Bedrock Geology of the Crooked Creek Area, Southern White Mountains, Eastern California

Clemens A. Nelson¹
W. G. Ernst²

Abstract. The Sage Hen Flat pluton is one of several isolated Middle to Late Mesozoic granite bodies in the White and Inyo mountains. It intruded uppermost Precambrian to Cambrian meta-sedimentary rocks of the western limb of the White Mountain anticlinorium. It is unique among the granitic plutons of the area in that the country rock shows little evidence of forcible emplacement by the magma; bedding, major lithologic contacts, and important faults are truncated by the intrusion with only minor deflection. In places, the trace of the contact suggests generally steep boundaries, but where discernible in outcrop, the intrusive contact is flat or dips outward 35° or less. As shown by Bilodeau and Nelson (1993), the granite is concentrically zoned in texture, mineralogy and composition; internal structures are faint, but both concentric and radial magmatic foliations are present. The pluton is inferred to have been emplaced passively by piecemeal stoping of the roof rocks aided by magma convection. The molten body rose along weak zones in the crust provided by pre-intrusive faults. Stoping ceased when the magma encountered carbonate-bearing rocks, dewatered, and crystals accreted to the roof and wall rocks. The melt probably continued to convect and slowly crystallized inward.

Previous Work

The first to include mention of the Sage Hen Flat pluton, although not so named, was Adolph Knopf (1918). In a reconnaissance of the Inyo Range, including the White Mountains, he showed this pluton on the geologic map, but did not describe it individually. Not until forty years later was the major part of the pluton studied, when Pittman (1958) completed a Master of Science thesis on the northwestern part of the Blanco Mountain quadrangle. In 1966, Nelson (1966) mapped the entire quadrangle, including most of the pluton. McKee and Nash (1967) provided the first radiometric age for the pluton, establishing a Late Jurassic age for the body. Krauskopf (1968) designated the granite as number 10 in his "Tale of Ten Plutons" and later (Krauskopf, 1971) included it in the map of the Mt. Barcroft quadrangle. Two studies concerning contact metamorphic effects of the pluton followed: Crawford (1972) and Ulbrich (1973) investigated the thermal upgrading within the adjacent Wyman Formation. At about the same time, in a review of the granitic rocks of the White Mountains area, Crowder et al. (1973) made reference to the earlier established age (138 Ma) of McKee and Nash (1967). Gillespie (1979) supplied the modern

¹Department of Earth and Space Sciences, University of California, Los Angeles. Current address: 2297 Macintosh Avenue, Bishop, California 93514.

²School of Earth Sciences, Stanford University, Stanford, California 94305-2210.
uranium-lead ages of 144 and 145 Ma for the pluton, which placed the Sage Hen body as closely related in time to the age of the Independence dike swarm (148 Ma) of Chen and Moore (1979). In a Master of Science thesis on the structure and emplacement of this body, Bilodeau (1981) was the first to include both the Blanco Mountain and the Mt. Barcroft quadrangles' segments of the Sage Hen Flat pluton. Ernst and Hall (1987) also showed the granite in a map of the Mt. Barcroft-Blanco Mountain area. Nelson et al. (1991) included the Sage Hen Flat pluton in a review paper and geologic map depicting the whole White-Inyo Range. Most recently, Bilodeau and Nelson (1993) provided a detailed map and report on the geology of the Sage Hen Flat pluton.

