

Evolution of Devonian carbonate-shelf margin, Nevada

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ABSTRACT

The north-trending, 550-km-long Nevada segment of the Devonian carbonate-shelf margin, which fringed western North America, evidences the complex interaction of paleotectonics, eustasy, biotic changes, and bolide impact-related influences. Margin reconstruction is complicated by mid-Paleozoic to Paleogene compressional tectonics and younger extensional and strike-slip faulting. Reports published during the past three decades identify 12 important events that influenced development of shelf-margin settings; in chronological order, these are: (1) Early Devonian inheritance of Silurian stable shelf margin, (2) formation of Early to early Middle Devonian shelf-margin basins, (3) progradation of later Middle Devonian shelf margin, (4) late Middle Devonian Taghanic onlap and continuing long-term Frasnian transgression, (5) initiation of latest Middle Devonian to early Frasnian proto-Antler orogenic forebulge, (6) mid-Frasnian Alamo Impact, (7) accelerated development of proto-Antler forebulge and backbulge Pilot basin, (8) global late Frasnian *semichatovae* sea-level rise, (9) end-Frasnian sea-level fluctuations and ensuing mass extinction, (10) long-term Famennian regression and continent-wide erosion, (11) late Famennian emergence of Antler orogenic highlands, and (12) end-Devonian eustatic sea-level fall.

Although of considerable value for understanding facies relationships and geometries, existing standard carbonate platform-margin models developed for passive settings elsewhere do not adequately describe the diverse depositional and structural settings along the Nevada Devonian platform margin. Recent structural and geochemical studies suggest

that the Early to Middle Devonian shelf-margin basins may have been fault bound and controlled by inherited Precambrian structure. Subsequently, the migrating latest Middle to Late Devonian Antler orogenic forebulge exerted a dominant control on shelf-margin position, morphology, and sedimentation.

Keywords: Devonian, Nevada, shelf-slope break, carbonate platforms, tectonism.

INTRODUCTION

This review is based on a large body of data published during the past three decades. It summarizes the ~57-m.y.-long Devonian geological history of the western margin of an extensive carbonate-dominated shelf extending north to south through present-day Nevada. The 550-km-long Nevada margin is part of the Devonian shelf edge that fringed western North America from Alaska and Arctic Canada to Mexico (Ziegler, 1989; Poole et al., 1992). Devonian shelf-margin rocks in Nevada record the complex tectonic transition from long-term older Paleozoic extensional modes to compressional modes such as the Antler orogeny. The Antler orogenic highland was the first in a series of middle Paleozoic to Mesozoic orogenic belts that developed over an incipient subduction zone fringing the western continental margin of North America (e.g., Stewart and Poole, 1974; Johnson and Pendergast, 1981; Speed and Sleep, 1982). In this paper, the term “carbonate shelf” is used as a “sedimentary-tectonic feature, the part of a stable, cratonic-type area of sedimentation, where it was bordered by a more rapidly subsiding, more mobile basin of sedimentation, generally a geosyncline” (Gary et al., 1974, p. 652).

During the mid-1970s to early 1990s, a series of landmark papers provided detailed stratigraphic, biostratigraphic, lithofacies, isopach, structural, and eustatic data on the Devonian continental margin in the western U.S., including multiple paleogeographic and paleotectonic time-slice maps constrained by high-resolution conodont biochronology. Some of the most important papers include Poole (1974), Stewart and Poole (1974), Johnson and Sandberg (1977, 1989), Matti and McKee (1977), Murphy (1977), Poole et al. (1977, 1992), Sandberg and Poole (1977), Johnson and Pendergast (1981), Gutschick and Sandberg (1983), Kendall et al. (1983), Johnson and Murphy (1984), Murphy et al. (1984), Johnson et al. (1985, 1986, 1989, 1991), Stevens (1986), Sandberg et al. (1988, 1989), Goebel (1991), Johnson and Bird (1991), D.M. Miller et al. (1991), and E.L. Miller et al. (1992).

Beginning in the mid-1990s, studies of the Devonian shelf margin in Nevada focused on refining aspects of its: (1) tectonic and structural history (e.g., Giles, 1994; Giles and Dickinson, 1995; Graham, 1997; Crafford and Grauch, 2002; Grauch et al., 2003; Sandberg et al., 2003); (2) depositional models and facies geometry (e.g., Elrick, 1995, 1996; LaMaskin and Elrick, 1997; Cook and Corboy, 2004); (3) conodont-based event stratigraphy and eustasy (e.g., Johnson et al., 1996; Sandberg et al., 2002, 2003; Morrow and Sandberg, 2003); (4) stratigraphic and structural development in relation to synsedimentary exhalative gold mineralization in the Carlin trend area, northern Nevada (e.g., Emsbo et al., 1999, 2006; Hofstra and Cline, 2000; Crafford and Grauch, 2002); and (5) relation to the early Late Devonian Alamo Impact Event, south-central Nevada (e.g., Warme and Sandberg, 1995; Sandberg et al., 1997, 2002, 2003; Warme and Kuehner,

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1998; Morrow et al., 2005; Warme and Pinto, 2006; Pinto and Warme, 2008).

The standard conodont zonation, which is used to date Devonian rocks and to time eustatic and tectonic events, is shown in Figure 1. The Devonian eustatic sea-level curve (Johnson et al., 1985, 1991; Johnson and Sandberg, 1989) is reconstructed herein (Fig. 2) in

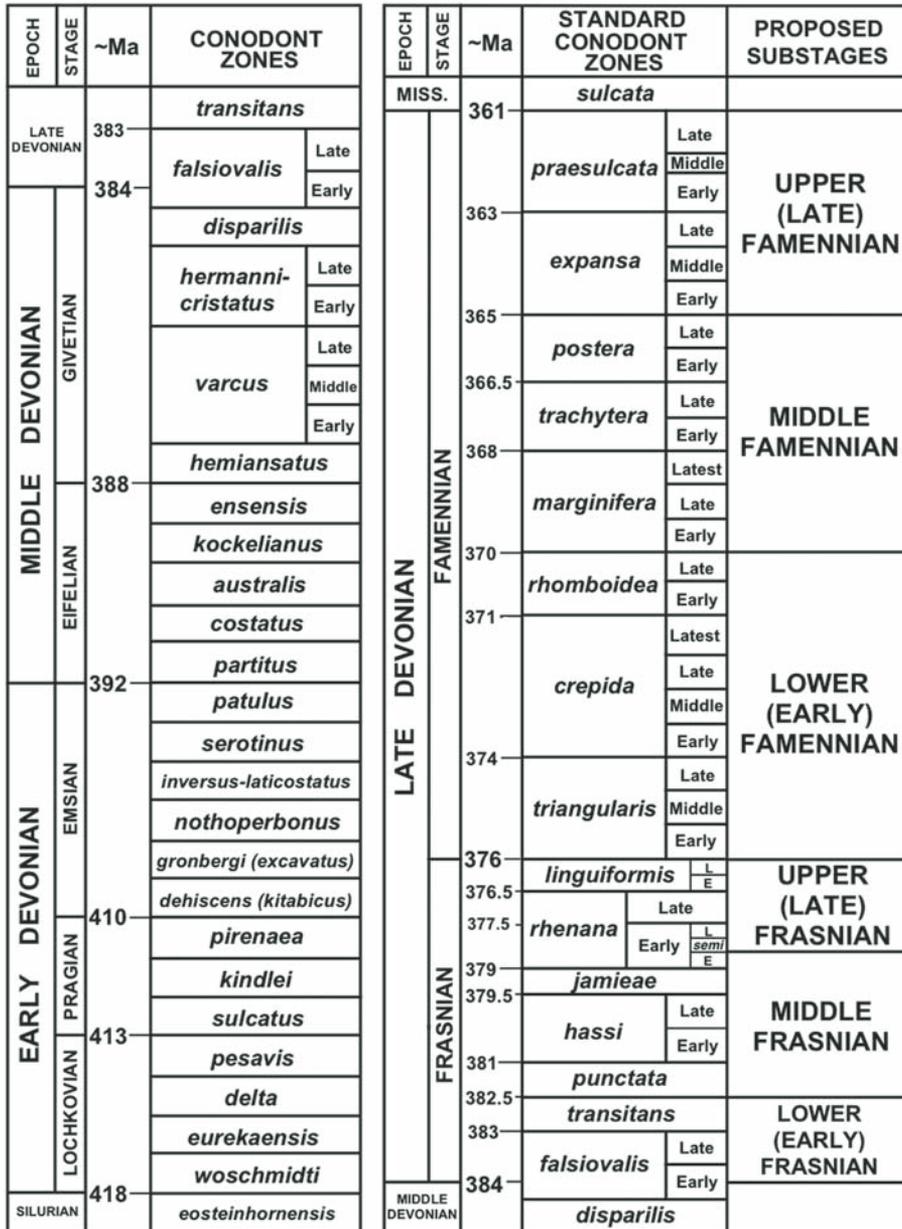
terms of later conodont biochronology (Sandberg and Ziegler, 1996) and scaled to fit the latest radiometric time scale (Kaufmann, 2006). This reconstruction shows some improvements over the original biochronologic dating but illustrates some weaknesses in the radiometric dating. In their final conclusion, Sandberg and Ziegler (1996, p. 264) stated: "Testing of

the conodont-based biochronologic dating must be accomplished by radiometric dating that is closely tied to the conodont zonation and particularly to conodont zonal boundaries. Only then can a refinement of and greater precision to our conodont-based dating be achieved." Kaufmann's (2006) time scale has increased both Frasnian and Famennian zonal lengths by a factor of 50%. This total duration of ~15 m.y. (Fig. 1) is in complete accord with the evidence provided by conodont phylogeny. However, the Emsian, and particularly the part represented by transgressive-regressive (T-R) cycle Ib (Fig. 2), has been more than doubled from ~8 m.y. to ~18 m.y. This increase has been made at the expense of the Eifelian, which has been made about equal to the Givetian, the conodont phylogeny and rock record of which suggest that it is one of the shortest Devonian stages, comparable in length to the Pragian. The crowding of the youngest Eifelian and oldest Givetian *australis* to *hemiansatus* conodont Zones is evident in Figure 2. The new radiometric dating has also greatly shortened the duration of the early Frasnian *transitans* and *punctata* Zones. This creates a serious problem, particularly in the case of the middle Frasnian *punctata* Zone, the thick global rock record of which suggests that its duration was much longer than other older Frasnian zones.

