PRELIMINARY FACIES ANALYSIS OF SILURIAN AND DEVONIAN AUTOCHTHONOUS ROCKS THAT HOST GOLD ALONG THE CARLIN TREND, NEVADA

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ABSTRACT

Sedimentary platform rocks in northern Nevada serve as hosts for the bulk of the gold in Carlin-type gold deposits. These deposits largely account for this region comprising the most significant gold province in North America. The most prolific part of the Carlin trend is the northern half, which extends from the Gold Quarry Mine on the south to the Dee Mine on the north. Although sedimentary rocks constitute a fundamental element of genetic models for Carlin-type deposits, the implications and impacts of Paleozoic sedimentary fabrics and diagenetic processes on deposit genesis have not been investigated as thoroughly as have the associated alteration, chemistry of the mineralizing fluids, and structural setting(s) of the deposits. Five Silurian-Devonian rock units below the Roberts Mountains thrust are the principal gold-hosting units in the Carlin trend; these are the Hanson Creek Formation, Roberts Mountains Formation, Bootstrap limestone, Popovich Formation, and the Rodeo Creek unit. Of these units, only the Roberts Mountains and Popovich Formations have the mineralogy and porosity which favors gold mineralization. In both the Roberts Mountains and the Popovich Formations, the sedimentary rocks are typically calcitic dolostones with primary intercrystalline vug porosity resulting essentially from diagenetic crystallization of dolomite. The Roberts Mountains and Popovich Formations thus had an inherent porosity due to primary early crystallization of dolomite in lime mud (micrite) and an abundance of intercrystalline sulfur-rich carbon has subsequently enhanced its reactivity to gold-bearing fluids that circulated there during the Cretaceous and (or) Tertiary.

The sequence of rocks discussed in this report lies below the regionally extensive Roberts Mountains thrust. They include a number of structurally autochthonous units: (**1**) The Ordovician to Silurian Hanson Creek Formation, which is composed of arenaceous dolostones, is the lowest unit studied. These sedimentary rocks were deposited as arenaceous, pellet, peloid, ooid, packstone, and grainstone in a shallow water, shoaling environment as the final phase in a thick, upward shoaling sequence. (**2**) The Silurian and Devonian Roberts Mountains Formation, lying disconformably above the Hanson Creek Formation, is a quartz silt, dolomitic, lime mudstone to packstone, and generally black in color due to carbon. Fossil fragments are common and usually include echinoderms and brachiopods. Siliciclastic sediments are angular silt-size quartz, and have abundant white mica, feldspar fragments, and rare zircons. (**3**) The Silurian and Devonian informally named Bootstrap limestone unit is typically a shallow marine carbonate shelf limestone that is dominated by multiple shoaling upward sequences. The Bootstrap limestone in core from the area of the Ren Mine has dolostones with intercrystalline pores and large vugs. Although the dolostones are vuggy, very low to no permeability is present. The dolomite rhombs, 0.1 to 3 mm in size, are subhedral to anhedral. Essentially all the dolomite rhombs, whether matrix or void filling, are cloudy. (**4**) The Devonian Popovich Formation is conformably above the Bootstrap limestone unit. It is composed of detrital silt size, angular to subrounded quartz, with minor amounts of feldspar, and some clay minerals. Carbonate minerals make up various percentages (approximately 15 to 40 volume percent) of the Popovich Formation, and are 30 to 100 µm-size rhombs of calcite and euhedral dolomite. The rock is typically a calcitic dolostone with some intercrystalline vug porosity. The Popovich Formation has four units that have been delineated in the area of the Meikle and Betze-Post gold deposits. From bottom to top, they are a sedimentary breccia/wispy unit, a fossil hash/planar unit, a soft-sediment-deformation (SSD) unit, and an upper limey mud to mud lime unit. The formation was deposited in a progressively drowned and deeper water environment. Sedimentation went from the foreslope to basin euxinic environments. (**5**) An additional ore host, the informally named late Middle to Late Devonian age Rodeo Creek unit, represents a largely siliceous sequence of sediments that lie conformably above the Popovich Formation in the West Carlin pit and at the Gold Quarry Mine. The Rodeo Creek unit is the highest stratigraphic unit present below the Roberts Mountains thrust in the area of the Carlin trend. Quartz silt, dolostone and quartz silt-dolomite, and argillaceous chert form the Rodeo Creek unit. The environment of its deposition was deep-water euxinic to toe-of-slope.

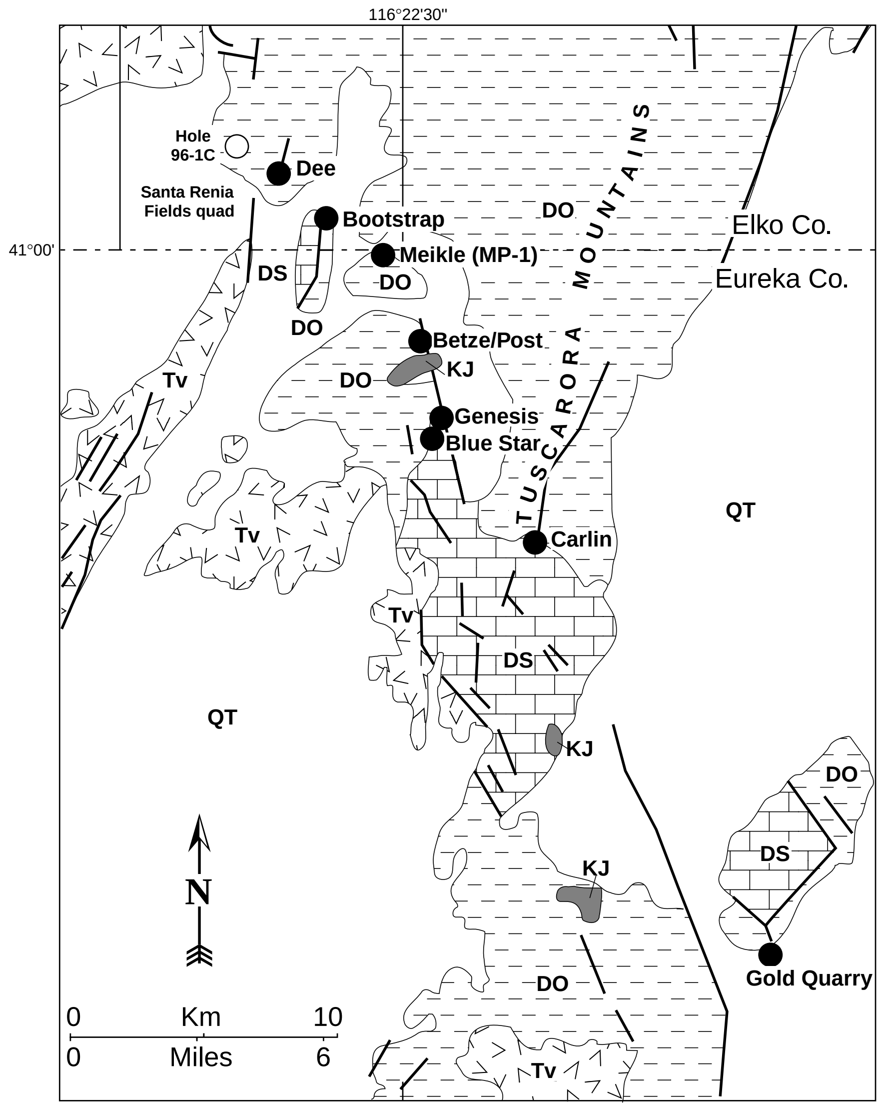
INTRODUCTION

Middle Paleozoic sedimentary platform rocks in northern Nevada serve as hosts for the bulk of the gold introduced into Carlin-type gold deposits (Roberts, 1966; Arehart and others, 1993a; Christensen, 1996). These deposits largely account for this region comprising the most significant gold province in North America. In 1998, approximately 7 million oz Au will be produced from the province, which amounts to approximately 64 percent of United States and 9 percent of world production (Dobra, 1997). Production since 1965 from the Carlin trend of deposits totals about 21 million oz Au (Christensen, 1996). The most prolific part of the 40 mile-long Carlin trend is its northern half which extends from the Gold Quarry Mine on the south to the Dee Mine on the north (fig. 1). Although sedimentary rocks constitute a fundamental element of the genetic model for Carlin-type deposits (Cox and Singer, 1986), the implications and impacts of Paleozoic sedimentary fabrics and diagenetic processes on the genesis of these deposits have not been investigated as thoroughly as have the types of associated alteration, chemistry of the mineralizing fluids, and structural setting(s) of the deposits. Cook (1993) in his discussion of submarine carbonate sedimentary breccias in Paleozoic carbonate of the eastern Great Basin suggests that diagenetically altered carbonate turbidites and megabreccias could form reservoirs for disseminated gold in the Roberts Mountains, Denay, Devils Gate, Pilot and other formations.

The purpose of this report is two fold: (**1**) to present a facies and diagenesis analysis of autochthonous Silurian and Devonian rocks that are the principal hosts for gold in the northern part of the Carlin trend (fig. 2); and (**2**) to suggest that some depositional and diagenetic parameters of these rocks contributed significantly to their becoming premier gold hosts.

The sequence of rocks discussed herein lies below the regionally extensive Roberts Mountains thrust (Roberts and others, 1967. It includes three distinct packages of autochthonous units, listed from base to top (fig. 2): (**1**) The Ordovician and Silurian Hanson Creek Formation, Silurian and Devonian Roberts Mountains Formation, Devonian Bootstrap limestone unit, an informally named unit in the uppermost part of the Silurian and Devonian Roberts Mountains Formation (see also, Merriam, 1940; Merriam and Anderson, 1942; Evans and Mullens, 1976; Mullens, 1980; Armstrong and others, 1987). (**2**) The Devonian Popovich Formation (Hardie, 1966; Evans, 1974; Ettner, 1989) which is dolomitic and calcareous rocks deposited conformably above the Bootstrap limestone unit. And (**3**) the informally named late Middle to Late Devonian Rodeo Creek unit (Ettner, 1989; Ettner and others, 1989). The Rodeo Creek is a mostly siliceous package of rocks which lies conformably above the Popovich Formation in the West Carlin pit and at the Gold Quarry Mine (F.G. Poole, oral commun., 1997). It also is present at the Meikle Mine and elsewhere in the northern part of the Carlin trend (fig. 1). Locally, there is some evidence that the contact between the Rodeo Creek unit and the Popovich Formation is depositional, although there may be a possible hiatus, with karsting. There is also evidence of faulting and the localization of intrusive sills along the contact between the two units in the Meikle and Betze-Post area (Volk and others, 1996). The Rodeo Creek unit probably is age equivalent to parts of the Devonian Woodruff Formation. The Woodruff Formation originally was described in the Carlin-Piñon Range area (Smith and Ketner, 1968, 1975), and it is equivalent in age to the Devonian Scott Canyon Formation (Roberts, 1964; Jones and others, 1978) and the Devonian Slaven Chert (Gilluly and Gates, 1965). The latter two units presumably make up part of the allochthonous siliceous assemblage overlying the Roberts Mountains thrust approximately 50 miles west of the Carlin trend. However, some parts of the Scott Canyon Formation in the Battle Mountain Range and the Slaven Chert in the Shoshone Range may, in fact, represent autochthonous rock packages that lie below the Roberts Mountains thrust rather than above the thrust as has been traditionally proposed (Roberts and others, 1958; Roberts, 1964; Gilluly and Gates, 1965). These two formations, if the herein amended regional tectonostratigraphic interpretations prove to be valid, then could be considered deep water, rifted margin equivalents of the Rodeo Creek unit, because of the presence in them of significant volumes of submarine basaltic rock (see also, Madrid, 1987). However, the presence of lower Paleozoic carbonate sequences of rock in the East Range approximately 40 miles west of the Battle Mountain Range, (Whitebread, 1994) appears to argue against such a hypothesis. The Rodeo Creek unit is the highest stratigraphic unit present below the Roberts Mountains thrust in the area of the Carlin trend (see also, Ettner, 1989).

This preliminary study is based on a large number of samples systematically collected and made into thin sections and polished sections from 12 deep exploration drill holes in the general area of gold deposits along the Carlin trend. Barrick Gold Corporation, Minorca Resources Inc., and Uranerz U. S. A., Inc. provided access to these drill holes. All samples were examined using standard petrographic techniques, and many polished sections were studied by scanning electron microscope (SEM). In addition, hand-specimen-scale structures and textural relations in all cores were studied; these examinations supplemented those previously completed by company geologists who initially logged the cores during their drilling. Our study also included material from a number of underground horizontal drill holes into the orebody at Barrick's Meikle Mine (fig. 1). Most deep holes penetrated a relatively intact sequence of autochothonous rocks below the Robert Mountains thrust near the northwest end of the Carlin trend. They provide an extraordinary opportunity to construct depositional environments during the Paleozoic for many rocks that host the bulk of the gold in the most significant gold province in North America. We emphasize that this report is a



EXPLANATION

QT Quaternary alluvial and playa deposits and Tertiary sedimentary,tuffaceous, and lacustrine rocks

VOLCANIC AND SHALLOW INTRUSIVE ROCKS

Tv Tertiary volcanic rocks including andesite flows and breccias, rhyolite flows, shallow intrusive rocks, and ash-flow tuffs

INTRUSIVE ROCKS

KJ Intrusive rocks of granitic to dioritic composition

SEDIMENTARY ROCKS

DO Devonian Woodruff and (or) Slaven Chert and Ordovician and Silurian Vinini Formation: shale, chert, siliceous argillite, limestone, minor quartzite, and greenstone

DS Devonian limestone and Silurian and Devonian Roberts Mountains Formation: limestone, dolomite, and calcareous siltstone. Locally includes Devonian Rodeo Creek unit, Popovich Formation, as well as several other Silurian and Devonian carbonate platform units

● Gold deposits

Figure 1. Geologic sketch map of the southern Tuscarora Mountains, Elko and Eureka Counties, Nevada. Modified from Christensen (1996).

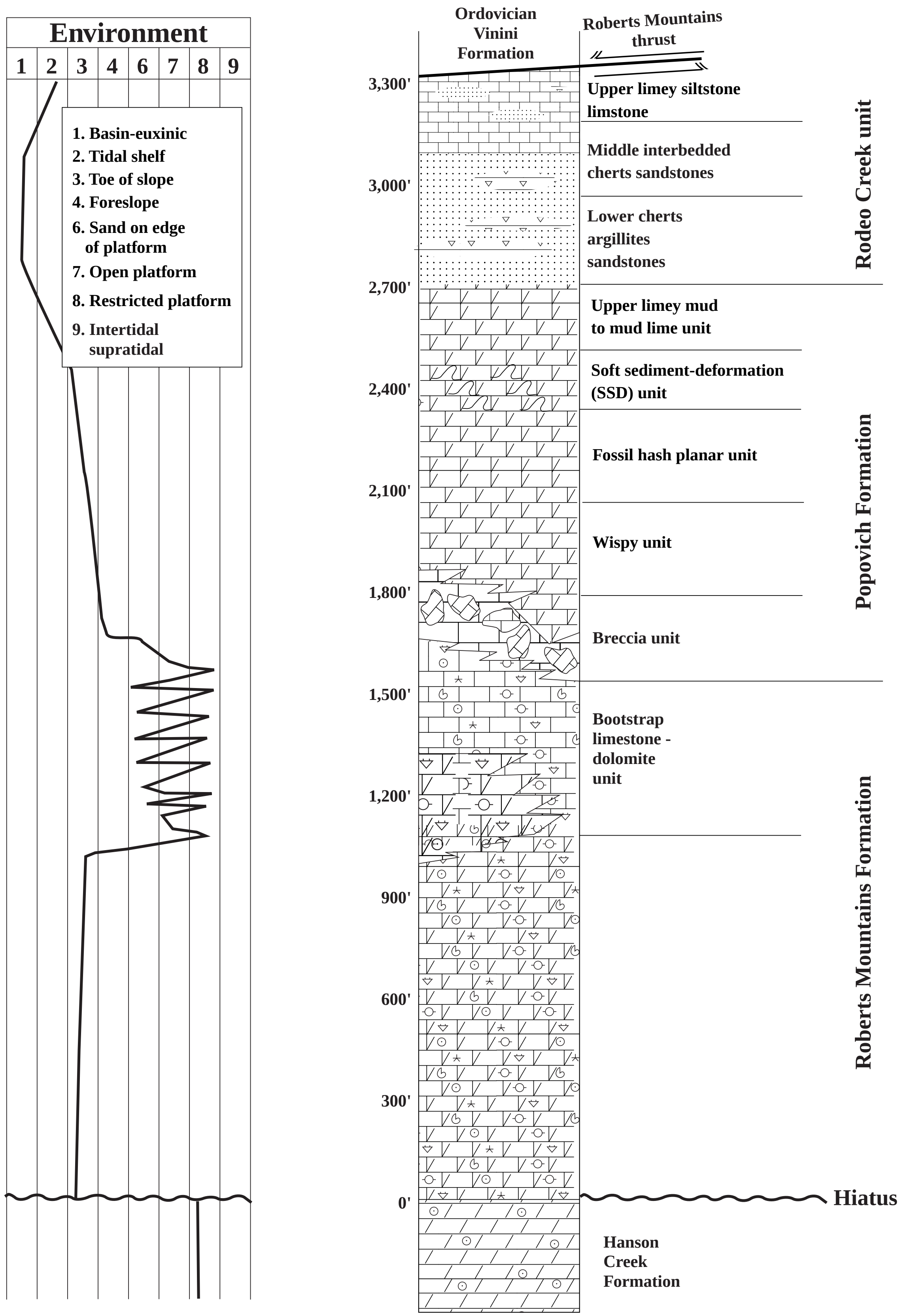


Figure 2. Schematic stratigraphic column in the general area of the Goldstrike Mine. In part modified from Volk and others (1996).

work in progress, and it represents a contribution towards establishment of a consistent regional stratigraphic nomenclature and understanding.