**IGNEOUS GEOLOGY**

Figure 1 shows the northwest quarter of the Sage Hen Flat pluton as mapped by Bilodeau and Nelson (1993). It illustrates a number of features which can be visited on foot by those interested while at the Crooked Creek facilities. The position of the pluton is as a passive intrusive unit within the west-dipping limb of the White Mountain anticlinorium. The latter consists of the uppermost Precambrian Wyman Formation and the overlying Lower Cambrian beds of the Reed Dolomite, Deep Spring Formation, and the Campito Formation. These layered rocks constitute the basal part of a very thick succession of platform sediments deposited in a shallow sea that covered the western edge of the North American continent about 500 to 600 m.y. ago (Nelson et al., 1991). The Wyman Formation, a succession of argillite, quartzite, and lenticular limestone, represents the upper part of a thick Precambrian section with no known base, the oldest strata in the White-Inyo Range. The overlying Reed Dolomite is the basal unit of an essentially conformable Cambrian sequence, the next overlying unit comprising the Deep Spring Formation, a succession of limestone, quartzite, and dolomite transitional between the Reed and the overlying dark-grey to black quartzite and phyllite of the Campito Formation.

The area of particular interest lies along the western margin of the Sage Hen Flat pluton. Here, from the northeast end of County Line Hill, the granite clearly intrudes the Campito Formation, then the contact abruptly turns and heads back south along the Deep Spring Formation where the contact is nearly horizontal, then turns again sharply northward through Big Prospector Meadow. The granite continues across the Crooked Creek road in an irregular penetrative contact with the lower two members of the Deep Spring Formation. Here, three small xenoliths of Deep Spring Formation occur in the granite. The contact then swings around the large hill and extends westward again in a low-angle slope until it encounters the Reed Dolomite. At this locality, it is deflected northward along a poorly exposed contact, with a dip as low as 10° against the Reed and trends toward the Golden Siren Mine.

The intrusive contact relations of the Sage Hen Flat pluton and the Reed Dolomite can also be clearly seen some 600 m (2,000 ft) directly north of the WMRS Crooked Creek facility. There, across Crooked Creek and on the ridge to the north, is an outcrop of Reed Dolomite, completely surrounded by granite; the border then proceeds eastward in an irregular
fashion down the slope to a small fault which drops the granite-dolomite contact to the stream bottom.

An important feature is the relation of the Sage Hen Flat granite to the later, dark-colored dike rocks, “Jd” on the geologic map. This Independence-like dike swarm, which can be seen just south of the Crooked Creek road 600 m (2,000 ft) southwest of the WMRS Crooked Creek facility, clearly crosscuts the granite. The dikes have a slightly older geochronologic apparent age—by three million years—than the granite, illustrating the margin of error inherent in radiometric dating.

The Sage Hen Flat pluton has been divided into four concentric zones by Bilodeau and Nelson (1993); only the outer two zones occur in the area shown in Figure 1. The outermost zone is medium-grained hornblende-bearing biotite granite. The next inner zone, marked by a very diffuse boundary, is present only in the southeast part of Figure 1, and is coarse-grained subporphyritic granite. Magmatic foliation in the Sage Hen Flat granite is generally very weak. Both concentric and radial patterns are present and are commonly nearly vertical; in many cases the fabric is not parallel to the walls of the magma body.

METAMORPHIC GEOLOGY

A contact aureole is irregularly developed concentric to the Sage Hen Flat pluton. In the wall rocks adjacent to the margin of the granite, one or more of the following phases have been produced in individual rocks (Ernst et al., 1993): grossular-andradite garnet, diopside-hedenbergite clinopyroxene, actinolite-edenite hornblende, fluorite, calcite, epidote and/or vesuvianite in dolomitic metasediments; and scapolite, K-feldspar, calcic plagioclase, cordierite, and andalusite or sillimanite in meta-argillites and feldspathic quartzites. Magnetite and pyrite are widespread, both as minor phases, and as sporadically distributed vein minerals in the metamorphosed strata. The neoblastic minerals have been formed somewhat haphazardly as an overprint on a pre-existing regional trend.

The regional metamorphic paragenesis consists of feebly metamorphosed chloritic mica schists near and west of the crest of the White Mountain Range. These lithologies grade imperceptibly eastward into biotitic analogues in the core of the anticlinorium around and east of the Crooked Creek facilities. It also must be noted that even the relatively high-grade, later, contact aureole minerals have been altered in part to more hydrous, oxidized assemblages, due to falling temperatures, hydrothermal alteration, and weathering accompanying uplift and erosion.