DEVONIAN SHELF-MARGIN SEDIMENTATION AND TECTONIC DEVELOPMENT

General Sedimentation Patterns

In Nevada, the position of the Devonian carbonate-shelf margin and the sedimentary facies deposited in outer-shelf to oceanic-basin settings was profoundly influenced by both eustasy and tectonics. Since the early work of Roberts et al. (1958), most later workers have agreed that Paleozoic sedimentary strata in western Utah and eastern and central Nevada document, from east to west, shallow- to deep-marine carbonate-shelf, shelf-margin, continental-slope, and oceanic-basin depositional settings. In general, Devonian shelf deposits are dominated by supratidal, intertidal, and shallow-subtidal carbonate rocks such as biolaminated dolostone, bioturbated lime mudstone and wackestone, bioclastic wackestone and packstone, stromatoporoid-dominated lime mud-rich biostromes, and intraformational conglomerate (Elrick, 1996; Poole et al., 1992; Cook and Corboy, 2004). During eustatic lowstands, craton-derived quartz sandstone was deposited in channels and basinward-prograding clastic wedges across large areas of the shelf.



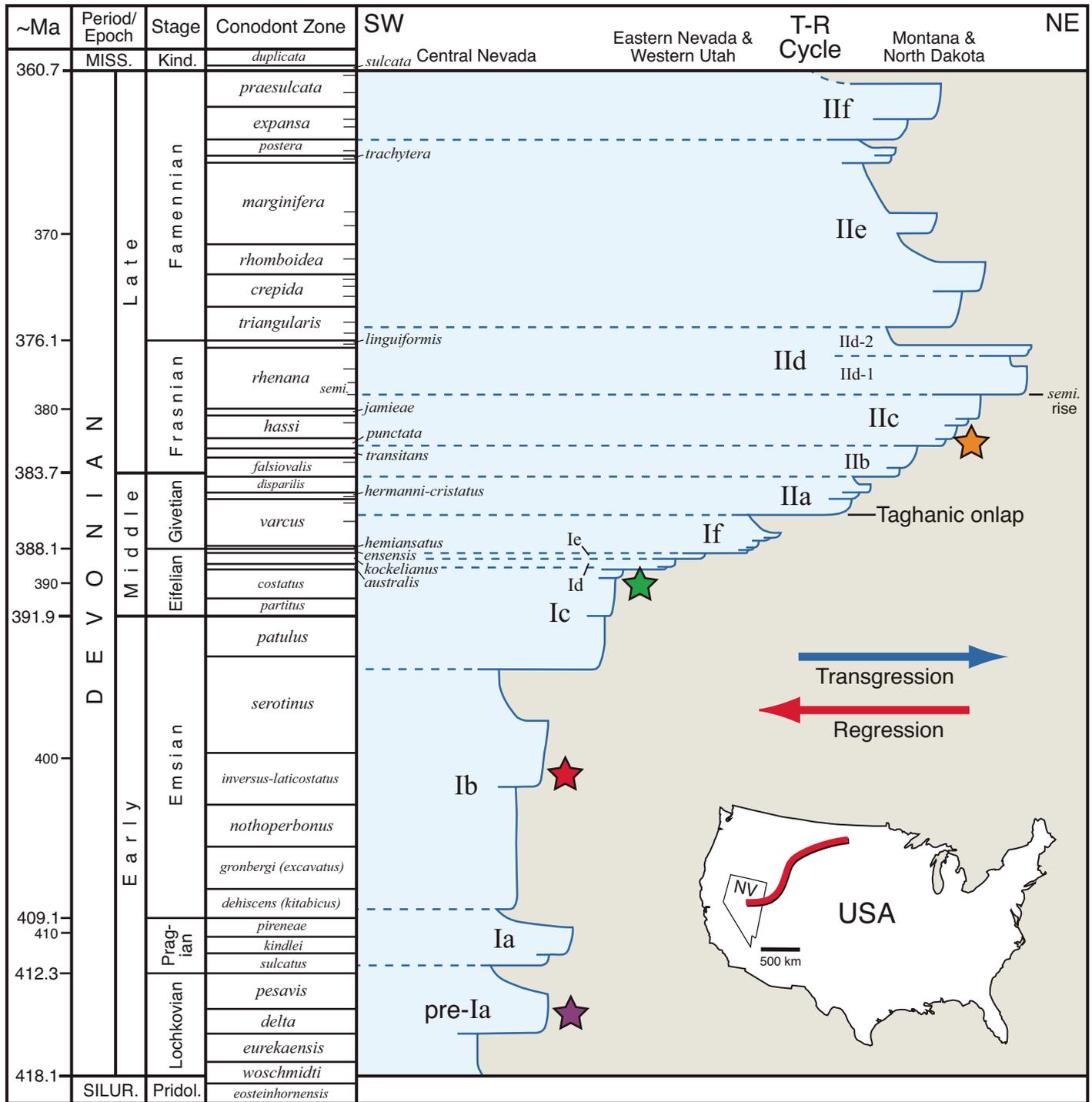


Figure 2. Devonian eustatic sea-level curve, transgressive-regressive (T-R) cycles, and conodont biochronology (Fig. 1) scaled to the numerical time scale of Kaufmann (2006). Additional subdivision of T-R cycle IId into subcycles IId-1 and IId-2 is after Morrow and Sandberg (2003). Colored stars mark carbonate-shelf margin positions shown in Figure 3. Inset shows transect depicted in figure. Abbreviations: MISS.—Mississippian; Kind.—Kinderhookian; NE—northeast; Pridol.—Pridolian; semi.—*semichatovae* Subzone interval and *semichatovae* rise; SILUR.—Silurian; SW—southwest. Modified from Johnson et al. (1985, 1991), Johnson and Sandberg (1989), Sandberg et al. (2002), Kaufmann (2006), and our personal observ.

Devonian outer-shelf to shelf-margin deposits in central Nevada consist of shallow- to deep-subtidal, bioturbated bioclastic wackestone, packstone, and grainstone. During parts of the Early and Middle Devonian when a flat-topped carbonate platform developed (Elrick, 1996; Cook and Corboy, 2004), margin deposits included stromatoporoid-dominated biostromes. Slope and basin rocks farther west in Nevada include bioclast- and quartz-sand-rich packstone and grainstone deposited within debris flows, fans, and turbidites, intraformational flat-clast conglomerate, and rhythmically bedded argillaceous carbonate and fine- to medium-grained siliciclastic units. In the most distal settings, rhythmically bedded radiolarian chert, very fine- to fine-grained siliciclastic beds, bedded barite, and minor mafic submarine volcanic units occur. The Early and Middle Devonian carbonate shelf to basin transition, which can be in part characterized using classic carbonate platform models (e.g., Wilson, 1975; Read, 1982; James and Mountjoy, 1983), was characterized by several paleotectonic settings including homoclinal ramps, distally steepened ramps, shallow-marine margins with intrashelf basins, and shallow-marine shelf margins flanked by subtidal platforms and slope aprons (Cook et al., 1983; Kendall et al., 1983; Johnson and Murphy, 1984; Schalla and Benedetto, 1991; Elrick, 1996; Cook and Corboy, 2004). Throughout the latter half of the Devonian, however, proto-Antler and Antler orogenic tectonism exerted a strong, and at times dominant, control on the geometry of the carbonate shelf-margin to basin settings.

Devonian Tectonic Modes

The Neoproterozoic to early Paleozoic was marked by a complex pattern of extensional tectonism and rifting along western North America as the proto-Pacific oceanic basin opened following the breakup of Rodinia at ca. 850–650 Ma (Stewart, 1972; Stewart and Suckek, 1977; Poole et al., 1992). Neoproterozoic and Lower Cambrian rocks across eastern and central Nevada are dominated by quartzite with interstratified argillite or phyllite, which were deposited in a westward-thickening sedimentary wedge over structurally complex, Paleoproterozoic to Neoproterozoic crystalline basement rocks (Poole et al., 1992). Outer-shelf and shelf-margin basins, which probably formed by reactivation of structures inherited from Neoproterozoic rifting of underlying crystalline continental basement (Stewart, 1972; Stewart and Poole, 1974), strongly influenced sedimentation patterns in Nevada during the Middle Cambrian to Middle Devonian (Johnson and Potter, 1975;

Matti and McKee, 1977; Johnson and Murphy, 1984; Miller et al., 1991; Poole et al., 1992). By the Ordovician (Ross, 1977) or Silurian (Poole et al., 1977), a volcanic island-arc system had developed over subducting oceanic crust west of the North American continent.