The carbonate classification used in this study is Dunham's (1962).

STRATIGRAPHY

Hanson Creek Formation

The name Hanson Creek Formation was first applied to upper Ordovician limestone beds in the Roberts Mountains (Merriam, 1940), approximately 70 miles south of the northern Carlin trend, where the type section is situated on Pete Hanson Creek (Merriam, 1963).

Within the general area of the northern terminus of the Carlin trend, exploration drilling has encountered only the upper part of the Hanson Creek Formation. The rocks are arenaceous dolostone. The sediments were deposited as arenaceous, pellet, peloid, ooid, packstone and grainstone in a shallow water environment as the final phase in a thick shoaling upwards sequence. The quartz sand is subrounded to rounded 0.3 to 1-mm sand grains and is supported by a dolomite matrix.

Diagenesis

Dunham and Olson (1980) published a study of the Hanson Creek Formation of Eureka County, Nevada. Their research included petrographic studies combined with the examination of trace element and isotope data. Their interpretation is that major dolomitization events which affected the Hanson Creek strata took place in the shallow subsurface as a result of the mixing of meteoric derived ground water and marine pore water in the Early Silurian. Incursion of freshwater into subtidally deposited sediments took place as a result of vertical and lateral extensions of freshwater lenses that developed beneath subaerially exposed tracts of an inner carbonate platform. Dolomite to limestone transition marked the maximum extent of freshwater lenses in the subsurface. Their study indicates that although the dolomite is diagenetic, it is not related to the depositional environment of the original carbonate sediment. The dolomite is early diagenetic, formed through surface-related processes before deposition of the overlying Roberts Mountains Formation. Regional stratigraphic evidence shows subaerial erosion at the top of the Hanson Creek Formation. Conodont data indicate the top of the Hanson Creek is early Silurian (middle Llandovery), and the base of the Roberts Mountain Formation is late Llandovery (late Early Silurian). Thus a depositional hiatus equivalent to the length of the middle Llandovery separates the Hanson Creek from the Roberts Mountains Formation. Hanson Creek dolomitization occurred during this hiatus (3 to 5 m.y.), probably early on, when the Hanson Creek marine carbonate sequences were exposed to fresh water recharge, and as a result of the mixing of meteoric derived ground water and marine pore water.

Roberts Mountains Formation

Many geologists (Merriam and Anderson, 1942; Nolan and others, 1956; Merriam, 1963, Roberts and others, 1958; Roberts, 1964, Gilluly and Gates, 1965; Smith and Ketner, 1968, 1975; Stewart and McKee, 1977, and Stewart and Poole, 1974) have studied the Roberts Mountain Formation.

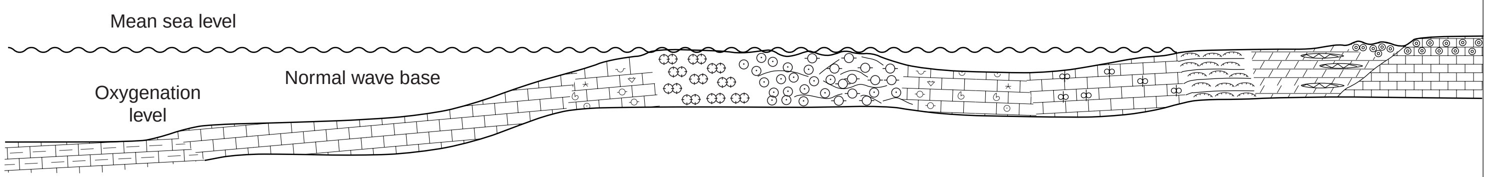
Mullens (1980) presents an excellent discussion of the regional distribution of the Roberts Mountains Formation for north-central Nevada. In the Roberts Mountains, the Roberts Mountain Formation interfingers with the shoal water equivalent of the Lone Mountain Dolomite. Within the Carlin trend, the Roberts Mountains Formation is quartz silt and dolomitic limestone (lime mudstone to packstone). Fossil fragments are common and are usually characterized by abundant echinoderms and brachiopods. Detrital sediments are angular silt-size quartz, abundant white mica, feldspar fragments, and rare zircons. Calcite was deposited as lime mud or micrite, pellets, well-worn rounded fossil bioclasts and occasionally large fragments of brachiopods and echinoderms. The Roberts Mountain Formation contains abundant carbonate turbidites comprised of allodapic components. Dolomite rhombs are abundant, are found in various amounts, and generally are floating in a matrix of calcite and quartz silt. The dolomite rhombs are typically subhedral to euhedral and are from 5 to 80 µm in size (fig. 4). Pyrite is abundant and is 1 to 30 µm in size, commonly framboidal, and believed to be primarily early diagenetic and related to sea floor organic (bacterial) activity. Pyrite is concentrated between the carbonate grains or crystals, and is most abundant in the dark carbon rich, millimeter laminations. Sphalerite (ZnS) crystals in the 1 to 30 µm size are not uncommon in the carbonate matrix.

Millimeter laminations are the most distinguishing characteristic of the Roberts Mountains Formation (Mullens, 1980). SEM studies show the intercrystalline spaces contain sulfur-rich carbon, which is interpreted as derived from "thermally altered" hydrocarbons.

Environment of Deposition.

The presence of pyrite, in particular framboidal pyrite, and the preservation of the laminations indicates a reducing environment existed during deposition and was toxic to an infauna or boring organisms (Mullens, 1980). The core samples indicate the Roberts Mountains Formation was deposited in an anoxic, "deep" water shelf or slope to basin, environment. The core samples studied have a consistency in mineralogy and petrology that indicates a relatively stable environment of deposition through time. Thin bands of bioclastic material, composed of large brachiopod and

Diagrammatic cross section for Paleozoic carbonate facies



Facies and facies numbers	Basin-euxinic facies 1	Tidal shelf facies 2	Toe of slope carbonates 3	Foreslope 4	Organic reef boundstone mass 5	Sands on edge of platform 6	Open platform 7	Restricted platform 8	Intertidal to supratidal facies 9	Vadose weathering of sabkha surface; carbonate dune sands; caliche-calcrete 10
Lithology	Shale, radiolarian cherts and siltstones	Interbedded thin to medium-bedded lime and mud-stone; dolomite and chert	Interbedded limestone and dark-gray shale	Variable depending on water energy upslope. Sedimentary breccia and lime sand or lime mudstone	Crust on accumulation of organic debris and lime mud. Massive limestone dolomite	Crinoid-bryozoan to ooid packstone and grainstone	Variable carbonate bryozoan-crinoid packstone; chert common	Finely and coarsely crystalline dolomite; dolomitic crinoid bryozoan wackestone and packstone; dolomitic pelletoid lime mudstone	Irregularly laminated dolomitic lime mudstone and dolomite; anhydrite and calcite pseudomorphs of anhydrite common; algal mats	Coated particles, peloid, pisolites, compound peloids, alternating microlaminae, limpid dolomite rhombs
Color	Dark brown to black	Gray to brown	Gray to dark brown	Gray to light gray	Light gray	Light gray	Light gray	Light gray to gray	Gray-yellow, brownish red	Gray-light gray, yellowish brown
Bedding and sedimentary structures	Very even millimeter laminations, rythmic bedding, ripple cross laminations, burrows, and worm trails on bedding surfaces	Thoroughly burrowed. Thin to medium wavy to nodular beds; bedding surfaces show diastems	Laminations may be minor, massive beds common, lenses of graded sediments; lithoclasts and exotic blocks	Slumps in soft sediments, foreset bedding, exotic blocks	Massive to thick beds, some cross bedding, to massive organic structures or open framework with roofed cavities	Medium to large-scale crossbedding; festoons common	Abundant burrows	Birdseye structures, algal mats on or near intertidal zone, stromatolites in very shallow water, graded cross bedding	Anhydrite-gypsum rhombs, bedded anhydrite, cracks, chips, algal mats	

Figure 3. Idealized sequence of facies belts for the Silurian and Devonian, including, Hanson Creek Formation, Roberts Mountains Formation, Bootstrap limestone, Popovich Formation, and Rodeo Creek unit. Concept modified from Wilson (1975).

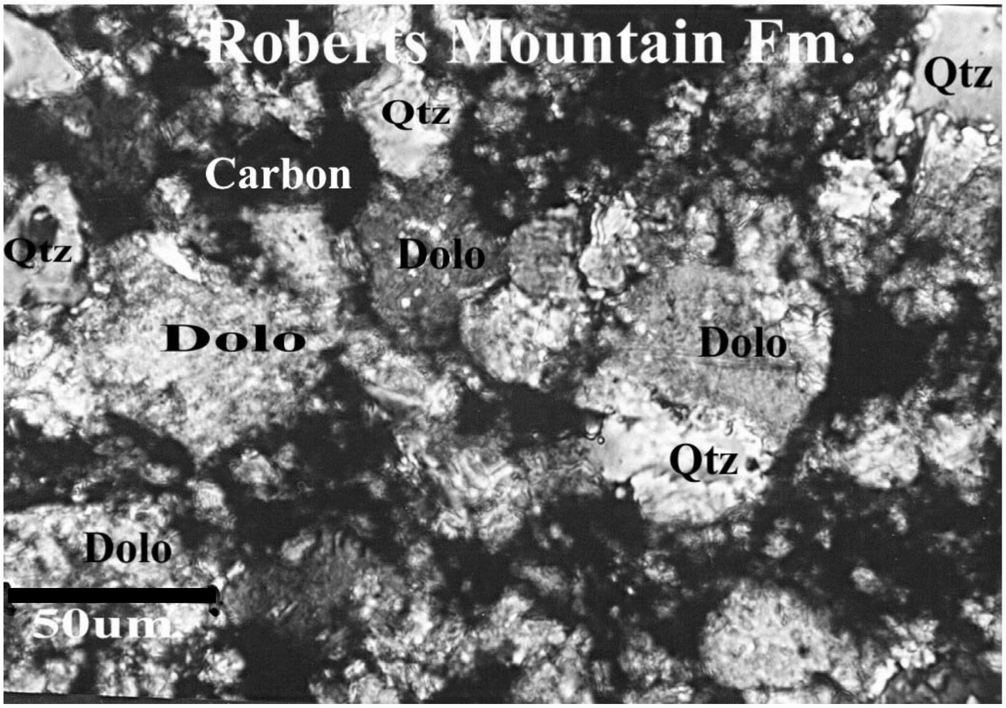


Figure 4. Photomicrograph of the carbon rich Roberts Mountains Formation. Rhombs of dolomite and detrital quartz silt in a matrix of black carbon. Polarized light.

echinoderm fragments, indicate a nearby source of shell material which, when alive, had to exist in normal, oxygenated seawater. No oolites were seen, but mud lumps and soft peloids were observed in some thin debris beds. Extensive soft-sediment deformation is absent within these specimens of the Roberts Mountains Formation. Nothing comparable to the soft sediment deformation (SSD) unit (see below) of the Popovich Formation was found. The mineralogy and petrography of the Roberts Mountains Formation, however, are similar to that in the Popovich Formation wispy unit, fossil hash/planar unit, and soft sediment unit.

The Roberts Mountains Formation was deposited in a tectonically stable euxinic basin. Deposition began on an eroded Hanson Creek dolomite surface. The depositional hiatus that separates the two formations encompass middle Llandovery time (Dunham and Olson, 1980). The basal Roberts Mountains Formation is a black, finely laminated carbonate mudstone which is dolomitic and lies on the Hanson Creek Formation, but rapidly grades into lime mudstone over a span of a few feet above the contact. The Roberts Mountains Formation in the area of this study appears to have been deposited on the tidal shelf and or on a very gentle foreslope (figs. 2 and 3). Cook (1972) and Cook and Mullins (1983) proposed a low-relief platform-margin model that appears consistent with facies of the Roberts Mountain Formation.

Bootstrap Limestone Unit, Carbonate Shelf Facies

The study of the informally named Silurian and Devonian Bootstrap limestone is based on a series of cores, which drilled into the Bootstrap limestone. These are the Minorca (96–1C), Meikle Mineshaft (MP–1), Dee Mine (DC95–01) and Uranerz (RU–8) cores. The Minorca (96–1C) was collared near the southwest corner of the Santa Renia Fields quadrangle and cored 970 ft of the Bootstrap limestone unit. The drill hole at the shaft site of the Meikle Mine (MP-1) cored 919 ft, and the Uranerz cored 1,201 ft of the Bootstrap limestone unit. Similar thickness for the Bootstrap limestone are reported to be present in exposures at the Bootstrap window (fig. 1) roughly 2–1/2 miles northwest of the Meikle Mine, where the Bootstrap limestone has an approximate 900 ft thickness (Evans and Mullens, 1976). Outcrops of the Bootstrap limestone unit were not available for investigation. Our study of the cores DC95–01 and conodont study of Uranerz RU–8 (see below) demonstrates the Bootstrap limestone unit is structurally complex and, in places, may have been repeated by cryptic faulting along bedding planes It is difficult to ascertain the true thickness of the Bootstrap limestone unit.

The Bootstrap limestone unit in the Meikle shaft MP–1, Minorca 96–1C, and the lower part of the Dee DC95–01 cores, is typical of shallow marine carbonate shelf limestones that are dominated by multiple shoaling upward sequences (Wilson, 1975, Moore, 1989).

Bootstrap lime mudstone to ooid grainstone (fig. 5) contains many lithoclasts, which are subrounded to rounded, and are as large as 10 cm. They appear to be storm rip-up clasts. Parts of the cores display many shoaling upward successions of facies, each several to tens of feet thick, that grade from fossiliferous ooid grainstones to packstone and wackestone, into poorly laminated, lime mudstone with birdseye structure. The Bootstrap limestone unit generally is a well-cemented carbonate rock with little or no inherent permeability or porosity.

Environments of Deposition

Ooid packstone, grainstone, wackestone, and lime mudstone in the upper parts of the Bootstrap limestone unit were deposited on a wide shallow, shelf margin adjacent to a basin in which the Popovich Formation (see below) was deposited. Shallow shelf environments are marked by sedimentation ratios that can generally track or outstrip even the most rapid sea level rise (Wilson, 1975; Moore, 1989). Rapid sedimentation to or above base level is the norm for carbonate shelves, and the result is the ubiquitous, stacked upward shoaling sequence that gives carbonate shelves their typical internal cyclic architecture. The thickness of the total cycles is controlled by a combination of the rate of shelf subsidence and eustatic fluctuation (Moore, 1989).

The numerous upward shoaling shelf cycles within the Bootstrap limestone resulted in repeated seaward progradation over the shelf margin environment. The sedimentary cycles within the Bootstrap limestone indicates there were a series of relative rapid rises of sea level that occurred repeatedly on a steadily subsiding shelf. These rapid sea level rises were followed by sedimentary progradation and a carbonate sediment fill-in of the inundated area. On the outer edges of the shelf, subsidence is too continuous and water is too deep for the effects of relatively small cyclic sea level fluctuations to be reflected in the sedimentary record (Wilson, 1975; Wilkinson and others, 1997). The well-formed ooids that are the base of each Bootstrap cycle are, by analogy with Holocene sediments, indicative of strong and regular tidal currents. The ooid shoal of Joulters Cay (Harris, 1979) and Cat Cay, Bahamas (Ball, 1967), are a reliable modern analog for the ooids in the Bootstrap limestone unit. The thickness of these shoaling cycles is controlled by the rate of shelf subsidence and carbonate sediment production (Read and others 1986; Moore, 1989).

In all the cores studied, well-defined coral reefs are absent. Ooid shoals do not form behind a well-developed barrier reef because the presence of the reef usually would restrict the flow of tidal currents—thick sequences of ooid sediments necessitate the presence of an unrestricted flow of tidal currents. Within each upward shoaling cycle the ooids grade up into bioclastic wackestone and birdseye (fenestral fabric) lime mudstone. The Bootstrap limestone during a relative sea level fall would be emergent and would undergo extensive meteoric diagenesis, cementation and karstification. The Bootstrap limestone was repeatedly exposed to the atmosphere and meteoric waters prior to deposition of the overlying cycle. Some cores from the Bootstrap limestone display textures indicative of karst that developed prior to deposition of the overlying Popovich Formation. These textures include large cavities now filled by collapse breccia, zebra-like textures, and spar calcite. Furthermore, one of the cores examined shows breccia and a spar-calcite-filled cavity that is cut by a 2 inch-wide igneous dike. Only in areas of karst and collapse breccia development in the Bootstrap limestone are there likely to be porous environments well suited for subsequent hydrothermal fluids and mineralization.