Evidently, regional dynamothermal recrystallization, possibly attending mountain building along the Late Paleozoic and/or Early-mid Mesozoic active margin of North America, was followed by a series of localized heating events—each related to the intrusion of a specific granitoid body. Emplacement of the Sage Hen Flat pluton signalled one such episode at 144 to 145 Ma in the vicinity of the Crooked Creek area. Metamorphic mineral assemblages here attest to a complex history of deformation and recrystallization accompanying orogeny and later magmatic intrusion, followed by cooling as a result of exhumation.
Figure 1. Geology of the northwestern portion of the Sage Hen Flat pluton, Crooked Creek area, after Bilodeau and Nelson (1993).
**EXPLANATION**

**A. Alluvial and Landslide deposits**
- Oa, stream gravel and sand alluvial fan deposits
- Ols, landslide deposits, gravel and sand of local bedrock derivation

**B. Mafic rocks**
- Fine-grained diorite and diabase in dikes and small bodies

**C. Jurassic**
- Sage Hen Flat Granite
  - Medium- to coarse-grained, locally porphyritic biotite and biotite hornblende granite
  - 144-145 Ma (Gillespie, 1979)

**D. Cretaceous**
- Campito Formation
  - Dark brown to black to greenish gray fine-grained quartzitic sandstone and quartzite, representing the lower 750 to 850m of the Andrews Mountain member. The overlying Montenegro member is not exposed in the map area

**E. Deep Spring Formation**
- Cdu, upper member, 75m, fine-grained dark brown to black quartzitic sandstone, overlain by massive fine-grained gray dolomite
- Cdm, middle member, 200 to 230m, fine-grained white to rust-colored cross-beded orthoquartzite, overlain by fine to very fine-grained dark brown sandstone capped by well-bedded blue-gray limestone, topped by fine-grained buff-colored dolomitic sandstone
- Cdi, lower member, 95m, comprises a sequence of basal fine-grained dolomite, overlain by fine-grained blue limestone and brown calcareous sandstone, capped by coarse-grained buff-colored dolomite

**F. Reed Dolomite**
- Sr, 1,000m, massive and poorly bedded, basal portion medium-grained buff-colored dolomite, upper part fine-grained white dolomite
- Sr, skarn: largely grossular garnet and feldspar

**G. Wyman Formation**
- P-Cw, brown to black argillite, locally phyllitic, hornfels, and fine-grained brown quartzite and sandstone
- P-Cwl, fine-grained blue-gray to nearly white lenticular limestone
- P-Cws, skarn: grossular garnet, diopside, calcite, feldspar
  - Base of formation not exposed

**GEOLOGIC SYMBOLS**

- **Contact**
  - Dashed where approximately located, all alluvial contacts dashed, pluton contact dotted beneath alluvium

- **Syncline**
  - Dashed where approximately located. Arrow indicates direction of plunge

- **Fault**
  - Dashed where approximately located, dotted where concealed. U, upthrown side. D, downthrown side

- **Anticline**
  - Dashed where approximately located. Arrow indicates direction of plunge

- **Inclined beds**
  - 60°
- **Inclined foliation**
  - 70°
- **Inclined joint**
  - 50°
- **Horizontal foliation**
  - 15°
- **Horizontal joint**
  - Vertical foliation
- **Vertical joint**

**Atitude of Planar and Linear Features**
The only mine in the Crooked Creek area is the Golden Siren Mine, now inactive. All the workings are slumped and caved, and are inaccessible. All that is left is a collapsing building, housing remnants of bedding and a notebook (of recent derivation) of reminiscences of prospectors, skiers, hikers, students, etc. The prospect is mentioned by Knopf (1918) who reported the main shaft to be “90 feet deep and to intersect the vein at 45 feet.” The ore was said to be of quartz and iron oxide to average at that time $14 to $18 a ton in gold (Au). Copper (Cu) stain as malachite and/or azurite is also common in such workings, indicating some values in Cu as well as Au.

