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

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By AUGUSTUS K. ARMSTRONG, WILLIAM C. BAGBY,
CHARLES EKBURG, and JOHN REPETSKI

A study of transmitted-light photomicrographs, scanning electron microscope micrographs, and X-ray diffractograms of unaltered, altered, and mineralized samples from the Roberts Mountains and Popovich Formations in the Carlin mine area, Nevada

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Petrographic and Scanning Electron Microscope Studies of Samples from the Roberts Mountains and Popovich Formations, Carlin Mine Area, Eureka County, Nevada

By Augustus K. Armstrong, William C. Bagby, Charles Ekburg[1], *and* John Repetski

ABSTRACT

The Carlin sediment-hosted, disseminated gold deposit in northern Nevada has been a major gold producer in the United States for more than 20 years. The major host formation for gold is the upper part of the Roberts Mountains Formation. Minor gold also occurs in the overlying Popovich Formation and unnamed siliceous (western) assemblage rocks. Our studies of samples of these rocks from the Carlin mine area included transmitted-light microscopy, scanning electron microscopy, and energy-dispersive X-ray analysis. The megascopically unaltered Roberts Mountains Formation within the Carlin district consists of arenaceous, argillaceous limestone and dolomitic limestone with fossil fragments of echinoderms, brachiopods, and ostracodes. Reconnaissance samples from the Roberts Mountains Formation in the Carlin mine are categorized into three types on the basis of microscopic hydrothermal alteration textures: (I) dark-gray, organically rich arenaceous dolomite containing pyrite and illitic material; (II) oxidized, light-yellow to orange and tan arenaceous rock composed of goethite-stained illitic material, quartz, and minor calcite; and (III) oxidized, reddish-brown jasperoid.

INTRODUCTION

The Carlin ore body is a sediment-hosted, disseminated gold deposit located in northern Nevada, northwest of Carlin (fig. 1). It was the first of seven known major gold deposits of this type to be discovered in the Lynn-Railroad trend, now commonly referred to as the Carlin trend, which was originally noted by Roberts (1966). This gold trend is defined by a series of sediment-hosted, disseminated gold deposits aligned in a northwesterly direction.

Host formations in the Carlin trend consist of the Roberts Mountains Formation, Popovich Formation, Vinini Formation, and Webb Formation; minor amounts of gold are also present in porphyritic dikes and granodioritic plutons. Although the gold occurs in several different formations, actual host lithologies within the formations are similar. They are characterized as either silty, argillaceous carbonate rocks or calcareous siltstones.

The Roberts Mountains Formation is part of the early Paleozoic autochthonous eastern carbonate assemblage of Roberts and others (1958). The Roberts Mountains Formation ranges in age from Silurian to Devonian, whereas the overlying Popovich Formation is Devonian. The Roberts Mountains Formation was studied regionally by Mullens (1980) to identify its stratigraphic and petrologic characteristics and, in particular, how these features may relate to ore deposition. Recently, however, it became apparent that a modern petrographic study of specimens from this formation from the Carlin mine and neighboring area might disclose additional information about favorability of these rocks as host rocks for ore. We used scanning electron microscopy coupled with energy-dispersive X-ray analysis and transmitted-light microscopy to examine the mineralogical and textural characteristics resulting from diagenesis, metamorphism, and hydrothermal alteration associated with gold deposition in these rocks. The Carlin open-pit mine was used for these investigations because of the deep exposures available and the substantial data base that already existed for the deposit (Hardie, 1966; Hausen, 1967; Evans, 1974; Radtke, 1985).

Sampling in July 1982 of host rocks in and outside of the Carlin pit was not based on detailed alteration mapping, nor were the samples collected for the purpose of systematic characterization of alteration. Instead, sampling was directed toward providing a suite of rocks for microscopic examination

[1]Carlin Gold Mining Company, Carlin, Nevada.

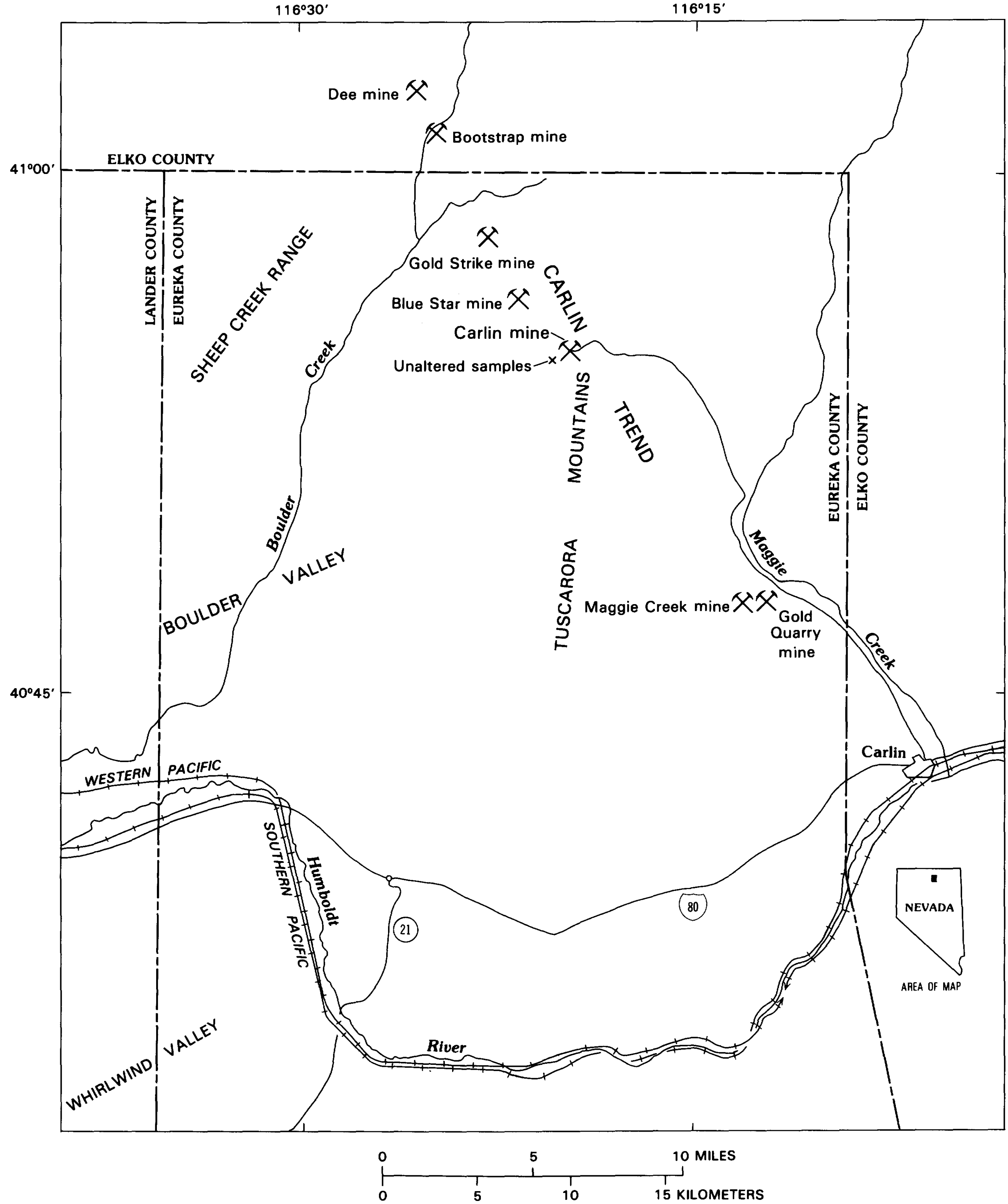

Figure 1. Index map showing location of the Carlin mine in north-central Nevada.

of textures. Pit sampling (fig. 2) of oxidized and unoxidized rocks was directed toward collecting representative samples from both ore and non-ore zones (identified by blast hole assay flags). Southwest of the Carlin pit, we collected hydrothermally unaltered, weathered rocks that are representative of host formation textures before hydrothermal alteration.

Several samples from the Roberts Mountains and Popovich Formations were taken for conodont analysis. These samples were from both the main body of the Carlin ore zones and from a locality 4 km south of the mine; they were meant to (1) confirm the dates of the respective formations and (2) yield, by the conodont color alteration index (CAI), minimum postdepositional host-rock temperature values as an additional constraint on reconstructing the thermal history of these rocks.

Carbonate rocks were stained for dolomite, calcite, and iron-rich carbonate minerals using the methods described by Friedman (1959) and were classified according to Dunham (1962). Scanning electron microscope (SEM) and energy-dispersive X-ray analyzer (EDX) systems were those described by Welton (1984). X-ray diffractograms were made at the following settings: 35 KV, 15 MA; chart speed, 1 in/min; scan speed, 2° θ; tungsten tube.

This study of alteration textures and mineralogy at the Carlin mine raises certain points that must be addressed in genetic modeling of the deposit. This is by no means an exhaustive study and is not meant to be. It is, however, a presentation of textural characteristics of altered rock at the Carlin deposits.

Acknowledgments.--We thank Robert Oscarson for his patient help with the scanning electron microscope. We thank Paul Russell for running the X-ray diffractograms. We thank R.T. Lierman for processing the conodont samples.

RESULTS

Roberts Mountains Formation: unaltered district samples

Samples of the megascopically unaltered Roberts Mountains Formation were collected about 4 km southwest (40°52'30" N., 116°20'00" W.) of the Carlin mine. Peloidal wackestone samples are composed of 10- to 15-μm calcite crystals, 30- to 70-μm grains of detrital quartz, and minor amounts of detrital feldspar. These samples contain various amounts of 5- to 50-μm clear, iron-free dolomite rhombs and 10- to 50-μm crystal agregates of euhedral pyrite. Fossil brachiopod and echinoderm fragments have been replaced by chalcedony, which is a common diagenetic feature in sedimentary rocks. Dolomite samples are composed of subhedral, 25- to 50-μm rhombs of dolomite crystals and minor 50- to 100-μm detrital quartz grains. Rare detrital monazite and framboidal pyrite 1 to 3 μm in diameter are also present in these samples (fig. 9).

The relatively large calcite crystals, 10 to 15 μm in diameter, in the wackestones and lime mudstones indicate thermal metamorphism. Three of these thermally metamorphosed samples, 82E-R12 (USGS fossil locality 11023-SD), 82E-R15 (11024-SD), and 82E-R17 (11025-SD) were dissolved to extract conodonts to determine the depositional age of the sample and the minimum temperature to which they were exposed during their subsequent history. Conodonts from specimen 82E-R17 are indicative of a Middle or early Late Silurian (Wenlockian or early Ludlovian) for the depositional age of the sample. Conodonts from each of these samples have color alteration indices (CAI) of about 5.5. A CAI in this range indicates that the enclosing strata were once heated to about 350 to 450 °C, depending on total time of 10,000 to 100,000,000 years at the elevated temperature, according to the CAI time-temperature correlation chart of Epstein and others (1977). X-ray diffractograms of unaltered samples 82E-R17 and 82E-R18 indicate that calcite and quartz were the dominant minerals. Illitic material[2] is noticeably absent (fig. 3).

Roberts Mountains Formation: altered Carlin mine samples

Samples from the Roberts Mountains Formation in the Carlin mine may be divided into the following categories: type I is dark-gray, organically rich arenaceous dolomite containing pyrite and illitic material; type II is oxidized, light-yellow to orange and tan arenaceous rock composed of goethite-stained illitic material, quartz, and minor calcite; and type III is oxidized, reddish-brown jasperoid.

Type I

In hand specimens, type-I rocks are medium-dark to dark gray and finely laminated; they contain mud chips, worm burrows, and weakly developed cross laminations. These very subtle sedimentary structures are well preserved. Framboidal pyrite is preserved and common. An X-ray diffractogram of a specimen of this rock type (82E-1+27) shows the rock to be composed principally of quartz, dolomite, calcite, and illitic material (fig. 4A). The X-ray diffractogram for sample 82E-1+35 indicates that quartz, calcite, and illitic material are the dominant minerals (fig. 4B).

