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REGIONAL HYDROTHERMAL ALTERATION OF THE
LEADVILLE LIMESTONE (MISSISSIPPIAN) OF
CENTRAL COLORADO

by

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PART IV OF 1973 PHD THESIS

Running Head: Hydrothermal Alteration of the Leadville
Limestone

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Massive metallic-sulfide deposits were implaced in the Leadville Limestone (Mississippian) of Central Colorado less than 70 million years ago. The thermal fluids which precipitated ore at Gilman, Colorado have regionally altered the Leadville Limestone. The sequence of alteration began with the recrystallization of limestone to a dark medium-grained dolomite containing a homogeneous distribution of Fe. This was followed by partial recrystallization of the medium-grained dolomite to coarse-clear dolomite which contains an inhomogeneous distribution of Fe. The resulting banded rock is known as "zebra rock". Precipitation of SiO_2 (jasperoid) occurred next. The jasperoid formed prior to the deposition of sulfides (O'Neil, 1951) which is the final event of the hydrothermal epoch.

The alteration sequence is essentially the same everywhere. The one exception is the presence of ferroan-calcite in localities outside the Leadville-Gilman hydrothermal aureole. This calcite was deposited prior to the formation of the homogeneous ferroan-dolomite.

Regional alteration of sediment by thermal fluids is herein proposed as a fundamental diagenetic process. This process may be the source of ferroan-carbonate cement which fills fractures and vugs in numerous sedimentary sequences.

4. Previous investigations of the region (Lovering and

Watts, 1944; Behre, 1953; Banks, 1967; Baisbaugh and others, 1968;

Metallic sulfide deposits are widespread in the sedimentary rocks of the central United States (Fig. 1). Studies of mineral paragenesis of the major lead-zinc deposits have shown both calcite and dolomite to have been deposited during the "hydrothermal" epoch (Heyl and others, 1959; Hagni and Grave, 1964; Jolly and Heyl, 1964). Many of these lead-zinc deposits lie at the periphery of major sedimentary basins such as the Illinois, Michigan and Forest City Basins. Presumably, the fluids from which the ore and gangue minerals were precipitated emanated from the sedimentary basins. It is the purpose of this paper to document the type and magnitude of alteration to the sedimentary aquifer through which mineralizing fluids have passed.

The central Colorado region (Fig. 2) provides an excellent framework for an investigation of regional hydrothermal alteration for the following reasons:

1. In the Leadville-Gilman area of central Colorado (Figs. 1 and 2), metallic-sulfide ore deposits occur in sediments of Mississippian age.
2. The hydrothermal epoch, during which the ore was emplaced, occurred late in the geologic history of the region (<70 million years B. P.). Thus, subsequent alteration is not likely to have reached major proportions.
3. Potentially-altered sediment (Leadville Limestone of Fig. 2) crops out over a large area and is easily accessible.
4. Previous investigations of the region (Lovering and Tweto, 1944; Behre, 1953; Banks, 1967; Radabaugh and others, 1968;

to name a few) provide a suitable background for a study of such limited scope as this.

SALIENT FEATURES OF THE LEADVILLE LIMESTONE

The Leadville Limestone of central Colorado crops out around the peripheries of two domal structures: the White River Plateau and the Sawatch Range (Fig. 2). Most of the Leadville Limestone appears essentially unaltered by hydrothermal events which included extensive sulfide mineralization near the towns of Leadville and Gilman.

The Leadville Limestone outside the area of sulfide mineralization consists of three members (Fig. 3). The lower member can be subdivided into two units. The Gilman Sandstone unit contains lenses and beds of quartz sand in a carbonate mud matrix. The carbonate matrix consists mainly of dolomite; however, in certain localities (Sweetwater Lake, Elk Creek) the carbonate matrix consists of lime mud or lime mud with dolomite clasts (Banks 1967). Above the Gilman Sandstone lies the Waxy Bed. This unit is everywhere a dolomite mudstone.

The middle member is composed of two units: the Cherty Zone and the Pink Breccia. Both of these units are lime mudstone. The Cherty Zone, as its name implies, is characterized by the presence of black chert.

The upper member of the Leadville Limestone is predominantly an oolitic-bioclastic lime-grainstone; although, some lime mud is present at both the bottom and top of the upper member.

At various places in the Sawatch Range the Leadville Limestone has been replaced by metal sulfides. Around the large

sulfide deposits near the towns of Leadville and Gilman, most or all the original limestone has been replaced by dolomite (Fig. 2). The consistent spatial relations of this dolomite to ore indicate that the dolomite is of hydrothermal origin and formed as a phase of the mineralizing epoch (Engel and others, 1958; Radabaugh and others, 1968).

PREVIOUS STUDIES OF HYDROTHERMAL ALTERATION OF THE
LEADVILLE LIMESTONE

Mineralization and Dolomitization

Radabaugh and others (1968) have summarized the paragenesis of the primary ore minerals deposited in the Gilman area. Manganosiderite ($\text{Fe}_{1-(x+y)} \text{Mn}_x \text{Mg}_y \text{CO}_3$) was deposited first. Pyrite (FeS_2) came next, followed by marmatite ($\text{Zn}_{1-x} \text{Fe}_x \text{S}$), galena (PbS), and chalcopyrite (CuFeS_2). The last stage of mineral deposition consisted of the formation of copper and silver sulfosalts.

The hydrothermally dolomitized Leadville Limestone is fine ($\sim 100\mu$) to coarsely crystalline ($\sim 2-3\text{cms.}$) and is characterized by the presence of "zebra rock" which consists of alternating layers of white coarsely-crystalline dolomite and dark fine-grained dolomite. The period of hydrothermal dolomitization including the formation of zebra rock has been shown to have taken place prior to the deposition of metal sulfide ore (Lovering and Tweto, 1944; Lovering, 1958).

Banks (1967) attempted to discriminate between hydrothermal and "diagenetic" dolomite in the Leadville Limestone. He concluded that diagenetic dolomite ($\text{Mn}=200\text{ppm}$, $\text{Sr}>35\text{ppm}$) was

compositionally distinct from hydrothermal dolomite ($Mn > 500\text{ppm}$, $Sr < 35\text{ppm}$.) This conclusion, however, is considered suspect as his initial categorization of dolomite samples prior to analysis was highly subjective.

Isotopic Composition

Engel and others (1966) studied the isotopic composition of oxygen and carbon in the hydrothermal dolomites surrounding the ore deposits at Gilman. Figure 4 is a summary of their oxygen isotope analyses on fine and coarse-grained hydrothermal dolomite. The dashed lines connect the δO^{18} values of fine and coarse-grained crystals from the same sample of zebra dolomite. It is apparent that the δO^{18} content of fine-grained dolomites is independent of proximity to ore. On the other hand, the δO^{18} content of coarse crystals decreases toward ore. Engel has interpreted the δO^{18} decrease as reflecting a temperature gradient which existed at the time the coarse-grained dolomite formed.

Thus it would appear that there were two phases of dolomitization at Gilman. The first period of dolomitization consisted of recrystallization of limestone to a fine or medium-grained dolomite and apparently took place in a water of fairly uniform temperature. The second period of dolomitization consisted of selective recrystallization of the medium-grained dolomite to coarse-grained sparry dolomite. During this period of recrystallization, a temperature gradient formed outward from the future site of ore.