During the Early and early Middle Devonian especially, facies patterns, rock isopachs, strontium and lead isotope isopleths, basement gravity signatures, and synsedimentary exhalative gold and barite deposits all suggest that the shelf margin was characterized by a complex series of restricted, active fault-bound subbasins. These strongly influenced the type, extent, and thickness of sedimentation (Grauch, 1998; Emsbo et al., 1999, 2006; Hofstra and Cline, 2000; Crafford and Grauch, 2002; Grauch et al., 2003; Emsbo and Morrow, 2005). Localized extensional or transtensional tectonics within a postulated backarc basin located between the volcanic arc and the continent may have further promoted the formation of fault-bound shelf-margin subbasins prior to late Middle to early Late Devonian compression and transpression associated with the approaching Antler orogen (Poole et al., 1977; Eisbacher, 1983; Crafford and Grauch, 2002).

In central Nevada, the earliest direct stratigraphic evidence for a switch to a convergent tectonic mode is indicated by uplift and erosion associated with development of the initial, shallow-marine to emergent proto-Antler forebulge during the latest Givetian to early Frasnian *disparilis*, *falsiovalis*, and *transitans* Zones (Sandberg et al., 2003). Subsequent Late Devonian and Mississippian depositional settings and facies patterns on the outer shelf and shelf margin were dominated by the tectonic effects of the converging North American continent and proto-Pacific oceanic plate (Poole, 1974). The resulting Antler orogenic belt formed an eastward-migrating system composed, from west to east, of an allochthon, foreland basin, forebulge, and backbulge basin (Pilot basin), which developed onto the carbonate-dominated shelf to the east (Poole, 1974; Poole and Sandberg, 1977; Goebel, 1991; Giles, 1994; Giles and Dickinson, 1995).

By the late middle Famennian Early *postera* Zone, widespread uplift driven by the continued eastward migration and expansion of the Antler orogen and its leading forebulge formed a regional unconformity that interrupted or removed most of the earlier Famennian depositional record across most of the carbonate shelf (Sandberg et al., 1989, 2003; Poole and Sandberg, 1991). The magnitude of this extensive unconformity was amplified by emergence of the Antler orogen and a major eustatic sea-level fall that began during the latest Famen-

nian Middle *praesulcata* Zone and persisted into the Mississippian (Sandberg et al., 1989, 2001, 2002). Final convergence of the Antler orogen with western North America during the Mississippian thrust Devonian and underlying lower Paleozoic basin and slope rocks over coeval shelf-margin and outer-shelf rocks, forming the Roberts Mountains thrust system (RMTS, Fig. 3; Johnson and Pendergast, 1981; Poole et al., 1992). Recent models of the Roberts Mountains thrust system characterize it as a complex zone of intercalated, folded, thrust, and imbricated Proterozoic to middle Paleozoic structural-stratigraphic units (e.g., Theodore et al., 1998; Noble and Finney, 1999; Crafford and Grauch, 2002). At the site of the former carbonate-shelf margin, the Mississippian (Kinderhookian–Chesterian) deep Antler foreland trough was filled by compositionally immature, syntectonic clastic submarine fans derived from the allochthon on the west and calciclastic fans derived from the forebulge on the east (Johnson and Pendergast, 1981; Poole and Sandberg, 1991; Sandberg et al., 2001).

EVENTS IN SHELF-MARGIN DEVELOPMENT

Evolving changes in the position of the Devonian carbonate-shelf margin in Nevada are shown in map view in Figure 3 and in a time-rock cross section in Figure 4, which is a modification of a cross section first published by Johnson and Sandberg (1977). This cross section was revised in several papers, e.g., Kendall et al. (1983), Johnson and Murphy (1984), and Johnson et al. (1985, 1989, 1996). On the basis of previous event-stratigraphic frameworks (Sandberg et al., 1988, 1989, 2002, 2003; Johnson et al., 1989) and compilation and reinterpretation of other previously published work, 12 major events that most strongly influenced the evolution of the margin are recognized (Table 1). These events, which encompass the transition from long-term extensional to compressional modes, include changes due to eustasy (Fig. 2), tectonism, carbonate-shelf productivity related to mass extinction, and shelf-margin position caused by the Alamo Impact Event. Where appropriate, the changes are related to their corresponding conodont zonal ages (Fig. 1). Additional discussion of these events, focusing on new interpretations, is presented in the next section.

(1) Early Devonian Shelf Margin

Lochkovian facies record the maximum westward extent of the Devonian carbonate-shelf margin (Fig. 4; Johnson et al., 1989; Sandberg et al., 1989), during T-R cycle pre-Ia (Fig. 2;

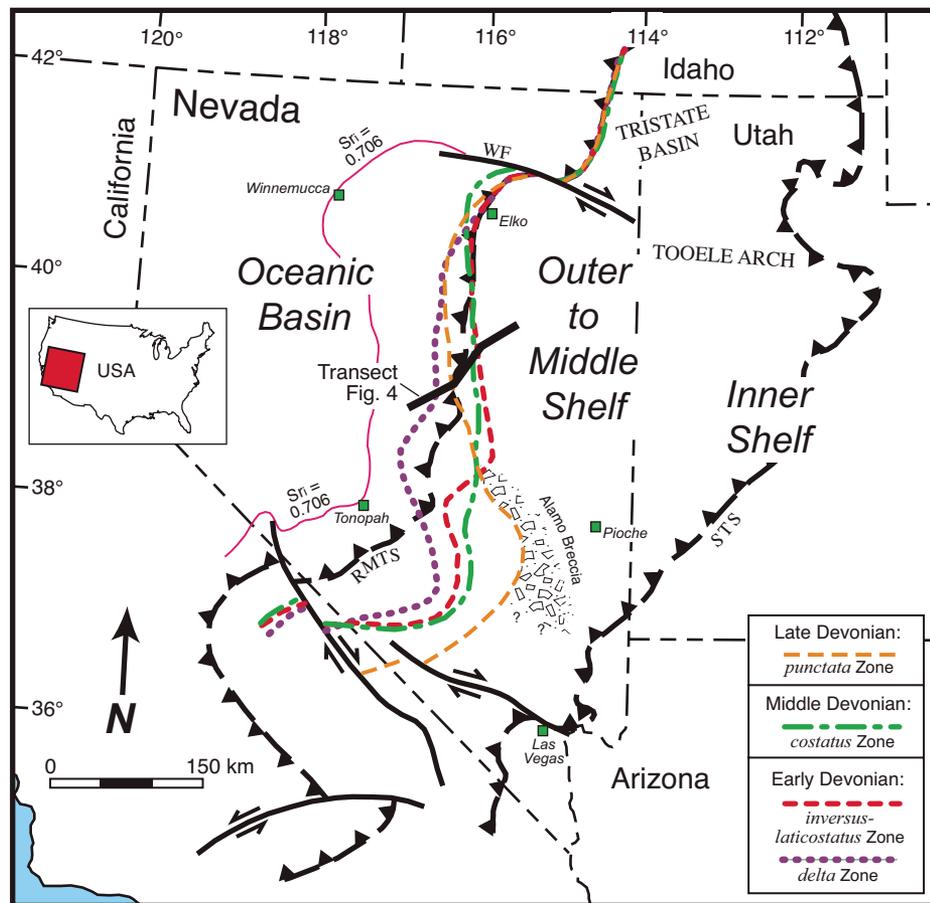


Figure 3. Partly restored paleogeographic map, Nevada and western Utah, showing representative positions of the carbonate-shelf margin through the Devonian; see Figure 1 for conodont biochronology. Position of *punctata* Zone margin is prior to eastward shift (Fig. 6) produced by the Alamo Impact and formation of the Alamo Breccia, indicated in figure. Apparent juxtaposition of carbonate-shelf margin positions in northern Nevada is largely due to Antler orogenic compression and overthrusting. Approximate position of western edge of continental crust is indicated by Sr_1 ($^{87}Sr/^{86}Sr$) = 0.706. Tristate basin and Tooele arch are broad, persistent Devonian structural features (Sandberg et al., 1989; Poole et al., 1992). Positions of other Devonian intrashelf basins, including depositional sites of Middle Devonian Woodpecker Limestone (Elrick, 1996) and Upper Devonian–Mississippian Pilot Shale (Sandberg et al., 1989, 2003), are omitted for simplicity. Abbreviations: RMTS—Roberts Mountains thrust system; STS—Sevier thrust system; WF—Wells fault. Major Cenozoic strike-slip faults and time-rock transect line (Fig. 4) are also shown. Data from Johnson et al. (1989) and Sandberg et al. (1989, 2002).