Type-I rocks typically contain clear dolomite rhombs (30-70 μm) in which zoning is defined by iron-rich and iron-poor layers. These zoned dolomite rhombs are commonly corroded (fig. 12F) and occur in a matrix of 5- to 10-μm iron-rich dolomite rhombs with detrital quartz grains, illitic material, and abundant pyrite (figs. 10; 11; 12A-C; 17A-E). The pyrite in these samples generally occurs as fine spheroidal

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[2]The term "illitic material" is used in this text as a general petrologic term to refer to clay-sized micaceous minerals with a 10-A component (see Środoń and Eberl, 1984). No oriented X-ray diffractograms were made to positively identify the clay fraction.

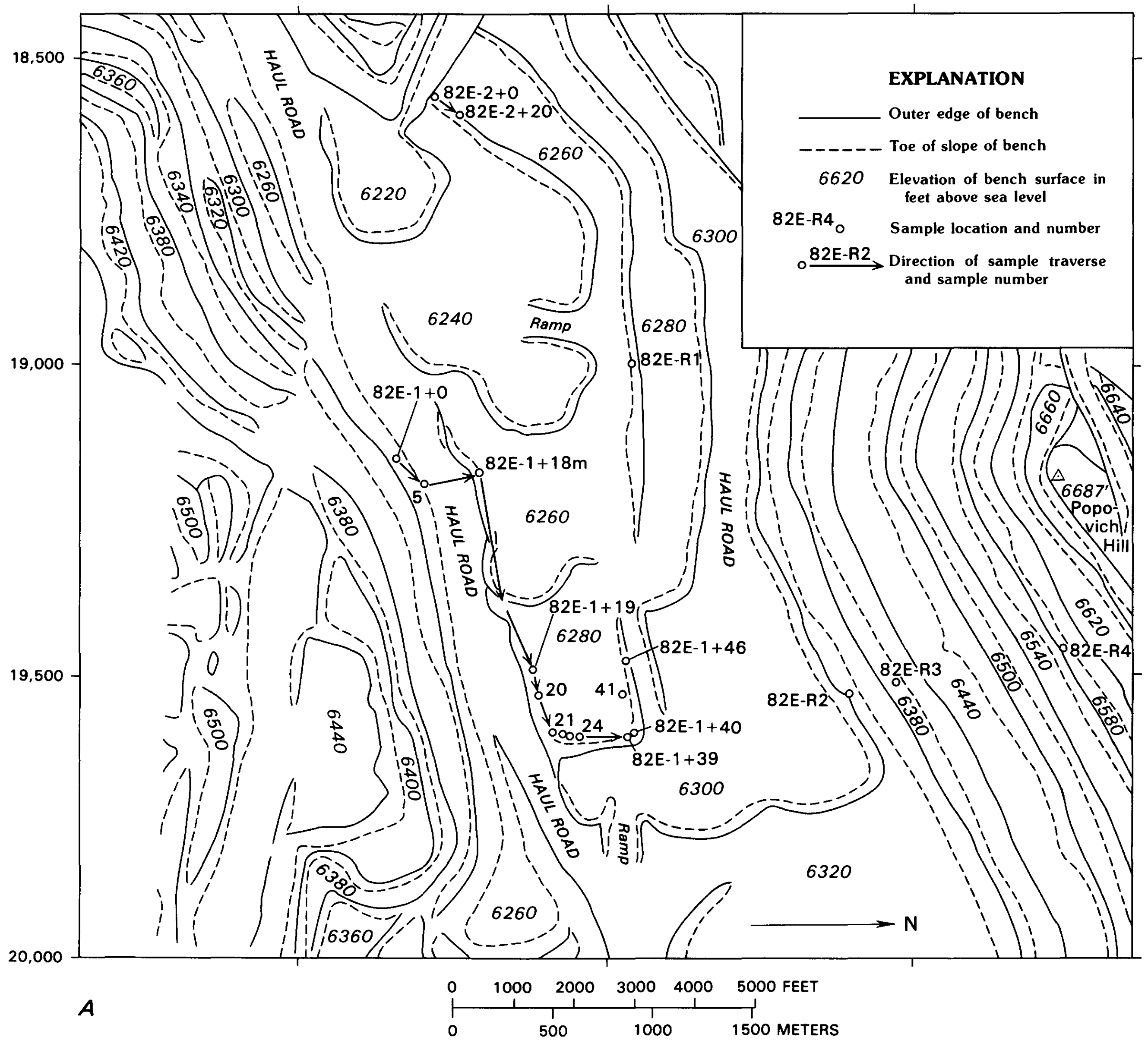


Figure 2. Sample locations within the Carlin mine pit. A, Contour map of the Carlin pit from Carlin Mine Company, late July 1982. Grid established by Carlin Mine Company. B, North wall of Carlin pit showing geology and some sample locations, 1982.

B

EXPLANATION

Kd	Dike (Cretaceous)
Dp	Popovich Formation (Devonian)
DSrm	Roberts Mountains Formation (Devonian and Silurian)
SOl	Limestone (Silurian and Ordovician)
SOc	Chert and shale (Silurian and Ordovician)
cb	Carbonaceous limestone and shale
——	Contact
═══	Fault zone—Arrows indicate direction of relative movement
▲▲▲	Roberts Mountains thrust fault
• 82E-R1	Sample location and number

Figure 2.--Continued

aggregates 4-10 µm long composed of tiny (1-µm) euhedral cubes of pyrite (figs. 12C, 14E, F). Carbonaceous material occurs along bedding planes. Vugs and cavities in some samples are lined by euhedral quartz crystals as long as 3 mm. The surfaces of these quartz crystals are coated by late sphalerite and arsenopyrite; in some cases these sulfides occur as inclusions in the quartz (figs. 11, 12A, B). Although small fractures and cavities are filled by spar calcite, these samples have much greater porosity and permeability than do the fresh, unaltered samples of the Roberts Mountains Formation collected 4 km southwest of the mine.

Type II

Typically, type-II rocks contain a pale yellowish-brown clay and are quartz rich. Notably, samples of this type are composed of abundant illitic material, detrital quartz grains, and limonite (a combination of goethite, hematite, and jarosite as a stain). Fractures and cavities commonly are filled by late crystalline quartz or calcite (fig. 17F). X-ray diffraction analysis indicates that rocks of this type are composed of illitic material, quartz, and late calcite (fig. 5).

Subtle sedimentary structures are preserved in the type-II samples. These structures include millimeter-scale cross bedding, fine laminations, mud clasts, rip-up clasts, and small worm burrows. Some samples have abundant ostracode casts that are preserved by replacement silica. Laminations of dark-gray, carbonaceous, iron-rich dolomite-bearing bands alternate with oxidized, yellowish-brown bands in some type-II samples.

SEM micrographs show that type-II rocks are highly porous (fig. 13). The pores are partly filled by clay and subhedral quartz crystals. Detrital grains include quartz and zircon (fig. 12E).

Type III

The third type of sample from the Roberts Mountains Formation collected from within the mine

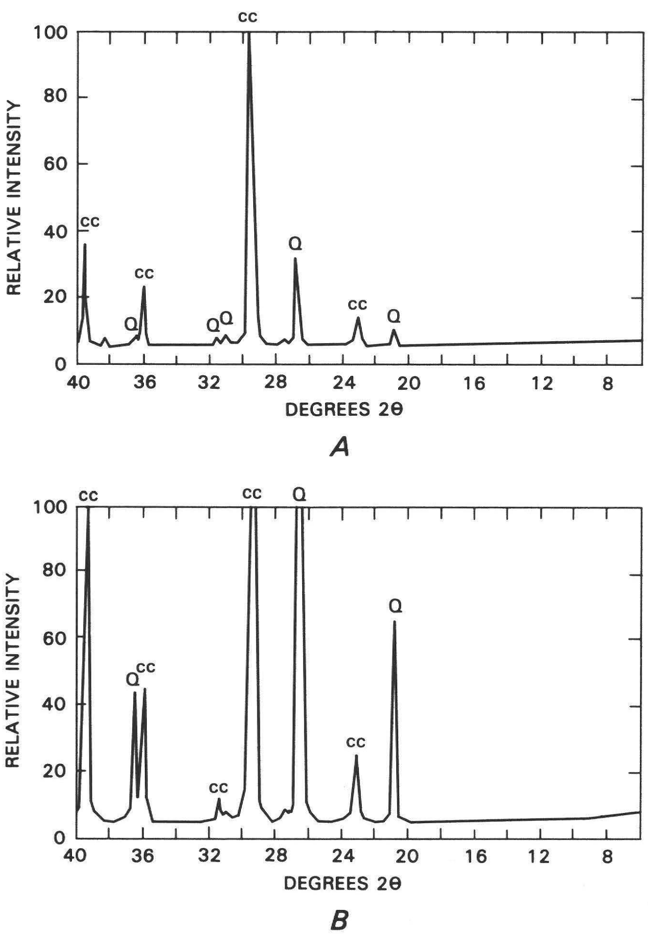


Figure 3. X-ray diffractograms for unaltered samples of the Roberts Mountains Formation from south of Carlin mine. Q, quartz; cc, calcite. A, 82E-R17. Wackestone thermally metamorphosed to temperatures between 350 and 450 °C. B, 82E-R18. Arenaceous peloidal fossiliferous wackestone.

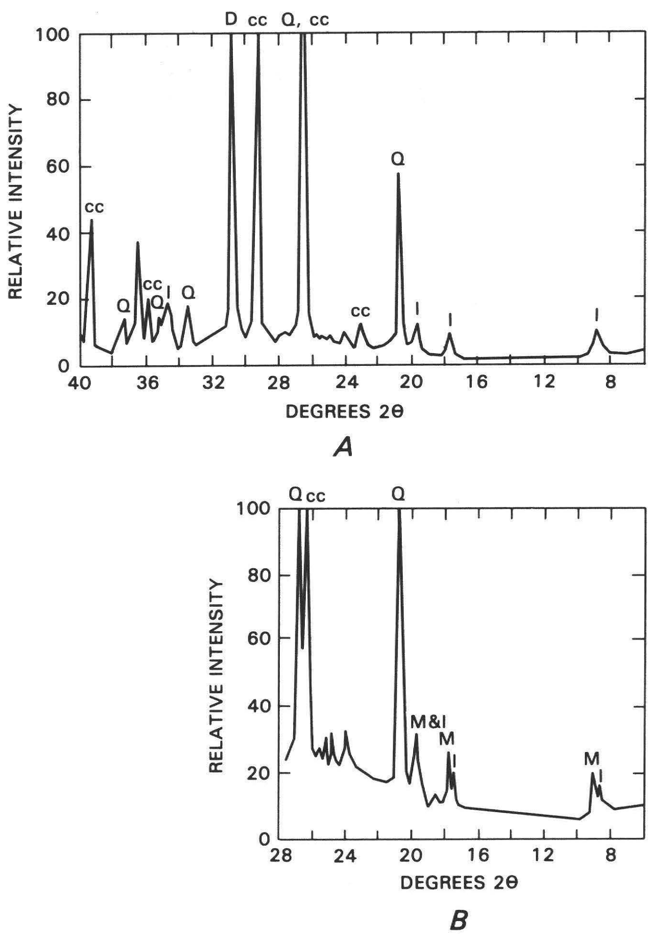


Figure 4. X-ray diffractograms for type-I altered, unoxidized samples of the Roberts Mountains Formation from the Carlin mine. Q, quartz; I, illitic material; cc, calcite; D, dolomite; M, muscovite. A, 82E-1+27. Silty limestone. B, 82E-1+35. Wackestone.

are silicified rocks (jasperoids). Fresh surfaces of the jasperoids are medium-dark-gray, whereas weathered surfaces range from very pale orange to dark yellowish orange to light brown. Most jasperoids are highly fractured, and many of the fractures and cavities are coated by iron oxides. The jasperoids typically contain euhedral quartz crystals that are coated by fine grains of iron oxide (fig. 14A, B). This silicic alteration is a metasomatic replacement of silty, fossiliferous dolomite, as indicated by pseudomorphs and relict textures of fossils preserved from the original carbonate rocks of the Roberts Mountains Formation. Very delicate fossil shells are preserved either as silica or as carbonate casts or molds of ostracodes, brachiopods, and echinoderms. Representative X-ray diffractograms are shown in figure 6.