Diagenetic History of the Oolite to Lime Mudstone

Davis (1996) found that, in less than 10 years, subaerially exposed oolitic sands on Eleuthera Island, Bahamas, was completely casehardened by freshwater vadose calcite cementation. This phenomenon demonstrates the rapidity of freshwater carbonate diagenesis and explains, in part, why carbonate platforms preferentially shed unconsolidated sediment during highstands and not during lowstands when they are subaerially exposed.

The Bootstrap fossiliferous oolitic packstone to lime mudstone was deposited in near-normal salinity on a shallow shelf, shoal water environment. Four distinct types of cement are present within the Bootstrap oolite. The first is a bladed to fibrous habit and lines the walls of pores and is on the surface of oolites, pellets and bioclasts. This was the first cement formed and these textures are generally interpreted to be of an early marine origin (James and Choquette, 1990b). Isopachous phreatic zone cement overlies the fibrous marine cement. Inter-ooid cements that indicate time within the vadose environment are meniscus and microstalactitic cements. A final phreatic event resulted in blocky, equant-grained cement that completely fills pores space. No other volumetrically significant types of cement have been observed in the oolitic grainstones. Pore-central ferroan calcite cement was not found. Ferroan calcite cement has been interpreted as late diagenetic and deep burial in origin in other limestones (Bathurst, 1975). This indicates that all porosity in the Bootstrap oolite packstone-grainstone was filled before deep burial. Choquette and James (1990, p. 65–66) stated shelf sediments “are varied and may include, in various combination limestones of mudstone to grainstone textures, peritidal limestones and dolomites and coastal plain evaporites. Because these shallow marine to coastal sediments are commonly exposed intermittently during accretion, they are periodically filled with meteoric ground water. Consequently, before they exit the meteoric environment they may have seen multiple generations of fresh to brackish to marine or even hypersaline water related

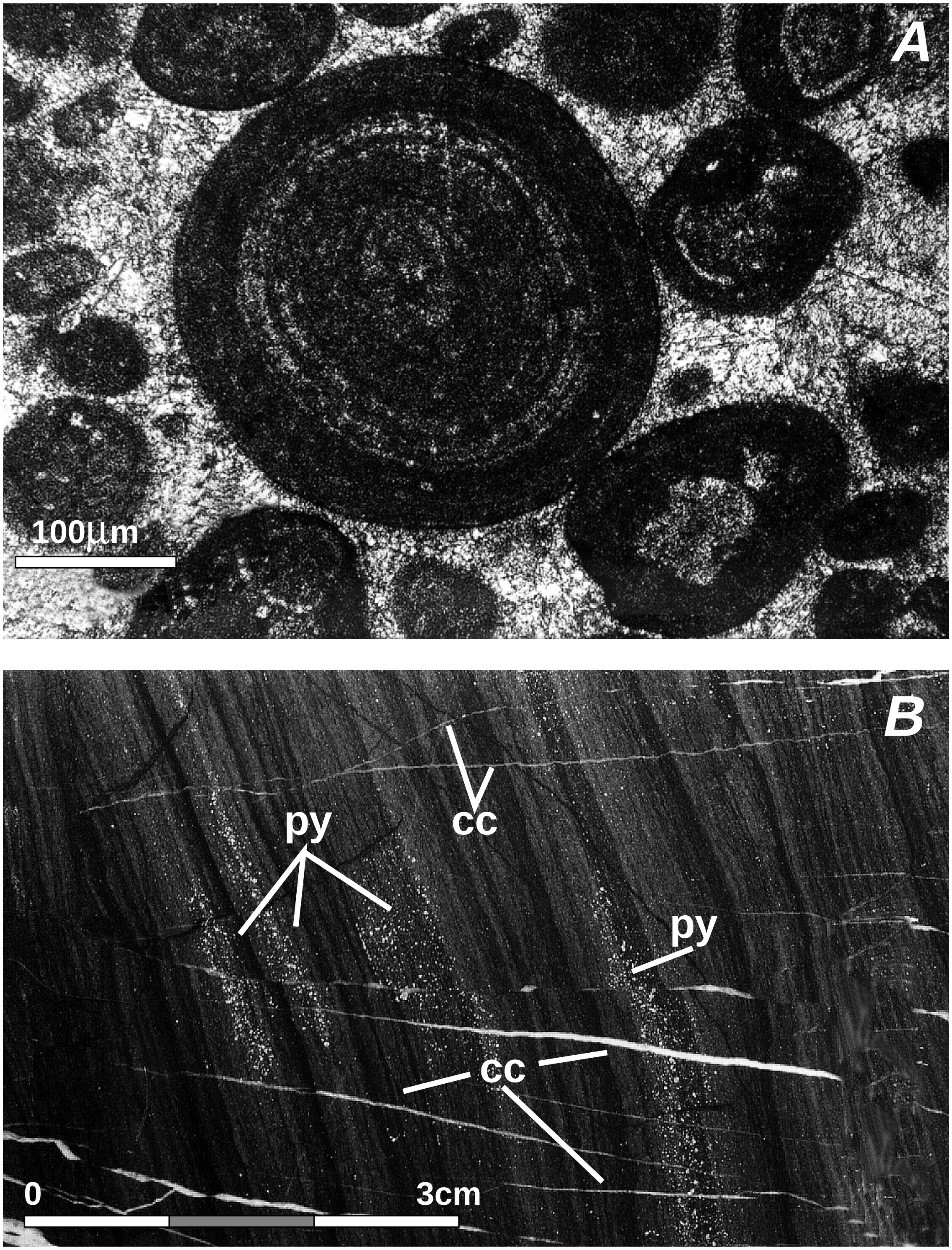


Figure 5. Photomicrographs of Devonian Bootstrap limestone and Devonian Popovich Formation. (***A***), Ooid grainstone in Bootstrap limestone. Variably sized, coated particles, some with broken fossils centers, all show dark micritic envelopes caused by boring algae and sponges into the surface of the particles. Spar calcite cement between particles. Sample no. 96–1C+4506. (***B***), Vertical cut core illustrating the mm–size laminations and graded bedding of the Popovich Formation and absence of bioturbation. py, fine-grained pyrite; cc, calcite along tension gashes, some of which show minor amounts of offsets of laminae. Sample no. 96–1C+3512.

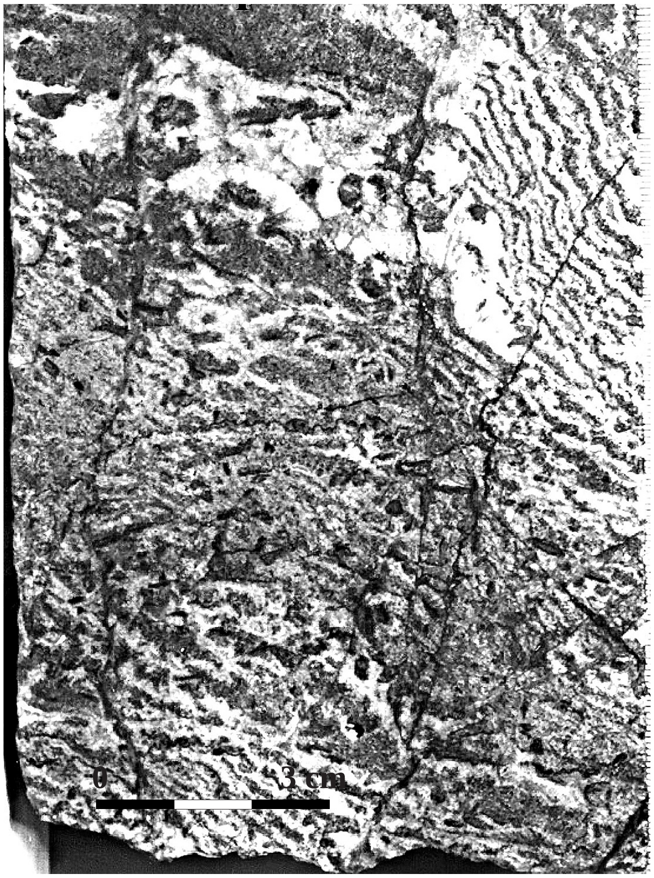


Figure 6. Zebra texture and structures from drill core within ore bodies of the Meikle Mine. The Bootstrap limestone has been altered hydrothermally. The zebra structures at the Meikle Mine are typically alternating 0.5 to 5 mm wide bands of dark gray and white dolomite.

to low and high stands of sea level."

Some of the limestones have disseminated dolomite. The dolomite crystals are characteristically 10 to 80 µm in size, euhedral, although locally ragged in their detailed outlines. These dolomite rhombs are clear, and are replacive in nature crosscutting bioclasts, oolites and cements. Folk (1974), and Cantrell and Walker (1985) proposed that dolomites of this type were precipitated by meteoric water probably deep in the subsurface.

Analysis of Uranerz RU-8 Bootstrap Limestone Core

Conodont studies on the Uranerz RU-8 core reveal the section is faulted and repeated (figs. 7 and 8). Furthermore, petrographic studies show that above and below the fault two distinct carbonate facies are present with two distinct diagenetic histories. The higher fault block, from 3,025 to 3,630 ft, is Lochkovian (Lower Devonian) to Wenlockian (Lower Silurian) in age. Within the lower fault block, this exact age distribution is repeated again from 3,630 to 4,226 ft. A fault is suggested at about 3,630 ft. The base of the upper block of Wenlockian (Silurian) age is faulted on Lochkovian (Early Devonian) dolostones of the lower block.

Environment of deposition and diagenesis, limestones, Upper Fault Block 3,025 to 3,500 ft.

The fossiliferous, oolitic to (micrite) lime mudstone in the upper block above the fault at 3,630 ft records periods of deposition in near-normal salinity on a shallow-shelf, shoaling water environment. This limestone is similar in its depositional and diagenetic history to the Bootstrap limestone from the Meikle Mine shaft and Minorca cores.

Analysis of Uranerz RU-8 Bootstrap Dolomite Core

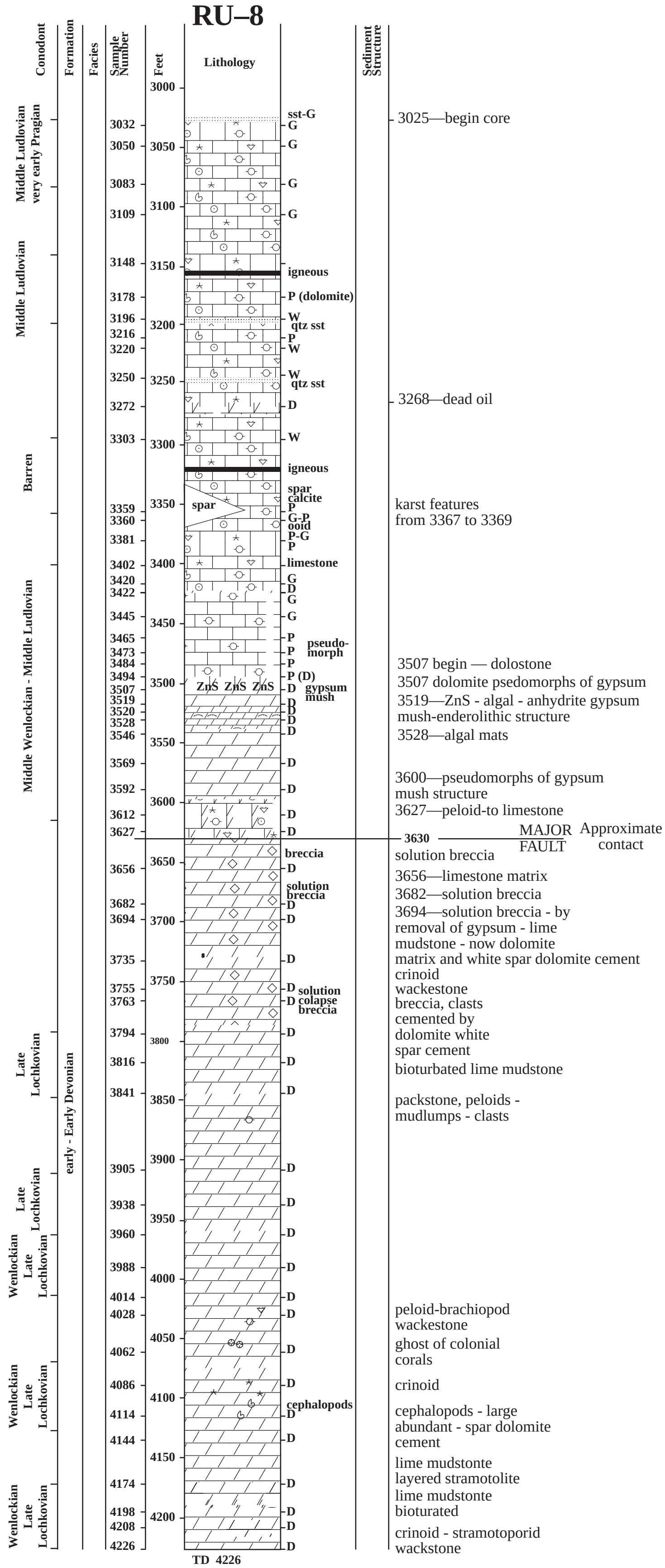
Petrology and Environment of Deposition, Dolomites

In the upper block, at the base of the section, from 3,510 to 3,630 ft, are dolostones. The dolostones contain algal mats (cyanobacteria microbialites at 3,510 to 3,530 ft), intraformational conglomerates, dolomite pseudomorphs of enterolithic fold structures, and gypsum mush and spar dolomite pseudomorphs of nodular anhydrite (see also, Schreiber, 1986; Demicco, and Hardie, 1994). The sedimentary structures and fabric indicate that this 130-ft interval of dolostones was deposited in subtidal, intertidal to supratidal sabkha environments (fig. 9).

Below the fault at 3,630 ft, the lower 599 feet of the Bootstrap limestone, in the lower block, is also Lochkovian (Lower Devonian) to Wenlockian (Lower Silurian) age. From 3,630 ft to the bottom of the hole at 4,226 ft is a complex suite of sedimentary structures and dolostones. Within the dolostones are abundant intercrystalline pores and large vugs. Although the dolostones are vuggy, very little to no permeability is present. With the exception of void-filling dolospar, the dolomite crystals are subhedral to anhedral. Essentially all the dolomite rhombs, whether matrix or void filling, are cloudy. Stylolites and microstylolites that postdate the dolomitization events are relatively common, as are healed fractures.

Solution breccias with rounded clasts and white dolomite spar cements are found from 3,727 to 3,790 ft. This solution breccia may be the result of early removal by meteoric waters of anhydrite and gypsum. The spaces between the breccia fragments are partially filled by spar dolomite. The sedimentary structures and fabric indicate that the dolostones were deposited in an intertidal to supratidal, sabkha environment.