Johnson et al., 1985). During the early Lochkovian, the carbonate shelf was characterized by a shallow-marine, basinward-prograding and aggrading outer-shelf margin, which separated an onshore, shallow-subtidal to peritidal shelf basin on the east (Lone Mountain Dolostone) from relatively steeply inclined, marginal slope and shelf-margin basin settings on the west (Roberts Mountains Formation; Mullens, 1980; Cook et al., 1983; Johnson and Murphy, 1984; Johnson et al., 1989; Cook and Corboy, 2004). Deposits of carbonate turbidites and debris

flows formed a deep-water, mass-transported, submarine apron facies within the Roberts Mountains Formation along the slope and basin to the west.

In the late Lochkovian, laminated, turbiditic, and debris-flow carbonates of the Windmill, Bastille, and McMonnigal Limestones continued to fill shelf-margin basins seaward of the Lone Mountain carbonate-shelf edge. Relatively small, isolated, carbonate banks or reefs of the Tor Limestone also developed west of the shelf margin (Matti and McKee, 1977; Johnson

et al., 1989). A regional Lochkovian-Pragian boundary depositional hiatus and unconformity marks the top of the Lone Mountain Dolostone (Fig. 4; Johnson et al., 1985, 1989). Following this hiatus, the Beacon Peak Dolostone, Kobeh Member of the McColley Canyon Formation, and Rabbit Hill Limestone evidence establishment, respectively, of shallow-subtidal to peritidal carbonate-shelf, distally steepened ramp, and outer shelf-margin slope to basin settings in the Pragian (Fig. 4).

(2) Early and Middle Devonian Shelf-Margin Basins

Relatively complex outer-shelf and shelf-margin basins characterized the western edge of the North American continent throughout the Early Silurian to Middle Devonian (Johnson and Potter, 1975; Johnson and Murphy, 1984; Johnson et al., 1989), persisting at least into the middle Eifelian (T-R cycles Ia–Ic; Johnson et al., 1985) and possibly into the Givetian. As evidenced by facies trends and depositional patterns defining a significant eastward shift of the carbonate-shelf margin in Nevada (Figs. 3 and 4), shelf-margin basin development reached a maximum extent during the Emsian to middle Eifelian (*dehiscens* to *costatus* Zones). In central and northern Nevada, shelf-margin and slope rocks of the Popovich Formation contain common mass-transport and soft-sediment deformation features and relatively abrupt lateral and vertical facies changes (Theodore et al., 1998; Furley, 2001), possibly reflecting deposition into or within restricted shelf-margin basins bound by active high-angle faults (Emsbo et al., 1999, 2006; Hofstra and Cline, 2000).

The hypothesis of a carbonate-shelf margin characterized by active fault-bound subbasins is further strengthened by the distribution patterns and abrupt thickness changes in Lower and Middle Devonian rocks along and adjacent to the margin in central and northern Nevada (Figs. 4 and 5; Poole et al., 1977, 1992; Armstrong et al., 1998; Emsbo et al., 2006). These depocenters also align closely with the linear, northwest-trending Battle Mountain–Eureka and Carlin gold trends, which are characterized in part by syngenetic or early diagenetic Devonian ore mineralization (Crafford and Grauch, 2002; Emsbo et al., 2006). Recognition in the Lower and Middle Devonian rocks of economically important, syngenic exhalative gold and barite deposits emplaced by hydrothermal brines provides additional evidence that deep-seated faulting within the underlying lower Paleozoic and Precambrian supracrustal and crustal rocks probably played a critical role in Devonian shelf-margin basin

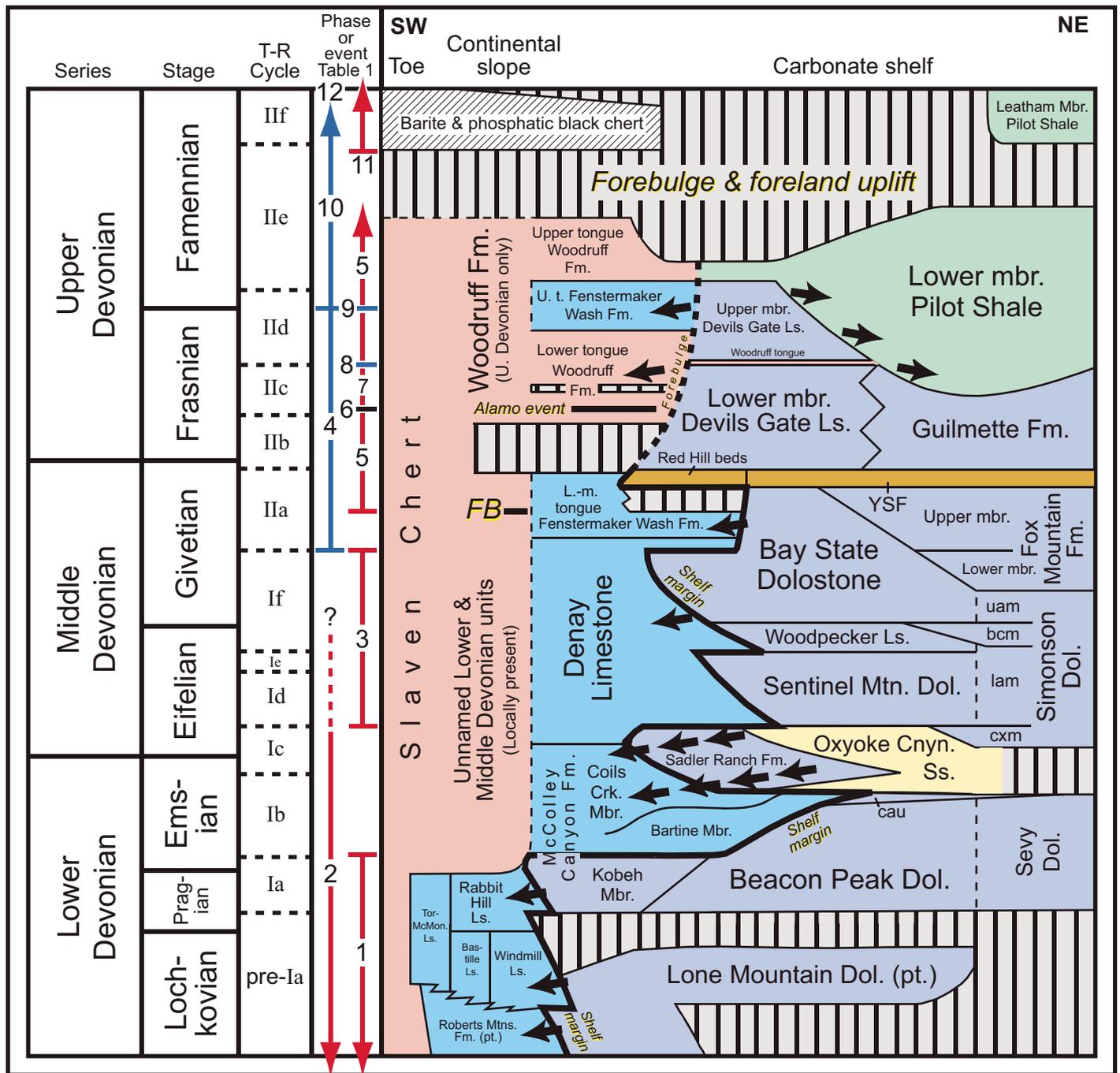


Figure 4. Northeast to southwest, Devonian time-rock transect across central and eastern Nevada (transect line shown in Fig. 3), showing carbonate-shelf, continental slope, and toe lithostratigraphic units and relative lateral shifts in shelf margin through time. Main phases or events in shelf-margin development (Table 1) are delineated: vertical blue lines denote eustatic changes; vertical red lines denote tectonic changes. Transgressive-regressive (T-R) cycles Ia–IIf (Johnson et al., 1985, 1991; Johnson and Sandberg, 1989), main intervals of turbidity current and debris-flow deposition (arrows), proto-Antler forebulge initiation (FB), and timing of Alamo Impact Event are indicated. Silty dolostone and siltstone of the yellow slope-forming member (YSF), which forms the basal unit of the Guilmette Formation and Devils Gate Limestone, constitute a widespread marker lithology distributed throughout western North America (Sandberg et al., 1989, 1997, 2002). The YSF is herein correlated with fish-bearing Red Hill beds in north-central Nevada. Four members of Simonson Dolostone: cxm—coarse crystalline member; lam—lower alternating member; bcm—brown cliff member; and uam—upper alternating member. Other abbreviations: cau—cherty argillaceous unit; Cnyn.—Canyon; Crk.—Creek; Dol.—Dolostone; Fm.—Formation; L.—Lower; Ls.—Limestone; m.—middle; mbr.—member; McMon.—McMonnigal; Mtns.—Mountains; pt.—part; Ss.—Sandstone; t.—tongue; U.—Upper. Modified from Johnson and Sandberg (1977), Johnson and Murphy (1984), Johnson et al. (1996), and M.A. Murphy (14 September 2007, personal commun.), with additional data from Sandberg et al. (1989, 1997, 2002, 2003) and our personal observ.