Another classification

Samples of rock of these three types may also be characterized in terms of Radtke's (1985) classification of alteration and ore at the Carlin mine. Radtke identified two types of ore: oxidized and unoxidized. The unoxidized ore was further broken into five types "on the basis of differences in mineral content, chemical composition, and associations of the gold" (Radtke, 1985, p. 49). Samples from type I fall into Radtke's normal unoxidized ore. Although we have no gold assays on the samples analyzed by SEM, the alteration textures identifed suggest that the rocks we studied were affected by epigenetic hydrothermal solutions. For this reason, we feel these samples are examples of Radtke's (1985) normal unoxidized ore and that they represent variations in alteration textures that are typical of this type of ore. Samples from both type II and type III fall into Radtke's oxidized ore classification. The intense bleaching and the mineral composition of the type-II samples suggest that they are examples of Radtke's acid-leached rocks from the oxidized zone (1985, p. 95). The oxidation of jasperoid samples in type III is limited to fractures and appears to be late stage. This suggests that type-III samples represent oxidized versions of Radtke's siliceous, unoxidized ore (1985, p. 54).

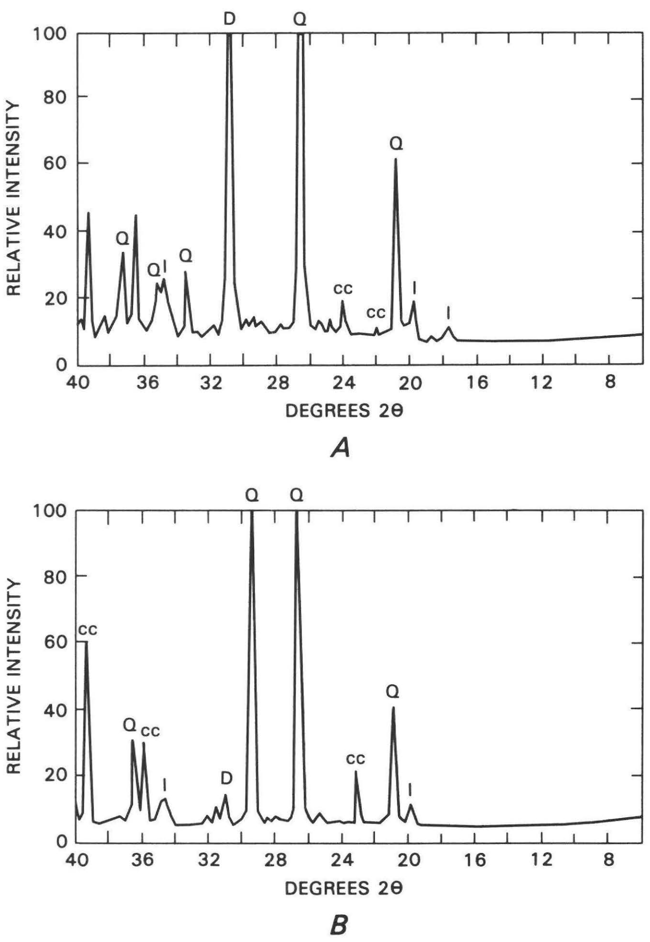


Figure 5. X-ray diffractograms for type-II altered, oxidized samples of the Roberts Mountains Formation from the Carlin mine. Q, quartz, I, illitic material; cc, calcite; D, dolomite. A, 82E-2+2. Quartz, illitic material. B, 82E-1+22. Quartz, calcite.

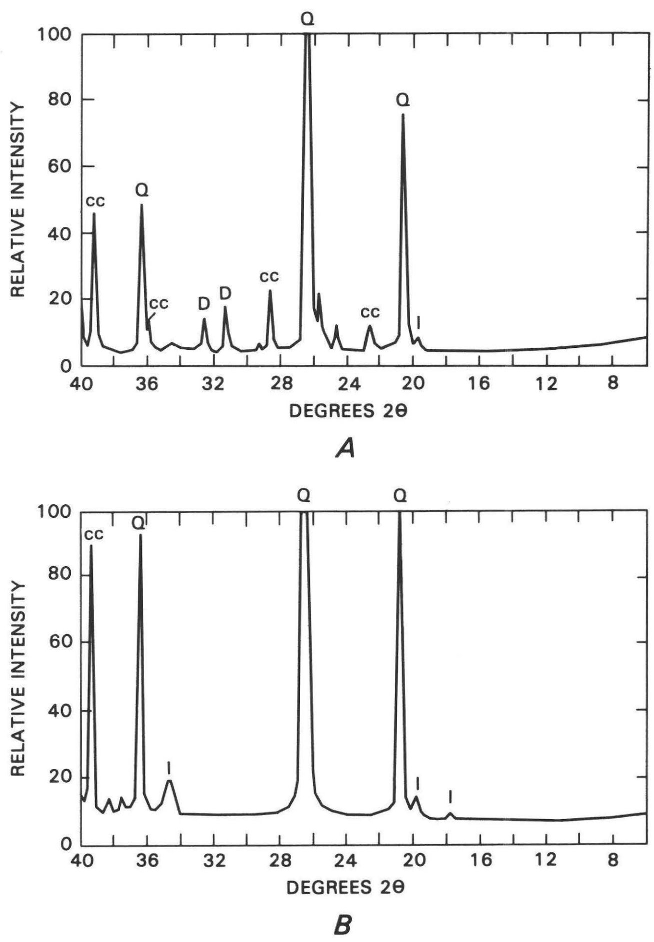


Figure 6. X-ray diffractograms for type-III jasperoid samples from the Carlin mine. Q, quartz; I, illitic material; cc, calcite; D, dolomite. A, 82E-1+20C. B, 82E-1+6A.

Conodont analysis

Eight samples of the Roberts Mountains Formation from the bottom of the Carlin mine pit were checked for conodonts. Of these samples, only three contained conodonts (USGS fossil localities 11026-SD, 11027-SD, and 11028-SD; from map localities 82E-1+26, 82E-1+42, and 82E-2+15, respectively), all of which indicate a Late Silurian age. The conodont samples show a variable degree of thermal alteration in this part of the mine. Two of the samples (11026-SD and 11027-SD) show elements having CAI of 4, indicating that the host-rock was heated to about 150 to 250 °C. The third sample (11028-SD) yielded conodont elements exhibiting a range of CAI values of 5 to 7. Mixed CAI values in a single collection commonly are found in mineralized zones. Sample 11026-SD is bleached and oxidized and sample 11027-SD is unoxidized, yet conodonts in both yield CAI values of 4. This suggests that bleaching of organic matter is not responsible for the mixed CAI values in sample 11028-SD which is partially bleached. An explanation for the mixed values is that fluids affecting the host rock of sample 11028-SD could have varied between 300 and 500 °C at different times and for different durations resulting in mixed CAI values between 5 and 7. It is unlikely that fluids in this temperature range were associated with gold mineralization.

Popovich Formation: Carlin mine samples

Samples from the Popovich Formation (Hardie, 1966) were collected from above its contact with the Roberts Mountains Formation along a traverse up the north wall (Popovich Hill) of the Carlin pit (fig. 2). Samples from near the contact show different degrees of hydrothermal alteration (fig. 18A, B, D). These samples are typically dark gray and carbonaceous, and they contain abundant pyrite and detrital quartz grains. Some samples contain iron-rich dolomite rhombs. Vugs and fractures are partly filled with spar calcite (fig. 18D, E). Scanning electron micrographs reveal a matrix of calcite between the dolomite rhombs (fig. 15C).

Samples from about 2 m above the contact with the Roberts Mountains Formation are carbonaceous, peloidal, arenaceous wackestone with ostracode, brachiopod, and echinoderm fragments. These rocks in turn are overlain by nonferroan dolomites that contain relict structures of brachiopod and ostracode shells (fig. 18F).

Samples of the Popovich Formation from the north wall of the mine are arenaceous calcitic dolomites and argillaceous dolomites (fig. 7). These rocks contain abundant pyrite as replacement of fossil fragments, including ostracodes, echinoderms, and tentaculites (fig. 18E). The rocks are carbonaceous, and fractures and voids are filled by calcite. Detrital quartz grains 40 to 70 µm in size are common. Barite is also a common mineral that occurs as interstitial grains between calcite crystals and is probably epigenetic (fig. 16F). The majority of samples from the Popovich Formation have undergone much less alteration than those from the Roberts Mountains Formation.

Four samples from the Popovich Formation along the north-wall traverse in the Carlin mine pit were checked for conodonts. Only one sample (USGS 10816-SD) from near the bottom of the pit at the base of the Popovich Formation yielded conodonts most likely of Devonian age. The CAI of conodonts from this sample is between 5 and 6, indicating that the host rock was heated to 300 to 350 °C, assuming a duration of heating of 10,000 years to 100 m.y. (CAI time-temperature chart, Epstein and others, 1977).

SUMMARY AND DISCUSSION

The Roberts Mountains Formation, 4 km southwest of the Carlin mine, consists of fossiliferous, arenaceous lime mudstones and wackestones that have been subjected to a thermal event in the 350- to 450 °C range during some part of their history. This thermal event caused the micritic calcite crystals to grow to about 15 µm in diameter. These rocks are composed of nonferroan dolomite and calcite and have very low porosity and permeability. There is no indication that the rocks have been subjected to the same hydrothermal fluids as those that altered similar rocks in the Carlin mine pit.

Carbonate rocks of the Roberts Mountains Formation in the Carlin mine pit show the effects of epigenetic hydrothermal alteration. This alteration is exemplified by porosity greater than that of the unaltered samples collected southwest of the mine. The Carlin mine rocks are organically rich, unoxidized dolomites composed of 30- to 100-µm rhombs of zoned ferroan dolomite, microcrystalline quartz, illitic material, and minor amounts of iron, zinc, and arsenic sulfides. In the mine pit, some of the carbonate rocks of the Roberts Mountains Formation have undergone an oxidizing event that removed most of the carbonate

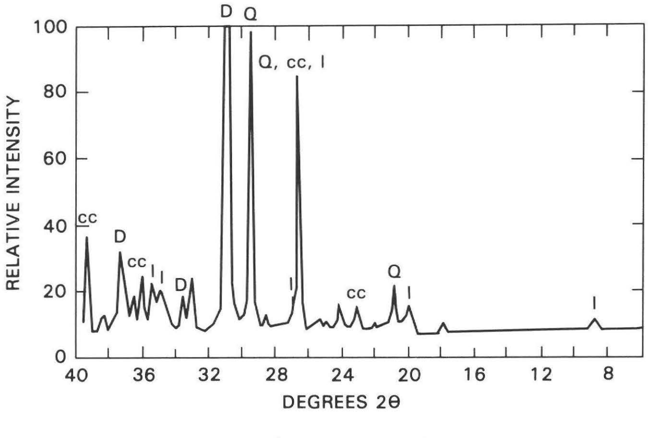


Figure 7. X-ray diffractogram for silty limestone sample of the Popovich Formation from the Carlin mine, 82E-23B. Q, quartz; I, illitic material; cc, calcite; D, dolomite.

