Pinyon Peak Limestone, which is restricted to the area directly east of the Cordilleran Hingeline (Fig. 5).

Deep Subtidal Carbonate Parasequences.—Deep subtidal carbonate parasequences range in thickness from 1 m to as much as 25 m. The base of each parasequence contains wavy-bedded argillaceous fossiliferous wackestone overlain gradationally by an intensely bioturbated wackestone–packstone consisting of abundant skeletal and nonskeletal grains.

The deep subtidal carbonate parasequences contain dominantly mid to deep ramp facies that shallow upward, but do so completely within subtidal levels and are bounded by marine flooding surfaces. Upward-shallowing facies successions within the deep subtidal are indicated by the following trends upsection: (1) increase in nonskeletal grain types, such as peloids and intraclasts; (2) increased bed thickness; (3) increase in bioturbation; and (4) increase in packstone relative to carbonate mud. Evidence for subaerial exposure of deep subtidal parasequences is rare but forms the basis for placement of sequence boundaries where present.

Deep subtidal carbonate parasequences constitute the West Range Limestone, which forms the bulk of the Upper Devonian strata west of the Cordilleran Hingeline. Directly west of the Cordilleran Hingeline, deep subtidal carbonate parasequences are interstratified with shoreface siliciclastic parasequences. The number and thickness of deep subtidal carbonate parasequences decrease with distance westward from the Cordilleran Hingeline, suggesting that deposition took place progressively deeper on the ramp, with concomitant reduced sedimentation rates basinward (Osleger 1991). Deep subtidal parasequences are present only west of the Cordilleran Hingeline.

Sequence-Stratigraphic Framework

A sequence-stratigraphic framework for lower Famennian strata based on conodont biostratigraphy and parasequence-based allostratigraphy permits identification of regional unconformities or sequence boundaries (e.g., Vail et al. 1977; Van Wagoner et al. 1990; Posamentier et al. 1992). Depositional systems tracts (i.e., lowstand, transgressive, and highstand systems tracts) were delineated within sequences on the basis of identification of parasequences, interpretation of marine flooding surfaces, stacking patterns of parasequence sets, and stratigraphic position within the sequence (Van Wagoner et al. 1990). Non-Waltherian vertical facies transitions across surfaces were identified as either marine flooding surfaces or sequence boundaries, depending on the nature and stratigraphic position of associated facies.

Three depositional sequences were defined within the stratigraphic framework of the lower Famennian strata (Fig. 4). Each sequence boundary coincides with either regional erosional truncation, a local subaerial exposure surface, and/or a basinward shift in facies, except the upper boundary of sequence 3, which corresponds to a marine flooding surface or drowning unconformity. Each of the three sequences contains a lowstand systems tract that identifies the lower contacts as type 1 sequence bound-