TABLE 1. MAJOR PHASES AND NUMBERED EVENTS, DEVONIAN SHELF MARGIN, NEVADA

Phase	No.	Event and geologic effects	Stage or conodont zone	Ref.*
Compressional	12	Sea-level fall accompanies end-Famennian mass extinction	Middle <i>praesulcata</i> Zone	19–22
	11	Widespread Antler orogenic uplift and erosion of former foreland basin and shelf-margin rocks, with eastward shift of shelf-margin	Middle Famennian (Early <i>postera</i> Zone) to Kinderhookian (Lower <i>crenulata</i> Zone)	11–12, 19–22
	10	Long-term eustatic sea-level fall and westward shift of shelf margin, punctuated by transgressive-regressive cycles of probable glacio-eustatic origin; partial post-extinction reestablishment of carbonate ecosystems	Famennian	11–12
	9	Short-term eustatic sea-level rise followed by prolonged fall; widespread exposure of carbonate shelf and collapse of carbonate-shelf margin; large carbonate productivity loss accompanies final steps of late Frasnian mass extinction	Frasnian-Famennian boundary	11, 18
	8	Major, short-term eustatic sea-level rise; eastward shift of deep-subtidal environment across outer- to middle-shelf settings; short-lived connection between Woodruff and Pilot basins	Late Frasnian (Early <i>rhenana</i> Zone, <i>semichatovae</i> Subzone)	11–13
	7	Increased development and eastward migration of proto-Antler forebulge and formation of Pilot backbulge basin in outer- to middle-shelf settings	Middle to late Frasnian (Early <i>hassi</i> to <i>rhenana</i> Zones)	13, 17
	6	Marine Alamo Impact Event, south-central Nevada; widespread shattering of outer-shelf rocks, downslope and craterward transport of carbonate-shelf debris, and instantaneous eastward shift of shelf margin	Early Middle Frasnian (middle part of <i>punctata</i> Zone)	11, 14–16
	5	Initiation of proto-Antler forebulge in central Nevada and offshore Woodruff basin to west of forebulge; earliest backbulge subsidence develops slowly	Late Givetian to early Frasnian (<i>disparilis</i> to <i>transitans</i> Zones)	13
Extensional	4	Taghanic onlap; stepped, long-term transgression and eastward shift of shelf margin; extensive carbonate platform develops over shelf	Early Givetian (Middle <i>varcus</i> Zone) to Frasnian	1–3, 11–12
	3	Middle Devonian reestablishment of basinward-prograding carbonate-shelf margin, characterized in part by shallow-marine margin with intrashelf Woodpecker basin and in part by distally steepened ramp to slope setting	Early Eifelian to Givetian	1–3, 10
	2	Early and Middle Devonian carbonate shelf-margin basins form; eastward backstepping of margin with distally steepened ramp to west; in northern Nevada, hydrothermal metal-rich brines vent into restricted shelf-margin basins	Emsian (<i>dehiscens</i> Zone) to mid-Eifelian (<i>costatus</i> Zone) and possibly younger	1–4, 6–10
	1	Basinward-prograding carbonate shelf; westernmost extent of Devonian shelf margin; shallow-marine shelf margin with slope-apron deposition into shelf-margin basins	Lochkovian to Pragian	1–6

*References: 1—Johnson and Murphy (1984); 2—Johnson et al. (1989); 3—Johnson et al. (1996); 4—Cook and Corboy (2004); 5—Matti and McKee (1977); 6—Johnson and Potter (1975); 7—Poole et al. (1977); 8—Kendall et al. (1983); 9—Emsbo et al. (2006); 10—Elrick (1996); 11—Sandberg et al. (2002); 12—Sandberg et al. (1989); 13—Sandberg et al. (2003); 14—Warme and Sandberg (1995); 15—Warme and Kuehner (1998); 16—Morrow et al. (2005); 17—Giles (1994); 18—Sandberg et al. (1988); 19—Poole and Sandberg (1977); 20—Poole and Sandberg (1991); 21—Poole et al. (1992); 22—Sandberg et al. (2001).

deposition (Emsbo et al., 1999, 2006; Hofstra and Cline, 2000; Crafford and Grauch, 2002). Strontium and lead isotope isopleths, which provide a proxy of the position of the edge of the continental crust, give further indication of a structurally complex margin that strongly influenced Early and Middle Devonian deposition (Crafford and Grauch, 2002; Grauch et al., 2003; Emsbo et al., 2006).

(3) Middle Devonian Prograding Shelf Margin

During the mid-Eifelian to mid-Givetian (*australis* to Middle *varcus* Zones, Fig. 1), the carbonate-shelf margin and adjacent shallow-marine shelf settings were again characterized by basinward progradation and aggradation (Fig. 4). This westward shift of the mar-

gin, which was as much as 100 km or more in central and southern Nevada (Johnson et al., 1989), corresponds to T-R cycles Id–If (Johnson et al., 1985). Lithostratigraphic units that evidence this westward expansion of the carbonate shelf include, from onshore to offshore, the lower alternating, brown cliff, and upper alternating members of the Simonson Dolostone, the lower member of the Fox

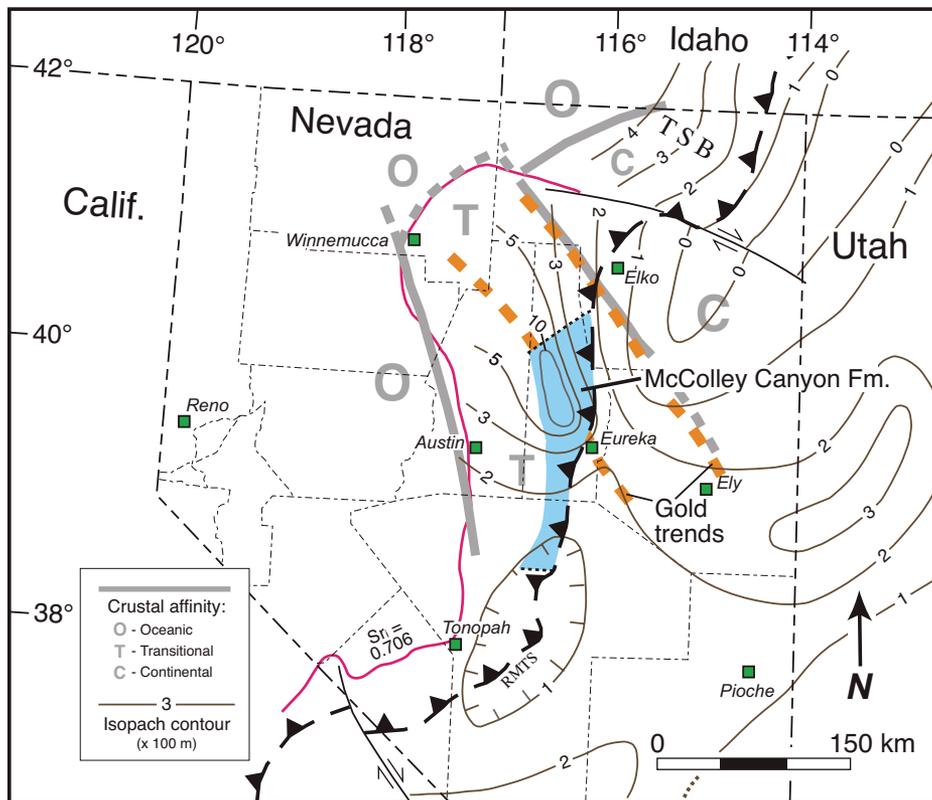


Figure 5. Partly restored base map of northern and central Nevada, showing plot of Lower Devonian isopachs (thin brown lines, contour interval is 100 m), Sr_1 ($^{87}Sr/^{86}Sr$) = 0.706 isopleth, crustal affinity (fields defined by bold gray lines), trends of Carlin-type gold deposits (bold dashed gold lines; Battle Mountain–Eureka trend is southwestern line, Carlin trend is northeastern line), and approximate present outcrop extent of Pragian–lower Eifelian McColley Canyon Formation. The thick McColley Canyon Formation is interpreted to record an Early–Middle Devonian shelf-margin basin flanked by syndepositional, deep-seated faults within underlying basement of inferred transitional continental to oceanic composition. The McColley Canyon depocenter also appears as an anomalous, eastward-projecting embayment of slope facies on the Lower Silurian–Middle Devonian lithofacies map of Poole et al. (1992, plate 3–2). Tristate basin (TSB), Nevada county boundaries, and major towns are shown. Abbreviations: RMTS—Roberts Mountains thrust system. Data compiled from Kendall (1975), Poole et al. (1977, 1992), Crafford and Grauch (2002), Emsbo et al. (2006), and M.A. Murphy (14 September 2007, personal commun.).

Mountain Formation, Sentinel Mountain Dolostone, Woodpecker Limestone, lower and middle parts of the Bay State Dolostone, and coeval part of the slope to basin Denay Limestone (Fig. 4). As documented by Elrick (1995, 1996), facies during this interval demonstrate that the transition from carbonate shelf to basin was marked by two distinct settings: (1) a distally steepened ramp evolving through time to a flat-topped carbonate platform (T-R cycles Id and If; *australis* to *kockelianus* Zones and *ensisensis* to *varcus* Zones, respectively), and (2) a shallow-marine carbonate-shelf margin that separated an intrashelf basin to the east (Woodpecker basin) from slope to basin settings to the west (T-R cycle Ie, *kockelianus* Zone).