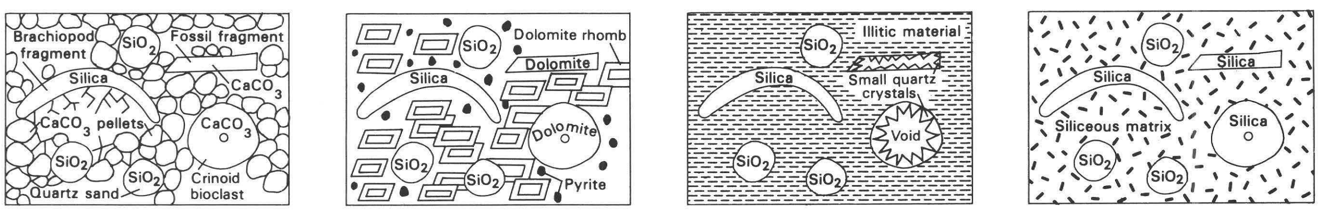
minerals and organic material from the rock and that oxidized the sulfide minerals to limonite. The oxidized rocks are extremely porous and are composed of silica, illitic material, and a late-stage, void-filling spar calcite. The jasperoid stage of alteration represents silica replacement and filling of all of the void spaces, producing a very nonporous rock. A schematic summary of the types of alteration is given in figure 8.

The Popovich Formation is also an arenaceous limestone, but it is not as strongly altered as the carbonate rocks of the Roberts Mountains Formation in the Carlin mine.

The different alteration effects between the Roberts Mountains Formation and the Popovich Formation apparently reflect different original lithologies of the two formations. The Roberts Mountains Formation is a thin- to medium-bedded, arenaceous, slightly argillaceous, bioclastic peloidal limestone and dolomite that has a possible inherent porosity and permeability. Thin 1- to 5-cm partings of shale and silty argillite are present between the carbonate beds. The Popovich Formation, in contrast, is considerably more massive and contains arenaceous micrites and pelletoidal lime-mudstones and wackestones that are impermeable.

Certain key characteristics of alteration are noted in this study. (1) Barite is present with sulfide minerals in unoxidized, weakly altered rock from the

UNALTERED	ALTERED		
	Type I	Type II	Type III
Fossiliferous, dolomitic, arenaceous, argillaceous limestone	Organically rich arenaceous Fe-dolomite having pyrite and some illitic material	Oxidized arenaceous illitic rock containing quartz and minor calcite; no dolomite	Oxidized jasperoid
Partially silicified organic material between carbonate crystals and detrital sand and clay minerals	Enriched organic material between dolomite rhombs, pyrite, and clay minerals	No organic material; bleached illitic and siliceous rock, low in carbonates; very vuggy and porous	No organic material; all jasperoid (SiO_2 n•H_2O); no porosity



UNALTERED	Type I	Type II	Type III
2- to 6-μm calcite crystals; 15-μm calcite crystals if heated to 300–350 °C; low-Mg calcite, some Fe-free dolomite	2- to 10-μm ferroan dolomite rhombs; 30- to 100-μm, clear, ferroan-zoned euhedral dolomite rhombs. Introduced pyrite and black organic material	Illitic material, quartz-filled voids, late-stage spar calcite; no pyrite	Original rock totally replaced by silica
Very low porosity and permeability	High porosity and permeability	High porosity and permeability	Very low porosity and permeability
Fe-poor carbonate rocks	Introduced metasomatic Fe; ferroan-rich dolomites	Introduction of Fe-poor spar calcite into fractures and cavities	Introduction of spar calcite into fractures and voids
Silicification of some fossil fragments by diagenetic chert	Hydrothermal silicification of matrix; quartz crystal growth into cavities and voids	Silicification by small quartz crystals into voids and space between crystals of illitic material	Replacement of carbonate minerals by silica, resulting in total silicification of rock
Sedimentary pyrite	Hydrothermal pyrite introduced into matrix	Pyrite oxidized to limonite and hematite	Oxidized to limonite and hematite
Sedimentary clay minerals	Introduction of illitic material	Illitic material predominates over microcrystalline quartz	Illitic material in part replaced by microcrystalline quartz
Possible detrital sedimentary sulfides	Introduction of Fe-, As-, and Zn-sulfide minerals	Oxidation of Fe-, As-, and Zn-sulfide minerals	

Figure 8. Schematic characterization of alteration of limestone from the Roberts Mountains Formation in the Carlin mine area.

Popovich Formation. This mineral assemblage of coexisting pyrite and barite helps constrain the oxygen fugacity during hydrothermal alteration. (2) The presence of illitic material in altered rocks, and its absence in unaltered rocks, helps to constrain the pH of fluids during hydrothermal alteration. (3) Ferroan dolomite formed during hydrothermal alteration. The precipitation and stability of this mineral during hydrothermal alteration certainly reflects the iron, magnesium, and carbonate content of the hydrothermal fluids. (4) Framboidal and euhedral pyrite occur in both altered and unaltered unoxidized samples. This bimodality of the pyrite population and the difficulty of identifying pyrite that is genetically associated with hydrothermal alteration from other pyrite must be considered in sulfur isotope studies of deposits of this type. Additional detailed documentation and modeling of this alteration should lead to an understanding of the fluid chemistry of gold deposition at Carlin.

The thermal alteration recorded by conodonts appears not to have been a regional event. Thermally metamorphosed unaltered rocks 4 km south of the mine reached the same or even higher temperatures as some of the hydrothermally altered samples in the mine. However, samples from unnamed Ordovician siliceous (western) assemblage rocks correlative with the Vinini Formation collected less than 3 km due east of the Carlin mine (USGS collections 8826-CO, 8827-CO, 8828-CO) contain conodonts having CAI values as low as 2 to 3, which indicate minimum host-rock heating in this area was between 60 and 100 °C.

The thermal metamorphism and resultant growth of large calcite crystals raise the question of how much the original rock permeability influenced the hydrothermal fluid flow. It is reasonable to assume that rocks at the Carlin mine contained large matrix crystals of calcite prior to initiation of the gold-depositing hydrothermal system. An alteration feature noted in the unoxidized but altered rocks (type I) from the mine is a porosity greater than that of the unaltered rocks. This porosity is a result of, and not an antecedent to, hydrothermal alteration. A review of the literature on sediment-hosted precious-metal deposits (Bagby and Berger, 1985) suggests that sandy and silty, finely laminated limestones are more favorable gold hosts than massive limestones are. The fact that more gold is deposited in laminated limestones of the Roberts Mountains Formation than in massive limestones of the Popovich Formation supports this contention. The growth of calcite during thermal metamorphism essentially turns sandy, silty limestones into massive, impermeable rocks. Calcite-dissolving hydrothermal solutions create permeability, and the presence of sand and silt particles in the limestone must maintain that porosity. Thus, the fluid flow rate, at first slow, is increased and brings more gold into the rocks.

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FIGURES 9-18

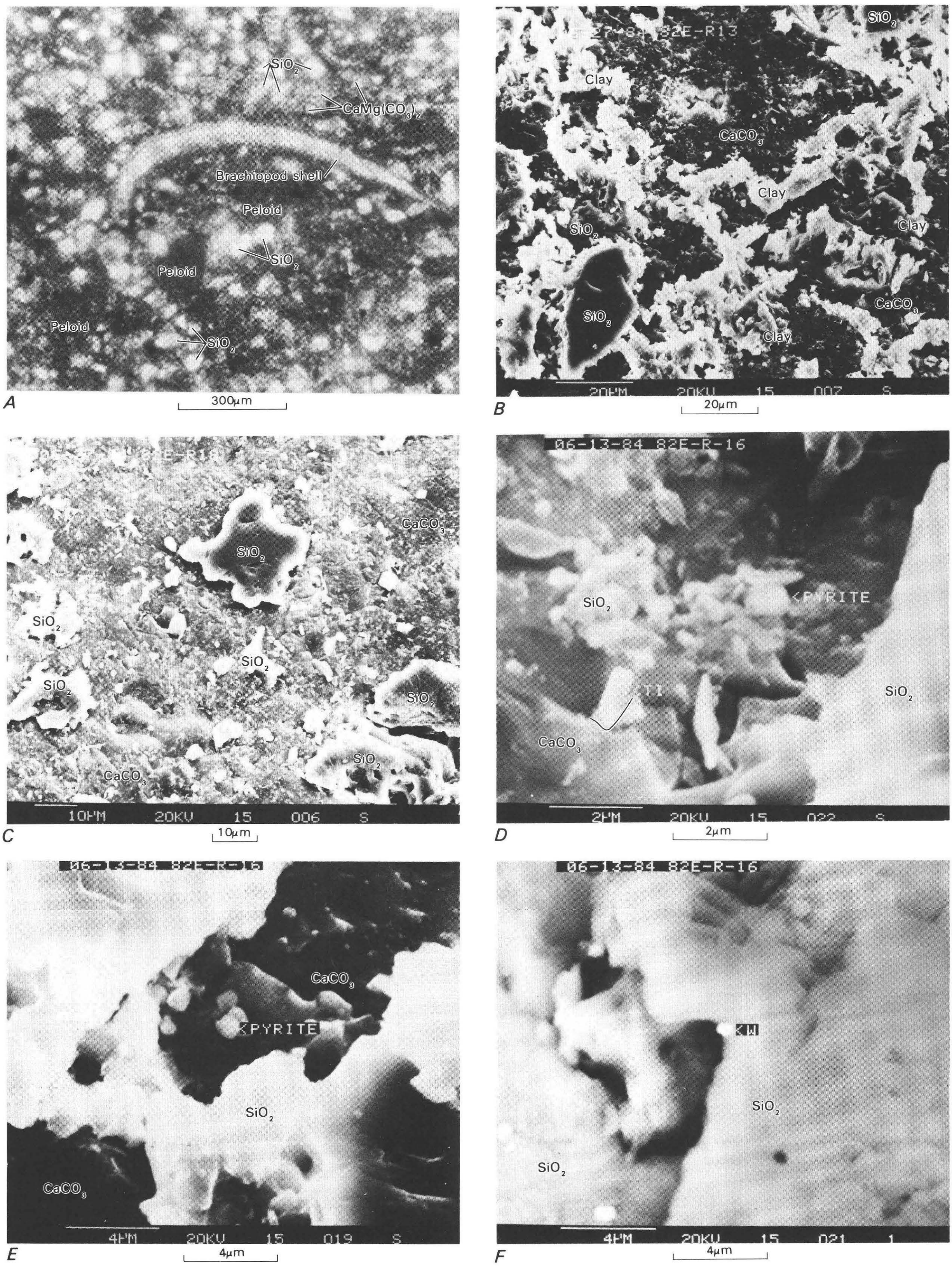


Figure 9. Specimens of unaltered rocks from the Roberts Mountains Formation, from an outcrop 4 km southwest of the Carlin mine in the SE1/4, sec. 27, R. 50 E., T. 35 N. A, Transmitted-light photomicrograph; B–F, SEM micrographs. A, 82E-R16. Arenaceous peloidal lime mudstone that contains 5- to 20-µm calcite rhombs and some clear iron-poor dolomite; brachiopod shell in center of photograph is replaced by calcite. B, 82E-R13. Arenaceous peloidal wackestone. Dark areas are calcite; large white areas are quartz and clay. C, 82E-R18. Arenaceous peloidal fossiliferous wackestone. Dark areas are calcite; large light areas are silica. Small amounts of clay between calcite crystals. D–E, 82E-R16. D, Small crystal of pyrite and rutile on a calcite surface. E, Small pyrite framboids on calcite surrounded by white quartz. F, Small grain of a tungsten mineral embedded in quartz.