PROCEDURE

Today there exist two distinct forms of Leadville Lime-

stone: Leadville Limestone outside the hydrothermal aureole which is predominantly calcite and Leadville Limestone within the aureole which is predominantly dolomite (Fig. 2). To gain an understanding of the regional effects of the hydrothermal epoch, sampling was done within the hydrothermal aureole (localities GM and BL) and outside of the aureole, both in the Sawatch Range (localities BC and FF) and in the White River Plateau (localities GS, GC, EC, SL, and WR). At each locality samples were taken of the entire Mississippian section at approximately five-foot intervals. The length of the sections ranged from 150-210 ft.

Five localities (GM, BL, BC, FF and GS) were investigated in detail. 177 thin sections were prepared and stained using a dual-stain technique. The staining allowed the discrimination of calcite, ferroan-calcite, dolomite, and ferroan-dolomite. X-ray diffraction (Norelco Model 42273/0) was done on 24 samples from GM and 3 samples from GS. Each slide was first scanned from $17-52^{\circ} 2\theta$ at a rate of $1^{\circ}/\text{min}$. in order to determine what mineral phases were present. Each sample was then analyzed twice from $28-32^{\circ} 2\theta$ at a rate of $\frac{1}{2}^{\circ}/\text{min}$. Percent dolomite and calcite were estimated using the procedure of Tennant and Berger (1957). Triplicate atomic absorption analyses (Perkin-Elmer Model 303; for procedure see Benson, 1973) for Mg, Sr, Fe, Mn and Na were made on standard #48.

Twenty-two highly polished thin sections were prepared for analysis with the electron-microprobe (A.R.L. Type EMX-SM). Electron microprobe analyses were done in the beam integration mode. Electron beam voltage was 15 KV. Chemical analyses were

made at 5-20 μ intervals using a 10-20 μ diameter beam. Analyses for Ca, Mg, Fe, Na, Sr, and Si were made using a 0.010 μ A sample current. Intergration time was approximately 20 seconds (2×10^5 current counts). Analyses for Na and Sr were subsequently repeated using a 0.030 μ A sample current and an integration time of approximately 30 seconds (1×10^6 current counts). Neither Na or Sr were detected in any of the analyses.

In order to test the possible effect due to "burning" of a specimen, a single 10 μ spot was analyzed repeatedly at three second intervals for two minutes. At the normal operating current (0.010 μ A) no change in counts Mg was apparent. However, the use of a 0.015 μ A sample current resulted in a steady increase of counts Mg after a period of 15 seconds.

Two naturally occurring standards and two silica glass standards were used. Standard #48 (1.25%Fe, 12.7%Mg, 20.7%Ca) was used to determine the Ca and Mg content of dolomite samples and the Fe content of dolomite and calcite samples. Standard #5 (2.30%Mg) was used to monitor the Mg content of low-Mg calcites samples. Standard #1 a silica glass (0.50%Sr, 0.50%Na) was used to determine the Na and Sr content of dolomite and calcite samples. Standard MR1-10 a silica glass (47.9%SiO₂) was used to determine the SiO₂ content of samples BL-18B and FF-17B. Drift on standards never exceeded the following: std. #48 (0.07%Fe, 0.43%Mg, 0.50%Ca); std. #5 (0.10%Mg).

The crystal sizes (long dimension) of 11 samples from locality GM were measured (30 measurements). The measured crystals were selected at random from samples which did not evidence zebra structure.

Alteration Within Hydrothermal Aureole (Localities GM & BL)

X-ray analysis of 24 samples from locality GM showed all samples to be predominantly (>90%) dolomite.

Staining was crucial in delineating the sequence of alteration experienced by carbonates from localities GM and BL. Initially the carbonate sections consisted of limestone above the top of the waxy bed and possibly dolomite below. The sequence of alteration in both localities took the following form:

1) Recrystallization of calcite to medium-grained ferroan-dolomite (25-5000 μ crystals). The ferroan-dolomite appears brown before staining (Fig. 5).

2a) Addition of a large amount of Fe to the medium-grained dolomite. This Fe is not zoned parallel to crystal growth directions but has been directly emplaced into any available surface surrounding preexisting voids and fractures (Fig. 6).

2b) Growth of coarse clear ferroan-dolomite. The crystals appear to have grown in a preexisting void. The Fe is zoned parallel to the directions of crystal growth and appears more abundant in the voidward portions of the crystals (Fig. 5).

3) Growth of euhedral or microcrystalline quartz around the coarse clear dolomite.

4) Deposition of clear sparry calcite in voids and fractures (Figs. 5 and 6).

5) Deposition of colloform calcite around the sparry calcite (Fig. 6). Recrystallization of some of the coarse ferroan-dolomite to calcite took place during this or the previous stage of calcite precipitation.

Crystal size of the dolomites (non-zebra) varies widely. The average long dimension is 1070μ . This is considerably coarser than both modern dolomite ($1-5\mu$: Shinn and Ginsburg, 1964; Illing and others, 1965; Defeyes and others, 1965) and ancient supratidal dolomite ($5-10\mu$ and $30-70\mu$: Laporte, 1967; $10-25\mu$: Schenk, 1967; $10-50\mu$: Matter, 1967)

Chemistry

Electron microprobe analysis served to characterize the compositional characteristics of the alteration sequence.

The medium-grained dolomite has a homogeneous distribution of Fe, Ca, and Mg (Fig. 7a & b). The absolute amount of Fe, Ca and Mg varied in the 4 samples analyzed ranging from 0.1-1.2%Fe, 12.1-21.6%Ca and 10.5-14.0%Mg.

The medium-grained dolomites which exchanged with the later Fe-rich fluid contain up to 1.0%Fe (Fig. 7c).

The coarse-grained sparry dolomite is characterized by an inhomogeneous distribution of Fe, Ca and Mg (Fig. 7a). The Fe content of the sparry dolomite increases voidward reaching a maximum of 2.5%, while the Mg (and Ca to some extent) content inversely reflects the Fe distribution.

The clear sparry calcite has a homogeneous distribution of Mg in the 3 samples analyzed. The absolute amount varies from 0.3 to 1.0% (Fig. 7a). Fe was not detected.

The colloform calcite in the one sample analyzed contains a homogeneous distribution of Mg (Fig. 7c). The absolute amount (0.3%) is the same as the Mg content of the sparry calcite it coats. Fe was not detected.

The calcite which replaced the clear coarse-grained dol-

omite contains the same amount of Mg and Fe as the nearby sparry calcite indicating they formed at the same time.

Fluid History of the Hydrothermal Aureole

The composition and temperature of thermal fluids which moved through the Gilman-Leadville region can be crudely approximated using their alteration products as a guide.

The Leadville Limestone was first recrystallized to a medium-grained dolomite in a fluid which contained appreciable Mg and Fe. The cause of this phase change was presumably not an increase in temperature, as the δO^{18} content of the medium-grained dolomites is uniform within the Gilman-Leadville region (Fig. 4). The Mg/Ca ratio of the fluid probably controlled the recrystallization process. Fluids flowing outward from primary conduits exchanged Mg for Ca becoming depleted in Mg. When the Mg/Ca ratio fell into the stability field of calcite, recrystallization ceased. The boundary of the alteration aureole (Fig. 2) marks this transition.