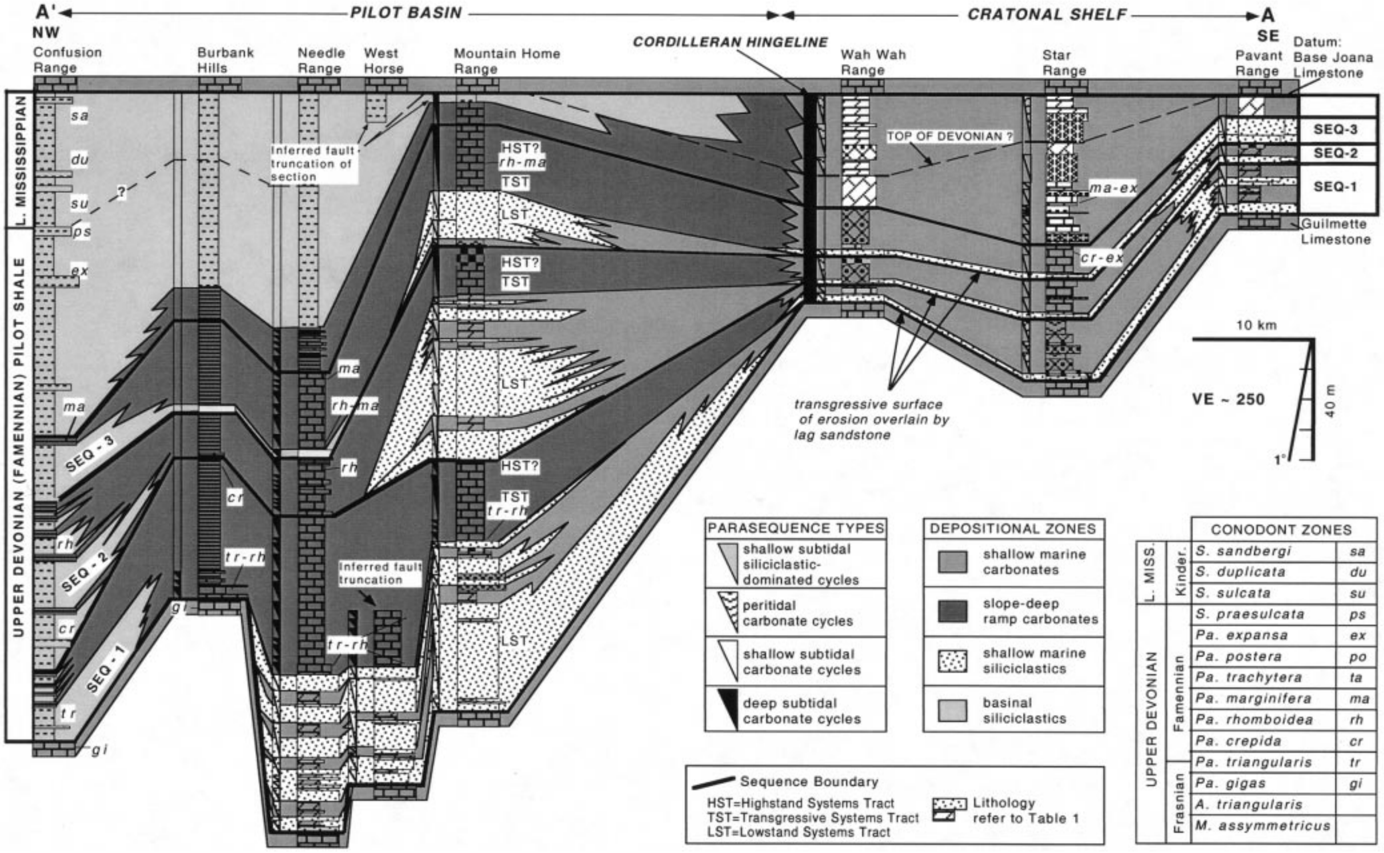


FIG. 4.—Cross section A to A′ displaying lithofacies distribution, parasequence types, and sequence-stratigraphic interpretation of Upper Devonian strata. Distances between measured sections are derived from distance between locations as sited perpendicularly onto cross section A to A′. Diagram modified from Bocko (1997).

aries (Van Wagoner et al. 1990). Carbonate strata directly underlying sequence boundaries are commonly dolomitized, possibly resulting from seaward movement of a freshwater lens, a process that can occur during formation of type 1 sequence boundaries (Sarg 1988).

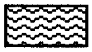
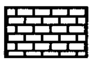
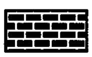
The three sequences display systematic trends in stratal thickening and facies along the northwest–southeast depositional profile of Fig. 1. Each of the sequences is thickest in the area directly west of the Cordilleran Hingeline (Fig. 4; Mountain Home Range, West Horse, and Needle Range), and all sequences thin both to the northwest and to the southeast. The thickest part of each sequence contains a wedge-shaped, largely subtidal, siliciclastic succession directly overlying the lower sequence boundary. This siliciclastic wedge is interpreted as a barrier bar complex within the lowstand systems tract (LST).