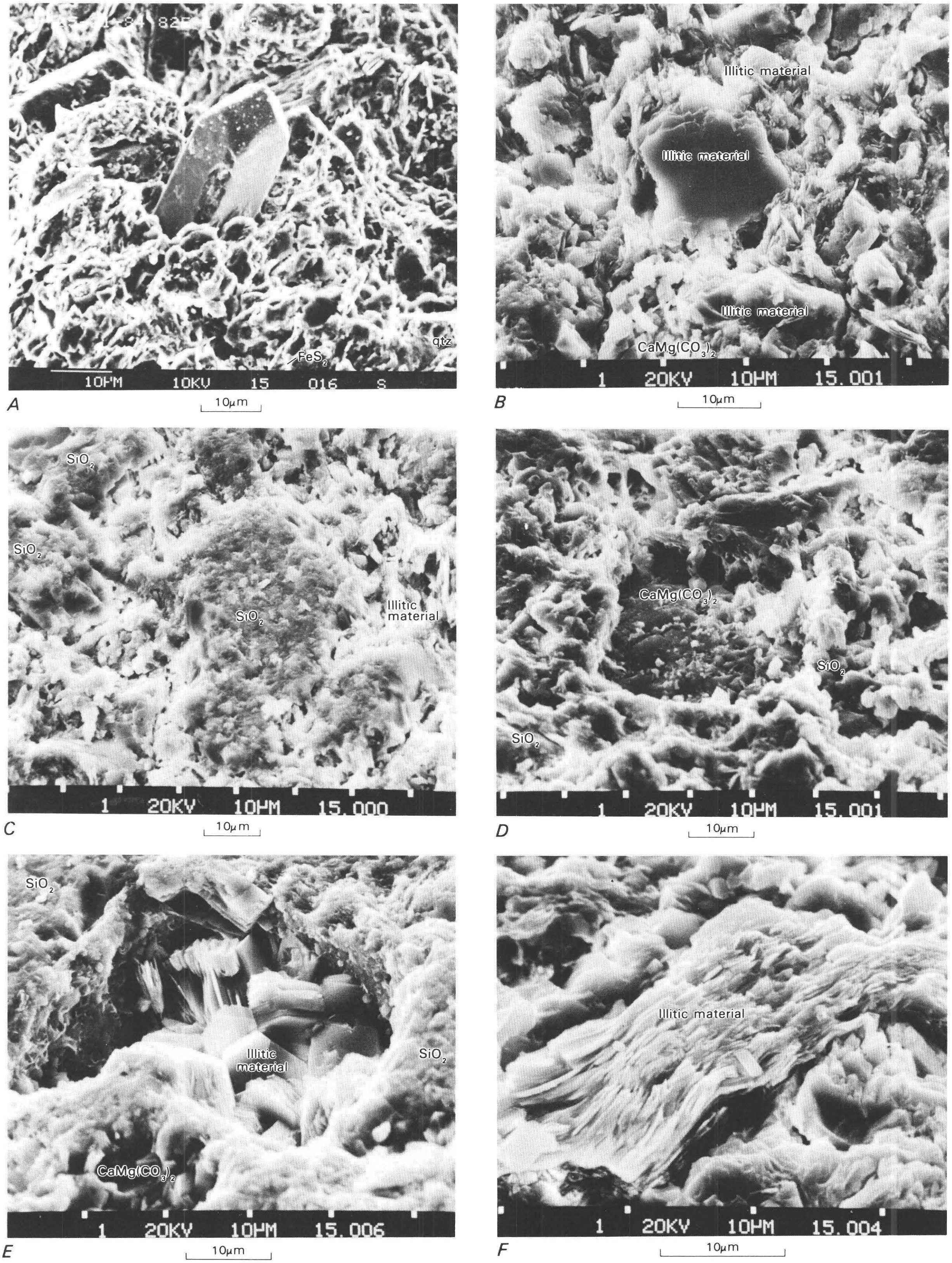


Figure 10. Specimens of altered rock type I from the Roberts Mountains Formation, Carlin mine, SEM micrographs. A. 82E-1+19. Nearly euhedral detrital zircon crystal in a matrix of porous authigenic clay minerals. Rock shows some evidence of oxidation. B, C, 82E-1+20. B, Illitic material, dolomite, and quartz; note size of crystals and porosity. C. Quartz, illitic material, and dolomite; note intracrystalline porosity. D. 82E-1+20. Dark-colored calcite surrounded by small crystals of quartz, illitic material, and minor amounts of dolomite. E-F. 82E-1+20. E, Crystallized epigenetic illitic material filling pores formed in a dolomite matrix. Sample is dark gray, organically rich, and composed of zoned, iron-rich dolomite rhombs, angular detrital quartz fragments, and pyrite cubes. F. Crystalline illitic material. Sample is dark gray, organically rich, and composed of zoned, iron-rich dolomite rhombs, detrital quartz grains, and pyrite cubes.

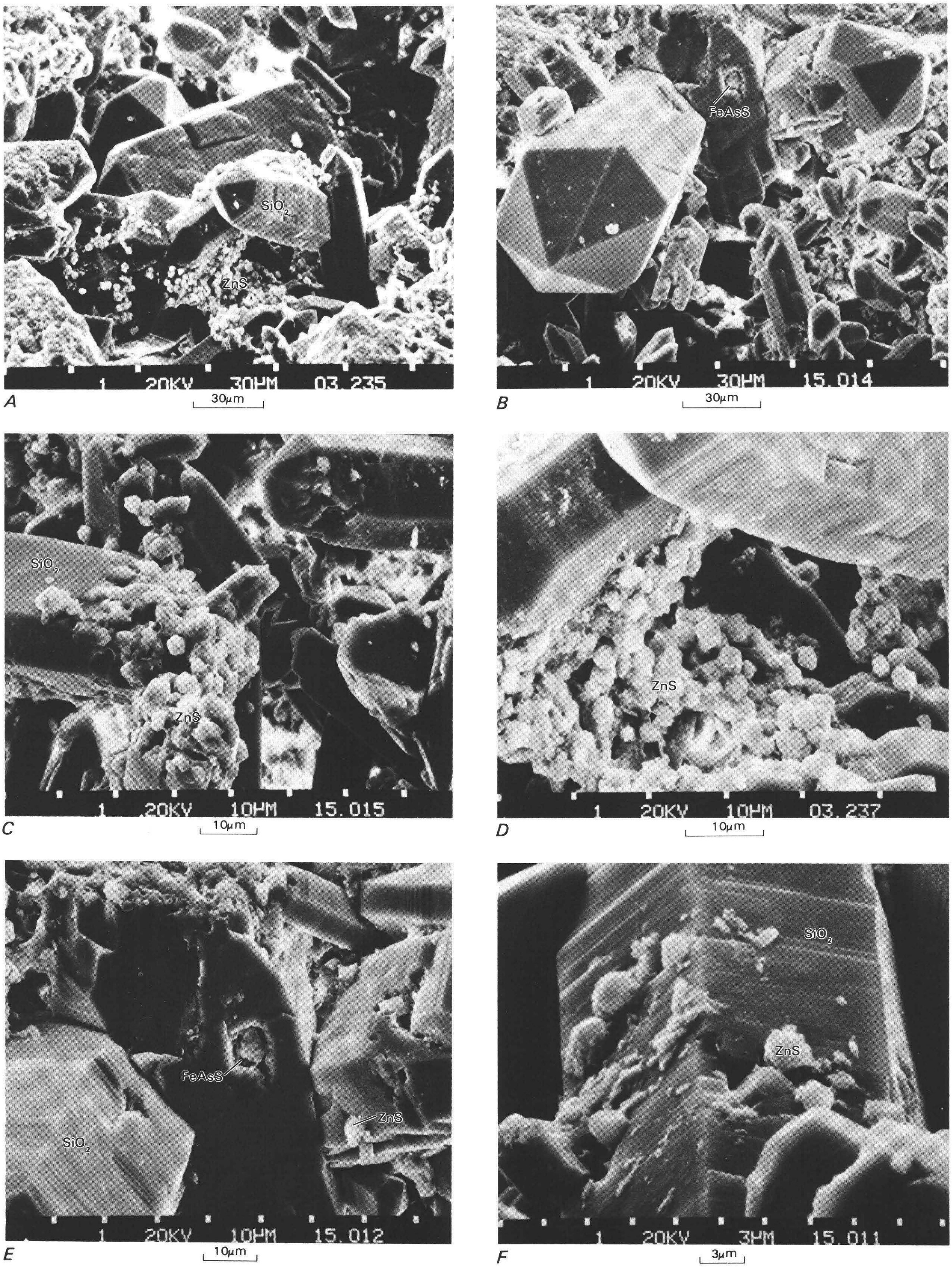


Figure 11. Specimens of altered rock type I from the Roberts Mountains Formation, Carlin mine; SEM micrographs of sample 82E-1+31. Clear, 10- to 50-µm subhedral dolomite rhombs in a matrix of iron-rich dolomite and detrital quartz. Rock, from an ore zone, is dark gray and organically rich and contains numerous small vugs lined with quartz crystals. Views are within one of these vugs. A, Quartz crystals within a vug; some surfaces are covered by small sphalerite crystals. B, Center quartz crystal contains an enclosed crystal of arsenopyrite, and floor of vug has scattered crystals of sphalerite. C, Sphalerite crystals on surfaces of quartz crystals. D, Enlargement of sphalerite crystals on quartz. E, Enlargement of arsenopyrite crystal within a quartz crystal that has a few sphalerite crystals on its surface. F, Detail of sphalerite crystals on surfaces of quartz.