REFERENCES
Walcott and the Early Cambrian of Eastern California: Geology in the White-Inyo Area, 1894 to 1897

Ellis L. Yochelson

Clemens A. Nelson

Abstract. During three field seasons in 1894, 1896, and 1897, Walcott spent approximately six weeks in the White-Inyo Range in the vicinity of present-day Bishop, California. Walcott’s daily diary entries, supplemented by fossil localities and field photographs, provide sufficient data so that his travels by horseback and wagon can be traced.

As a result of his first season’s work, Walcott published two short papers. In one, he reported the presence of Cambrian rocks in their westernmost exposure in the United States. He also outlined the basic Lower Cambrian stratigraphic units still in use. In the second, he remarked on the general structure of the range and emphasized that folding of strata had preceded block faulting.

His 1896 field work is partially recorded in a publication on a former desert lake. Walcott noted that the lake beds were tilted and used these data to draw inferences as to uplift and tilting of the range. No publications resulted directly from the 1897 field season, but later he published the section which is the type for the Waucoban, a term Walcott introduced for the Early Cambrian of the United States.

INTRODUCTION

Charles Doolittle Walcott made the first stratigraphic investigation of Cambrian rocks in the White-Inyo Mountains. During three field seasons he also touched on other aspects of the geology. Because of the increasing interest in Early Cambrian fossils and the still-unresolved problem of placement of the Precambrian-Cambrian boundary in this region, we judge that a documentation of these trips may be of interest to the geologic community. They provide a glimpse of field methods used a century ago by our forebears, without easy transport and when one was forced to camp by water sources and not commute to the nearest town.

Walcott kept a pocket diary in which he jotted a few lines each day. A few pages of his field notes for one year do exist to prove that there was such a document; all other traces of field notes have vanished. However, with the diary entries it is possible to determine the general route followed by the camp wagon. Photographs that Walcott took and locality descriptions assigned to some of the fossil collections have been used to supplement his diary. This portion of the White-Inyo Range has been mapped in considerable detail

12303 Stafford Lane, Bowie, Maryland 20715.

2297 Macintosh Avenue, Bishop, California 93514.
16—ELLIS YOCHELSON AND CLEMENS A. NELSON

(e.g. Nelson, 1966, 1971, 1978) and the data have been used to explain Walcott’s comments in light of present-day stratigraphic nomenclature.

Then, as now, the Owens Valley was remote from major urban centers, although it boasted a railroad, long since forgotten by even the older inhabitants of the valley. Then, as now, the range was difficult of access, and the road system has been little changed since Walcott’s day. Because this aspect of cultural geography has been virtually frozen in time, tracing Walcott’s route is comparatively easy. We find it interesting to note how much of the field seasons were taken up with movement from camp to camp and how much of the observation was, of necessity, done while on the move. Viewed in this context, his geologic accomplishments are even more remarkable.

We have not been able to determine why Walcott chose to investigate this area. It may have been chance remarks by G. K. Gilbert, or it may have been comments by H. W. Turner. Whatever the trigger, this turned out to be the ideal area for Walcott to extend his earlier observations on the Cambrian, downward in the section.

1894 FIELD WORK

Early in September, the 44-year-old Walcott, Director of the United States Geological Survey only since July 1, left Washington for the west, conducting business in Chicago and Denver before reaching Reno, Nevada. From there he took the Colorado and Carson Railroad southward and eventually arrived at Big Pine, California. On Monday, September 24, Walcott met F. B. Weeks, a younger Geological Survey employee noted later for his bibliographies of geology, whom he had sent ahead to arrange for a camping outfit. Walcott’s diary entries are given below and followed by comments, as needed.