Within available porosity (vugs and fractures), coarse-grained dolomite crystals began to form. Initially these crystals were dark in color and contained the same Fe content as the medium-grained dolomite crystals which they replaced. Later the Fe content of the fluid increased dramatically. This compositional change occurred shortly after or during a change in the temperature of the fluid. The change in temperature evidenced by the δO^{18} content of the coarse-grained crystals (Fig. 4) may in itself have controlled the amount of Fe partitioned into the dolomite. In any case, the dolomites continued to grow for some time in an Fe-bearing water. After this phase of dolomiti-

zation a small amount of SiO_2 was precipitated.

The next event in the alteration process was the emplacement of Fe-Mn-Pb-Cu bearing deposits at Gilman. The only indication of this event in the surrounding aureole is the presence of pyrite (FeS_2) in fractures.

After the completion of ore deposition, fluids passed through the hydrothermal aureole precipitating calcite. These fluids contained no Fe and only a small amount of Mg. These fluids probably occurred after the hydrothermal epoch had ended, and represented a return to normal meteoric conditions.

Alteration Outside the Hydrothermal Aureole

(Localities FF, BC, & GS)

Mineralogy

X-ray analysis and staining show calcite to be the sole carbonate phase above the Waxy Bed except for the following occurrences of dolomite:

- 1) Coarse-grain zebra dolomite occurs in the cherty zone at locality GS.
- 2) Ellipsoidal pods (30x10x2 ft.) of dolomite occur in the upper member at locality GS (Fig. 3). In places the dolomite has been recrystallized to the zebra variety.
- 3) Coarse-grained dolomite lines fractures and replaces portions of certain beds such as the Pink Breccia at locality FF.
- 4) Dolomite replaces calcite cement around oolites in the upper member at localities GS, BC, and FF (Fig. 8).

With the exception of the cement-replacing dolomite, other workers (Banks, 1967 for example) have previously noted the

as conduits for the dolomitizing fluid. The pods are surrounded by a reaction rim 1-2" in width. The country rock up to the rim consists solely of bioclastic calcite. The rim itself consists of calcite and dolomite with dolomite increasing toward the main body of the pod. The pods are composed of medium-grained brown dolomite (0.3%Fe, 13.6%Mg, 20.3%Ca) which has been recrystallized to zebra dolomite in places. The clear coarse-grained dolomite of the zebra is chemically similar to the zebra found at locality GM. Sparry calcite containing a homogeneous distribution of Mg (0.2%) fills in around the coarse-grained dolomite.

Portions of the middle member of the Leadville Limestone which were lime mudstone, have been completely recrystallized to a medium-grained dolomite. Besides zebra dolomite, which has replaced the medium-grained dolomite, the medium-grained dolomite contains a large amount of SiO_2 in the form of quartz (Fig. 12a). The quartz-invaded dolomite is cut by calcite veins containing 0.3 to 0.6%Mg and usually no detectable Fe.

Summary

The alteration sequence outside the hydrothermal aureole is essentially the same as the sequence inside the aureole. The prime difference rests in the magnitude and not the type of alteration. Inside the hydrothermal aureole the entire section has been converted to ferroan-dolomite. Outside the aureole, dolomitization was not nearly so pervasive. However, the emplacement of silica (quartz) after dolomitization attains major proportions. In both areas, the hydrothermal alteration consists of 3 components: dolomite, Fe, and quartz.

Sediment within and below the Waxy Bed has experienced the same sequence of alteration discussed above. The sequence is usually confined to the areas surrounding fractures (Fig. 12b and c). The magnitude of alteration is not great even within the hydrothermal aureole. Grain size remains small ($<100\mu$) for the most part. The lack of pervasive recrystallization to coarse-grained dolomite was probably due to the impermeable nature of the rock.

COMPARISON OF δO^{18} AND FE CONTENT OF ZEBRA ROCK

As was discussed previously, Engel and others (1958) have shown that the formation of zebra dolomite in the Gilman area took place in two stages. The initial dolomitization took place in a fluid of fairly constant temperature. The recrystallization of the medium-grained dolomite occurred in a fluid having a temperature gradient from the Eagle mine.

Considering the Fe distribution in the zebra dolomite, a parallelism is evident. The medium-grained dolomite which formed in a water of constant temperature contains a homogeneous distribution of Fe. The absolute amount of Fe varies from sample to sample; but, in no case does it exceed 2.0%. The clear coarse-grained crystals whose δO^{18} content varies as a function of distance from ore, contain an inhomogeneous distribution of Fe. The Fe content of these crystals sometimes reaches a maximum of 2.5%.

RETENTION OF ORIGINAL MINOR ELEMENT DISTRIBUTION PATTERNS

Benson and others (1972) have shown that cements of ancient carbonates often retain their primary minor element

distributions. The Leadville Limestone provides an excellent source of information regarding the alteration of primary minor element distributions by hydrothermal processes.

Prior to the hydrothermal epoch, the Leadville Limestone had acquired two petrographic generations of cement (Fig. 9). Both cements contained around 0.2-0.3%Mg and less than 0.1%Fe (Fig. 10). Since the hydrothermal fluids contained abundant Fe, their reaction with the preexisting low-Fe cement can be rapidly determined with the use of an Fe-sensitive stain.

The degree of alteration was found to vary greatly between samples and sample localities. Samples from the upper member of locality FF have in some instances been totally impregnated with Fe. However, samples from the upper member of locality GS did not exchange with the Fe-bearing thermal fluids and have, therefore retained their former minor element composition.

The Fe has been emplaced discordantly to preexisting crystal fabric. Fe cuts across grain-cement boundaries and cement-cement boundaries. Thus one can easily detect alteration to primary cement. By selectively analyzing those samples which evidence no alteration, the primary minor element distribution patterns can still be obtained. One should exercise caution when performing electron microprobe analysis of ancient carbonate cements, especially if hydrothermal alteration is suspected. If alteration by an Fe-bearing fluid took place, then staining can serve to document the degree of alteration. If, however, the fluid did not contain a stain-sensitive cation; then multiple electron microprobe traverses will have to be made in order to check the symmetry of the minor element distribution.

SUMMARY AND CONCLUSIONS

It has been shown that the hydrothermal activity responsible for ore deposition in the Leadville-Gilman area of Central Colorado, also caused regional alteration of the Leadville Limestone. The absolute magnitude of alteration (chiefly dolomitization) is not constant throughout the region being greatest near the site of ore deposition. However, the sequence of alteration is the same everywhere.

Recrystallization of calcite to a medium-grained dolomite containing a homogeneous distribution of Fe, occurred first. In certain sections, the medium-grained dolomite was partially replaced by clear coarse-grained crystals which possess an inhomogeneous distribution of Fe. This was followed by the emplacement of SiO_2 (jasperoid) into available fractures and vugs. The exact time of ore deposition is not precisely known, but probably occurred after the deposition of SiO_2 .

Regional alteration of a sedimentary sequence via thermal fluids is an intriguing process to consider. Ore deposits, which have presumably been deposited by through-flowing thermal fluids, occur throughout the United States. If these fluids altered the rock through which they passed, the result would entail porosity modification on a basin-wide scale. In addition, these fluids might be the source of "late" ferroan-carbonate so common to sedimentary sequences.

Hydrothermal fluids can drastically alter primary minor element distributions of carbonate cements. However, these alterations can be detected by the use of stains and the electron-microprobe.