Siliciclastic shoreface parasequences of the LST form individual stratal wedges that thin both shoreward and basinward from as much as 65 m to less than a few meters over a distance of approximately 30 km. Parasequences comprise alternating shoreface and lagoonal facies of the back-barrier environment. Parasequence thickness decreases upward within parasequence sets, and each parasequence contains a greater component of lagoonal dolomicrite, indicating overall progradation of the lowstand wedges. Facies correlative to the LST are not present east of the Cordilleran Hingeline; therefore, the siliciclastics forming the wedge bypassed the shallow shelf during a relative sea-level fall and were carried out into the basin. Sediment bypass may have taken place by eolian transport of sand across the exposed shelf to a depositional site along the lowstand shoreline of the Pilot basin. Sediment bypass may have also taken place in areally isolated fluvial systems that traversed the shelf to the lowstand shoreline followed by sediment dispersal along the shoreline via longshore drift.

Deep subtidal carbonates directly above lowstand shoreface deposits represent flooding of the shelf margin and initiation of the transgressive systems tract (TST). The deep subtidal carbonates form parasequences with a retrogradational stacking pattern, which is characteristic of the transgressive systems tract (e.g., Van Wagoner et al. 1990; Sonnenfeld 1996). Basinward of the lowstand wedges, strata within the TST contain apparently noncyclic, deep-water facies comprising laminated micrite and shale. A condensed section in the lowermost subtidal carbonate deposits of the TST of sequence 1 is recorded by an unusually high abundance of conodonts (Bocko 1997). A transgressive surface of erosion overlying the LST records a rise in sea level, drowning of the barrier-bar complex, and an abrupt shift to very slow, deep subtidal carbonate deposition. Thin (< 0.5 m) transgressive lags comprising dolomite-clast conglomerate interbedded with deep-water carbonate strata lie directly on the transgressive surface in a position basinward of the lowstand pinchout (i.e., Burbank Hills for sequence 1 and Needle Range for sequences 2 and 3). Dolomitic clasts within the conglomerates were probably transported offshore as the earlier exposed shelf was reworked by surf-zone erosion during transgression (e.g., Tucker and Wright 1990). Transgressive beds are represented in the sections southeast of the Cordilleran Hingeline (Wah Wah and Star ranges) by relatively thin (< 2.5 m) horizons of thick-bedded quartz arenite at the bases of sequences 1 and 2. The quartz arenite grades upward into peritidal and shallow subtidal carbonates. The siliciclastic horizons are interpreted as reworked beach bar sands transported landward during sea-level rise. In this area the lower sequence boundary coincides with a transgressive surface of erosion at the base of the TST.

The highstand systems tract (HST) in each sequence is dominated by deep subtidal carbonate parasequences with aggradational followed by pro-

TABLE 1.—*Lithofacies description and interpretation of the Cove Fort Quartzite and associated facies*

Lithofacies	Symbol	Bedding	Primary Grain Types	Sedimentary Structures	Depositional Setting
Algal - Laminated Mudstone		medium, planar	Pellets, molluscs, silt to fine sand sized quartz grains, and pyrite.	simple alternating, undulate to smooth laminae, fenestrae	tidal flat, intertidal zone
Sandy Dolomicrite		thin to thick, forms rubble	5-20% silt to coarse sand-sized, angular to rounded monocrystalline quartz grains admixed within carbonate mud.	planar laminae and local bioturbation	shallow water, lagoon restricted peritidal
Calcareous Quartz Arenite		thin to thick, planar; forms ledges	Up to 95% fine to coarse sand-sized monocrystalline quartz grains, rounded and moderate to well-sorted.	planar current laminae & foresets, trough & hummocky	lower to upper shoreface & foreshore barrier bar complex
Intraclastic-Peloidal Limestone		medium to thick, planar	Peloids, intraclasts, molluscs, calcispheres, dasyclads (green algae), ostracods, sponge spicules, & silt to sand-sized quartz grains.	planar and algal laminae, bioturbation	intertidal, tidal channel, and lagoonal
Massive Fossiliferous Peloidal Wackestone		massive, forms ledges	Abundant peloids, stromatoporoids. Intraclasts present locally. Quartz silt to fine sand-sized quartz.	mottled, patchy surfaces, intense bioturbation	normal marine, open shelf within photic zone, localized patch reefs/bioherms
Echinoderm Packstone-Grainstone		medium, planar	Echinoderms, and in lesser amounts: bryozoans, brachiopods, molluscs, and rugose corals, especially in packstone textures.	planar current laminae	normal marine, lime sand shoals, shallow shelf
Fossiliferous Wackestone-Packstone		thin - medium, rubbly, locally argil. & wavy	Echinoderms, brachiopods, molluscs, bryozoans, trilobites, sponge spicules, and calcispheres. 5% silt to fine sand-sized quartz.	bioturbated, discontinuous current-laminated packstone lenses	open shelf, normal marine, below wave base
Fossiliferous Laminated Micrite		medium, planar, forms rubble	Pellet-sized peloids, calcispheres, and lesser amounts of ostracods, molluscs, echinoderms, sponge spicules.	planar millimeter micritic and fossiliferous laminations	basinal or deep ramp, turbidites
Laminated Shale		thin, platey	clay to silt sized grains	lamination, local cross-laminae	deep basinal, hemipelagic fines
Graded Quartz Arenite		thin - medium planar	Fine to medium quartz sand with carbonate clast	graded (Bouma A) current-laminated	basin-floor turbidites