The dolomites from 3,790 to 4,226 ft show evidence of deposition in shallow shelf marine environments. Polished



Explanation

Classification of carbonate particles other than fossils

	Size mm	Rounded mud	Any shape mud	Coated particles: one layer	Coated particles: two or more layers
Silt	.20 / .063	⌽	∞		
Sand	2.0	○	◇	Super-ficial ooid	Oolite
Granule	4.0	⌽	◇	Super-ficial ooid	Pisooid
Pebble		◍	◇	Super-ficial ooid	◎

Composition, in percent

Dolomite	0	10	50	90	100
Limestone	100	90	50	10	0

Sandstone — Shale — Nodular chert — Nodular limestone

Symbols for fossil particles

- Algal mats
- Calcareous algae
- Foraminifers
- Molluscan in general
- Ostracodes
- Echinoderms
- Brachiopod
- Coral

Sedimentary structures

- xln Crystallin calcite
- Solution breccia

Dunham's (1962) carbonate rock classification

M	Lime mudstone	G	Grainstone
W	Wackestone	D	Dolomite
P	Packstone		

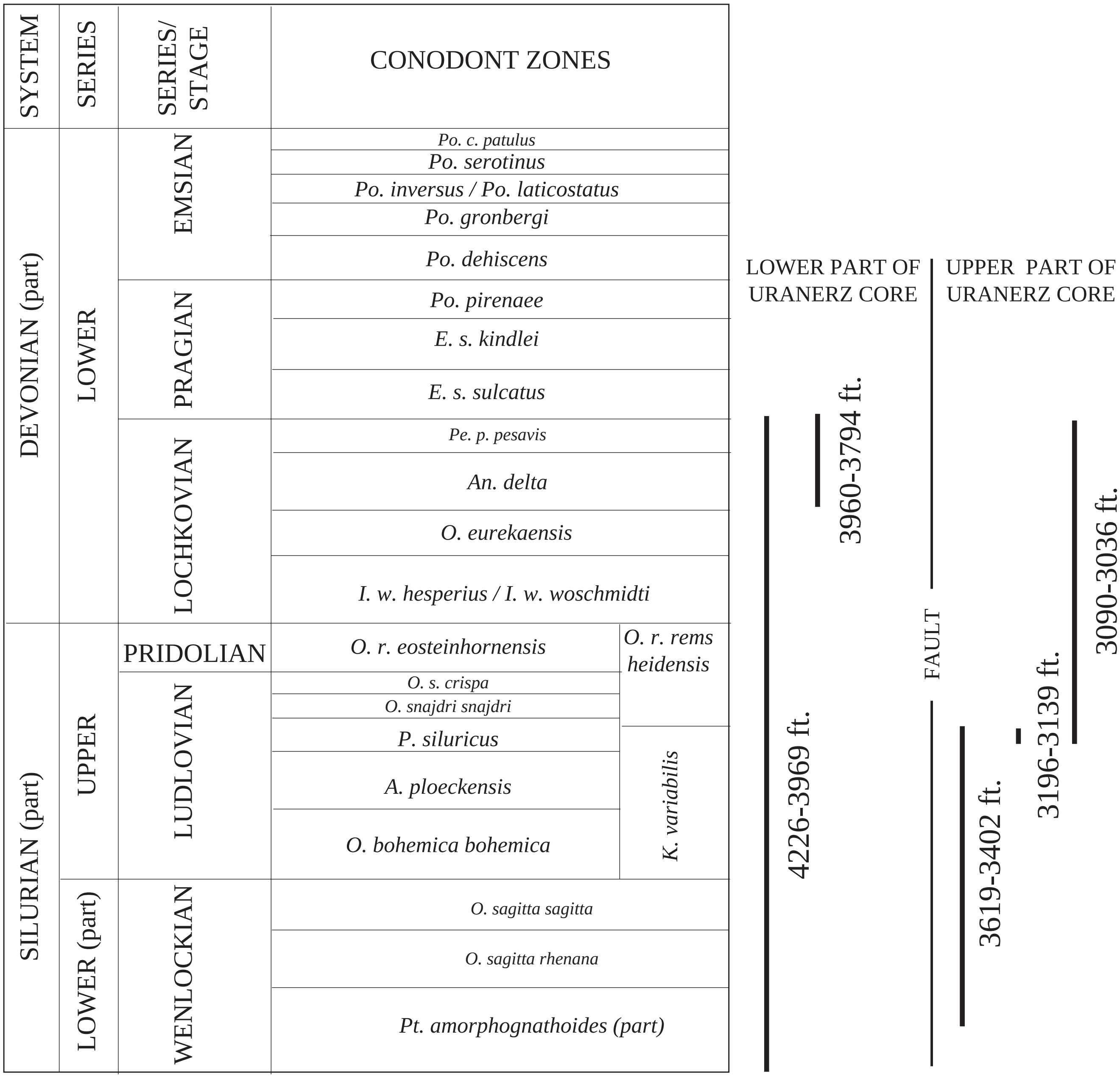


Figure 8. Conodont zonation for the two fault blocks in the Uranerz RU–8 Bootstrap limestone core. Both fault blocks have the same age from Wenlockian (Lower Silurian) to Lochkovian (lower Devonian). A full listing of the conodont paleontology and zonation is in Appendix A.

Figure 7. (Located on page 48) Stratigraphic section of the Uranerz core RU–8. The lower fault block is almost pure dolomite. The higher fault block, from 3,025 to 3,630 ft, is Lochkovian (Lower Devonian) to Wenlockian (Lower Silurian) in age. Within the lower fault block this exact age distribution is repeated again from 3,630 to 4,226 ft. A fault is suggested at about 3,630 ft. The base of the upper block of Wenlockian, Silurian age is faulted on early Devonian, Lochkovian dolostones of the lower block.

Figure 9. Dolostones at 3,519 ft has intraformational conglomerates, dolomite pseudomorphs of enterolithic fold structures, and gypsum mush and spar dolomite pseudomorphs of nodular anhydrite. The sedimentary structures and fabric indicate the dolostones were deposited in supratidal sabkha environments. Sphalerite (ZnS) mineralization appears to be associated with geopetal, crystal silts.

core samples have fragments of echinoderms, crinoids, brachiopods, rugosa and tabulate corals, stromatoporoids and numerous nautiloid cephalopods. These beds represent dolomitized open shelf carbonate strata. Intertidal to supratidal sedimentation is indicated at 4,170 to 4,180 ft by algal mats (cyanobacteria microbialites).

Diagenetic History of the Dolostones

Morse and Mackenzie (1990) have shown that the transformation of aragonite and high magnesium calcite to low magnesium calcite and the dolomitization of carbonate sediments and rocks are among the most important processes in the diagenesis of carbonate sediments, but major aspects of these processes are still poorly understood. One of the primary reasons for this is that although reactions may occur over geologically short times, their kinetics are too slow to be studied in the laboratory under conditions closely approaching those in natural systems. Consequently, our understanding of the chemical processes and mechanisms that are reliably applicable to these major phase transformations is relatively limited. Morrow (1990a) also states the inability to precipitate dolomite under controlled laboratory conditions constitutes the essence of the problem of the origin of dolomite.

Three models for the dolomitization of this thick sequence of shelf limestone are presented. The dolostones result from mesogenetic replacement of early dolomitization followed by neomorphism in the burial environment, or some combination of these two end member models.

(1) Sabkha Reflux Model. A close association of supratidal sabkha sedimentary features and dolomitization apparently exists with dolostone in the lowest 130 ft of the upper block and also all the dolostone of the lower block. The well-documented setting for penecontemporaneous dolomite is the sabkha environment (Beales and Hardy, 1980; Morrow, 1990a, b). It is restricted to those dolomites with accompanying evaporite minerals. Dolomites in the sabkhas of the Persian Gulf are most abundant as 1 to 5 μm euhedral crystals in the high intertidal zone close to the strandline and are strongly controlled by the network flood channels across the sabkha. Storm driven tides reach furthest inland along these channel courses. The frequency of flooding decreases landward across the sabkha but the Mg/Ca ratio of floodwaters rises uniformly landward by means of gypsum precipitation so that the zone of optimum dolomite formation is less than a half a mile wide straddling the boundary between high intertidal and supratidal areas (Morrow, 1990b). The presence in the upper block of the Uranerz core at 3,500 to 3,600 ft of sabkha sedimentary structures such as algal mat laminations, rip-up clasts, and intraformational conglomerates indicates this part of the Bootstrap dolostone was deposited at times in subtidal to supratidal environments. Intertidal to supratidal sedimentary structures also are present in the lower block of dolostones at 3,630 to 3,790 ft and again at 4,170 to 4,180 ft. Dolomite pseudomorphs of gypsum and anhydrite indicate the existence during deposition of laterally adjacent or overlying evaporites that could have provided sources of Mg–bearing hypersaline solutions capable of dolomitizing by seepage-refluxion this sequence of dolostones.

(2) *Burial Compaction Model*. The petrographic textures of the Bootstrap dolostones are similar to those described by Gregg (1988) for the Cambrian Bonneterre Formation, Viburnum trend, southeast Missouri. The dolostones in the Bonneterre were

formed by late diagenetic events that were warm basinal waters circulating through the carbonate strata. A similar origin for the Bootstrap dolomite is not unreasonable. This would explain the appearance of the iron free, honey colored, late pore filling sphalerite in the dolostones at 3,507 to 3,519 ft. A possible weak Mississippi Valley type of mineralization may be responsible for the sphalerite mineralization.

(3). *Hydrothermal Convection Model*. In this model, brines probably have interacted with crustal rocks (Morrow, 1990b). Dense hypersaline brines migrate to great depths in the earth's crust and are recirculated to shallow depths by thermal convection where they can dolomitize porous limestone. The dolomites in the Meikle Mine ore bodies that are associated with the gold-mineralized rocks and massive amounts of pyrite clearly belong to the hydrothermal convection model. The dolomites in the Uranerz core were extensively studied with the SEM and EDAX and were found to be essentially devoid of any minerals except dolomite, rare calcite and quartz, and exceptionally rare pyrite. No barite or other sulfide minerals were found. The absence of any minerals except the sphalerite at 3,507 to 3,519 ft suggests the dolomitizing fluids were not hydrothermal. The sphalerite crystals (figs. 9 and 10) are associated with geopetal dolomite crystal silts. It is possible that the crystal silt was deposited in the vadose environment from meteoric water. If this is truly geopetal silt, then their environment of deposition fits the vadose environment as defined by Dunham (1969).

Comparison of the Uranerz RU-8 Dolostone

The dolostones in the base of the upper block from 3,500 to 3,630 ft and the massive coarse crystalline dolomite in the lower block from 3,630 to 4,226 ft have not been recognized in other drill cores from this part of the district. Zenger and Dunham (1988) describe a similar suite of shelf carbonate rocks (limestone overlying dolomite) and diagenetic history for the subsurface Silurian-Devonian rocks of southeastern Mexico.

Hydrothermal Alteration of Bootstrap Limestone

The Bootstrap limestone unit in the Meikle Mine has been altered into coarse dolomite. Dolostone samples from Meikle Mine drill hole MS–19, for example, are so altered to clay and silica mineral assemblages that there is not the faintest suggestion as to their original microfabric or microfacies.

Zebra Spar at the Meikle Mine

The Bootstrap limestone unit in the area of the Meikle ore bodies has been subjected to strong hydrothermal alteration. The zebra structures at the Meikle Mine comprise alternating 0.5 to 5 mm wide bands of dark gray and white dolomite (fig. 6). The altered Bootstrap dolostones are remarkably similar to those from the Mississippian Leadville Dolostone of the Colorado mineral belt. In that area, the zebra structures of the Leadville Dolostone have been interpreted differently by a number of authors. The zebra rocks from the Meikle Mine also are similar to zebra rock in the Metaline Mining District, Washington, (Fischer, 1988) as well as the Mississippi Valley, the East Tennessee mining areas, and the Devonian Presqu'ile Dolostone, Pine Point Mines, Canada (Beales and Hardy, 1980). Whatever the inherent cause of dolomitization and recrystallization in these areas, the dolomites of the Carlin trend share the riddle of zebra structure development with them.

Beales and Hardy (1980) suggested that zebra dolomite is the product of precipitation of white sparry dolomite in vugs formed by the dissolution of primary evaporite nodules. Horton and DeVoto (1990) found that zebra dolostones at Leadville, Colorado, are intimately associated with karst breccia bodies. Incipient zebra dolostones are found in Uranerz core RU–8 in association with sabkha sedimentary structures and karsting, as well as carbonate collapse structure. Elsewhere, areas of intense zebra development commonly are adjacent to well-developed breccia bodies, and, at the Meikle Mine, they are proximal to north-northwest striking fault zones that apparently acted as feeder zones for gold-bearing fluids. In some cases, zebra spar is present as isopachous rims on karst breccia. This relation indicates that the cavities into which zebra spar dolomite precipitated formed after regional dolomitization was essentially completed and suggests that the cavities formed during karst development. Studies of particular interest in understanding and deciphering the Meikle Mine zebra and dolomite beds are Horton (1985a, b) and Horton and Geisman (1990), which focused on zebra textures in the Leadville Dolostone. Their research demonstrated that during an Early Pennsylvanian marine transgression, zebra spar precipitated into open spaces that had been created during karst erosion. The solutions from which zebra spar precipitated were hotter and more saline than those from which sucrose or coarsely crystalline dolomites had formed. They further stated that, in the Leadville dolomites, hydrothermal fluids associated with Laramide and Tertiary igneous activity caused dedolomitization in places, and minor dolomite recrystallization and deposition of pyrite as open-space fill, as well as some replacement dolomite elsewhere.

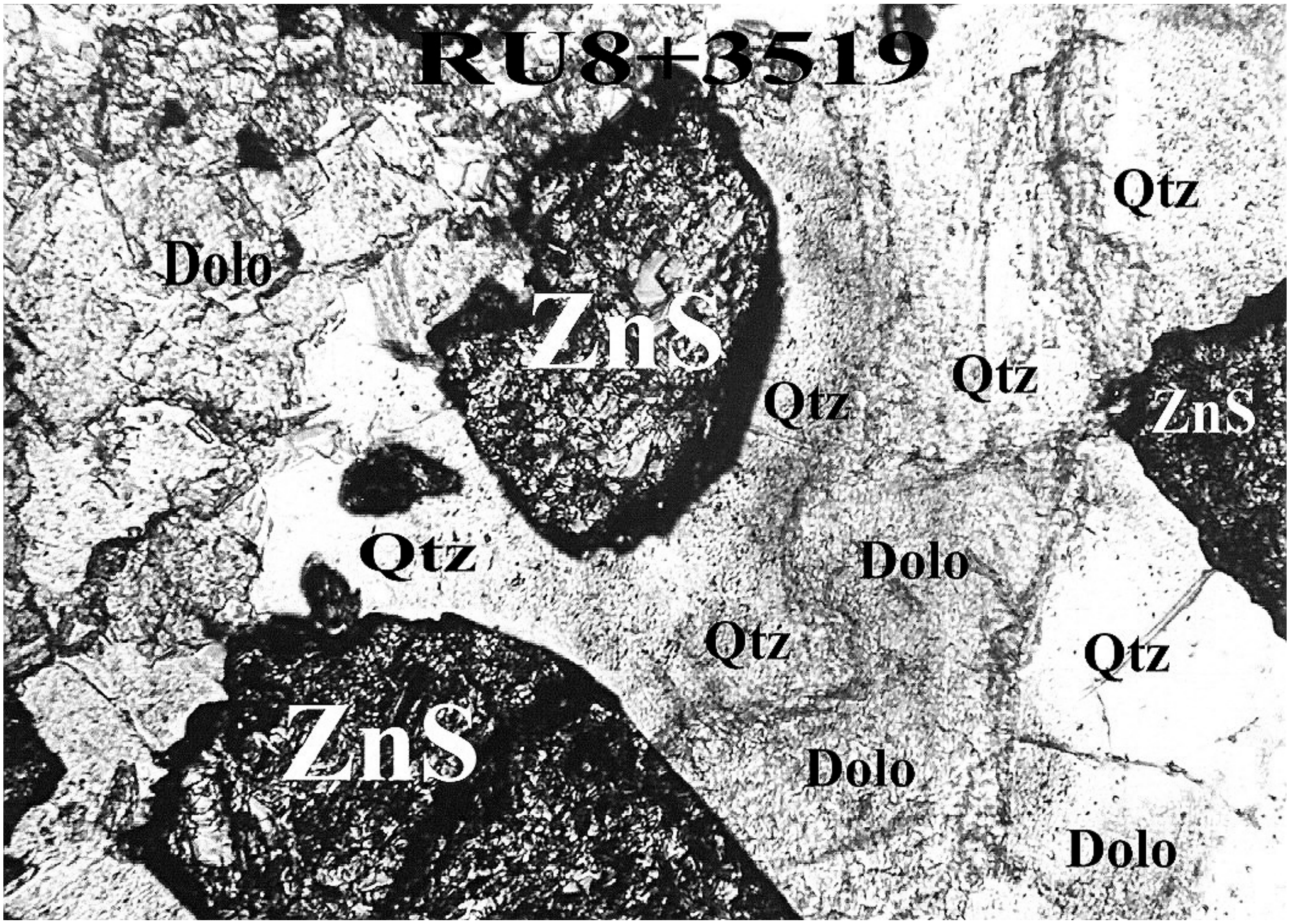


Figure 10. Photomicrograph of thin section RU–8+3519 that contains dolomite, quartz and sphalerite. Dolomite rhombs are 0.2 to 1 mm in size and are pure $CaMg(CO_3)_2$. The sphalerite is pure ZnS devoid of Fe in its lattice. The photograph shows large sphalerite crystals filling intercrystalline pore space in dolomite and illustrates sphalerite as the final pore space fill on silica. This illustration graphically shows the sequence of dolomite, then silica pore fill and final filling by sphalerite.

Popovich Formation

Four units have been delineated within the Popovich Formation in the area of the Meikle and Betze-Post deposits (fig. 2; see also Volk and others, 1996). From bottom to top, they are: a sedimentary breccia/wispy unit; a fossil hash/planar unit; a soft-sediment-deformation (SSD) unit; and an upper limey mud to mud lime unit.

The **sedimentary breccia/wispy unit** is an overall fining upward sequence of rocks. Thick debris-flow beds (megabreccia) are formed of various clast sizes and are composed of peloid, bioclastic, wackestones (biomicrites). Cook and others (1972) define megabreccia as a deposit in which angular clasts larger than 1-m across are conspicuous components. Many clasts of these deposits are smaller than 1 meter and may be rounded rather than angular. Spencer and Tucker (1997) define megabreccias as all the products of major catastrophic gravitational instability events. Megabreccias may contain slides and slumps (fig. 11) of lithified or semi-lithified seafloor sediment. They are involved in either sliding as large coherent blocks (megablocks), reflecting elastic behavior, or as debris flows with large boulders freighted along in a disaggregated matrix of greatly reduced shear strength, reflecting plastic behavior, or a composite of both styles (Schatzinder, 1985). Megabreccias are distinct from carbonate grain flows and turbidity currents, both of which are flows of loose particulate sediment. Megabreccia flows may develop into turbidity currents through sediment disaggregation and increased incorporation of water during transport (Cook and Mullins, 1983).