(4) Middle Devonian Taghanic Onlap and Long-Term Transgression

The base of T-R cycle IIa, within the mid-Givetian Middle *varcus* Zone, is defined by the Taghanic onlap, which is a major long-term episode of stepped eustatic sea-level rise that reached a maximum in the late Frasnian. This onlap was terminated by rapid eustatic sea-level fall within T-R cycle IIc, during the end-Frasnian *linguiformis* Zone (Johnson et al., 1985; Sandberg et al., 1989, 2002). This transgression marks a major turning point in biotic distribution throughout Laurussia, separating an earlier, Early to Middle Devonian interval of faunal provincialism from a later interval of cos-

mopolitanism that persisted until the latter steps of the late Frasnian mass extinction (Johnson, 1970; Klapper and Johnson, 1980; Ziegler and Lane, 1987; Sandberg et al., 1988, 2002; Johnson and Sandberg, 1989). The Taghanic onlap shifted the carbonate-shelf margin eastward (Figs. 2–4), although facies patterns during this overall transgressive episode were punctuated by several intervening T-R fluctuations (i.e., cycles IIb–IIc; Johnson et al., 1985) and the superimposed tectonic effects associated with the formation of the Antler orogenic belt.

(5) Proto-Antler Forebulge Initiation

During the latest Middle Devonian to early Late Devonian, an eastward-migrating system composed of, from west to east, the proto-Antler allochthon, foreland basin, forebulge, and backbulge basin developed and expanded. Initially, the Woodruff basin developed to the west of the forebulge. Shortly thereafter, the expanding, backbulge Pilot basin formed in outer- to middle-shelf settings as a result of increased tectonic flexure and subsidence in front of the impinging Antler allochthon (Fig. 6; Sandberg et al., 1989, 2003; Goebel, 1991; Giles, 1994; Giles and Dickinson, 1995).

In central and northern Nevada, the earliest evidence of shallowing and emergence associated with the developing proto-Antler forebulge is an unconformity recording an ~1–1.5-m.y.-long period of nondeposition and erosion that spanned the late Givetian to early Frasnian, *disparilis* Zone to *transitans* Zone interval (Sandberg et al., 2003). This depositional break separates the underlying Givetian, middle and lower tongues of the Fenstermaker Wash Formation and intercalated units, which are equivalent to the Red Hill beds of central Eureka County, from the overlying early to middle Frasnian, conglomeratic turbidite event beds characterizing the basal part of the lower tongue of the Woodruff Formation (Fig. 4).

Both the Devonian shelf margin in central Nevada and the adjacent carbonate shelf in eastern Nevada and western Utah were permanently altered by the Antler orogenic system, which marked the switch from extensional to compressional tectonic modes. With full development of the forebulge and rapidly subsiding backbulge basin by the late Frasnian, the previous area of the carbonate-shelf margin was largely reduced and, where preserved, slope rocks deposited west of the forebulge axis overlie former shelf-margin strata (Fig. 4; Sandberg et al., 2003). In the backbulge basin to the east, deep-water slope and basin facies of the lower member of the Pilot Shale covered a large part of the former shallow-water outer to middle carbonate-shelf

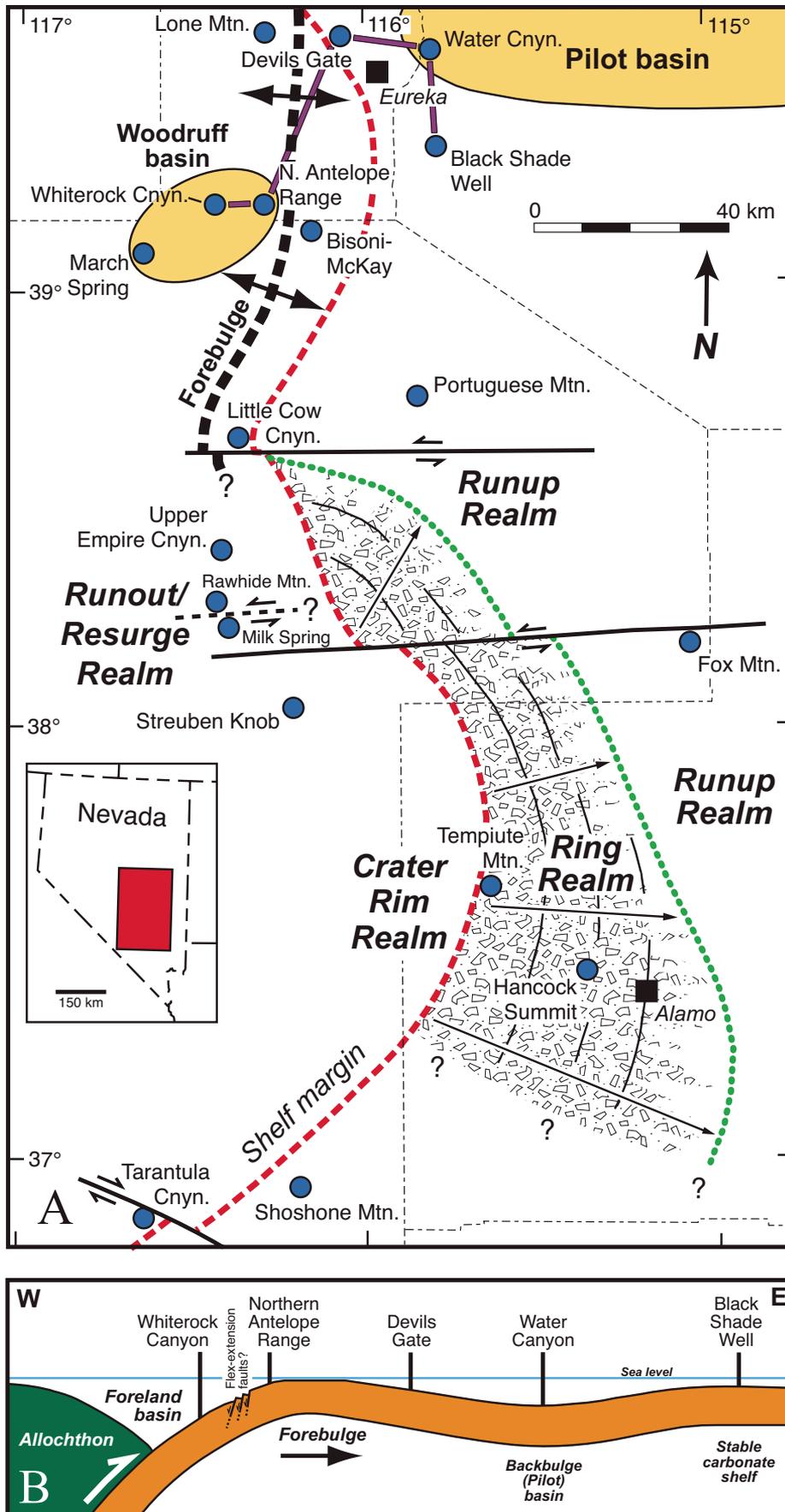


Figure 6. Partly restored, early Late Devonian paleogeographic map and tectonic cross section, southeastern Nevada. (A) Map showing inferred position of *punctata* Zone shelf margin (dashed red line) prior to Alamo Impact Event and diagrammatic eastward shift in margin (arrows and breccia fill pattern) as a result of shattering and downslope and craterward transport of shelf-margin rocks following the event. Genetic Alamo Event realms (Warne and Pinto, 2006; Pinto and Warne, 2008) are indicated. Black concentric curved lines within Ring Realm depict inferred annular ring faults, which are related to the Alamo Event, discussed by Warne and Kuehner (1998) and Pinto and Warne (2008). Maximum possible post-impact eastward shift in shelf margin (green dotted line) corresponds to onshore limit of Ring Realm (or Alamo Breccia Zone 2 of Warne and Sandberg, 1995; Warne and Kuehner, 1998; Morrow et al., 2005). Also shown are positions of initial Pilot and Woodruff basins that formed adjacent to the proto-Antler forebulge (bold dashed black line) during the succeeding Early *hassi* Zone. Closed blue circles denote selected important localities used to constrain map. Purple line connecting White-rock Canyon and Black Shade Well localities marks cross section in Figure 6B. Fine dashed lines delineate Nevada county boundaries. Abbreviations: Cnyn.—Canyon; Mtn.—Mountain; N.—Northern. Modified from Sandberg et al. (2003) and Warne and Pinto (2006). (B) Schematic west to east tectonic cross section during Early *hassi* Zone, showing positions of Antler allochthon, foreland basin, eastward-migrating proto-Antler forebulge, initial backbulge (Pilot) basin, and carbonate shelf. Inferred flexural loading extensional faults west of the forebulge are after Silberling et al. (1997), who proposed such features for the Mississippian foreland system. A similar tectonic model was proposed for the Late Devonian and Mississippian by Poole (1974). By the Early *rhenana* Zone, Black Shade Well was within the expanding Pilot basin (Sandberg et al., 1989; Morrow and Sandberg, 2003). Not to scale; actual west to east distance from toe of allochthon to forebulge axis may have been as much as 200–250 km. Modified from Goebel (1991), Giles (1994), and Giles and Dickinson (1995).

settings. In south-central Nevada, south of the area of the Pilot basin, the carbonate-shelf margin remained intact until the middle Frasnian, when the Alamo Impact Event occurred.