gradational stacking patterns. Aggradation followed by progradation is characteristic of the HST (Sarg 1988; Van Wagoner et al. 1990) although significant aggradation has been attributed to the latest TST. Correlative shoreward peritidal carbonate and siliciclastic shoreface parasequences east of the Cordilleran Hingeline display progradational stacking patterns. The relatively thin HST in each sequence may reflect erosional truncation beneath the overlying sequence boundary (Van Wagoner et al. 1990).

Lowstand Systems Tracts as Forced-Regression Deposits

Marine regression refers to withdrawal of the sea from a large area of land by basinward migration of the shoreline (Curray 1964). Regression is controlled primarily by the balance between two variables, rate of new space available for deposition (accommodation) and net sediment influx. Regression takes place in depositional settings where the change in ratio of accommodation to sediment flux is less than 1 over an interval of time. Posamentier et al. (1992) distinguish two types of regressions, which they refer to as ''normal'' and ''forced''. Normal regression takes place when sediment flux to the shoreline exceeds the rate of accommodation increase, resulting in progradation even in the absence of eustatic sea-level fall. In contrast, ''forced'' regression takes place when accommodation decreases in response to a relative sea-level fall, causing the shoreline to shift abruptly basinward regardless of net sediment influx. Forced regressions can generate isolated shoreline-detached sand bodies encased in shelfal deposits of the preceding systems tract and subsequent transgressive systems tract.

The lowstand systems tracts of the three lower Famennian sequences of this study display many features characteristic of forced regressions as defined by Posamentier et al. (1992). These features include: (1) coarse-grained lowstand or proximal (shoreline) deposits overlying an erosional surface cut into fine-grained distal-marine carbonate facies; (2) lowstand deposits detached and separated from a complex of previously formed highstand shoreface deposits, approximately 60 km seaward of a zone of sedimentary bypass; (3) a sharp, erosional surface underlying the proximal part of the lowstand deposits and becoming gradational or conformable seaward; (4) shoreface deposits confined to a relatively narrow zone approximately 30 km in width; (5) transgressive systems tract deposits consisting of deep subtidal carbonates that onlap the distal limits of and overlie the lowstand shoreface and lagoonal deposits; and (6) a sequence-bounding unconformity merging with a transgressive surface of erosion landward of the lowstand shoreline pinch-out.

The lowstand systems tract of sequence 1 contains fine- to coarse-grained siliciclastic shoreface deposits that abruptly overlie subtidal open shelf or ramp carbonate facies of the Guilmette Limestone (Fig. 4, Mountain Home, West Horse, and Needle Range sections). The lowstand systems tracts of sequences 2 and 3 directly overlie deep subtidal ramp facies of the West