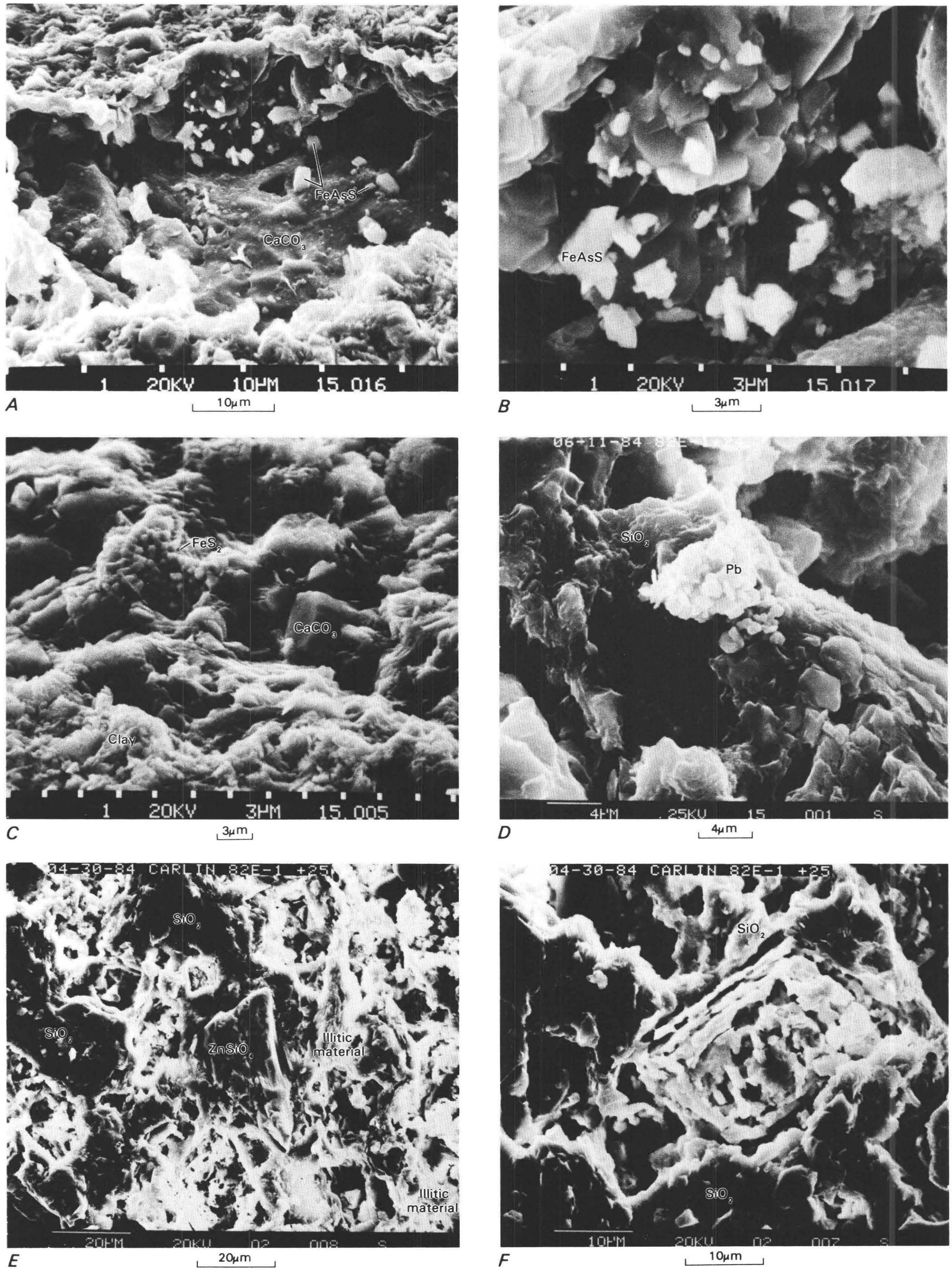


Figure 12. Specimens of altered rocks type I (_A_–_C_) and type II (_D_–_F_) from the Roberts Mountains Formation, Carlin mine; SEM micrographs. _A_–_C_, 82E-1+20B. Dark-gray, organically rich rock with iron-rich dolomite and detrital silt-size quartz grains. _A_, Cavity containing and floored by calcite with white crystals of arsenopyrite. _B_, Enlarged view of cavity wall illustrating white arsenopyrite crystals on calcite. _C_, Pyrite framboids in matrix of calcite, dolomite, and clay minerals. _D_, 82E-1+24. Yellowish-brown, oxidized rock. Quartz and clay matrix having extensive porosity formed by interconnected vugs. Small white cluster in center is composed of nonsulfur-bearing lead mineral (possibly lead carbonate?). _E_, _F_, 82E-1+25. _E_, Illitic material and detrital crystals of zircon and quartz. _F_, Iron-rich, zoned dolomite rhomb that is partly corroded and preserved in a matrix of silica and clays. Note vuggy porosity of matrix and dolomite rhomb.

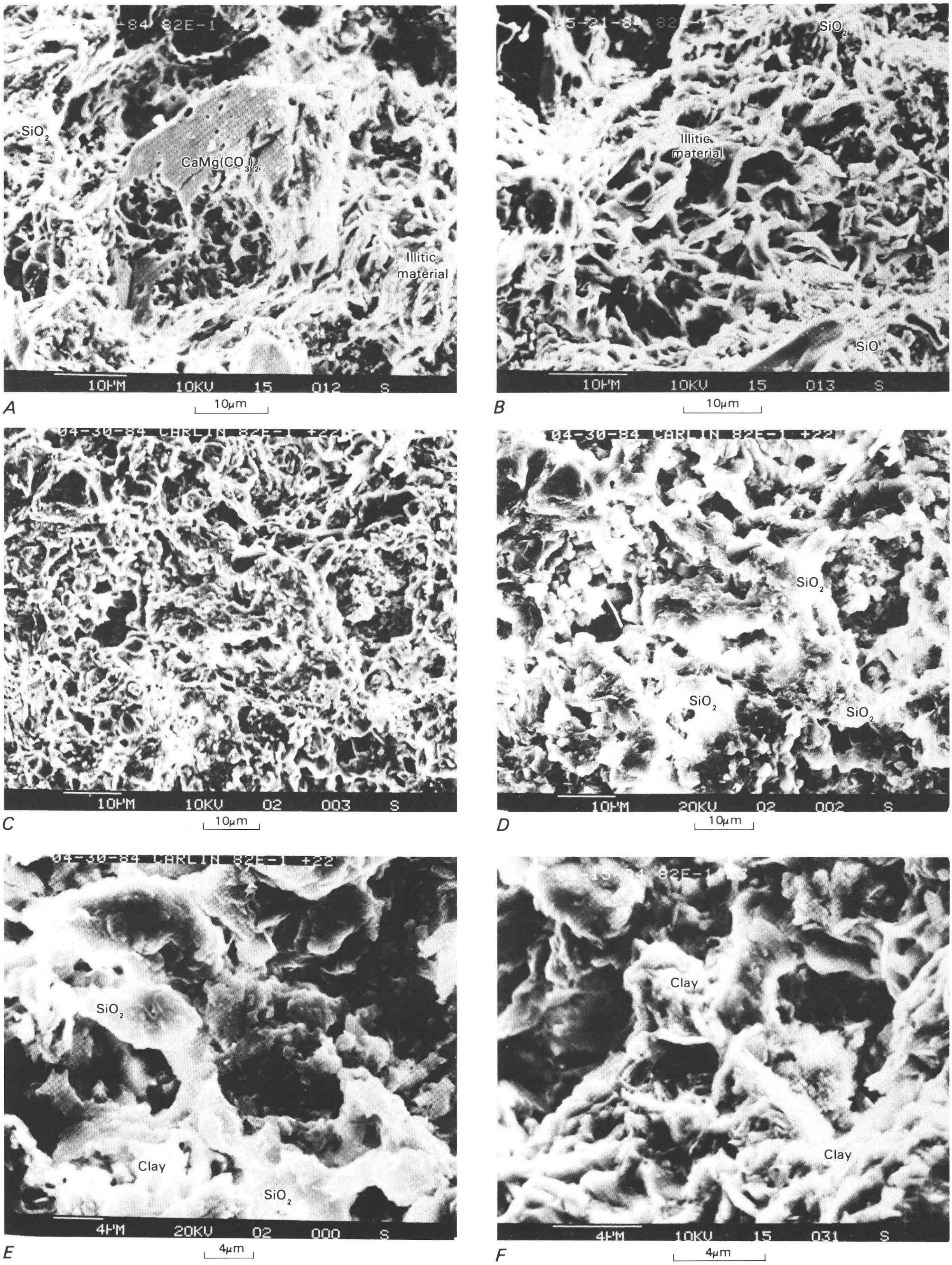


Figure 13. Specimens of altered rock type II from the Roberts Mountains Formation, Carlin mine; SEM micrographs. _A_, _B_, 82E-1+2. Intensely altered, yellowish-brown oxidized rock. _A_, Silica, illitic material, and etched dolomite rhombs, in center of photograph; note porosity. _B_, Highly porous rock of illitic material and quartz. _C_-_E_, 82E-1+22. Intensely altered, yellowish-brown oxidized rock. _C_, _D_, Very porous vuggy matrix composed of clay and detrital quartz with authigenic silica overgrowths. _E_, Enlarged, detailed view of vuggy porous silica and clay matrix. _F_, 82E-1+23. Vuggy porosity in a matrix of clay and quartz.

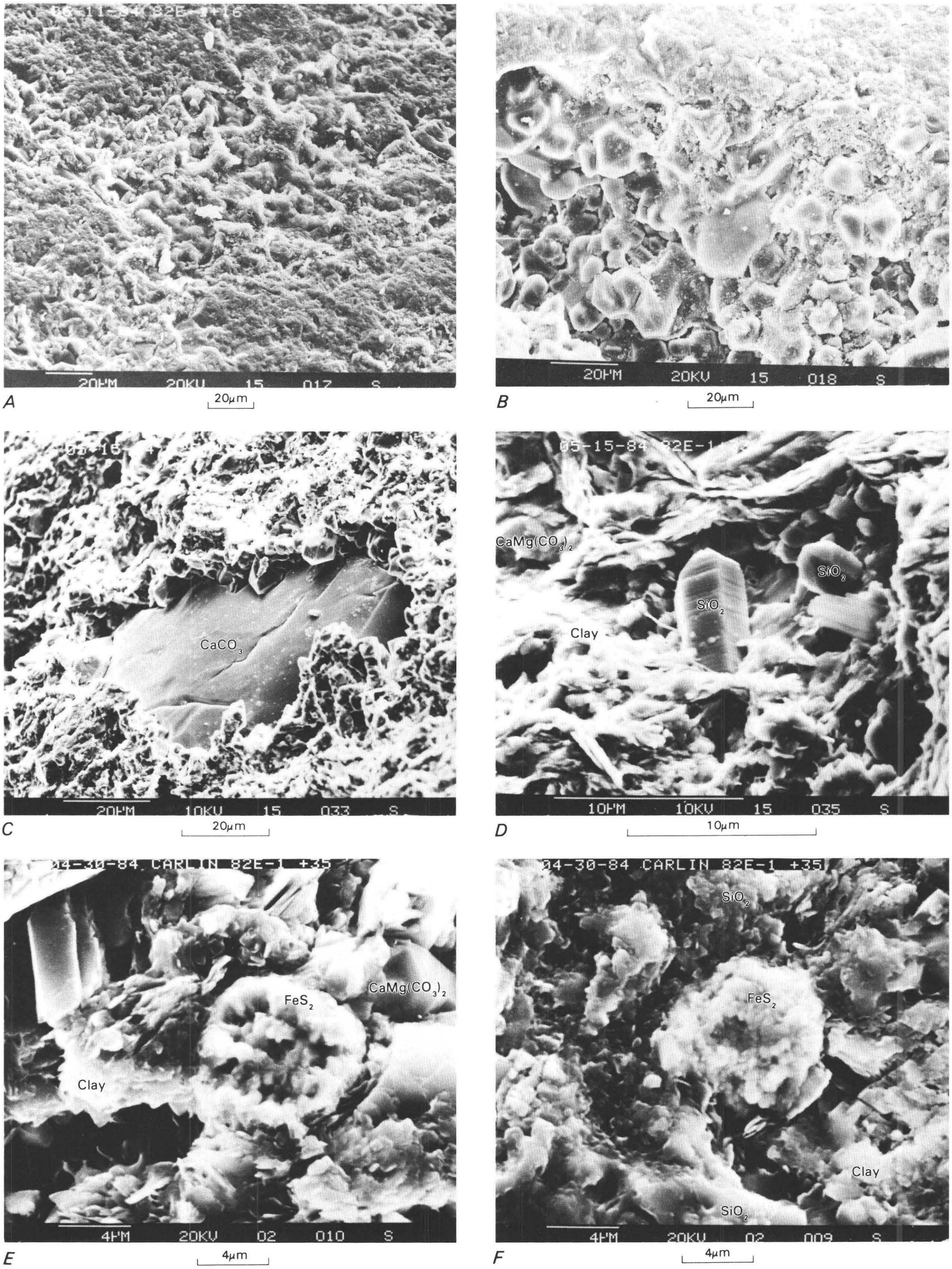


Figure 14. Specimens of all three altered rock types from the Roberts Mountains Formation, Carlin mine; SEM micrographs. A, B, 82E-1+16. Altered rock type III. A, Surface of jasperoid. B Cavity within jasperoid, showing subhedral crystals of quartz coated by thin dusting of iron oxide crystals. C, 82E-1+23. Altered rock type II. Quartz-rich rock showing quartz and clay matrix with a cavity filled by late sparry calcite. D-F, Altered rock type I. D, 82E-1+33. Organically rich, dark-gray dolomitic arenaceous rock. Epigenetic quartz crystals in matrix of dolomite and clay minerals. E, F, 82E-1+35. Pyrite framboids in porous matrix of clay, quartz, and iron-rich dolomite. Thin sections of this rock show relict outlines of small fragments of echinoderms, ostracodes, and brachiopods preserved in dolomite.