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- Fig. 1 Mississippi Valley-type main mineral districts and minor sulfide deposits in the central United States. Modification of Figure 1 of Heyl (1968).
- Fig. 2 Generalized geologic map of central Colorado showing the distribution of the Leadville Limestone and associated hydrothermal dolomite. Compiled from Engel et. al. (1958) and Banks (1967).
- Fig. 3 Generalized Leadville Limestone stratigraphy of central Colorado. For description see text.
- Fig. 4 Graph of the relations between texture, oxygen isotope composition, and distance from ore of samples of hydrothermal dolomite collected in the Gilman area, Colorado. Modification of Figure 5 of Engel et. al. (1958).
- Fig. 5 Photomicrograph of "zebra" dolomite showing the principal stages of the alteration sequence. This rock, originally a limestone, was first recrystallized to a medium-grained dolomite (dark crystals on either side of figure). Clear coarse-grained dolomite crystals were then deposited in available porosity (large white crystals in center of figure). The remaining pore space was later filled with sparry calcite (gray material situated between large white crystals). Scale in microns.
- Fig. 6 Photomicrograph of a sample from inside the Leadville-Gilman hydrothermal aureole showing a slightly different form of the alteration sequence. Original limestone was recrystallized into a medium-grained dolomite shown

in the far right portion of the figure. A high-Fe fluid exchanged with this dolomite along available porosity. The Fe-rich dolomite which resulted has since been oxidized (arrow 1). Concurrently with the emplacement of Fe, ferroan-dolomite rhombs began to grow into voids (arrow 2). These rhombs contain an Fe-rich core and are zoned. After the dolomite precipitation ceased, two generations of calcite were deposited. The first generation is sparry (arrow 3); the second generation has a colloform texture (arrow 4). Scale in microns.

Fig. 7 Graphical representation showing chemical composition of various forms of the alteration sequence found inside the Gilman-Leadville hydrothermal aureole. Vertical axis represents weight % of the metal; the horizontal axis represents distance along the microprobe traverse. 7a and b are traverses run on a zebra dolomite. The medium-grained dolomite (MD), located between layers of coarse-grained dolomite, possesses a homogeneous concentration of Fe (0.2%). The coarse dolomite (CD) possesses an inhomogeneous distribution of Fe (0.0-2.5%). The sparry calcite (C) which was precipitated after the zebra dolomite contains no Fe and 0.9%Mg. 7c is a traverse run on a slightly more complicated sample. Here after, the initial recrystallization of calcite to medium-grained dolomite (MD) solution along grain boundaries occurred (v=void). A fluid containing appreciable Fe passed through the newly formed porosity and exchanged with the dolomite. This

produced dolomite crystals possessing an outer high-Fe "fringe". Sparry calcite (C_1) containing no Fe and around 0.3%Mg was precipitated next. During this time some of the high-Fe dolomite was recrystallized to calcite (small c), which retained a portion of its former Fe content. The last calcite to form was the colloform variety which contains 0.3%Mg and no Fe.

Fig. 8 Photomicrograph of ferroan dolomite (light area surrounding dark oolitic grain) replacing calcite cement. See figure 10d. Scale in microns.

Fig. 9 Photomicrograph of the two petrographic generations of cement deposited prior to the hydrothermal epoch. See figure 10a. Scale in microns.

Fig. 10 Electron microprobe analyses of representative samples from outside the Leadville-Gilman hydrothermal aureole. The graphs have been arranged to show the alteration sequence. 10a shown the composition of the two petrographic generations of cement (C_1 and C_2) deposited prior to the hydrothermal epoch. The first stage of alteration consisted of the emplacement of ferroan calcite along fractures (C_3 of 7b) and the recrystallization of former cement in an Fe-bearing water (C_1 and C_2 of 7c). Dolomitization of some cement followed (D of 7d). The last event was the precipitation of non-ferroan calcite (C_4 of 7e) in fractures. Note that G stands for sediment grain.

Fig. 11 Photomicrograph of ferroan-calcite filling a fracture which cuts the two pre-hydrothermal generations of cement. Compare with figure 10b. Scale in microns.

Fig. 12 Electron microprobe analyses of samples from outside the hydrothermal aureole which demonstrate additional typical forms of alteration. 12a documents the subtle emplacement of SiO_2 into medium-grained dolomites (MD). Weight % SiO_2 is indicated by scale to the left which runs from 0-50%. Note the inverse relation between Mg, Ca, and SiO_2 content and the inhomogeneous Fe distribution. 12b and c demonstrate the most common form of alteration to sediments found below the top of the Waxy Bed. Medium-grained dolomite (MD) is first invaded by SiO_2 . This is evidenced by the parallelism of Mg and Ca inhomogeneities. Ferroan-dolomite (D of 12 b) is then precipitated along preexisting fractures. This is followed by the precipitation of non-ferroan calcite within the remaining fracture porosity (C of 12c).