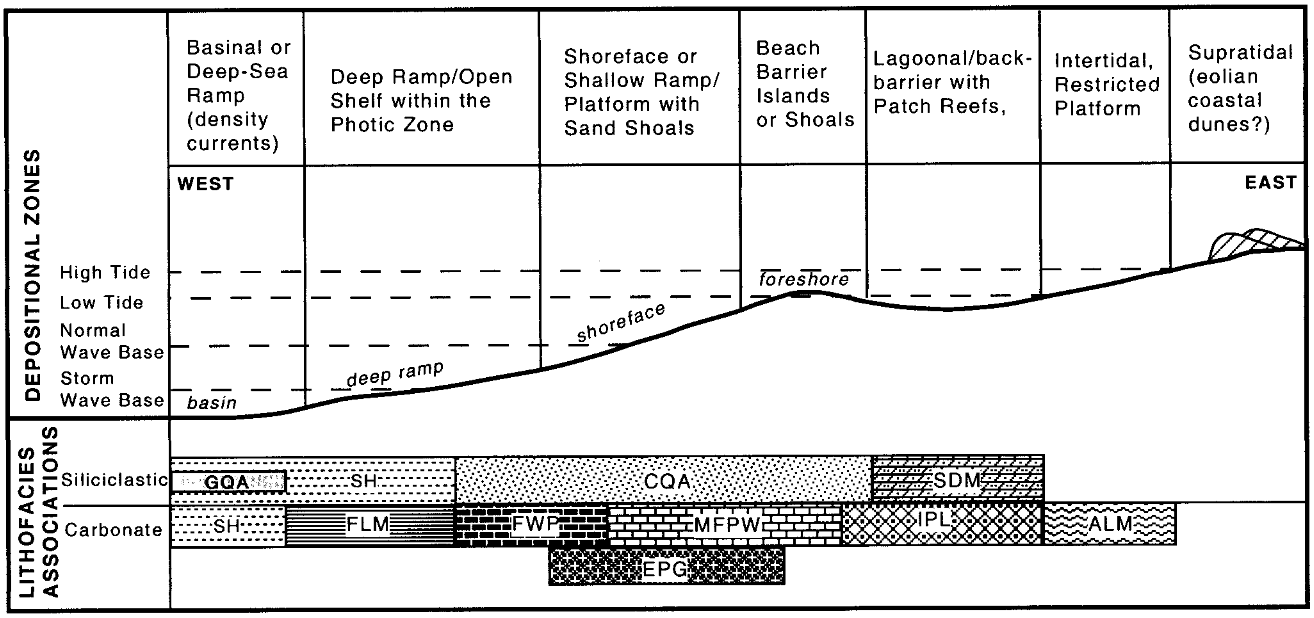


FIG. 5.—Schematic depositional profile displaying the relative position of lithofacies documented in this study. Lithofacies acronyms are: ALM = algal laminated mudstone, SDM = sandy dolomicrite, CQA = calcareous quartz arenite, IPL = intraclastic-peloidal limestone, MFPW = massive fossiliferous peloidal wackestone, FWP = fossiliferous wackestone to packstone, EPG = echinoderm packstone to grainstone, FLM = fossiliferous laminated mudstone to wackestone, SH = laminated shale, and GQA = graded quartz arenite.

Range Limestone (Fig. 4, Mountain Home Range). The lowstand shoreface facies are not present in sections to the east (shoreward), where shallow subtidal to peritidal carbonate facies directly overlie a transgressive surface of erosion. Evidence for this erosional/transgressive surface is present in the Wah Wah and Star ranges, where a thin (< 0.5 m) lag of quartz sandstone overlies an erosional scour surface and grades upward into shallow subtidal carbonate facies of the transgressive systems tract of sequence 1 (Giles 1994; Bocko 1997). The lowstand shoreface deposits are thus ''detached'' or separated from shoreface deposits present to the east (Pavant Range) by a zone of sedimentary bypass (Wah Wah and Star range area). The lowstand deposits of sequences 2 and 3 have a relationship similar to siliciclastic shoreface deposits to the east but are progressively thinner and have a narrower down-dip lateral distribution. The lowstand shoreface sandstones are abruptly overlain by deep-ramp carbonates and form isolated, shallow-water sandstone bodies encased in deep-water distal marine carbonate facies.