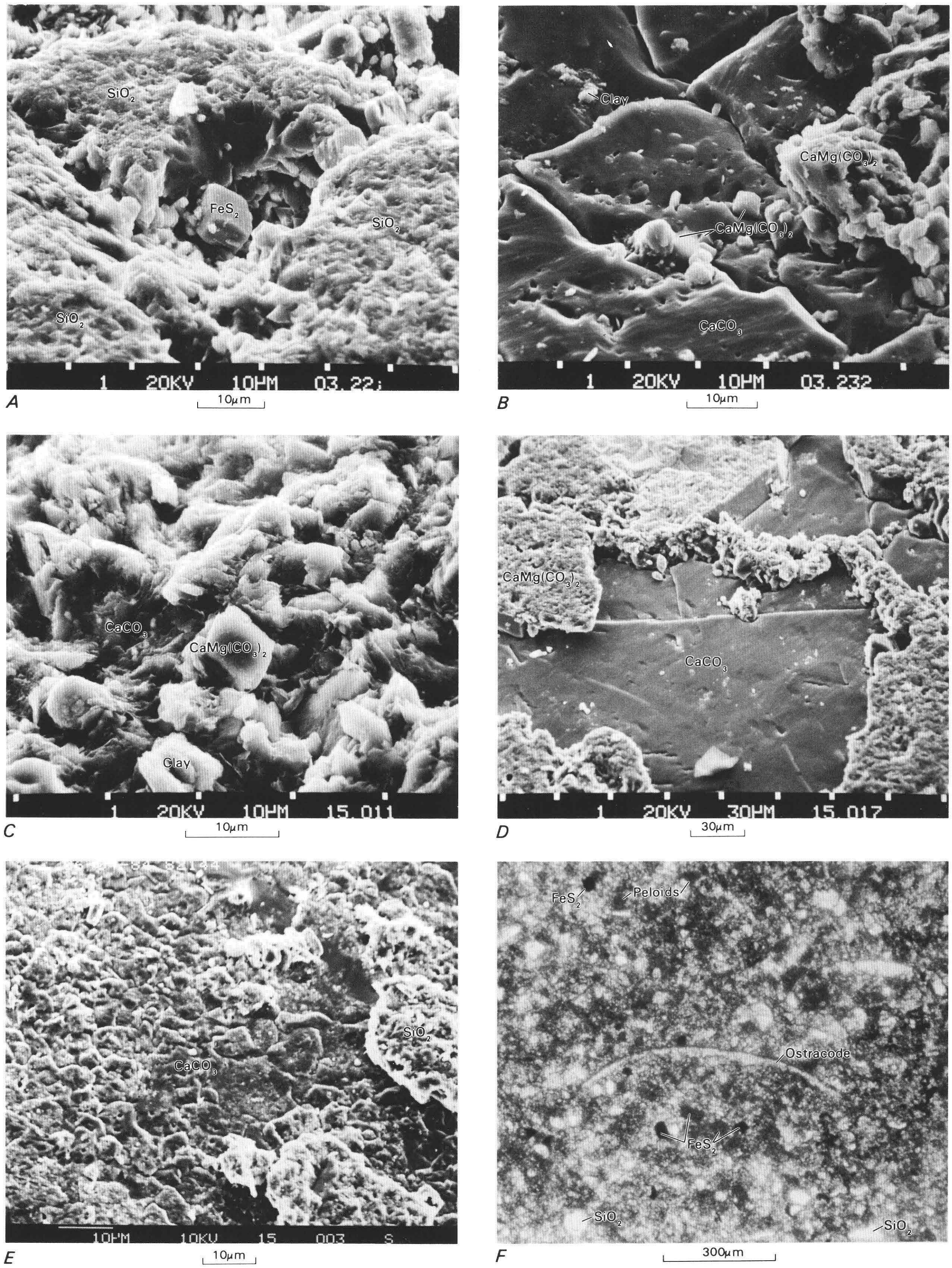


Figure 15. Specimens from the Popovich Formation, Carlin mine. A–E, SEM micrographs, F, Transmitted-light photomicrograph. A, B, 82E-1+42. Dark-gray limestone. A, Pyrite cube, in center, fills a cavity between quartz grains. B, Typical limestone of the Popovich Formation, composed of large calcite crystals with inclusions of small dolomite rhombs and minor amounts of unidentified clay minerals. Sample was collected about 2 m above a faulted contact with the highly altered Roberts Mountains Formation. C–F, 82E-1+44. C, Calcite matrix with rhombs of dolomite and clay minerals. D, Typical surfaces of large calcite crystals and subhedral light-colored dolomite rhombs. E, Small, 2- to 20-µm calcite crystals with dolomite and quartz. F, Ostracode shells, peloids, black pyrite cubes, and clear detrital quartz grains.

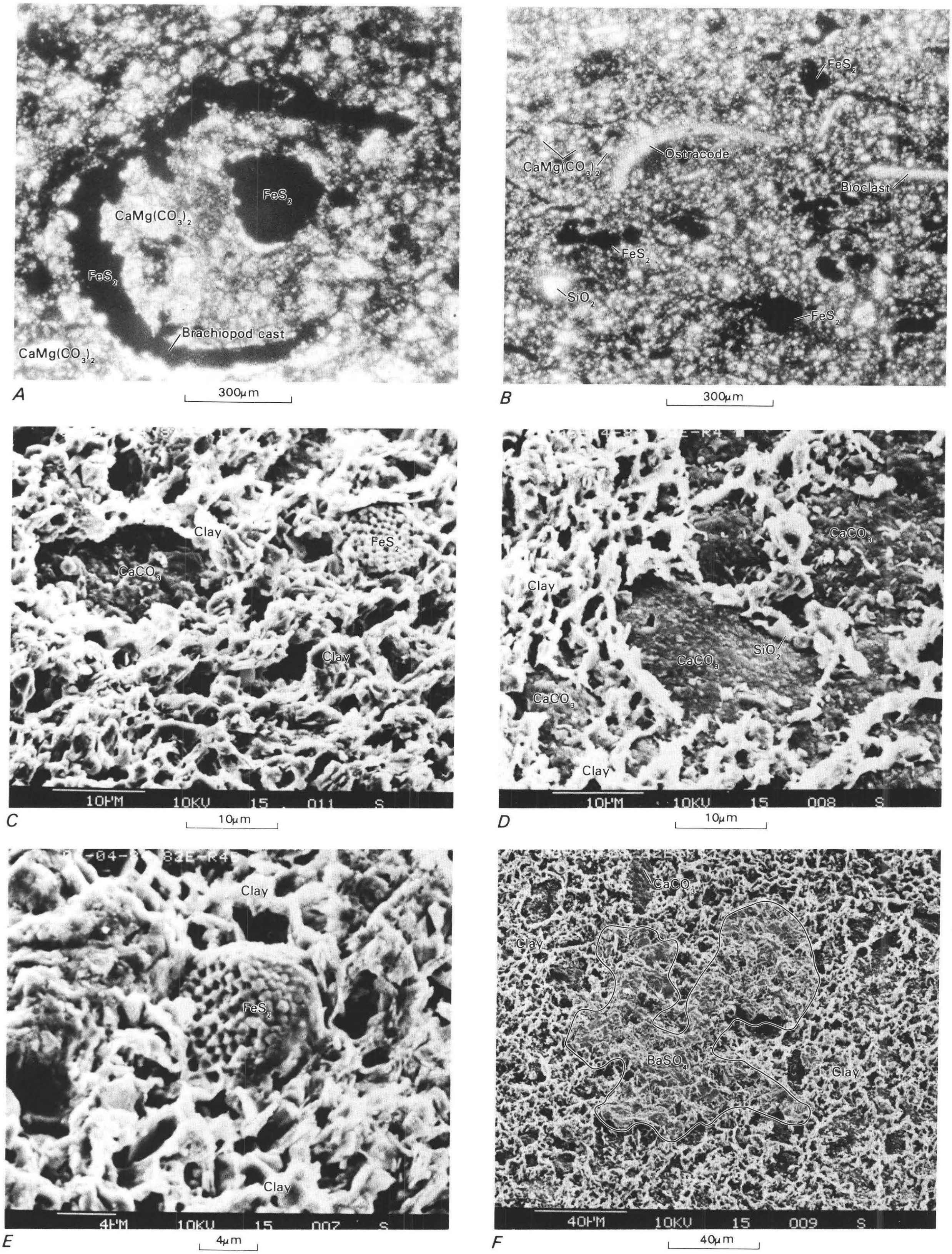
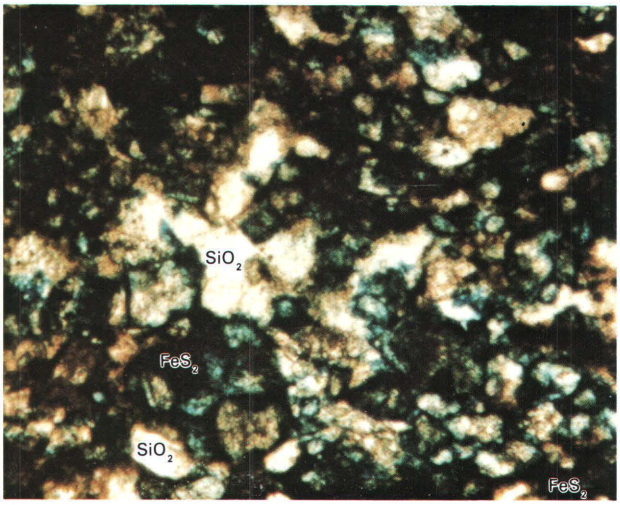
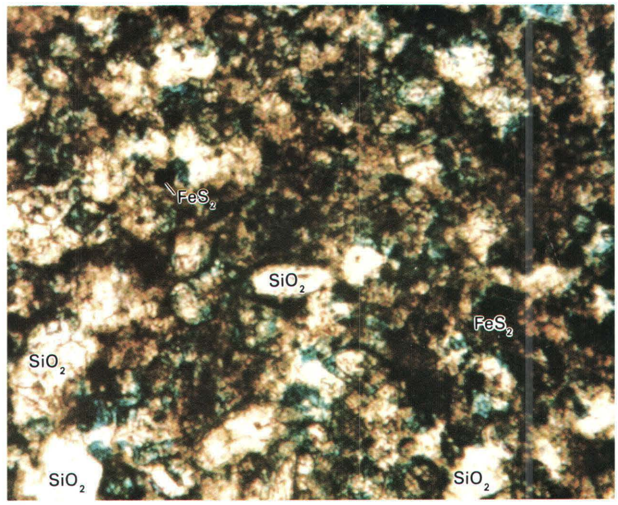


Figure 16. Specimens from the Popovich Formation, Carlin mine. A, B, transmitted-light photomicrographs; C–F, SEM micrographs. A, B, 82E-R3B. A, 20- to 100-µm dolomite rhombs; calcite fills spaces between dolomite crystals. Black pyrite fills voids in fossil mold. B, Abundant relict molds and casts of ostracode and brachiopod shells parallel to bedding; black areas are pyrite. C, 82E-R1. Calcite with abundant clay and minor quartz. Note framboidal pyrite in upper right. D–F, 82E-R4. D, Calcite crystal matrix with intracrystalline clay minerals and quartz. E, Clay matrix with framboidal pyrite in center. F, Mass of barite in center of calcite-rich matrix with intercrystalline clay and quartz.