(6) Alamo Impact Event

As evidenced by the catastrophically deposited Alamo Breccia and related impact features, the middle Frasnian (mid-*punctata* Zone), marine Alamo Event was produced by a relatively large bolide impact into an offshore setting west of the carbonate-shelf margin in south-central Nevada. Although post-impact geologic processes have largely obscured the >44-km-wide, >1.7-km-deep crater, which is preserved in a single, tectonically dismembered and displaced fragment of the original crater rim, abundant documented evidence has verified the impact event (e.g., Warme and Sandberg, 1995; Warme and Kuehner, 1998; Sandberg et al., 2002; Warme et al., 2002; Morrow et al., 2005; Warme and Pinto, 2006; Pinto and Warme, 2008). This evidence consists of megabreccias, impact ejecta, tsunamites, onshore channels, and seismically disrupted underlying rocks in at least 25 mountain ranges of Nevada and western Utah. Impact deposits are composed primarily of: (1) proximal to distal, shoreward-thinning belts of megabreccia and breccia that were deposited across outer to inner carbonate-shelf settings east of the shattered shelf margin; (2) proximal, deep-water breccia channels and olistoliths emplaced by downslope and craterward transport of impact debris and ejecta; and (3) distal, tsunami-related uprush and/or backwash breccia and conglomerate channels deposited radially from the impact site on the carbonate shelf, as distant as the inner shelf in western Utah.

Recent work has documented a preserved segment of the eastern rim of the Alamo crater at Tempiute Mountain, Nevada, and has proposed that deposits resulting from the Alamo Event can be classified into six realms based on genetic impact processes: (1) Crater Rim Realm, (2) Runout and/or Resurge Realm, (3) Ring Realm, (4) Runup Realm, (5) Runoff Realm, and (6) Seismite Realm (Fig. 6; Pinto and Warme, 2004, 2008; Warme and Pinto, 2006). The Crater Rim, Ring, and Runup Realms correspond, respectively, to the previously defined, nongenetic Alamo Breccia Zones 1, 2, and 3 of Warme and Sandberg (1995), Warme and Kuehner (1998), Sandberg et al. (2002), and Morrow et al. (2005).

A major effect of the Alamo Impact was the widespread shattering and catastrophic downslope and craterward transport of a huge quantity of lithified and semilithified carbonate-shelf and shelf-margin debris, includ-

ing megablocks, blocks, sediment, and fossil fragments. Deposits of the Alamo Breccia preserved in the Crater Rim and Ring Realms alone cover an area of ~10,000 km² and have an estimated volume of >500 km³ (Warme and Kuehner, 1998). Accompanying this large-scale, offshore transport of impact-shocked and disaggregated debris was the geologically instantaneous reorganization and eastward shift of the pre-impact carbonate-shelf margin (Fig. 6).

Within the Crater Rim Realm at Tempiute Mountain, post-Alamo Breccia rocks consist of dark, organic-rich, laminated, turbiditic and debris-flow carbonate and siliciclastic units deposited in a deep-water, oxygen-poor, slope or basin setting (Warme and Sandberg, 1995; Morrow and Sandberg, 2003), possibly within a partially preserved segment of the crater (Pinto and Warme, 2008). In the Ring Realm, conodont biofacies analysis of beds directly overlying the Alamo Breccia indicate that, following emplacement of the breccia and its capping tsunamites, the water depth over the former outer- to middle-shelf setting may have been locally >100 m (Warme and Sandberg, 1995; Morrow et al., 2005). At this time, the carbonate-shelf margin surrounding the impact site probably consisted of an extremely irregular, unstable, concentrically shaped zone of autochthonous and paraautochthonous fractured, rotated, and displaced carbonate megablocks and blocks draped and injected by a heterolithic mix of sediments emplaced via impact megatsunami and ejecta processes (Warme and Sandberg, 1995; Warme and Kuehner, 1998; Pinto and Warme, 2008). The relief and water depth of the seafloor between the newly formed carbonate-shelf margin and the Alamo crater would have been quite variable, resulting in a complex juxtaposition of small, deep- and shallow-water microenvironments formed by localized accumulations of rotated, imbricated, and stacked megaclasts that were intercalated with variable amounts of breccia and breccia matrix.

(7) Increased Development of Proto-Antler Forebulge and Backbulge Basin

Middle to upper Frasnian facies patterns in central Nevada evidence the increased development, rise, and eastward migration of the proto-Antler forebulge. This was associated with the formation and subsidence of the initial backbulge Pilot basin on the carbonate shelf to the east. In the Early *hassi* Zone, deep-tidal slope rocks consisting of nodular limestone, siltstone, and turbiditic and debris-flow units of the lower Pilot Shale were deposited over shallow-water carbonate shelf rocks of the lower member of the Devils Gate Limestone and upper

member of the Guilmette Formation (Sandberg et al., 1989). The early backbulge Pilot basin was small and nearly circular (Fig. 6), centered in the Cherry Creek Range, northern White Pine County, Nevada (Sandberg et al., 1989, 2003). With increased subsidence during the remainder of the Frasnian, the backbulge Pilot basin expanded as a north-south-trending, elliptical, deep-water, sediment-starved basin extending across the former shelf setting in eastern Nevada and western Utah (Sandberg et al., 1989).

In the Northern Antelope Range, southern Eureka County, evidence of increased tectonic activity along the forebulge is indicated by an intraformational unconformity within the lower part of the lower tongue of the Woodruff Formation. This unconformity separates *transitans*, *punctata*, and Early *hassi* Zone condensed, conglomeratic turbidite beds below from Late *rhenana* Zone turbiditic and debris-flow siltstone units above (Sandberg et al., 2003). The occurrence of reworked Alamo Impact shocked-quartz grains within Late *rhenana* Zone sandy debris-flow beds of the lower Woodruff tongue further documents the uplift and unroofing of rocks as part of the rise and eastward migration of the forebulge.

Along the paleoshoreline in north-central Utah, which was located northeast of the backbulge basin, distal tectonic effects of the eastward-migrating Antler orogen may be recorded by the enigmatic, upper Frasnian(?) to Famennian, peritidal to continental conglomerate and quartz arenite of the Stansbury Formation. This formation, which is dominated locally by lithic clasts eroded from underlying middle to lower Paleozoic and possibly upper Proterozoic shelf rocks, was probably deposited in a syntectonic clastic fan system adjacent to small, actively uplifting fault blocks, or cuestas (Teichert, 1959; Sandberg et al., 1989; Trexler, 1991).

As shown schematically in Figure 6B, Late Devonian loading and downwarping of the continental crust margin in front of the impinging Antler allochthon may have generated flexural-extensional faults. Such faults are inferred along the western side of the forebulge during the Mississippian (Silberling et al., 1997). We suggest that older, deep-seated, active faults were present along the carbonate-shelf margin during the Early to Middle Devonian and that these pre-existing zones of weakness were probably reactivated during the Late Devonian by downward flexure associated with the developing foreland basin system.

(8) *semichatovae* Sea-Level Rise

The late Frasnian, Early *rhenana* Zone transgression defining the base of T-R cycle IId marks

the highest eustatic sea level of the Devonian. Associated with this major eustatic rise was the global, opportunistic expansion of the short-lived conodont species *Palmatolepis semichatovae* into shallow-water, outer and middle carbonate-shelf settings not previously inhabited by this genus. The rapid cosmopolitan expansion and subsequent extinction of this species is used to define the proposed *semichatovae* Subzone, a biostratigraphic interval range zone, within the middle part of the Early *rhenana* Zone (Sandberg et al., 2002). In central and northern Nevada, the *semichatovae* rise (Fig. 2) created a short-term marine strait across the proto-Antler forebulge, temporarily connecting the foreland Woodruff and backbulge Pilot basins (Fig. 4; Sandberg et al., 2003). This deepening event separates the lower and upper members of the Devils Gate Limestone (Sandberg and Poole, 1977; Sandberg et al., 1989, 2003).

(9) Frasnian-Famennian Boundary Events

Following a short-lived regression spanning the Early and Late *rhenana* Zones, sea level once again rose during the latest Frasnian *linguiformis* Zone. This last Frasnian transgression is associated with global marine anoxia tied to the final pulse of the stepped, late Frasnian (or Frasnian-Famennian, F-F) Kellwasser biotic crisis, which ranks among one of the "Big Five" Phanerozoic mass extinction episodes (e.g., McGhee, 1996; Sepkoski, 1996; Hallam and Wignall, 1997). The intensity of the late Frasnian extinction was further amplified by a rapid, prolonged eustatic sea-level fall, which began in the *linguiformis* Zone, ~100 k.y. before the end of the Frasnian, and continued into the early Famennian Middle *triangularis* Zone (Sandberg et al., 1988, 1997, 2002). A hallmark of the late Frasnian mass extinction was global-scale biomass reduction linked to decimation of low-latitude, shallow-water, carbonate-producing ecosystems (Sandberg et al., 1988; McGhee, 1996). The upper Frasnian carbonate shelf in Nevada is characterized by moderate- to high-diversity, amphiporid-, massive stromatoporoid-, coral-, megalodont bivalve-, and brachiopod-dominated biostromes and mudmounds. In contrast, the lower Famennian shelf consists of micrite-, quartz sand-, and peloid-rich carbonates containing a low-diversity macrofauna including mollusks, brachiopods, and microbial laminite communities (Sandberg et al., 1988; Morrow and Sandberg, 2003). The net result of this benthic bioproductivity loss was that, for the first time during the Devonian, short-term carbonate production could not keep up with available accommodation space.