The lime mud matrix-supported fossiliferous debris flows, and sparse intraformational debris flows have interbeds of

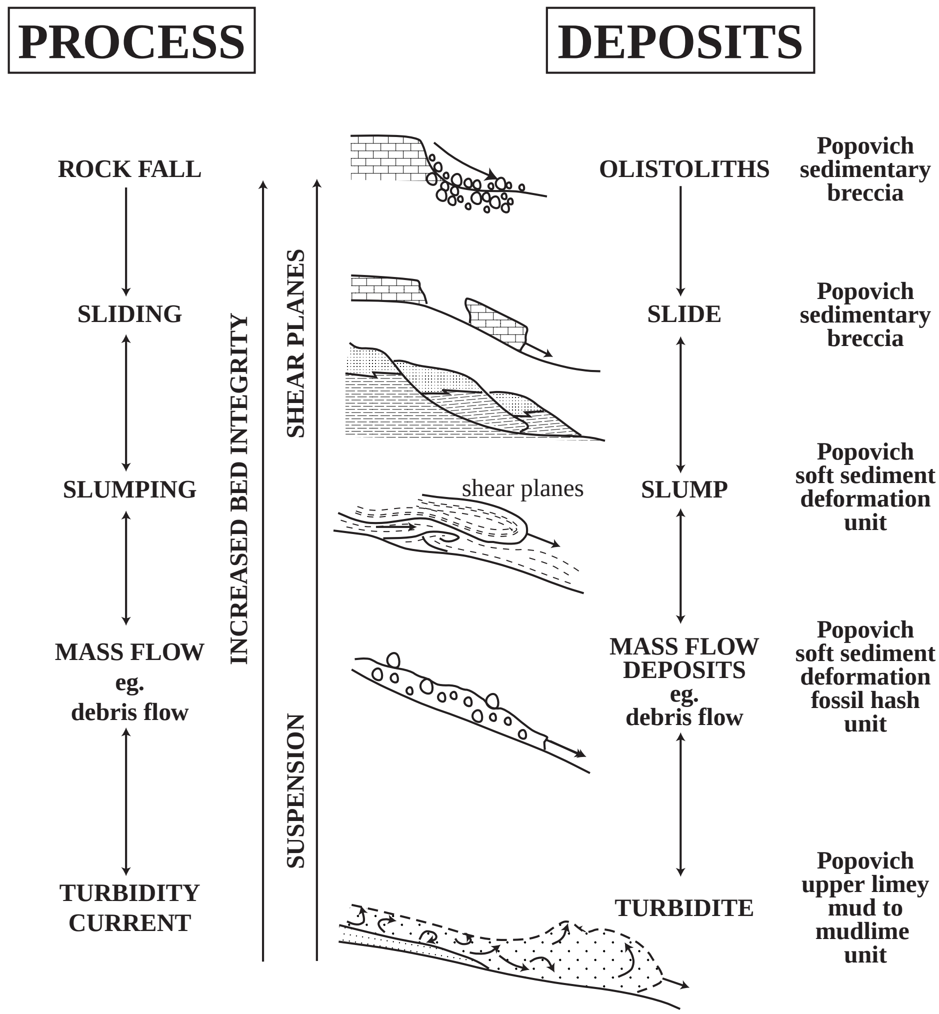


Figure 11. The relationship between mass-gravity processes including slides, slumps, debris-flows and turbidity flows. Modified from Schatzinger, and others (1985).

"wispy" laminated muddy limestone. Wispy laminations are interpreted as burrowed-bioturbated lime mudstones. Ichnofossils are rare to common in the unit. The unit contains foreslope carbonate breccia or oolite shelf talus with inclined beds and with boulders and redeposited fossils. Fine-grained beds are lithoclasts of redeposited fossiliferous wackestone. A significant part of these talus deposits is believed to form during sea level low stands by erosion of the shelf margin. Talus and rock-fall deposits are believed to form the major part of coarse, steeply deeply dipping deposits on the forereef of the Permian Capitan Formation (Melim and Scholle, 1995), Triassic Latemar buildup (Harris, 1994); and the Quaternary foreslope of the Tongue of the Ocean (Grammer and Ginsburg, 1992). The contact with the overlying fossil bioclastic/planar unit is gradational and conformable. The "wispy" beds grade upward into planar laminated arenaceous limestone and thin fossiliferous debris flows. These are replaced by thin to medium beds of fine-to-coarse fragment bioclasts in wackestone allodapic beds. The latter are sediments transported into the basin by turbidity currents (Flugel, 1982).

Fossil hash/planar unit contains rare slump features. They also are rare in the underlying sedimentary breccia/wispy unit. A nearly ubiquitous horizon that contains abundant well-preserved graptolites is present just below the contact with the overlying SSD unit. The most abundant graptolite is *Monograptus* sp., but dendroidal graptolites also are common. The presence of pelagic *Monograptus* sp. as well as neritic dendroidal varieties, literally within the same bedding-plane parting surface, indicates that an anoxic environment was in close proximity to a shallow oxygenated environment from whence the dendroid graptolites were transported. The fossil hash/planar unit is conformable with the underlying sedimentary breccia/wispy unit and apparently marks the transition from oxygenated to anoxic deep-water conditions. This change to a starved basin environment of deposition occurs in the upper one-third of the unit. The contact with the overlying SSD unit is abrupt and commonly occupied by an intraformational slump with sparse fossil bioclasts. Some workers who studied drill cores in the district interpret the contact between the fossil hash/planar unit and the SSD unit as marking a surface of nondeposition. The graptolite zone near the contact with the SSD represents a “condensed time zone” related to a maxima flooding of the shoaling sequence resulting in a very slow to nondeposition environment.

Soft-sediment-deformation (SSD) unit is a sequence of thin- to thick-bedded (micritic) lime mudstone turbidites. This unit contains thick intervals of slump and (or) slide deformational features. Near to and adjacent to the Meikle Mine, the SSD unit contains rare lime mud, matrix-supported, sparsely fossiliferous wackestone debris flows. These debris flows indicate a juxtaposed upper slope and shelf facies with high carbonate sediment production. An alternative interpretation would be a relative lowering of the sea level that would result in transportation of bioclastic sediments from the shelf edge into the upper slope, toe-of-slope and silled basin environments (fig. 3). Near and adjacent to the Meikle mine the SSD unit is composed of a lime mud matrix limestone with numerous ooid, peloid, fossiliferous wackestone and packstone interbeds. These are formed by coarse debris flows up to boulder size. This indicates that much of the SSD in the area of the Meikle mine was deposited as part of the inner shelf to upper slope.

Upper limey mud to mud lime unit is variable in its lithology and sedimentary structures. Primarily the sedimentary structures are plane-laminated carbonate mud to dolomitic lime mudstone. The sediments are dark gray carbon rich, lime mudstone with numerous distal debris beds of small bioclasts and mud lumps and rare ooids. Sedimentary structures include inclined foresets, abundant slump structures (or, soft sediment deformation), carbonate mud lumps, and boulder beds. However, some beds of this unit have fossiliferous debris flows, moderately developed wispy laminations, and even rare micritic turbidites. The “pinstripe beds”, characteristic of the top of the unit consist of laminated dolomitic lime mudstone with thin millimeter thick, discontinuous laminations of brass colored pyrite. Carbonate lime mud and quartz silt carried by distal turbidity currents and finally by contour currents (bottom currents) probably account for most of the sediments in the submillimeter laminations seen in this and the above units. The environment of deposition was anoxic. The contact with the overlying Rodeo Creek unit apparently is conformable, but, on the basis of preliminary ages from conodonts, it may be a hiatus or diastem.

Petrography

Petrographic microscope and SEM studies reveal that the matrix of the units in the Popovich Formation is composed of detrital silt size, angular to subrounded quartz, with minor amounts of feldspar, and some clay minerals. The carbonate minerals make up various percentages of the rock (approximately 15 to 40 volume percent), and include 30 to 100 µm rhombs of calcite and euhedral dolomite. The rock is typically a calcitic dolostone with some intercrystalline vug porosity. Petrographic microscope studies reveal the rocks have micromillimeter, micrograded laminations that formed by variable amounts of detrital quartz, clays and carbonate minerals (fig. 12). Within the Popovich Formation are fine, millimeter thick, laminae of bioclastic debris including some derived from the Bootstrap oolitic shelf. These interbeds include micritic mud lumps, ooids and oolites, and fragments of shallow water marine organisms (brachiopod, crinoid, gastropod) that lived on the shelf.

The Popovich Formation shows a wide range of mineralogy. Samples from Minorca’s 96–1C hole are calcitic dolomicrite composed, in part, of bimodal dolomite rhombs. The large rhombs are 30 to 50 µm wide and they float in a matrix of 2 to 20 µm subhedral dolomite and calcite rhombs. SEM studies reveal the presence of clay minerals in the matrix with minor amounts of quartz silt. Framboidal pyrite grains, 2 to 10 µm wide, are common in the dolomite matrix. Also present are abundant intercrystalline vugs and pore spaces that are filled by sulfur-rich carbon. The carbon is composed of extremely fine-grained aggregates with individual crystals approximately 10^{-3} mm wide of graphite as revealed by Raman spectroscopic studies (Leventhal and Hofstra, 1991). This carbon in pore spaces of the Popovich Formation has been shown to be sulfur rich by our SEM studies. It was derived from thermally altered petroleum.

Environments of Deposition

The Popovich Formation was deposited in a progressively deeping basin that developed over the drowned Bootstrap oolitic shoaling shelf. The base of the Popovich Formation was deposited on a fore slope and the basal deposits contain debris, which were derived from the oolitic shelf. They represent olistholiths, slide and slump transported ooid-shelf sediments that are mixed and interbedded with basinal silty dolostones and lime mud. These include slump blocks of fossiliferous ooid grainstones in wedge-shaped foresets. This shallow-shelf ooid and bioclastic debris was mixed and interbedded with lime mud, dolomicrite, and silt during downslope transport. The fossiliferous ooid grainstones and wedge-shaped foresets grade upward to the deeper water toe-of-slope carbonate facies of the Popovich Formation which contain abundant soft sediment slump structures (SSD unit, see above) and minor amounts of distal interbedded debris bioclasts derived from the shelf. Thick intervals of SSD are not a single genetic package but rather they are complex accumulations of multiple slumps of soft sediments. The Minorca core and the cores from the Meikle Mine shaft, however, indicate that the stratigraphically higher beds of the Popovich Formation (upper limey mud to mud lime unit, see above) were deposited in deep shelf margin to basin or starved

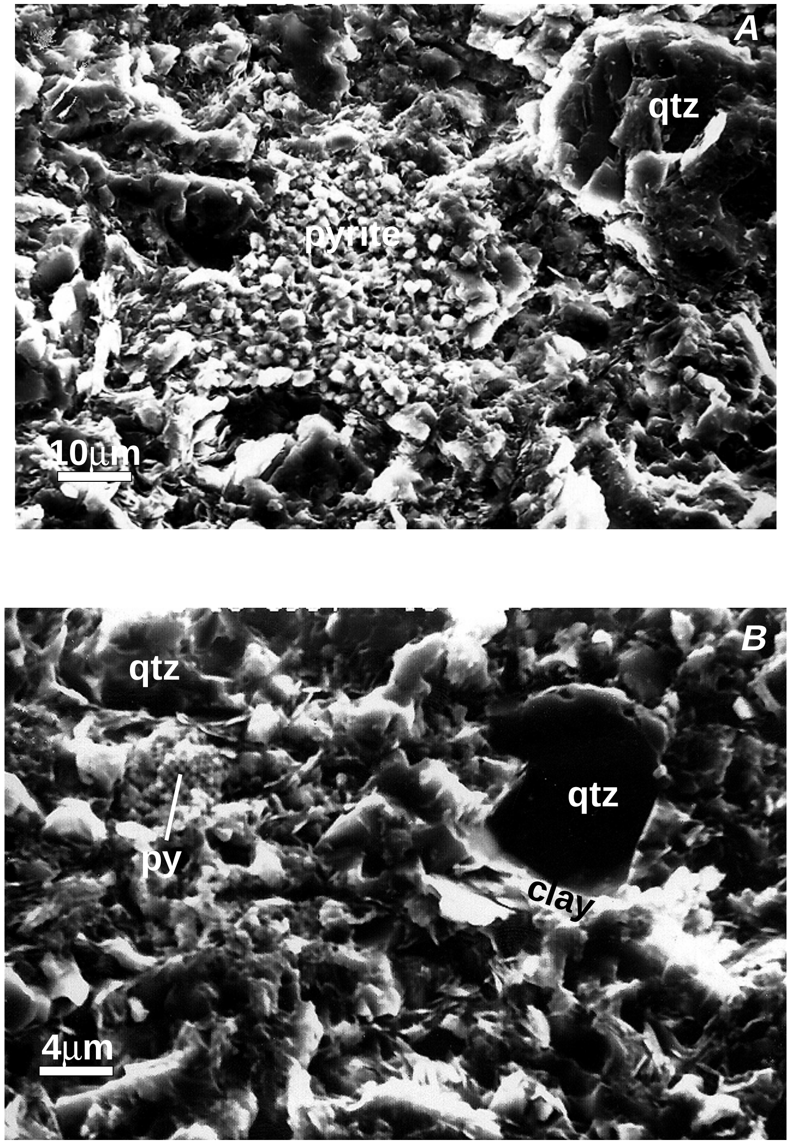


Figure 12. Scanning electron micrographs of Devonian Popovich Formation. (***A***), Calcitic-dolostone composed of very fine grained, intimate mixture of calcite, dolomite, and detrital quartz. Rare apatite crystals and a rare-earth phosphate with La and Ce are accessory minerals. Framboidal pyrite in center of photograph. Sample 96–1C+3269. (***B***), Silica and clay replacement of typical calcitic dolostone fabric showing framboidal pyrite, hydrothermal silica, clay minerals, and detrital quartz.

basin environments. The sediments are framboidal pyrite rich, contain detrital quartz silt and white mica, and are well-bedded, platy, and laminated micrograded. The partly siliceous upper limey mud to mud lime unit of the Popovich Formation, which includes some argillite and cherty material, appears to have been deposited in an euxinic (starved) environment. Sparse fossil bioclasts in the upper limey mud to mud lime unit are fossil debris derived from higher up the slope or from the oolite shelf. The well-preserved micro-laminations and micrograded laminations reflect an absence of burrowing organisms because the water generally was poorly oxygenated or anoxic. Farther to the south near the Carlin Mine, the basal parts of the Popovich Formation reflect a much more shallow environment that was closer to a carbonate sediment source (fig. 13) and contain massive biomicrites made up of ostracods, trilobites, and ichnofossils (Ettner, 1989). An anoxia environment in the northern part of Carlin trend also is indicated by an abundance of framboidal pyrite and rare hematite (Yukio, 1997). The terrigenous sediment admixture in the Popovich Formation includes highly angular fragments of quartz,

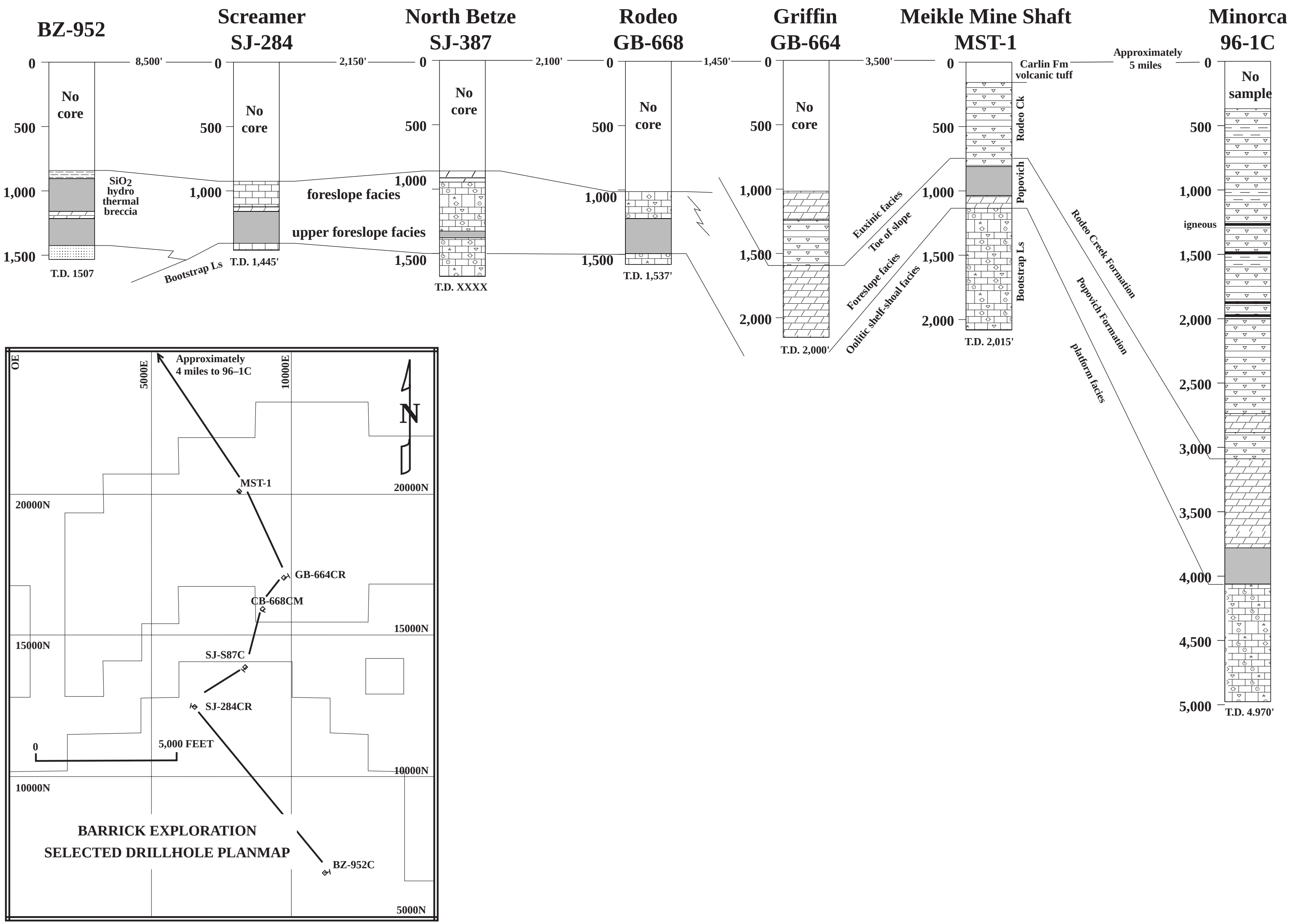


Figure 13. Stratigraphic north-south section of the Popovich Formation from the Minorca core hole 96-1C to the Meikle Mine shaft MST-1, Griffin GB-664, Rodeo GB-668, North Betze SJ-387, Screamer SJ-284, and SJ-952. Above the Bootstrap limestone, the Popovich Formation thins to the south and changes facies to more shallow water with more abundant debris beds and interbeds of crinoid, brachiopod, mollusk and corals. Local mine coordinates are shown.

feldspar, white mica, and rare zircon, as well as clay minerals which are silt sized or smaller and are the results of turbidity currents and eolian transport.