FIGURE 1

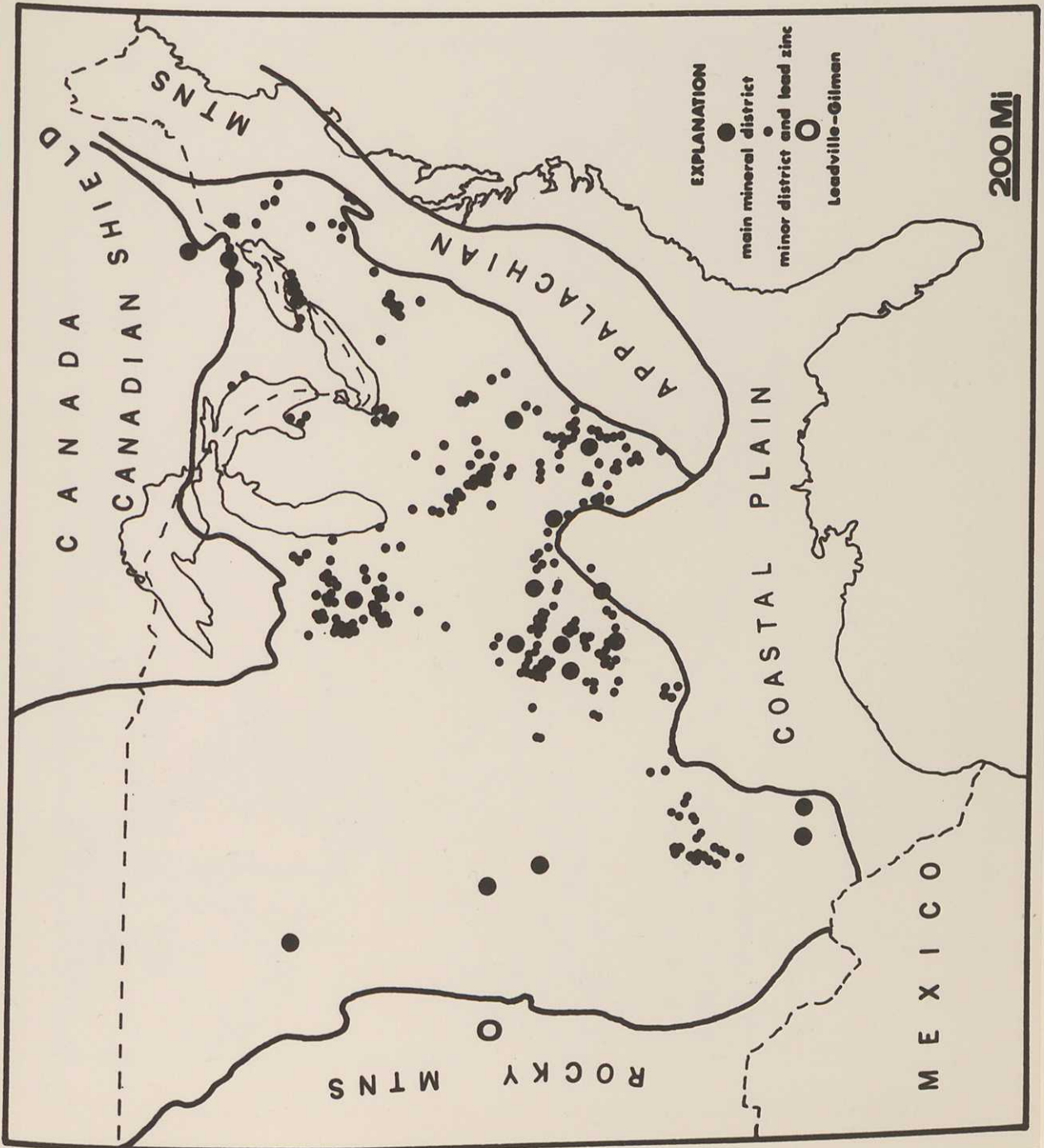


FIGURE 2

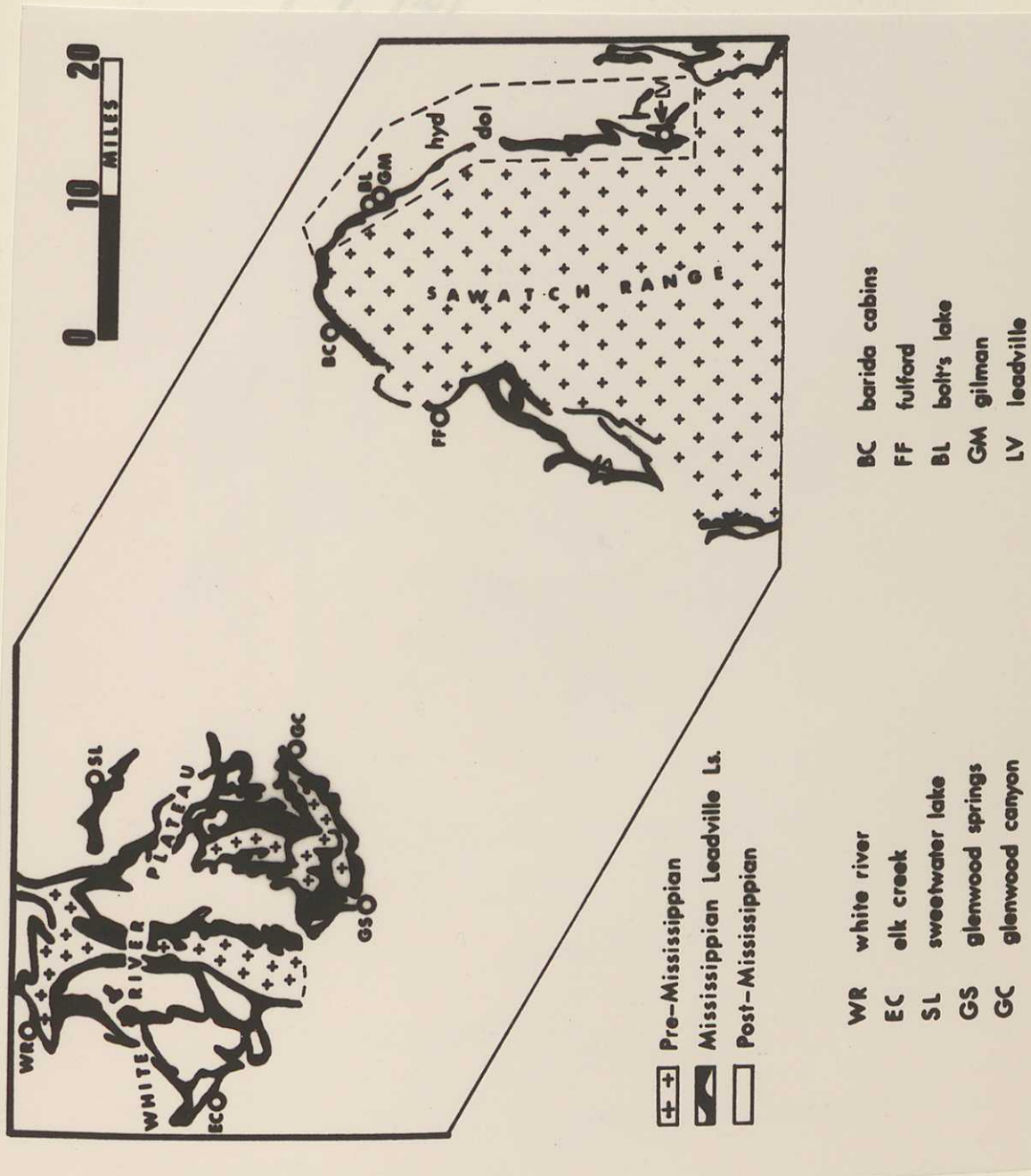