Effects of the major eustatic fall at the Frasnian-Famennian boundary interval, which may have dropped sea level by as much as 100 m (Sandberg et al., 2002), were development of a widespread exposure surface and unconformity across the carbonate shelf (Sandberg et al., 1988, 1989, 2002). Only deeper water backbulge-basin, slope, and foreland-basin settings fully record the geologic and biologic events that characterize the boundary interval. During the early Famennian, Early to Late *triangularis* Zones, the prolonged eustatic fall also led to widespread erosion and downslope collapse of the former carbonate-shelf margin and older proto-Antler forebulge areas. Submarine debris flows and turbidites, originating from the adjacent shallower water shelf or forebulge, swept downslope and eroded into the underlying lowest Famennian and upper Frasnian strata. Evidence of this shelf-margin erosion is found at numerous localities in Nevada, including Devils Gate, Northern Antelope Range, Black Shade Well, and Tempiute Mountain (Fig. 6; Sandberg et al., 1988, 1989, 1997; Morrow and Sandberg, 2003). The Frasnian-Famennian boundary sea-level fall corresponds to the end of T-R cycle IId (Johnson et al., 1985).

(10) Long-Term Famennian Regression

Following an early Famennian, Middle *triangularis* Zone transgression marking the start of T-R cycle IId (Johnson et al., 1985), the remainder of the Famennian was characterized by a general regressive trend (Sandberg et al., 1989, 1997). This trend was interrupted by four significant transgressive-regressive pulses, which are linked to postulated changes in Southern Hemisphere glacial ice volumes (Sandberg et al., 2002). In Nevada, these transgressive-regressive episodes resulted in temporary eastward shifts in the paleoshoreline and concomitant deepening over the carbonate-shelf and shelf-margin settings.

During the Early *crepida* Zone, increased subsidence of the backbulge basin drove lateral expansion and deepening of the Pilot depocenter. In central and northern Nevada, this expansion allowed a localized, short-term connection over the forebulge between the Pilot and Woodruff basins (Fig. 4; Sandberg and Poole, 1977; Johnson and Murphy, 1984; Sandberg et al., 2003). By the time of the first deepening pulse during the Middle *crepida* Zone, biotic recovery following the late Frasnian mass extinction resulted in micrite-, peloid-, and biolaminar-rich carbonate banks on shelf areas surrounding the Pilot basin in northeastern Nevada and western Utah (Sandberg et al., 1989, 2002). Unlike their Frasnian counterparts, however,

these carbonate buildups are composed of a low-diversity megafauna that included rare bulbous and encrusting stromatoporoids, sponges, gastropods, brachiopods, and nautiloid cephalopods (Biller, 1976; Smith, 1984; Williams, 1984). Similar early Famennian carbonate-shelf buildups extended northward, where they are correlated with Palliser bank facies of western Montana and Alberta, Canada (Sandberg et al., 1989).

Following the second glacio-eustatic rise, which is associated with lateral expansion of the Pilot basin, a major regression beginning in the Latest *marginifera* Zone ended carbonate bank growth over the shelf. The third and fourth Famennian transgressive pulses briefly interrupted a prolonged interval of accelerated regression driven by both regional tectonic uplift and glacio-eustatic sea-level fall due to long-term ice volume expansion in the Southern Hemisphere (Sandberg et al., 2002).

(11) Antler Orogenic Uplift and Erosion

Between the third and fourth glacio-eustatic rises, within the Early *postera* Zone, regional epeirogeny associated with the converging Antler orogenic system initiated an episode of prolonged relative sea-level fall that ultimately eroded virtually all of the former middle and upper Famennian shelf-margin and outer-shelf rocks in central Nevada (Fig. 4). This long-term, tectonically driven regression, which continued until the Mississippian Lower *crenulata* Zone (Poole et al., 1992; Sandberg et al., 2001), was interrupted by the fourth, Early *expansa* Zone glacio-eustatic transgression that deposited the Leatham Member of the Pilot Shale (Sandberg et al., 1989) and phosphatic chert and bedded barite in central Nevada. Regional uplift by the impinging Antler belt pushed the shelf margin eastward, so that by the Middle and Late *expansa* Zone interval it trended northeastward from southern Nevada into northeastern Utah (Gutschick and Sandberg, 1983; Johnson and Murphy, 1984; Sandberg et al., 1989).

(12) End-Devonian Sea-Level Fall

A major eustatic sea-level fall, which is recorded primarily by shallow-water rocks outside Nevada, began during the very late Famennian Middle *praesulcata* Zone and continued into the Mississippian (Sandberg et al., 1989). This regression accompanied the terminal end-Famennian mass extinction, which, although less severe than the late Frasnian crisis, strongly affected pelagic and nektonic organisms, together with selected groups of brachiopods, corals, and cephalopods (Walliser,

1996; Sandberg et al., 2002). When eustatic sea level rose again in the Mississippian (mid-Kinderhookian, Lower *crenulata* Zone), the site of the former Devonian carbonate-shelf margin was replaced by the eastward-migrating Antler foreland basin, which was being filled by clastic material shed off the newly emergent allochthon to the west (Poole and Sandberg, 1991; Sandberg et al., 2001).

FUTURE RESEARCH

As summarized herein, the Nevada Devonian carbonate-shelf margin records a complex interplay of eustatic, structural, biotic, and impact events superimposed on the larger scale background transition from extensional to compressional tectonic regimes. Although of considerable value for understanding and reconstructing facies relationships and depositional geometries, standard carbonate-platform and platform-margin models developed for passive settings elsewhere do not adequately describe the diverse depositional settings evidenced along the Nevada margin. Many unanswered questions remain regarding details of the carbonate shelf-margin evolution, especially where Antler and younger orogenic episodes have structurally juxtaposed or removed critical stratigraphic intervals and facies transitions. Specific areas of future research, which may help answer these questions, include the following:

1. Conduct additional detailed, high-resolution biostratigraphic studies in critical central Nevada areas that may contain key information for verifying proposed and new structural and depositional hypotheses. An existing, extensive biostratigraphic and stratigraphic data set, based on a huge time and resource commitment by government, academic, and industry geologists in the past six decades, can serve as a framework for further interpreting complex and poorly understood, but pivotal, regions. Isolated, altered, and fault-bound outcrops and subcrops typically characterize such critical regions. Only by integrating data from more completely preserved rock sequences in adjacent districts can these critical units be identified. Investing in this knowledge database will yield important new results that can support fundamental advances in understanding Devonian Great Basin metallogeny, petroleum geology, and geologic history.

2. Expand the existing Devonian sequence- and event-stratigraphic approach, which was developed largely from surface outcrops, to encompass more readily the economically important units in the Carlin trend and Battle Mountain–Eureka trend gold districts of northern Nevada. This project will require a multidisciplinary effort to synonymize strati-

graphic nomenclature and correlate correctly between subsurface and surface units. If the event-stratigraphic model is valid, it should provide a unifying framework to help integrate and understand seemingly disparate data sets, which have grown from historically complex nomenclature schemes and from a scarcity of high-resolution biostratigraphic or other independent correlation tools.

3. Apply Devonian structural models developed along the Carlin and Battle Mountain–Eureka trends to help better understand the Early and Middle Devonian structural development of the carbonate-shelf margin elsewhere in central and southern Nevada. Robust, detailed geochemical studies of Devonian metal-bearing host rocks in the mining districts of northern Nevada demonstrate the value of this approach for unraveling the complex history of superimposed synsedimentary and younger structural, hydrothermal, and diagenetic episodes. Similar studies in other parts of Nevada might yield important new data for understanding the character of the shelf margin.

4. Initiate additional regional-scale studies to help resolve the controversy regarding the presence and relative importance of active Devonian tectonism associated with deep-seated, continental-margin structural features, which were likely inherited from the Neoproterozoic breakup of Rodinia. Work in northern Nevada, previously cited, indicates that deep-seated, syndepositional faulting linked to development of restricted shelf-margin basins profoundly influenced the resulting depositional patterns and economic mineral deposits. Remaining questions include: how prevalent were similar marginal basins farther to the south in central and southern Nevada, and what were the effects of inherited structural trends on depositional patterns in more distal, onshore shelf settings? More refined biostratigraphic, facies boundary, and facies thickness data sets may help to answer these questions.

5. Construct and apply improved models of crustal response during the early compressional phases of foreland basin system development. Physical evidence of the morphology of the initial proto-Antler foreland basin and related features is largely lost or obscured by younger tectonism. However, detailed modeling may provide valuable hypotheses, possibly still testable in the field, about the transition from extensional to compressional modes and the evolution of the foreland system. Anomalous conglomeratic units such as the Stansbury Formation suggest that early effects of the Antler orogeny may have extended to the inner-shelf setting. The excellent exposures of Devonian strata in the central Great Basin, coupled with the existing

robust stratigraphic, biostratigraphic, geochemical, and event-stratigraphic data sets, can provide an excellent empirical proving ground for future tectonic models.

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