An incised-valley feeder system for the lowstand deposits was not identified in the exposures studied and is commonly not preserved in forced-regression systems (Posamentier et al. 1992). Bocko (1997) suggested at least a partial eolian source for these facies, on the basis of the textural and compositional maturity of the sand and the presence of deflation spheres (outsized, spherical, rounded quartz grains). If sediment delivery

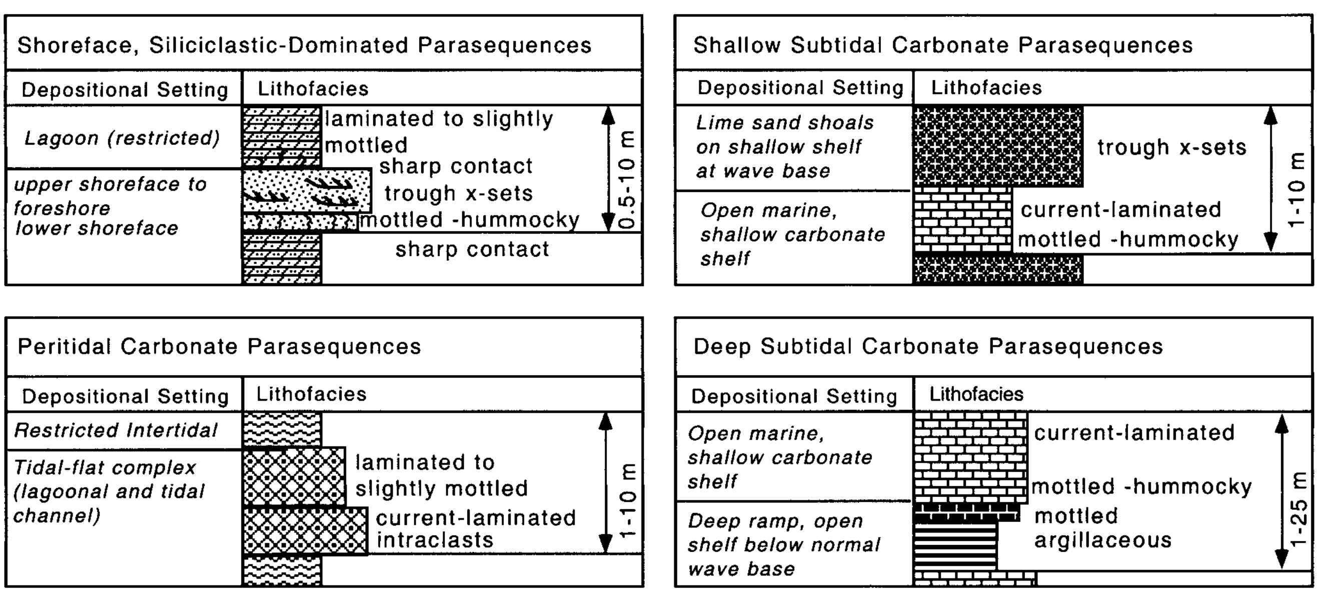


FIG. 6.—Types of parasequences documented in the Cove Fort Quartzite and associated facies. Refer to Figure 4 for lithofacies symbols.

to the LST was eolian, a fluvial incised-valley system would not be required to provide quartz sand to the lowstand shoreline. In an eolian scenario, wind-generated dunes migrated from a distal eastern source in Utah, crossing the sabkha or supratidal-flat environment preserved in the Pinyon Peak Limestone, and were ultimately reworked and deposited in the coastal zone of the Pilot basin, west of the Cordilleran Hingeline. A modern analog for this type of setting is the southeast coast of Qatar Peninsula, Persian Gulf, where eolian quartz sand dune complexes are currently migrating into the sea (Shinn 1973). Alternatively, the lowstand siliciclastics may have entered the Pilot basin by a fluvial feeder system that is not exposed in the Basin and Range uplifts and was transported into the area by longshore drift.

Controls on the Nature of Forced-Regression Clastic Wedges

Geographic Distribution.—The LST siliciclastic wedges are confined geographically to a narrow zone (less than 30 km wide) directly west of the position of the Cordilleran Hingeline (Fig. 3). These deposits form the bulk of the Upper Devonian stratigraphy in the Mountain Home Range, where the depositional sequences are thicker (90 m) than at locations east of the Cordilleran Hingeline (15 m). Subsidence rates higher to the west of the Cordilleran Hingeline than to the east are suggested by the unusual thickness of the forced-regression deposits (as much as 65 m) within each sequence along with their consistent stratigraphic dominance in the Mountain Home Range, the abrupt increase in thickness of each sequence and overall retrogradational nature of the succession west of the Cordilleran Hingeline, and the confinement of thin TST and HST peritidal carbonates to the east of the Cordilleran Hingeline.