The deep water or starved basin lime mudstone possibly are the result of redistribution of distal axial turbidity currents and bottom currents (contour currents) and the slow rain of pelagic skeleton and of eolian quartz and clay to the sea floor (Galloway and McGilvery, 1995). The cores also show a spectrum of resedimentation features interpreted as the product of distal slump, debris flow and turbidity currents (Shhanmugan and others, 1995).

Diagenesis

The Popovich is silty, dolomitic limestone (micrite) to calcitic dolostone (dolomicrite). The dolomitization process within the Popovich Formation is incomplete. Sperber and others (1984) examined Paleozoic dolomites from North America that provide insight into how different types of dolomitization processes may be reflected in carbonate rocks. Their data indicates that two separate processes may lead to two distinct populations of sedimentary dolomites. The processes are divided into closed and open systems. Closed system dolomitization is associated with micrites that contained initially substantial amounts of magnesium calcite and resulted in dolomitic limestone. Dolomites in these limestones are generally calcium-rich if they have undergone only shallow burial. Open system dolostones, where most of the carbonate minerals have been converted to nearly stoichiometric dolomite, are believed to be the result of large-scale circulation of fluids capable of providing the Mg necessary for dolomitization.

The Popovich Formation contains abundant pyrite with the dolomite and this suggests that sulfate reduction was an important process. Baker and Kastner (1981) also emphasize the importance of dolomite in the geologic record and suggest that reduction of marine sulfate have a causative relationship to the formation of dolomite. Studies by Vasconceblos and others (1997) indicate that when dolomite is associated with sediments rich in organic carbon, biologic parameters must be considered as an important influence on the process of dolomitization. Mullins and others (1988) demonstrated in their study of Florida-Bahamas Neogene deep-water (475 to 2,767 m) carbonate strata that relatively small concentrations of dolomite are a natural consequence of early submarine, shallow-burial diagenesis of deep-water periplatform carbonate minerals originally rich in metastable components. Their conclusions are: (**1**) calcium-rich dolomite is a common (<20 percent) but rarely abundant authigenetic component of deep water periplatform carbonate that contains metastable aragonite and magnesium calcite; (**2**) deep-water dolomite is present mostly as scattered euhedral rhombs 5 to 20 µm wide, precipitated as pore fillings; and (**3**) along discontinuities, deep-water dolomites can constitute as much as 86 percent of the carbonate fraction in hardgrounds, occurring as both pore fill and as calcite replacement.

Morrow (1990b) describes the organogenic sea floor penecontemporaneous to the early dolomitization model. The dolomite beds form by precipitation from marine-derived fluids only a few meters beneath the sediment-water interface in offshore deeper marine continental margin settings. The intrasediment diagenetic environment is strongly reducing, leading to sulfate depletion by sulfate reduction and the oxidation of organic material. Both the reduction in sulfate concentration and the generation of carbon alkalinity are thought to enhance dolomitization (Baker and Burns, 1985).

Hydrothermal Alteration

Pervasive hydrothermal replacement of the Popovich Formation is present primarily in the foreslope facies. The Popovich Formation had an inherent porosity due to primary early crystallization of dolomite in the lime mud (micrite) and the development of intercrystalline porosity (figs. 4*A–C*). The porous foreslope facies of the Popovich Formation was deposited on the well-cemented ooid facies of the Bootstrap limestone, which probably was well cemented prior to deposition of the Popovich Formation as described above. Relations in some cores of the Bootstrap limestone indicate that parts of the Bootstrap limestone shelf were subjected to meteoric water and karsting. The debris flows of the foreslope facies of the Popovich Formation contained particularly well developed primary vuggy porosity. Furthermore, this porous calcite fossil debris was subject to reaction with ascending hydrothermal fluids which occurred much later during Cretaceous (Arehart and others, 1993b) or Tertiary (Seedorff, 1991) time. Initial stages of hydrothermal alteration associated with mineralization in the foreslope facies were the dissolution and removal of calcite minerals and bioclasts that greatly increased its porosity.

Hydrothermal replacement is, moreover, manifested by the introduction of hydrothermal dolomite and an increased crystal size of the dolomite rhombs, which further increases overall porosity of the rocks. It is because of the multiple generations of dolomite that plots of molar ratios of Ca/Ti versus Mg/Ti for gold-bearing and altered carbonate rocks in many Carlin-type deposits show a clustering of data points largely along the model line for dolomite (Madeisky, 1996). Introduction of microcrystalline silica, in places, gave rise to a near perfect silica pseudomorphic replacement of the original rock fabric. Pore space is infilled by coarse crystalline quartz, and silicified breccia contains irregular veins of white silica, residual carbon, pyrite, and bands of orange-brown sphalerite. Some relict dolomite and late vein calcite also are present. Examination of a limited number of these silicified samples by SEM reveals those relatively large anhedral mattes of apatite, locally hundreds of mm wide, are concentrated on the leading edges of silica fronts that have developed in the Popovich Formation. In addition, in some samples, pyrite and brannerite (ideally $(UO,TiO,UO_2)TiO_3$), which typically are approximately 5 to 10 mm wide, also are present along the apatite-hydrothermal silica contacts. The textural relations and crystal habits of the brannerite strongly suggest that it was completely recrystallized or reconstituted during the hydrothermal event associated with introduction of silica, pyrite, and gold.

At the Meikle Mine, the Popovich Formation is altered completely by hydrothermal fluids, and now is predominantly silica, hydrothermal collapse breccia, including variable amounts of clay minerals. In the Genesis and Blue Star gold deposits (fig. 1), most gold is hosted by silicic-argillic altered rocks, decalcified and containing approximately 10 to 35 volume percent mostly 1M illite (Drews-Armitage and others, 1996).

Rodeo Creek Unit

Cored sections of the Rodeo Creek unit are available for study from the Minorca (1,800 ft? thick) and Meikle Mine shaft drill holes (554 ft thick). At the latter locality, the Rodeo Creek unit is tectonically overlain along the Roberts Mountains thrust by rocks of the Ordovician Vinini Formation, Silurian Elder Formation (Merriam and Anderson, 1942; Smith and Ketner, 1975; Clure, 1997) and Devonian Slaven Chert (E.A. Lauha, written commun., 1997), all of which are, in turn, unconformably overlain by the Miocene Carlin Formation. The Rodeo Creek unit includes some quartz silt-dolostone and quartz silt-dolomite-argillaceous chert. The hand-specimen scale porosity of these rocks is similar to that described above in the Popovich Formation, but the overall extent of the sequences of carbonate rocks in the Rodeo Creek unit is relatively limited. Widespread chert in the Rodeo Creek unit is gray to black, distinctly thin bedded, rich in carbon, and rich in framboidal pyrite (fig. 14*C*). The rocks of this unit are essentially devoid of fossils except for radiolarians and sparse conodonts in some of the calcareous siltstone interbeds near the West Bazza pit. Rare sedimentary structures include slump structures, abundant siliceous mud lumps, and pervasive millimeter-size laminations, as well as medium-scale cross beds in silt-size beds. The Rodeo Creek unit, as recorded in these drill holes, is a monotonous sequence of chert with variations in percentages of clay minerals, silt, dolomite, and calcite content.

The Rodeo Creek unit exposed in the Betze-Post pit, two miles south of the Meikle shaft, is composed of three lithologic packages. They are: (**1**) a lower 200 ft of thin-bedded chert and argillite with minor siltstone, sandstone, and quartzite; (**2**) a middle 250 ft of interbedded chert, siltstone, and sandstone; and (**3**) an upper 150 ft of limy siltstone, micritic limestone, and minor chert (Bettles and Lauha, 1991; Leonardson and Rahn, 1996).

Environment of Deposition

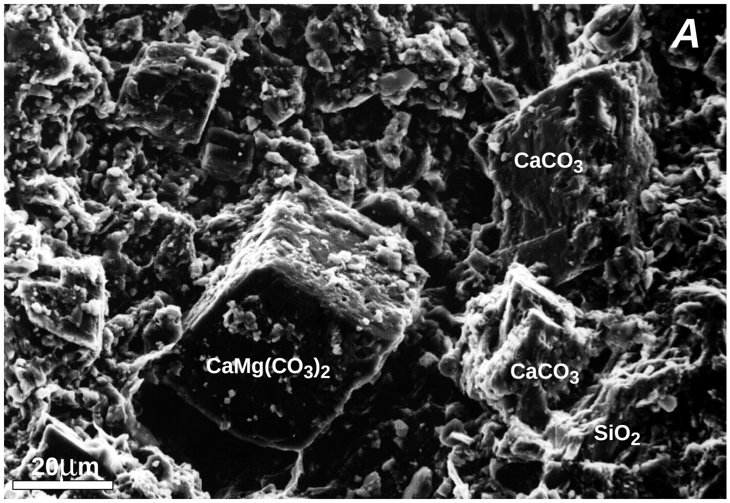
The Rodeo Creek unit was deposited in a silled starved basin, anoxic environment as was previously described by Ettner (1989). The chert may be the result of pelagic radiolarian sedimentation—sponge spicules are quite rare. The terrestrial sediment in the unit is silt size quartz, clay, white micas, and rare feldspars, all of probable eolian origin. The absence of bioturbation and presence of well preserved and persistent millimeter laminations indicate no infauna in the sedimentary rocks and support deposition under anoxic conditions (see also, Ettner, 1989). The carbonate materials may have been carried in suspension by seawater from the oolitic shelf and, in part, derived from pelagic organisms that settled to the sea floor (fig. 14).

Mineralization

Many of the original oxide-zone gold deposits in the area that predated large-scale mining in the northern part of the Carlin trend were confined to rocks of the Rodeo Creek unit. This unit is present in the Minorca hole and the Meikle Mine shaft, and mineralized rocks in the unit appear to be quite limited and confined to favorable structural settings or traps associated with fractures and faults. In the Betze-Post pit area, the Rodeo Creek unit was the primary host for the Post Oxide portion of the pit, as well as the open pits (Long Lac, Bazza, and West Bazza) mined by previous owner Western States Minerals Corporation (WSMC) in the early to middle 1980s. Approximately 1.5 million oz Au were mined from the Post Oxide deposit by Barrick, and 300,000 oz Au were mined by WSMC in the other oxide pits. When compared to Carlin-type deposits away from the Carlin trend and other types of gold deposits elsewhere in Nevada, gold deposits that formed in the Rodeo Creek unit are nonetheless quite substantial. In all, oxidized and highly fractured gold deposits in the Rodeo Creek unit have yielded approximately 2 million oz Au from the general area of the northern Carlin trend (fig. 2; see also, Volk and others, 1996).

Environment of Deposition

An idealized sequence of standard facies belts for the depositional environments of the Bootstrap limestone, Popovich Formation and Rodeo Creek unit is shown in figures 2 and 3. The concept for this model is from Wilson (1975). The Bootstrap limestone was deposited as ooid, grapestone, and bioclastic sands to lime mudstones on a shoaling shallow shelf environment. A modern analog for the Bootstrap carbonate sand is the Holocene ooid sediments of Joulters Cay, Bahamas (Harris 1979). The schematic block diagram of Ball (1967) that illustrates the sedimentary structures and grain types that typify marine sand belts of the western Great Bahama Banks, at Cat Cay also is an analog for the Devonian Bootstrap ooid depositional environments (fig. 3). As described above,



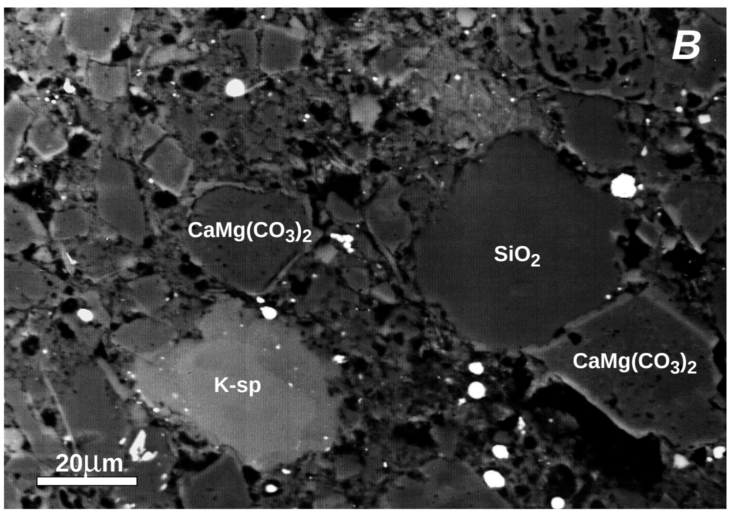


Figure 14. Scanning electron micrographs of Devonian Rodeo Creek unit. (***A***), Calcite and dolomite crystals and detrital quartz. Intercrystalline and interparticle porosity is well developed and pore space is filled by sulfur-rich carbon determined by SEM. Sample no. GB664–1047. (***B***), Polished section of rock showing an admixture of dolomite, calcite, detrital K–feldspar (K–sp), quartz, and framboidal pyrite. Pore space is black. Sample no. GB664+1150. (***C***), Mixture of calcite and dolomite rhombs with round framboidal pyrite crystal (py) in center of electron photomicromicrograph. Sample no. GB664+1031. (on page 60)

cores studied from the Bootstrap limestone provide no evidence for the presence of a coral barrier reef. The presence in the lower part of the Uranerz core at 3,500 to 3,600 ft of sabkha sedimentary structures such as algal mat laminations, rip-up clasts, and intraformational conglomerates indicates this part of the Bootstrap dolostone was deposited at times in subtidal to supratidal sabkha environments. Intertidal to supratidal sedimentary structures also are present in the lower part of the core. Dolostones at 3,630 to 3,790 ft and again 4,170 to 4,180 ft have pseudomorphs of gypsum and anhydrite, which indicate existence during deposition of laterally adjacent or overlying evaporites that could have provided sources of Mg–bearing hypersaline solutions capable of dolomitizing, by seepage-refluxion, this sequence of dolostones.

The base of the Popovich Formation represents drowning of the Bootstrap shelf, possibly because of downwarping and (or) faulting. The three upper units of the Popovich Formation represent foreslope deposits in an oxygenated to anoxic environment at the edge of the Bootstrap ooid shoals. They represent slide- and slump-transported ooid-shelf sediments

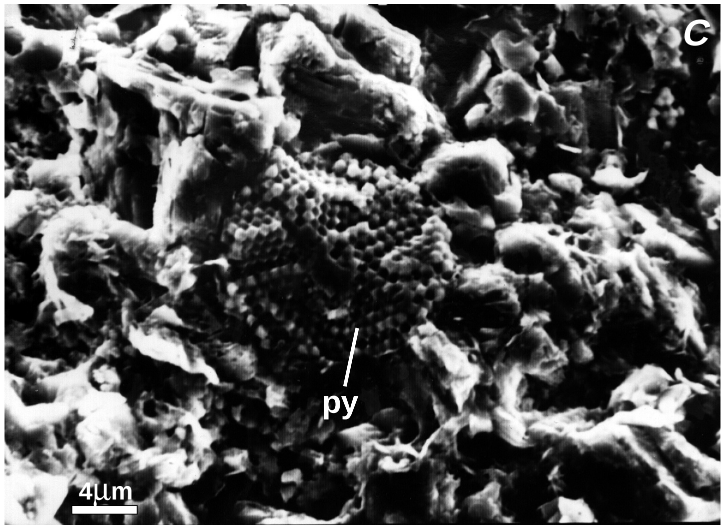


Figure 14. (***C***), Mixture of calcite and dolomite rhombs with round framboidal pyrite crystal (py) in center of electron photomicromicrograph. Sample no. GB664+1031

that are mixed and interbedded with basinal silty dolostones and lime mud. The rocks included are talus blocks, slump deposits, debris-flows, and turbidites. Features indicative of slope deposits in the Popovich Formation are: (**1**) synsedimentary folds formed by slump or creep; (**2**) low-angle truncation surfaces; and (**3**) slump scares (Emos and Moore, 1983). The middle and upper parts of the Popovich Formation were deposited in the toe-of-slope and deep shelf environments. The rocks are carbonate turbidites and distal base-of-slope sediments similar to those described elegantly by Ettner (1989) farther to the south along the Carlin trend.