FIGURE 3

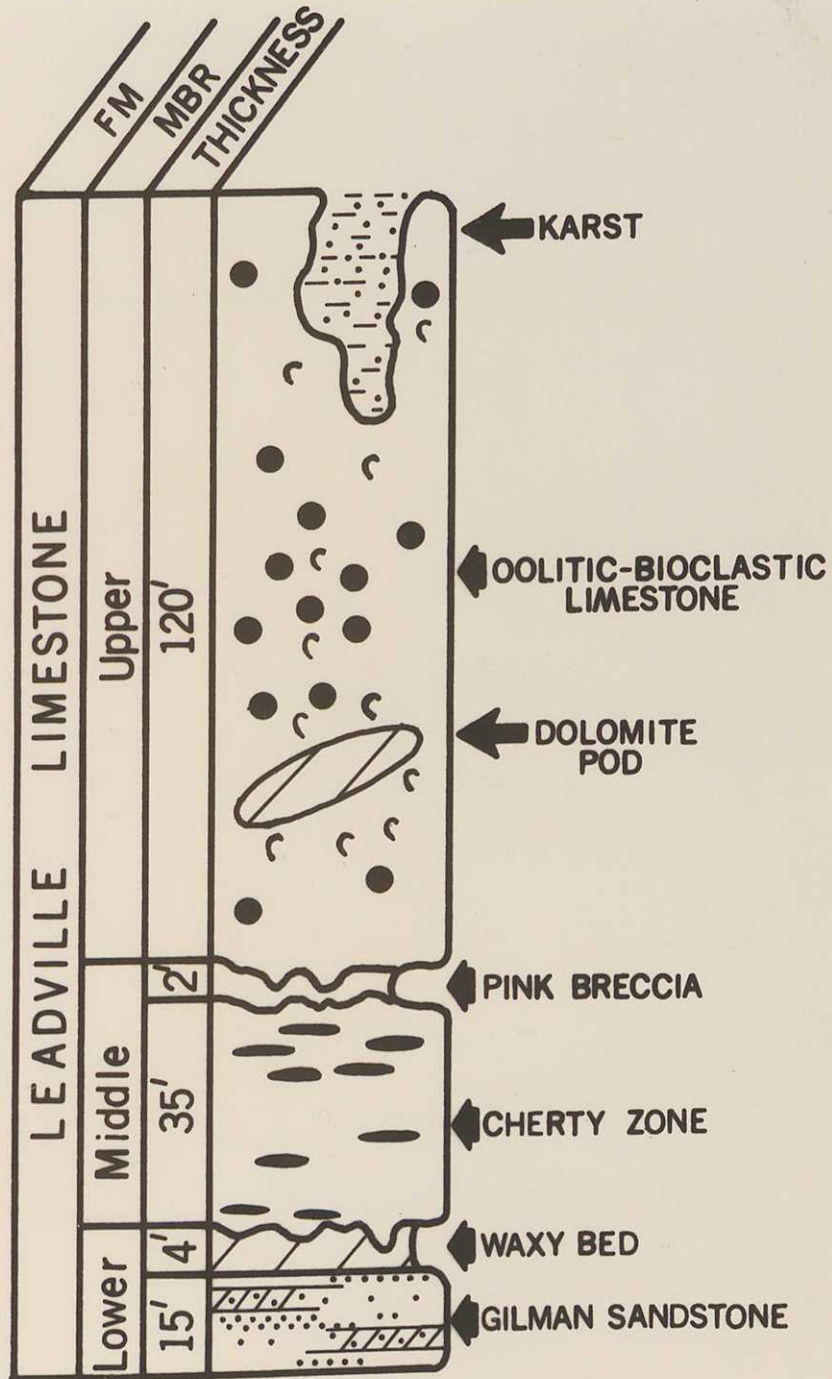
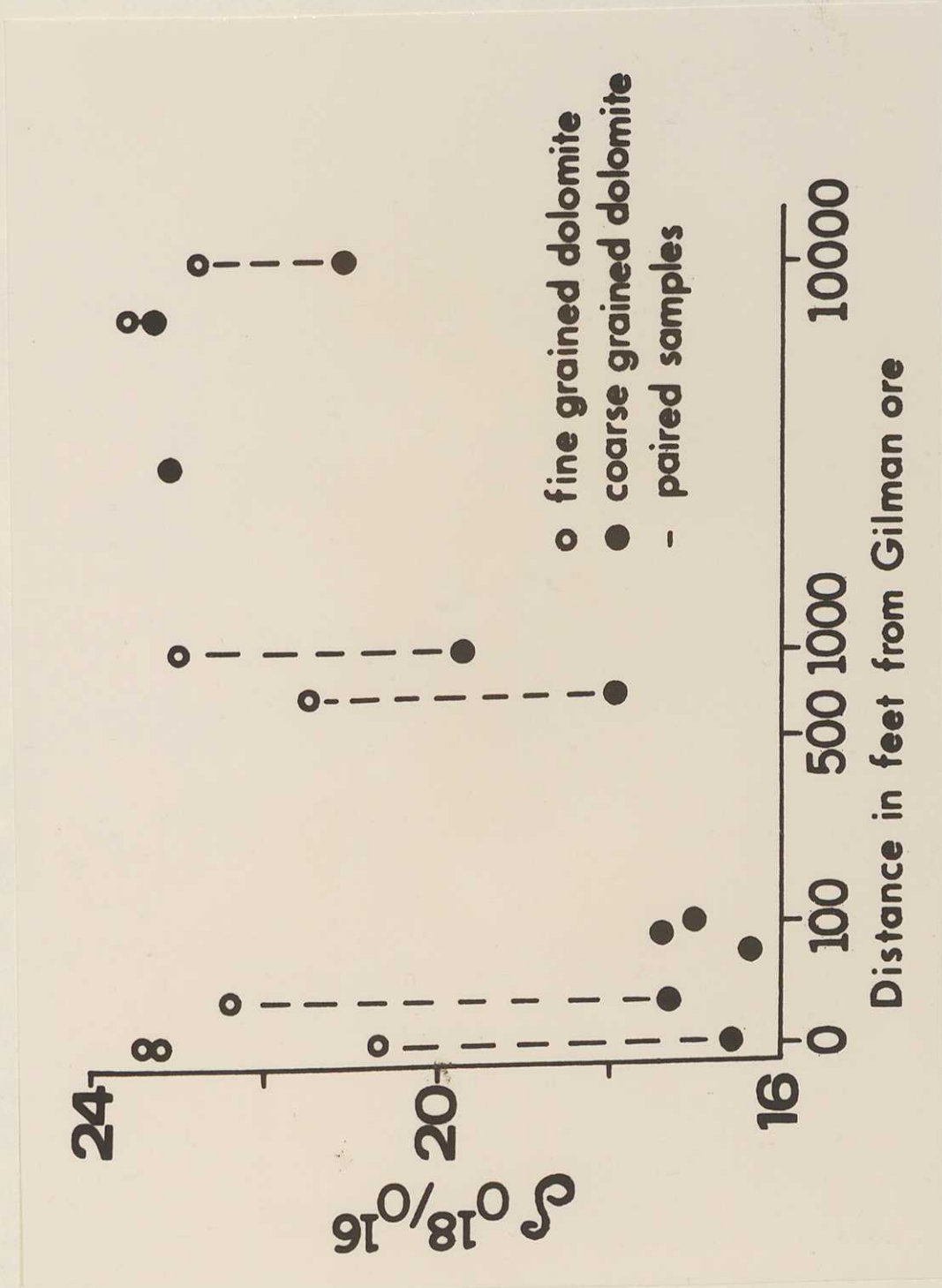