Stratal thickening west of the Cordilleran Hingeline defines the eastern margin of the Pilot basin (Figs. 1, 3). The Pilot basin represents differential subsidence, during the early stages of the Antler orogeny, of what had formerly been a regionally extensive, upper Precambrian to Upper Devonian passive margin. The western margin of the Pilot basin was deformed by final emplacement of the Roberts Mountains allochthon during early Mississippian time and by later tectonism. The magnitude and geometry of Pilot basin subsidence are consistent with an origin as a flexural back-bulge basin within the Antler foreland system (Goebel 1991; Giles and Dickinson 1995; Giles 1994; DeCelles and Giles 1996). Modeling studies show that flexural subsidence rates in back-bulge basins (depozones) are several orders of magnitude less than subsidence rates in the foredeep (Goebel 1991; DeCelles and Giles 1996), but this subsidence is still sufficient (on the order of several hundred meters) to influence depositional geometry and stratigraphic distribution of lithofacies.

Lithospheric flexural subsidence during Antler orogenesis can account for the timing and magnitude of subsidence west of the Cordilleran Hingeline, but the width of the Pilot basin is inconsistent with that predicted by flexural modeling. Goebel's (1991) flexural models of the Antler system using standard parameters for continental crust predicted a foreland basin approximately 1.3 km deep and 270 km across from the axis of foredeep to the axis of forebulge. The modeled back-bulge basin is less than 300 m deep at the axis and the distance between forebulge axis to back-bulge basin axis is 290 km. The overall width of the modeled back-bulge basin is over 400 km, with very gently sloping margins. Although the map in Figure 3 has not been palinspastically restored for Mesozoic and Cenozoic contraction and Cenozoic extension, it is clear that the actual width of the Pilot basin, less than 300 km, is not consistent with the flexurally modeled width.

The abrupt increase in sequence thickness and the depositional facies of the Upper Devonian strata reflect a steep rather than gradual slope on the eastern margin of the Pilot basin, at a position that corresponds with the trace of the Cordilleran Hingeline. The Cordilleran Hingeline represents a zone of crustal transition between the stable craton and attenuated continental crust that formed during late Precambrian rifting (Burchfiel and Davis 1972; Poole 1974; Picha and Gibson 1985). The northeastern orientation of the Cordilleran Hingeline has localized other younger structural and stratigraphic trends, such as fold-and-thrust belts (Armstrong and Hansen 1966; Picha and Gibson 1985) and platform-margin facies (Burchfiel and Davis 1971; Harbaugh and Dickinson 1981), suggesting that this area was a zone of crustal weakness throughout the Phanerozoic. The zone of lithospheric weakness at the Cordilleran Hingeline may have resulted in decoupling of the lithospheric flexural beam during Antler orogenic loading, resulting in failure of the flexural stresses to be transmitted across the structure. As a result, the transitional crust to the west of the Cordilleran Hingeline was flexurally warped and subsided dramatically, whereas the thick continental crust to the east experienced little or no simultaneous flexural subsidence.

During the early Mississippian, differential uplift and erosion of the former Pilot basin occurred as a result of flexural inversion created by the passage of the migrating forebulge during continued Antler orogenesis (Goebel 1991; Giles and Dickinson 1995). The early Mississippian flexural forebulge also reactivated the Cordilleran Hingeline structure (Giles 1996).