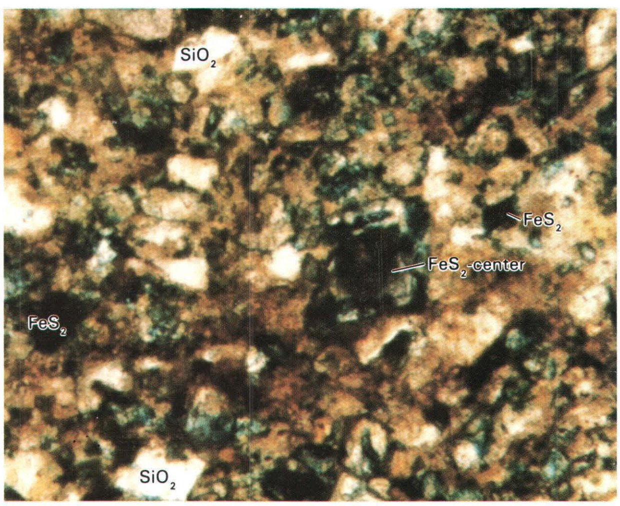
Figure 17. Specimens from the Roberts Mountains Formation; transmitted-light photomicrographs. _A_, _B_, _D_, _E_, altered rock type I; _C_, _F_, altered rock type II. _A_, 82E-1+20B. Unoxidized and organically rich rock that contains abundant pyrite crystals. Angular, clear quartz grains, brown dolomite crystals, blue ferroan dolomite matrix, and dark-gray to black pyrite and clay mixture. _B_, 82E-1+32. Organically rich rock that has undergone oxidation. Clear grains of detrital angular quartz 50 to 75 µm in diameter in matrix of dark-brown clay and fine pyrite. Blue-stained ferroan dolomite crystals 3 to 10 µm in diameter. _C_, 82E-1+30. Organically rich, dark-colored rock with abundant pyrite. Clear, detrital, angular quartz grains in matrix of brown clay and black pyrite crystals. Small, 5- to 30-µm crystals of blue-stained, corroded, ferroan dolomite. Large dolomite rhomb at center has black pyrite crystal in its center. Rhomb is zoned by clear dolomite and blue-stained ferroan dolomite. All dolomite in this photograph has been subjected to dissolution. _D_, 82E-1+34. Organically rich, unoxidized rock. Angular, clear quartz grains 50 to 80 µm in diameter; light-brown, iron-free, 30- to 50-µm dolomite rhombs and blue-stained, iron-rich, 1- to 10-µm dolomite rhombs. _E_, 82E-1+30. Organically rich, dark-colored rock. Clear to translucent dolomite rhombs and dolomite-replaced brachiopod shell; black cubes are small pyrite crystals. Small, 1- to 10-µm, blue-stained, iron-rich dolomite rhombs between clear dolomite rhombs. Iron-rich dolomite has replaced iron-free dolomite. _F_, 82E-1+39. Oxidized rock. Clear, angular, detrital quartz grains; brown, oxidized clay minerals; black iron minerals; and curved red area of late-stage alizarin-stained calcite vein.



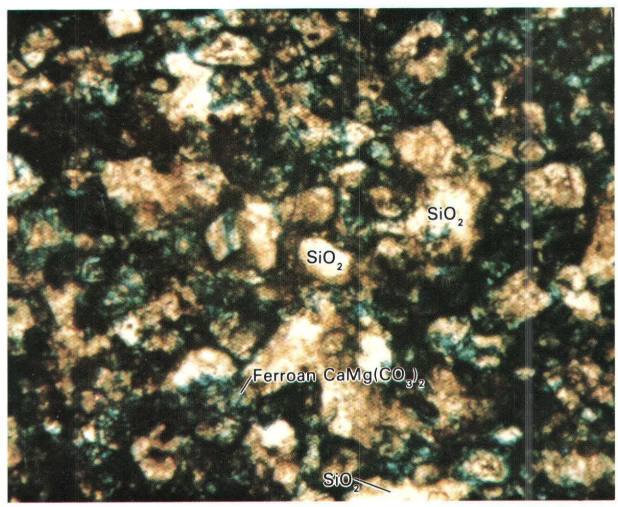
A



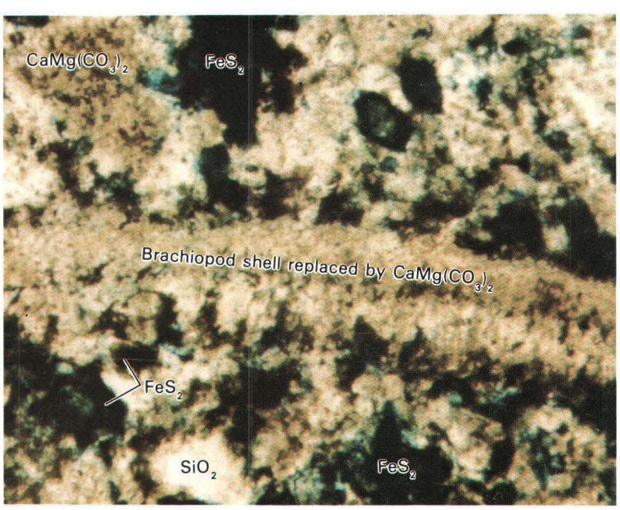
B



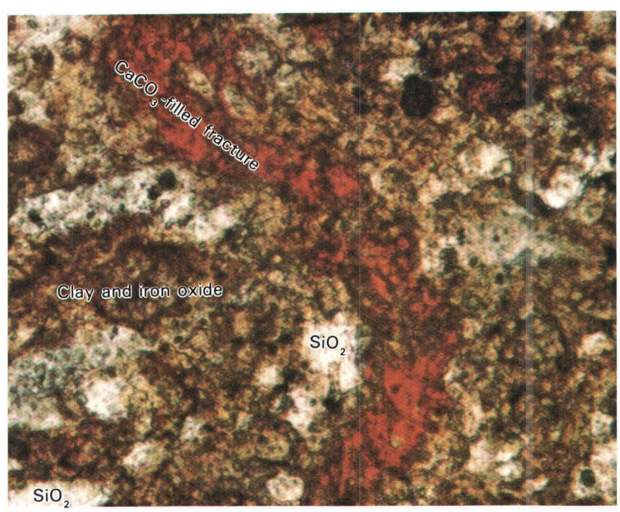
C



D



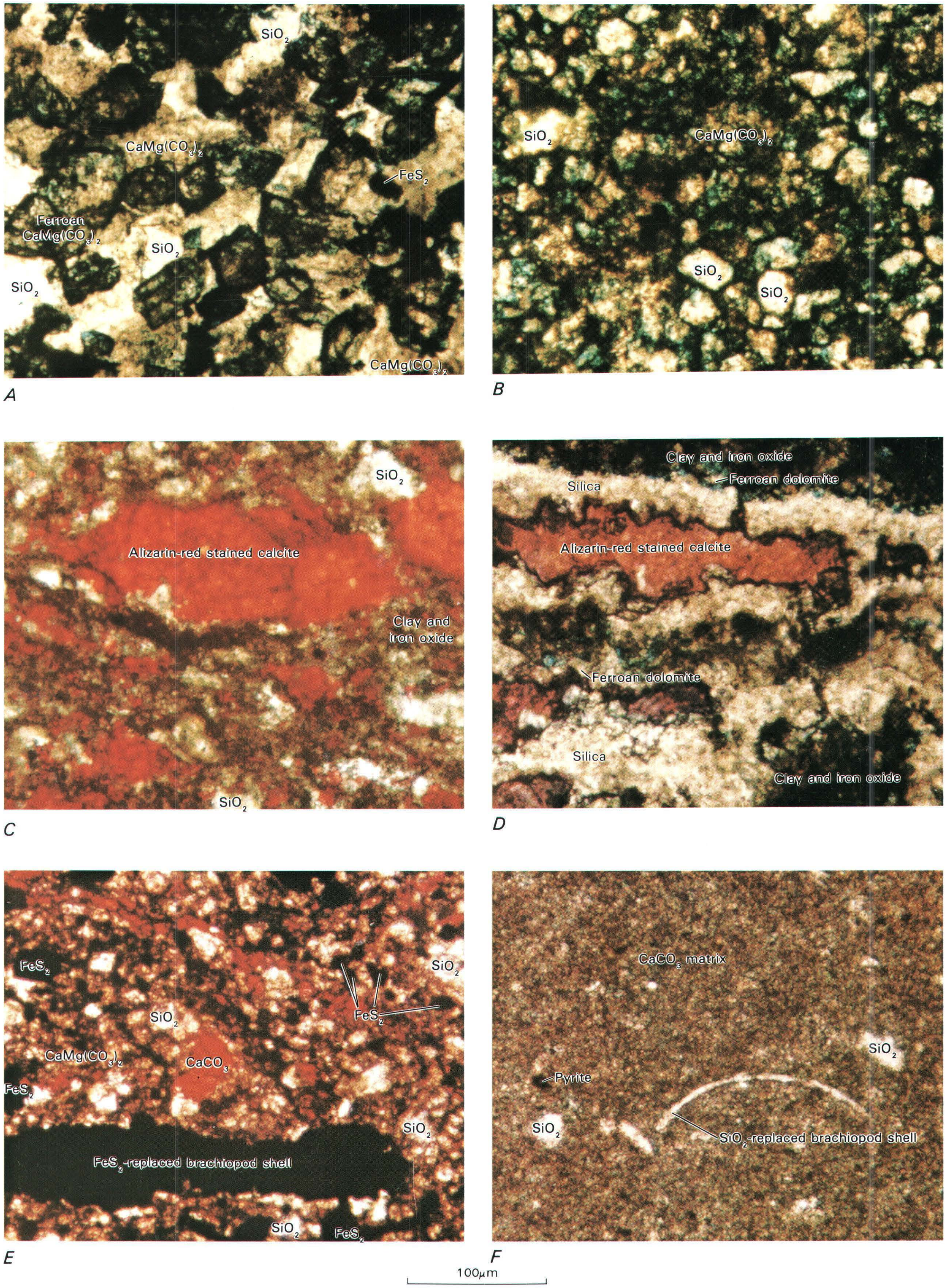
E



F

100μm

Figure 18. Specimens from the Popovich Formation (A, B, D-F) and the Roberts Mountains Formation (C), Carlin mine; transmitted-light photomicrographs. A, 82E-1+42. Organically rich, dark-gray rock collected about 1 m above contact with the Roberts Mountains Formation. Clear, angular, detrital quartz grains in matrix of brown and dark-brown, 50- to 80-μm dolomite rhombs; some blue-stained 10-μm ferroan dolomite rhombs; black of pyrite grains. Some clay minerals occur between dolomite rhombs. B, 82E-2+21. Dark-gray, organically rich rock near contact with Roberts Mountains Formation. Clear, angular, detrital quartz grains floating in matrix of 5- to 10-μm, brown and blue-stained ferroan dolomite, some clay minerals, and black pyrite grains. C, 82E-2+0. Bleached and oxidized type II rock of the Roberts Mountains Formation. Clear, angular, detrital quartz in matrix of brown clay and iron oxides. Alizarin-red stained calcite fills voids and fractures in clay. D, 82E-2+21. Same rocks as in B. Clay, organically rich dark material, and 2- to 30-μm crystals of blue-stained ferroan dolomite. Large crystals of clear silica, at center, whose voids are filled by spar calcite that has been stained red by alizarin dye. Large brown areas are iron oxides. E, 82E-R3A. Dark-gray, organically rich rock from bench on east wall of Carlin mine pit (fig. 2). Large black area is pyrite replacement of brachiopod shell, and small, dark-brown to black areas are pyrite crystals in matrix of light-brown, 5- to 20-μm dolomite rhombs and clear (white) detrital quartz grains. Calcite crystals are stained red by alizarin dye. Clay minerals are between carbonate grains. F, 82E-R4. Dark-gray, organically rich, dolomitic ostracode-, brachiopod-, and echinoderm-bearing wackestone from bench on east wall of Carlin mine pit (fig. 2). Calcite crystals are weakly stained red by alizarin dye. Fossil shells are replaced by quartz (white). Angular detrital quartz grains are 40 to 70 μm in diameter. Black, crystalline pyrite grains are 5 to 10 μm in size. About 10 percent of rock is 5- to 10-μm dolomite rhombs.


A
SiO$_2$
CaMg(CO$_3$)$_2$
FeS$_2$
Ferroan CaMg(CO$_3$)$_2$
SiO$_2$
SiO$_2$
CaMg(CO$_3$)$_2$
B
SiO$_2$
CaMg(CO$_3$)$_2$
SiO$_2$
SiO$_2$
C
SiO$_2$
Alizarin-red stained calcite
Clay and iron oxide
SiO$_2$
D
Clay and iron oxide
Silica
Ferroan dolomite
Alizarin-red stained calcite
Ferroan dolomite
Silica
Clay and iron oxide
E
FeS$_2$
SiO$_2$
SiO$_2$
FeS$_2$
CaMg(CO$_3$)$_2$
CaCO$_3$
FeS$_2$
SiO$_2$
FeS$_2$-replaced brachiopod shell
SiO$_2$
FeS$_2$
F
CaCO$_3$ matrix
SiO$_2$
Pyrite
SiO$_2$
SiO$_2$-replaced brachiopod shell
100μm

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