FIGURE 4



100

FIGURE 5



200

FIGURE 6

200

1

2

3

4



FIGURE 7

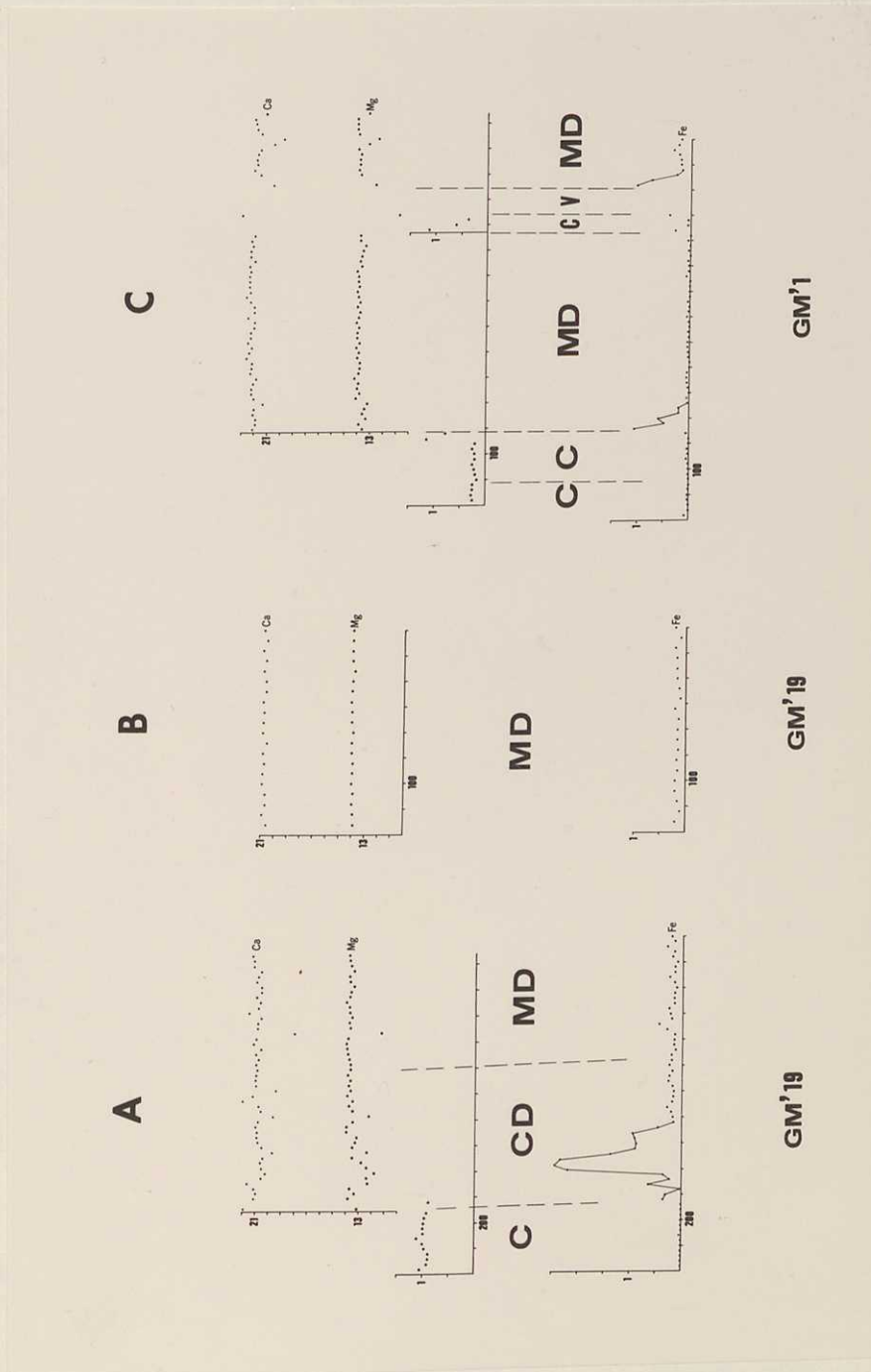
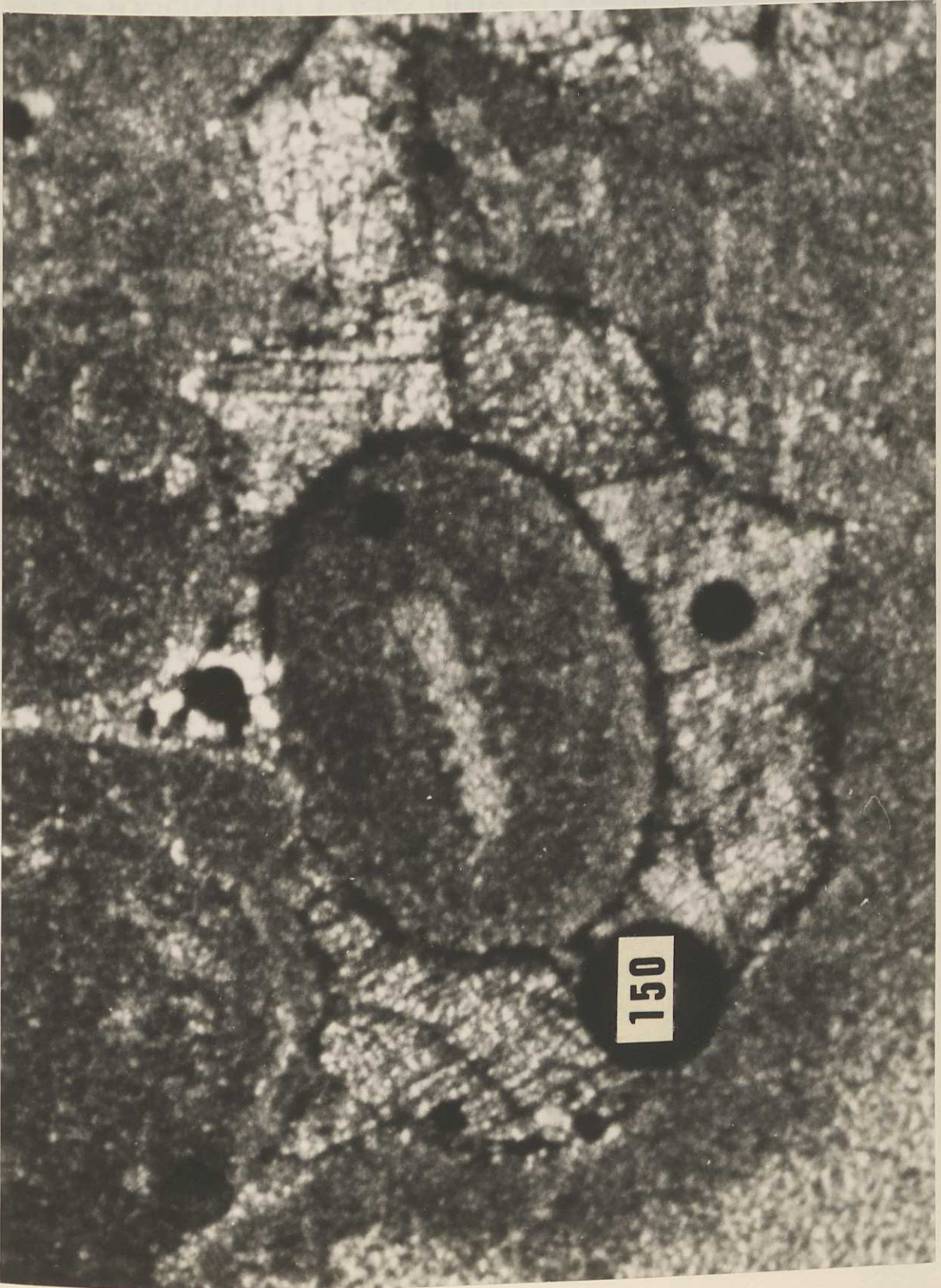