Stratigraphic Distribution.—By definition (Posamentier et al. 1992), forced regressions are generated by decreasing accommodation that is independent of sediment supply. In the Pilot basin, accommodation decreased on the cratonal shelf as a result of eustatic sea-level fall, tectonic uplift, or some combination of the two. Tectonic uplift appears unlikely in this case, because during the Late Devonian the area of eastern Nevada and western Utah was regionally subsiding to form the Pilot basin (Sandberg et al. 1989; Giles and Dickinson 1995; Giles 1996). Three pulses of tectonic uplift followed by substantial rapid subsidence would be required to generate the stratigraphic succession documented. We know of no plausible tectonic mechanism to explain such a scenario and thus regard it as unlikely. Correlation of the three Upper Devonian sequences to the eustatic sea-level curve of Johnson et al. (1991) using conodont biostratigraphy shows an excellent correspondence between the LST clastic wedge of each sequence and three major eustatic sea-level minima in the time interval (Fig. 2); therefore, we conclude that the stratigraphic position of the forced-regression siliciclastic wedges was controlled mainly by eustatic sea-level falls.

Eustatic sea-level trends do not appear to have controlled the long-term retrogradational behavior of the lower Famennian strata. The eustatic sea-level curve for the lower to middle Famennian displays progressive decline (Fig. 2); therefore, stratigraphic sequences controlled exclusively by eustatic accommodation changes would be expected to display a long-term progradational pattern. Instead, the lower Famennian strata display an overall retrogradational pattern in which sequences within the basin become progressively dominated by deep-water carbonates at the expense of shoreface quartz arenite. The carbonate strata are ultimately overlain by basinal shale facies (Figs. 2, 4). Peritidal carbonate deposition continued east of the Cordilleran Hingeline, indicating that decreased carbonate production rates were not responsible for the retrogradational pattern observed. We infer that water depths in the basin west of the Cordilleran Hingeline became too great for continued carbonate deposition as long-term tectonic subsidence outpaced carbonate accumulation in that area.

The LST of each sequence contains a barrier-bar complex associated with a lagoon. By comparison with Holocene examples, barrier bar/lagoon complexes are typical of the TST because a relative rise in sea level causes a decrease in flux of siliciclastic sediment to the basin (Demarest and Kraft 1987; Nummedal and Swift 1987). When compared to the Holocene examples, our interpretation presents a bit of a paradox because during the LST, regional relative sea level decreases and sediment supply to the basin generally increases. In the Devonian case, the area west of the Cordilleran Hingeline experienced local increased tectonic subsidence that produced a local relative sea-level rise during deposition of the LST. In this scenario, local tectonic subsidence exceeded regional eustatic fall rates during the LST. The barrier bar/lagoon complex was not eroded by subsequent transgressive ravinement but rather preserved by increased local subsidence.

Progradation within the LST of sequences 1 and 2 resulted when increased sediment influx exceeded local tectonic subsidence rates.

CONCLUSIONS

Application of sequence stratigraphy to the Upper Devonian Cove Fort Quartzite and associated strata permits a rational correlation between seemingly disparate stratigraphic sections, which was unfeasible using conventional biostratigraphic or lithostratigraphic methods. It also reveals that the Cove Fort Quartzite displays attributes characteristic of forced-regressive lowstand deposits as defined by Posamentier et al. (1992). These attributes are: (1) coarse-grained lowstand or proximal (shoreline) deposits overlying an erosional surface on fine-grained distal-marine carbonate facies; (2) lowstand deposits detached and separated from the immediately preceding highstand shorefaces, seaward of a zone of sedimentary bypass; (3) a sharp, erosional surface underlying the proximal part of the lowstand deposits and becoming gradational or conformable seaward; (4) shoreface deposits confined to a relatively narrow zone approximately 30 km in width; (5) transgressive systems tract deposits consisting of deep subtidal carbonates that onlap the distal limits of and overlie the lowstand shoreface and lagoonal deposits; and (6) a sequence-bounding unconformity that merges with a transgressive surface of erosion landward of the lowstand shoreline pinchout.

The Cove Fort depositional system records an unusually thick succession of stacked lowstand barrier bar and lagoon deposits concentrated in the area west of the Cordilleran Hingeline. The tremendous thickness, LST barrier-bar character, and vertical stacking are interpreted here as the result of increased subsidence west of the Cordilleran Hingeline associated with flexural subsidence of the Pilot basin during the Antler orogeny. The stratigraphic position of the lowstand systems tract resulted from migration of the shoreline across the position of the hingeline, during decline of eustatic sea level.

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