The petrology, diagenesis, and depositional environments of the Rodeo Creek unit currently are under further study. The sediments represented by this unit, however, appear to have been deposited in the toe-of-slope, deep shelf, and euxinic basin environments. The rocks generally are quite siliceous with quartz silt and clays suggesting, in part, an eolian and pelagic (radiolarian) source for them.

CONCLUSION

Of the five Silurian-Devonian host-rock units below the Roberts Mountain thrust in the Carlin trend, the Hanson Creek Formation, Roberts Mountains Formation, Bootstrap Limestone, Popovich Formation, and the Rodeo Creek unit, only the Roberts Mountains and Popovich Formation have the mineralogy and porosity which favors gold mineralization. In both the Roberts Mountains and the Popovich Formations, sediments are typically calcitic dolostones with primary intercrystalline vug porosity resulting essentially from diagenetic crystallization of dolomite. The Roberts Mountains and Popovich Formations thus had an inherent porosity due to primary early crystallization of dolomite in lime mud (micrite) and abundance of intercrystalline sulfur rich carbon has subsequently enhanced its reactivity to gold-bearing fluids that circulated there during the Cretaceous and (or) Tertiary.

REFERENCES CIITED

Arehart, G. B., Chryssoulis, S. L., and Kesler, S. E., 1993a, Gold and arsenic in iron sulfides from sediment-hosted disseminated gold deposits: Implications for depositional processes: Economic Geology, v. 88, p. 171–185.

Arehart, G. B., Foland, K. A., Naeser, C.W., and Kesler, S.E., 1993b, $^{40}Ar/^{39}Ar$, K/Ar, and fission track geochronology of sediment-hosted disseminated gold deposits at Post-Betze, Carlin trend, northeastern Nevada: Economic Geology, v. 88, p. 622–646.

Armstrong, A. K., Bagby, W. C., Ekburg, C., and Repetski, J., 1987, Petrographic and scanning electron microscope studies of samples from the Roberts Mountains and Popovich Formations, Carlin Mine area, Eureka County, Nevada: U. S. Geological Survey Bulletin 1684, 23 p.

Baker, P. A, and Kastner, M., 1981, Constraints on the formation of sedimentary dolomites: Science, v. 213, p. 214-216.

Baker, P. A., and Burns, S. J., 1985, Occurrence and formation of dolomite in organic-rich continental margin sediments: American Association of Petroleum Geologists, Bulletin, v. 69, p. 1917-1930.

Ball, M. M., 1967, Carbonate sand bodies of Florida and the Bahamas: Journal of Sedimentary Petrology, v. 37, p. 556–591.

Bathurst, R. G. C., 1975, Carbonate Sediments and Their Diagenesis, Developments in Sedimentology, no. 12: New York, Elsevier, 658 p.

Beales, F. W., and Hardy J. L., 1980, Criteria for the recognition of diverse dolomite types with an emphasis on studies on host rocks for Mississippi Valley-type ore deposits: Society of Economic Paleontologists and Mineralogists Special Publication 28, p.197-213.

Bettles, K. H., and Lauha, E. A., 1991, Gold deposits of the Carlin Trend, Nevada: World '91, Forum on Technology and Practice: Second Australian Institute of Mining and Metallurgy-Society of Mining and Metallurgy Joint Conference, 21–26 April, Cairns, Australia, p. 251–257.

Cantrell, D. L., and Walker, K. R., 1985, Depositional and diagenetic patterns, ancient oolites Middle Ordovician, Eastern Tennessee: Journal of Sedimentary Petrology, v. 54, p.518-531.

Choquette, P. W., and James, N. P., 1990, Limestones-The burial diagenetic environment, *in* Mcllreath, I. A., and Morrow, D. W, eds., Diagenesis: Geoscience Canada reprint series no. 4, p. 75-111.

Christensen, O. D., 1996, Carlin trend geologic overview, *in* Peters, S.G., Williams, C. L., and Volk, Jeff, Field trip guidebook for Trip B—Structural geology of the Carlin trend, *in* Green, S.M., and Struhsacker, Eric, eds., Field Trip Guidebook Compendium: Reno, Nevada, Geological Society of Nevada, p. 147–156.

Cluer, J. Kelly, Cellura, B. R., Keith, S. B., Finney, S. C., and Bellert, S. J., 1997, Stratigraphy and structure of the Bell Creek nappe (Antler orogen), Ren Property, northern Carlin trend, Nevada, *in* Perry, A. J., and Abbott, E. A., eds., 1997 Fieldtrip Guidebook: Nevada Petroleum Society, p. 41-53.

Cook, H. E., 1972, Miette platform evolution and relation to overlying bank (reef) localization, Upper Devonian, Alberta: Bulletin Canadian Petroleum Geology, v. 20, no. 3, p. 375-411.

———1993, Submarine carbonate breccias: Criteria for their recognition, depositional models, and their role in petroleum and hydrothermal mineral exploration, *in* William C. L., ed., Northeastern Nevada breccia bodies: Geological Society of Nevada Symposium Proceedings, p. 1-7.

Cook, H. E., McDaniel, P. N., Mountjoy, E. W., and Prey, L. C.,.1972, Allochthonous carbonate debris flow at Devonian bank wall (reef) margins, Alberta, Canada: Bulletin of Canadian Petroleum Geology: v. 20, no. 3, p. 439-497.

Cook, H. E., Mullins, H. T., 1983, Basin margins, *in* Scholle, P.A., Bebout, D.G., and Moore, C.H. eds., Carbonate depositional environments: American Association of Petroleum Geologists, Memoir 33, p. 539-618.

Cox, D. P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.

Davis, J. J., 1996, Rapidity of freshwater calcite cementation-implications for carbonate diagenesis and sequence stratigraphy: Sedimentary Geology, v. 107, p. 1-10.

Demicco, R. V., and Hardie, L.W., 1994, Sedimentary structure and early diagenetic features of shallow marine carbonate deposits: Society of Economic Paleontologists and Mineralogists Atlas Series no. 1, Tulsa Oklahoma, 265 p.

Dobra, J.L., 1997, The U.S. gold industry 1996: Nevada Bureau of Mines and Geology, Special Publication 21, 32 p.

Drews-Armitage, S. P., Romberger, S. B., Whitney, C. G., 1996, Clay alteration and gold deposition in the Genesis and Blue Star deposits, Eureka County, Nevada: Economic Geology, v. 91, p. 1,383–1,393.

Dunham, J.B., and Olson, E. R., 1980, Shallow subsurface dolomitization of subtidally deposited carbonate sediments in the Hanson Creek Formation (Ordovician-Silurian) of central Nevada: Society of Economic Paleontologist and Mineralogist, Special Publication no. 28, p. 139-161.

Dunham, R. J., 1962, Classification of carbonate rocks according to depositional texture, *in* Ham, W. E., ed., Classification of carbonate rocks: American Association of Petroleum Geologists, Memoir 1, p. 108-121.

Dunham, R. J., 1969, Early vadose silt in Townsend mound (reef), New Mexico, *in* G. M. Friedman, ed., Depositional Environments in Carbonate Rocks: a Symposium: Society of Economic Paleontologist and Mineralogist, Special Publication1 14, p. 182-191.

Emos, P., and Moore, C. H., 1983, Fore-reef slope environments, *in* Scholle, P. A., Bebout, D. G., and Moore, C. H., eds., Carbonate depositional environments: American Association Petroleum Geologist, Memoir 33, p. 508–537.

Ettner, D. C., 1989, Stratigraphy and structure of the Devonian autochthonous rocks, north-central Carlin trend of the southern Tuscarora Mountains, northern Eureka County, Nevada: Pocatello, Idaho, Idaho State University, M.Sc. thesis, 177 p.

Ettner, D. C., Snyder, W. S., and Zimmerman, C., 1989, Roberts Mountains thrust: Reevaluation in the Carlin trend, southern Tuscarora Mountains, Nevada: Geological Society of America, Abstracts with Programs, v. 21, p. 76–77.

Evans, J. G., 1974, Geologic map of the Welches Canyon quadrangle, Eureka County, Nevada: U. S. Geological Survey Geological Quadrangle Map GQ–1117 [scale 1:24,000].

Evans, J. G., and Mullens, T. E., 1976, Bootstrap window, Elko and Eureka Counties: U.S. Geological Survey, Journal of Research, v. 4, p. 119–125.

Fischer, H. J., 1988, Dolomite diagenesis in the Metaline Formation, northeastern Washington state, *in* Shukla, V., and Baker, P. A., eds., Sedimentology and geochemistry of dolostone: Society of Economic Paleontologists and Mineralogists Special Publication, no. 43, p. 209-219.

Folk, R. L., 1974, The natural history of crystalline calcium carbonate: effects of magnesium content and salinity: Journal of Sedimentary Petrology, v. 44, p. 40-53.

Flügel, E, 1982, Microfacies analysis of limestones: Springer-Verlag, New York, 633 p.

Hardie, B. S., 1966, Carlin gold mine, Lynn District, *in* AIME Pacific Southwest Mineral Industry Conference, Sparks, Nevada: Nevada Bureau of Mines Report 13, Part A, p. 73–83.

Galloway, W. F., and McGilvery, T. A., 1995, Facies of a submarine canyon fill reservoir complex, lower Wilcox Group, (Paleocene), central Texas coastal plain, *in* Winn, R. D. Jr. and Armentrout, J. M., eds., Turbidites and associated deep-water facies: Society of Economic Paleontologists and Mineralogists, core workshop no. 20, p. 1-23.

Gilluly, James, and Gates, O., 1965, Tectonic and igneous geology of the northern Shoshone Range, Nevada: U. S. Geological Survey Professional Paper 465, 153 p.

Grammer, G. M., and Ginsburg, R. N., 1992, Highstand versus lowstand deposition on carbonate margins; insight from Quaternary foreslope in the Bahamas: Marine Geology, v. 103, p. 125-136.

Gregg, J. M., 1988, Origin of the dolomites in the offshore facies in the Bonneterre Formation (Cambrian), southeast Missouri, *in* Shukla, V., and Baker, P. A., eds., Sedimentology and Geochemistry of Dolostones: Society of Economic Paleontologists and Mineralogists, Special Publication no. 43, p. 67-83.

Harris, M. T., 1994, The foreslope and toe of the slope facies of the middle Triassic Latemar buildup (Dolomite, northern Italy): Journal of Sedimentary Research, v. B64, p. 132-145.

Harris, P. M., 1979, Facies anatomy and diagenesis of a Bahamian ooid shoal, *in* Ginsburg, R. N., ed., Sedimenta VII, The comparative sedimentology laboratory: University of Miami, Florida, 163 p.

Horton, R. A., 1985a, Dolomitization and diagenesis of the Leadville Limestone (Mississippian), central Colorado: Ph.D. Dissertation, Colorado School of Mines, 178 p.

Horton, R. A., 1985b, Dolomitization of the Leadville Limestone: Rocky Mountain section, Society of Economic Paleontologists and Mineralogists, 1985 SEPM midyear meeting field guide no. 2, p. 6–57 to 6–69.

Horton, R. A., Jr., and DeVoto, R. H., 1990, Dolomitization and diagenesis of the Leadville Limestone (Mississippian) central Colorado, *in* Beaty, D.W., Landis, G. P. and Thompson, T. B., eds., Carbonate-hosted sulfide deposits of the central Colorado Mineral Belt: Economic Geology Monograph 7, p. 86–107.

Horton, R. A., Jr., and Geisman, J. W., 1990, Geochemistry of the Leadville Dolomite (Mississippian), central Colorado, *in* Beaty, D.W., Landis, G. P. and Thompson, T. B., eds., Carbonate-hosted sulfide deposits of the central Colorado Mineral Belt: Economic Geology Monograph 7, p. 66–85.

James, N. P., and Choquette, P. W., 1990a, Limestones—The sea-floor diagenetic environment., Geoscience Canada, Reprint Series 4, p. 13-29.

James, N. P., and Choquette, P. W., 1990b, Diagenesis-Limestones—The meteoric diagenetic environment, Geoscience Canada, Reprint Series 4, P.35-73.

Jones, D. L., Wrucke, C. T., Holdsworth, Brian, and Suczek, C. A., 1978, Revised ages of chert in the Roberts Mountains allochthon, northern Nevada: Geological Society of America Abstracts with Programs, v. 10., no. 3, p. 111.

Leonardson, R. W., and Rahn, J. E., 1996, Geology of the Betze-Post gold deposits, Eureka County, Nevada, *in* Coyner, A. R., and Fahey, P. L., eds., Geology and ore deposits of the American Cordillera: Geological Society of Nevada Symposium Proceedings, Reno/Sparks, Nevada, April 1995, v. 2, p. 61–94.

Leventhal, J. S., and Hofstra, A. H., 1991, Characterization of carbon in sediment hosted disseminated gold deposits, north-central Nevada, *in* Hausen, D.M., and others, eds., Gold'90: Denver, Society for Mining, Metallurgy, and Exploration, p. 365–368.

Madeisky, H. E., 1996, Application of Pearce element analysis to lithogeochemical exploration of Carlin-type carbonate-hosted gold deposits, *in* Coyner, A. R., and Fahey, P. L., eds., Geology and ore deposits of the American Cordillera: Geological Society of Nevada Symposium Proceedings, Reno/Sparks, Nevada, April, 1995, v. 2, p. 709–732.

Madrid, R. J., 1987, Stratigraphy of the Roberts Mountains allochthon in north-central Nevada: Stanford, California, Stanford University, Ph.D. dissertation, 341 p.

Melim, L. A., and Scholle, P. A., 1995, The forereef facies of the Permian Capitan Formation: the role of sediment supply versus sea-level changes: Journal of Sedimentary Research, v. B65, p. 107-118.

Merriam, C. W., 1940, Devonian stratigraphy and paleontology of the Roberts Mountains region, Nevada: Geological Society of America Special Paper 25, 114 p.

Merriam, C. W., 1963, Paleozoic rocks of Antelope Valley Eureka and Nye Counties Nevada: U. S. Geological Survey Professional Paper 423, 67 p.

Merriam, C. W., and Anderson, C. A., 1942, Reconnaissance survey of the Roberts Mountains, Nevada: Geological Society of America Bulletin, v. 53, p. 1,675–1,728.

Moore, C. H., 1989, Carbonate diagenesis and porosity: Developments in Sedimentology 46, Elsevier, Amsterdam, 338 p.

Morrow, D. W., 1990a, Dolomite-part 1: the chemistry of dolomitization and dolomite precipitation, *in* Mcllreath, I. A., and Morrow, D. W., eds., Digenesis: Geoscience Canada, Reprint Series 4, p. 113-123.

Morrow, D. W., 1990b, Dolomite part 2: dolomitization models and ancient dolomites, *in* Mcllreath, I. A., and Morrow, D. W., eds., Digenesis: Geoscience Canada, Reprint Series 4, p.125-139.

Morse, J. W., and Mackenzie, J. A., 1990, Geochemistry of sedimentary carbonates: Elsevier, Amsterdam, 707 p.

Mullens, T. E., 1980, Stratigraphy, petrology, and some fossil data of the Roberts Mountains Formation, north-central Nevada: U. S. Geological Survey Professional Paper 1063, 67 p.

Mullins, H. T., Dix, G. R., Gardulski, G., and Land, L. S.,1988, Neogene deep-water dolomite from the Florida-Bahamas platform, *in* Shukla, V., and Baker, P. A., eds., Sedimentology and geochemistry of dolostones: Society of Economic Paleontologists and Mineralogists, Special Publication no. 43, p. 236-243.

Nolan, T. B., Merriam, C. W., and Williams, J. S., 1956, The stratigraphic section in the vicinity of Eureka Nevada: U. S. Geological Survey Professional Paper 276, 77 p.

Read, J. F., Grotzinger, J. B., Bova, J. A., and Koerschner, W. F, 1986, Model for generation of carbonate cycles: Geology, v. 14, p. 107-110.

Roberts, R. J., 1964, Stratigraphy and structure of the Antler Peak quadrangle, Humboldt and Lander Counties, Nevada: U.S. Geological Survey Professional Paper 459–A, 93 p.

Roberts, R. J., 1966, Metallogenic provinces and mineral belts in Nevada: Nevada Bureau of Mines Report 13, part A, p. 47–72.