FIGURE 8



104

FIGURE 9



100

FIGURE 10

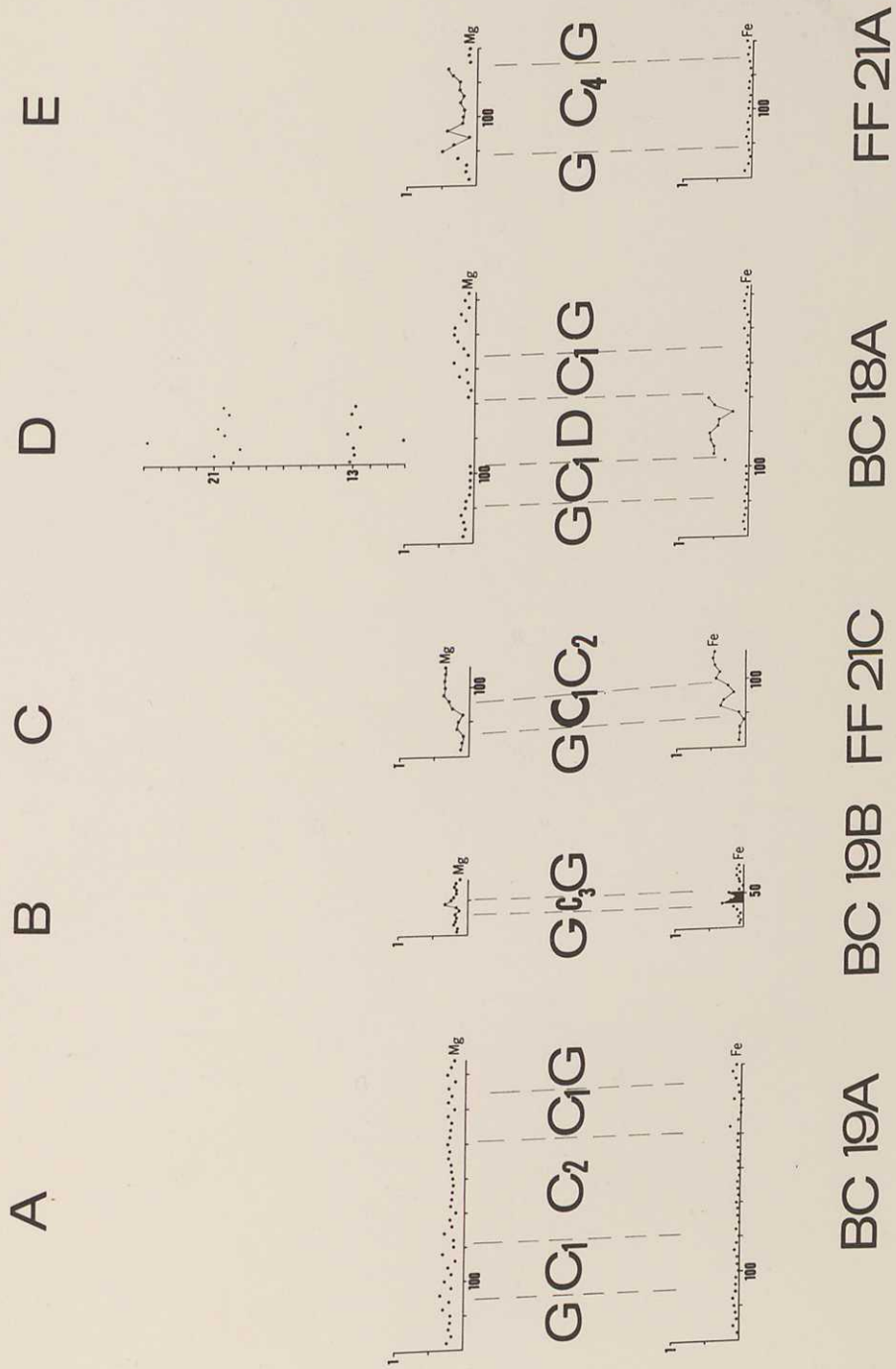
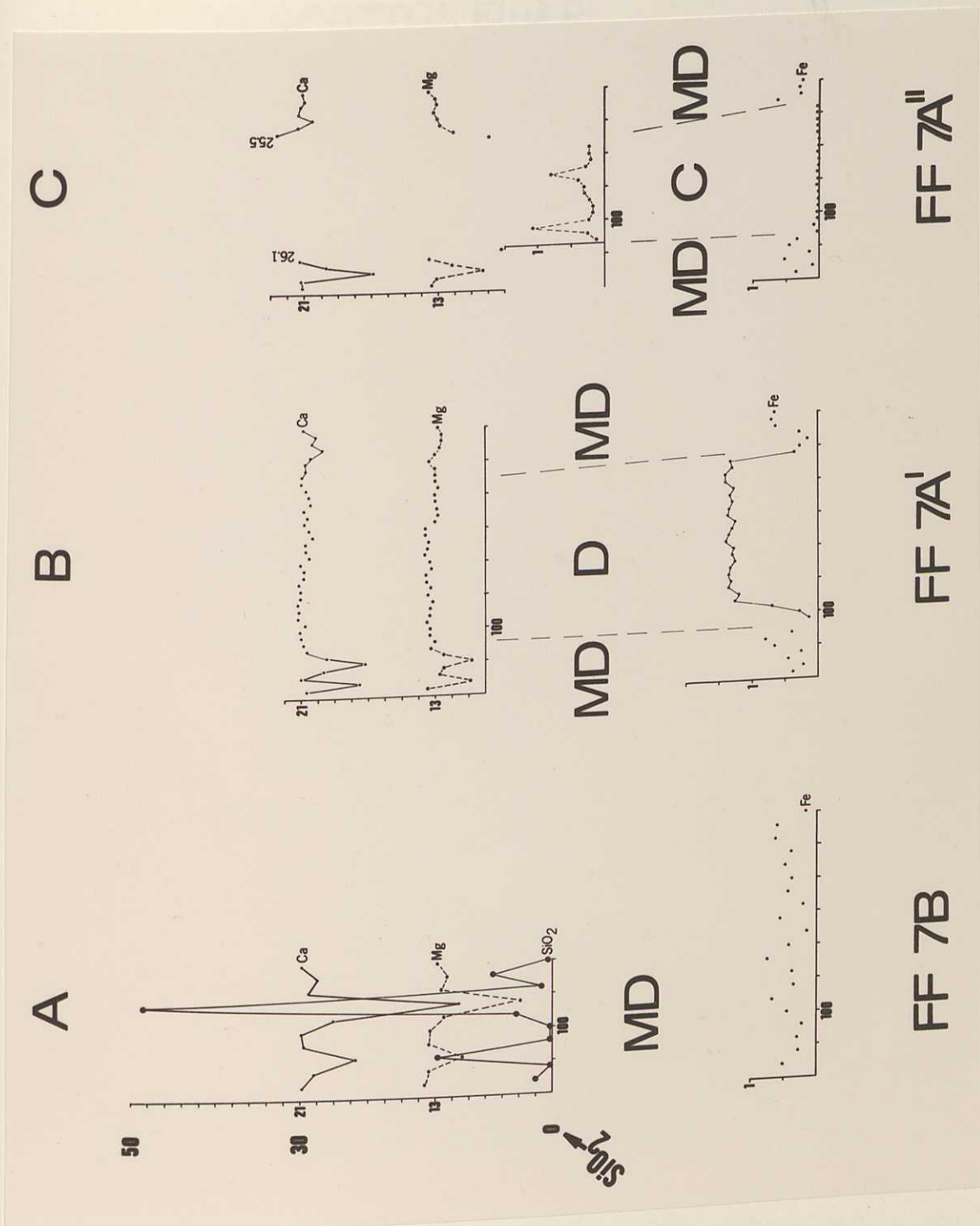


FIGURE 11



FIGURE 12



occurrence of these types of dolomite in the Leadville Limestone throughout the central Colorado region.

Chemistry and Sequence of Events

The sequence of alteration to the Leadville Limestone outside the hydrothermal aureole differs only in magnitude from the alteration sequence within the hydrothermal aureole.

The upper member (predominantly an oolite) had been thoroughly cemented with two petrographic generations of calcite, prior to hydrothermal alteration (Fig. 9). This cement contains a homogeneous concentration of Mg (0.2-0.3%) and no Fe (Fig. 10a). In places this cement is cut by fractures filled with ferroan calcite (0.2%Fe, 0.2%Mg) (Figs. 10b and 11). The fluid which precipitated the ferroan calcite has in places exchanged with the preexisting calcite cement. The calcite cement now contains an inhomogeneous distribution of Fe and Mg (Fig. 10c). Ferroan-dolomite (0.5-0.7% Fe) replaced the calcite cement and the ferroan-calcite veins (Fig. 10d). In some samples microcrystalline quartz cuts exsolved ferroan-dolomite. The last event in the alteration sequence consisted of calcite containing 0.4-0.5%Mg and no Fe being precipitated along fractures (Fig. 10e).

Ellipsoidal dolomite pods cut the lower portion of the upper member in several localities. The best and most accessible development of these bodies occurs at locality GS where the ellipsoids cut a lime packstone. Banks (1967) has figured one of these bodies showing the close association of the pods to joints containing coarse-grained dolomite which presumably acted