Roberts, R. J., Hotz, P. E., Gilluly, James, and Ferguson, H. G., 1958, Paleozoic rocks in north-central Nevada: American Association of Petroleum Geologists Bulletin, v. 42, no. 12, p. 2,813–2,857.

Roberts, R. J., Montgomery, K. M., and Lehner, R. E., 1967, Geology and mineral resources of Eureka County, Nevada: Nevada Bureau of Mines and Geology Bulletin 64, 152 p.

Schatzinger, R. A., Feazel, C. T., and Henry, W. E.,1985, Evidence of resedimentation in chalk from the central graben, North Sea, *in* Crevello, P. D. and Harris, P. M., eds., Deep water carbonates: buildup, turbidites, debris flow and chalk, a core workshop: Society of Economic Paleontologist and Mineralogist workshop no. 6, p.342-385.

Schreiber, B. C., 1986, Arid shorelines and evaporites, *in* Reading, H. G., ed., second edition, Sedimentary environments and facies: Blackwell Scientific Publications, p. 189-228.

Seedorff, Eric, 1991, Magmatism, extension, and ore deposits of Eocene to Holocene age in the Great Basin—mutual effects and preliminary proposed genetic relationships, *in* Raines, G. L., Lisle, R. E., Schafer, R. W., and Wilkinson, W. H., eds., Geology and ore deposits of the Great Basin, Symposium Proceedings: Reno, Nevada, Geological Society of Nevada, p. 133–178.

Shanmugam, G., Salding, T. D., and Rofheart, D. H., 1995, Deep-marine bottom reworked sands (Pliocene and Pleistocene), Ewing bank 826, field, Gulf of Mexico, *in* Winn, R. D. Jr. and Armentrout, J. M., eds., Turbidites and associated deep-water facies: Society of Economic Paleontologist and Mineralogist, core workshop no. 20, p. 25- 54.

Smith, J. F., Jr., and Ketner, K. B., 1968, Devonian and Mississippian rocks and the date of the Roberts Mountains thrust in the Carlin-Piñon area, Nevada: U.S. Geological Survey Bulletin 1251–I, 18 p.

Smith, J. F., Jr., and Ketner, K. B., 1975, Stratigraphy of the Paleozoic rocks in the Carlin-Piñon area, Nevada: U.S. Geological Survey Professional Paper 867–A, 87 p.

Stewart, J. H., and McKee, E. H., 1977, Geology of Lander County Nevada: Nevada Bureau of Mines and Geology Bulletin 88, 106 p.

Stewart, J. H., and Poole, F. G., 1974, Upper Precambrian and Lower Paleozoic miogeoscline, Great Basin, western United States: Society of Economic Paleontologists and Mineralogists Special Paper 22, p. 28-57.

Spencer, G. H., and Tucker, M. E., 1997, Genesis of limestone megabreccias and their significance in carbonate sequence stratigraphic models: a review: Sedimentary Geology, V. 112, p.163-193.

Sperber, C. M., Wilkinson, B. H., and Peacor, D. R., 1984, Rock composition, dolomite stoichiometry and rock/water reaction in dolomite carbonate rocks: Journal of Geology, v. 92, p. 609-622.

Vasconceblos, C., and Mckenzie, J., A., 1997, Microbia mediation of modern dolomite precipitation and diagenesis under anoxic conditions (Largo Vermelha Rio de Janerio, Brazil): Journal of Sedimentary Research, v. 67, p. 378-390.

Volk, J. A., Lauha, Eric, Leonardson, R. W., and Rahn, J. E., 1996, Structural geology of the Betze-Post and Meikle deposits, Elko and Eureka Counties, *in* Peters, S.G., Williams, C. L., and Volk, Jeff, Field trip guidebook for Trip B—Structural geology of the Carlin trend, *in* Green, S. M., and Struhsacker, Eric, eds., Field Trip Guidebook Compendium: Reno, Nevada, Geological Society of Nevada, p. 180–194.

Whitebread, D. H., 1994, Geologic map of the Dun Glenn quadrangle, Pershing County, Nevada: U. S. Geological Survey Miscellaneous Investigations Series Map I–1209, 1 sheet, scale 1:48,000.

Wilkinson, B., H., Diedrick, N., W., and Drummond, C., N., 1997, Facies successions in pertidal carbonate sequences: Journal of Sedimentary Research, v. 66, p. 1065- 1078.

Wilson, J. L., 1975, Carbonate facies in geologic history: New York, Springer-Verlag, 471 p.

Yukio, I., 1997, Permo-Triassic boundary superanoxia and stratified superocean: records from lost deep seas: Science, v. 276, p. 235-238.

Zenger, D. H., and Dunham, J. B., 1988, Dolomitization of Siluro-Devonian limestones in a deep core (5350 m), southeastern New Mexico, *in* Shukla, V., and Baker, P. A., eds., Sedimentology and geochemistry of dolostones: Society of Economic Paleontologists and Mineralogists, Special Publication, No. 43, p. 161-173.

Appendix A Summary of conodant paleontology and zonation from the Bootstrap limestone recovered from Uranerz RU-8 drill hole.

Field no. (USGS col. no.)	**LITHOLOGY & STRATIGRAPHIC UNIT**	**CONODONT FAUNA**	**AGE**	**CAI**	**CONODONT BIOFACIES & DEPOSITIONAL ENVIRONMENT**	**REMARKS**
Ru-8-3036'-3090' (**12780-SD**)	Light-gray lime mudstone containing bryozoans, gastropods (<0.5 cm in diameter), and small pelmatozoan plates.	1 Pa element *Ozarkodina remscheidensis remscheidensis* (Ziegler) 1 indet. bar, blade, or platform fragment	middle Ludlovian-very earliest Pragian (middle early Late Silurian-early Early Devonian).	4	Indeterminate (too few conodonts); probably shallow-water near restricted depositional setting.	3.3 kg of rock processed (160 g +20 and 10 g 20-200 mesh insoluble residue). Heavy-mineral concentrate: chiefly dolomite, phosphatic argillaceous flakes containing fine pyrite and minor argillaceous composite flakes and pyrite.
Ru-8-3139'-3196' (**12779-SD**)	Light-gray lime mudstone/wackestone containing abundant small pelmatozoan plates and sparse calcite-filled vugs.	1 Pa element fragment *Ozarkodina douroensis* Uyeno 1 Pa element *Ozarkodina excavata excavata* (Branson & Mehl) 5 *Panderodus unicostatus* Branson & Mehl 2 indet. coniform and blade fragment	middle Ludfordian (=middle Ludlovian (early Late Silurian); thus far only found in the very lowermost *O. remscheidensis* Zone (known from the Canadian Arctic Islands, Great Basin, and Appalachian basin).	4.5-5	Indeterminate (too few conodonts); probably shallow-water depositional setting.	4.3 kg of rock processed (180 g +20 and 20 g 20-200 mesh insoluble residue). Heavy-mineral concentrate: chiefly fine euhedral and anhedral pyrite and composite anhedral dolomite with and without pyrite, and very rare euhedral biotite.
Ru-8-3305'-3359'	Medium-light- to medium-gray lime mudstone/wackestone containing common small pelmatozoan plates and white calcite fracture fills.	Barren.				6.2 kg of rock processed (220 g +20 and 16 g 20-200 mesh insoluble residue). Heavy-mineral concentrate: chiefly phosphatized carbonaceous and argillaceous very fine pyrite-bearing flakes and minor barite.

Appendix A. (*continued*)

Field no. (USGS colln. no.)	LITHOLOGY & STRATIGRAPHIC UNIT	CONODONT FAUNA	AGE	CAI	CONODONT BIOFACIES & DEPOSITIONAL ENVIRONMENT	REMARKS
Ru-8-3402'-3466' (**12778-SD**)	Light-gray lime mudstone containing rare pelmatozoan plates and white calcite vein fillings.	1 Pa element *Ozarkodina confluens* (Branson & Mehl)? 1 *Panderodus* sp. element 1 unassigned M element	middle Wenlockian-middle Ludlovian (late Early-middle early Late Silurian)	4	Indeterminate (too few conodonts); probably shallow-water depositional setting.	6.0 kg of rock processed (310 g +20 and 60 g 20-200 mesh insoluble residue). Heavy-mineral concentrate: chiefly anhedral and lesser rhombohedral dolomite, common euhedral pyrite and pyritic dolomite, and minor to rare composite ferruginous and (or) pyritic grains.
Ru-8-3574'-3619' (**12777-SD**)	Core interval contains three lithologies: 1) Light- to very light-gray, stylolitic, brecciated dolomite to limestone containing vugs. 2) Light- to medium-gray, fossiliferous (including echinoderm columnals and moldic brachiopods) packstone/wackestone. Most of core has mottled bioturbated texture. 3) Light-gray, vuggy dolo to lime micrite with no visible fossils or bedding.	1 incomplete Pa element *Ozarkodina confluens* (Branson & Mehl)?		~4.5-5	Indeterminate (too few conodonts); probably shallow-water depositional setting.	5.3 kg of rock processed (380 g +20 and 569 g 20-200 mesh insoluble residue). Heavy-mineral concentrate: chiefly composite dolomitic and (or) pyritic argillaceous grains, relatively rare composite ferruginous flakes, and rare euhedral pyrite.

Appendix A. (*continued*)

Field no. (USGS colln. no.)	**LITHOLOGY & STRATIGRAPHIC UNIT**	**CONODONT FAUNA**	**AGE**	**CAI**	**CONODONT BIOFACIES & DEPOSITIONAL ENVIRONMENT**	**REMARKS**
Ru-8-3794'-3849' (**12776-SD**)	Core interval contains two lithologies: 1) majority of core is light-gray, mottled/bioturbated, vuggy porosity, no visible fossils or bedding, few stylolites, some possible muddy intraclasts. 2) Dark-gray, pyritic, stylolitic mudstone with no visible bedding.	1 Pa element fragment *Ozarkodina excavata excavata* (Branson & Mehl)	*An. delta* Zone through succeeding *Pe. pesavis* Zone (=late Lochkovian; =early Early Devonian)	~4.5-5	Indeterminate (too few conodonts).	5.4 kg of rock processed (240 g +20 and 508 g 20-200 mesh insoluble residue). Heavy-mineral concentrate: chiefly rhombohedral and anhedral dolomite and lesser euhedral pyrite, composite fine-grained pyrite, composite ferruginous flakes, and minor siltstone.
RU-8-3906'-3960' (**12775-SD**)	Core interval has two lithologies: 1) light- to medium-gray, burrow-mottled, dolomitized, vuggy micrite (vugs 1-3 cm) micrite containing a few calcite veins (mainly 2-3 mm that are vertical to subvertical); no visible fossils or bedding; 2) light- to dark-gray, brecciated dolomite with many fractures, a few vugs and many calcite veins with random orientation. Remnant mm-scale bedding in clasts within breccia.	4 *Belodella* sp. elements *Icriodus* sp. indet. of Lochkovian morphotype 1 juvenile P & 4 M & S coniform elements 2 icriodontid P element fragments 1 Pa(?) *Oulodus*? sp. indet. element *Ozarkodina excavata excavata* (Branson & Mehl) 6 Pa, 4 Pb, 6 M, 2 Sa, 6 Sb & 10 Sc elements (mostly incomplete) 5 Pa (chiefly incomplete) elements *Ozarkodina pandora* Murphy, Matti & Walliser _ morphotype 4 *Panderodus unicostatus* (Branson & Mehl) elements 3 M & S coniform elements *Pedavis* sp. indet.		4.5-5 & minor 5.5 & 5.5-6	Ozarkodinid biofacies; normal-marine middle shelf or deeper water depositional setting.	6.1 kg of rock processed (520 g +20 and 495 g 20-200 mesh insoluble residue). Heavy-mineral concentrate: chiefly composite anhedral dolomite grains, composite dolomite and carbonaceous grains with and without pyrite, and lesser euhedral and anhedral pyrite.

Appendix A. (*continued*)

Field no. (USGS colln. no.)	**LITHOLOGY & STRATIGRAPHIC UNIT**	**CONODONT FAUNA**	**AGE**	**CAI**	**CONODONT BIOFACIES & DEPOSITIONAL ENVIRONMENT**	**REMARKS**
RU-8-3969'-4014' (**12774-SD**)	Core interval has three lithologies: two are like those in previous core interval and C is a medium-gray, vuggy, dolomitized dolomicrite. Vugs small (4 cm), no visible bedding or fossils.	1 Pb? element fragment *Oulodus*? sp. indet. *Ozarkodina excavata excavata* (Branson & Mehl) 2 Pa, 2 Pb, 1 M, 4 Sb & 1 Sc elements 4 *Panderodus* sp. elements 6 indet. bar, blade, and platform fragments	Wenlockian-late Lochkovian (no younger than *Pe. pedavis* Zone)	4.5 and minor 5.5 & 6	Indeterminate (too few conodonts); presence of *O. excavata* indicates normal-marine depositional setting.	4.7 kg of rock processed (140 g +20 and 385 g 20-200 mesh insoluble residue). Heavy-mineral concentrate: chiefly anhedral dolomite, anhedral pyrite, dolomitized bioclasts (brachiopods), and composite pyritiferous and carbonaceous grains.
RU-8-4014'-4069' (**12773-SD**)	Two major lithologies: 1) Medium-light- to light-gray, bioturbated, dense limestone to dolostone (wackestone/mudstone) containing large bioclasts (>5 cm) of ramose bryozoans, favositid? corals, calcite veins, vuggy porosity locally, moldic porosity (after fossil fragments) in other places, locally stylolitic, and some quartz filled vugs. 2) Medium-dark-gray limestone containing calcite veins, abundant stylolites (no apparent bedding).	1 adenticulate *Belodella*? sp. indet. element		5-6	Indeterminate (too few conodonts).	5.5 kg of rock processed (200 g +20 and 448 g 20-200 mesh insoluble residue). Heavy-mineral concentrate: chiefly composite carbonaceous, slight pyritiferous argillaceous flakes, anhedral and minor rhombohedral dolomite, lesser euhedral pyrite.

Appendix A. (*continued*)

Field no. (USGS colln. no.)	LITHOLOGY & STRATIGRAPHIC UNIT	CONODONT FAUNA	AGE	CAI	CONODONT BIOFACIES & DEPOSITIONAL ENVIRONMENT	REMARKS
RU-8-4069'-4124' (**12772-SD**)	Same as lithofacies (1) above but including wispy stylolites, possible intraclasts of mudstone, and a few pelmatozoan ossicles. Minor amounts of breccia occur in this core interval: breccia is light-gray limestone with extensive calcite veins and angular clasts.	1 coniform Sc element of an icriodontid(?) *Ozarkodina excavata excavata* (Branson & Mehl) 11 Pa, 7 Pb, 1 M, 1 Sb & 6 Sc elements 3 *Panderodus unicostatus* (Branson & Mehl) elements 20 indet. bar, blade, and platform fragments	Wenlockian-late Lochkovian (no younger than *Pe. pedavis* Zone)	4.5 and rare 5.5 and 5.5-6	*O. excavata* biofacies: middle shelf or deeper water depositional setting.	6.0 kg of rock processed (80 g +20 and 494 g 20-200 mesh insoluble residue). Heavy-mineral concentrate: chiefly anhedral and rhombohedral dolomite, minor euhedral pyrite, and rare chalcopyrite?
RU-8-4132'-4176' (**12571-SD**)	Light- and medium-gray burrow-mottled dense lime mudstone containing abundant, tight fractures (mostly subvertical). Some beds are graded where burrowing is absent. Parts of the core are vuggy (as much as 0.3 cm) and contain quartz crystal (as much as ~3 mm in size.	2 Pa elements *Ozarkodina excavata excavata* (Branson & Mehl) 3 *Panderodus unicostatus* (Branson & Mehl) elements		5-7	Indeterminate (too few conodonts); presence of *O. excavata* indicates normal-marine depositional setting.	4.4 kg of rock processed (160 g +20 and 502 g 20-200 mesh insoluble residue). Heavy-mineral concentrate: chiefly composite dolomitized grains, rhombohedral dolomite, composite pyritized grains, and lesser composite ferruginous flakes.
RU-8-4176'-4226' (**12570-SD**)	Three lithologies noted: A) medium-gray, bioturbated, dolomitized wackestone with no apparent bedding and containing echinoderm and other shell fragments (some appear coated), small vugs, and calcite veins; B) light-gray, burrow-mottled, dolomitized micrite with small vugs and fractures; C) brecciated, light- to dark-gray, burrow-mottled, dolomitized micrite that is abundantly fractured.	1 *Belodella* sp. indet. element 1 dapsilodid(?) element *Ozarkodina excavata excavata* (Branson & Mehl) 12 Pa, 6 Pb, 2 M, 4 Sb & 1 Sc elements 14 *Panderodus unicostatus* (Branson & Mehl) elements 11 indet. bar, blade, and platform fragments		5-5.5 and rare 6	*O. excavata* biofacies: normal-marine middle shelf or deeper water depositional setting.	5.0 kg of rock processed (140 g +20 and 511 g 20-200 mesh insoluble residue). Heavy-mineral concentrate: chiefly rhombohedral and lesser anhedral dolomite, composite carbonaceous dolomite-pyrite grains, and lesser euhedral pyrite and pyritic flakes.