September 25: “At 10 a.m. started with wagon & driver & two saddle animals. Worked on section up to Tollgate 8 mi east of Big Pine. Found Lower Cambrian fauna in limestone of ridge north of Tollgate.”

The most direct route across the range from Owens Valley to Deep Springs Valley is via Tollgate Canyon. The name is derived from the toll of one silver dollar for each wagonload of hay transported across the range. Above the site of the former Tollgate, the Poleta Limestone is exposed; and it was in this unit that fossils were found on the first day of field work. Although it is not recorded, undoubtedly the fossils were archaeocyathids, at that time considered to be corals.

September 26: “Went on east as far as Gilbert’s ranch in Big Spg. valley. Geology very much broken up—Lower Cambrian fossils occur in limestone 3 mi above Tollgate.”

The Big Spring Valley of Walcott was later rendered Deep Spring, and on the current topographic map it is now Deep Springs; the original name was more logical. The Poleta Limestone occurs higher in the canyon and is exposed almost 5 km (3 mi by odometer) from the Tollgate. Thus, we are reasonably sure that the various distances Walcott recorded later were fairly accurate. We have not checked the early land records in Nevada, but Gilbert’s Ranch may be the site of Deep Springs College.
September 27: “Examined section to within 2 mi of Piper’s ranch. Turned back at noon & went to Antelope Spg at head of Big Spg valley.”

After the road up Tollgate Canyon crosses the summit of the range, it proceeds down what is now called Payson Canyon. Antelope spring is to the north of the road. Walcott and Weeks must have ridden northward along the east side of the range, probably up to the divide between Deep Springs and Fish Lake valleys. Along this route they would have seen only granite overlain by basalt at the north end of Deep Springs Valley. Piper’s Ranch was at what is now Oasis, California, in Fish Lake Valley.

September 28: “Returned to Tollgate via Soldiers Canyon. Collected a lot of Lower Cambrian fossils at N.W. end of Big Spg Valley and also near head of Tollgate Canyon.”

During the years, the term Soldiers Canyon has been lost and the name Payson Canyon has been used for the route of the road on the east side of the range. Along the road, shales of the Montenegro Member of the Campito Formation and shales of the Middle Poleta Formation are exposed; Walcott may have collected from either or from both. There is no indication of the camp site that night in the diary, but the only place where water could be obtained with any certainty was at the Tollgate; the comment the following day confirms this interpretation.

September 29: “Moved from Tollgate to Walsh’s ranch near mouth of Silver canyon & Laws station on the C & C R R.”

Laws, California, is now preserved as an outdoor museum along U.S. Highway 6, about 6 km (4 mi) north of Bishop, California, and gives one a sense of what the culture was a century ago. In contrast, the town of Bishop, now the obvious point of departure for the field area, did not then exist. By the present-day road system, it is 40 km (25 mi) from the Tollgate to Laws. Probably the road is in essentially the same place as it was then; and once Tollgate Canyon was left, this trip would have been an easy, gently uphill trip for the animals, compared to the pull up Tollgate Canyon.

September 30: “Went up Silver Canyon to limekilns. Examined section on south side of canyon.”

This was a Sunday; and when it was feasible, Walcott avoided fieldwork on that day. If it was not feasible, he generally did a lesser amount. Although we do not know the exact location of the lime kilns, it can be surmised they were about 5 km (3 mi) east from Laws. Walcott prepared a sketch of an overturned syncline; four pages of his diary in which he sketched structure are shown in Figure 1. The only place in the lower part of the canyon where such a structure can be seen is 5 to 6 km (3 to 4 mi) up the canyon. Figure C of Walcott (1895b), shown in Figure 2, is reported to be on the north side of the canyon and more or less matches a sketch in his diary. Compared to the horseback rides of other days, this day was relatively easy.
October 1: “Collected a lot of fossils in Cambrian limestones & went south to mouth of Black Canyon stopping at Collin’s ranch at night.”

Black Canyon is intermediate in location between Silver Canyon to the north and Tollgate Canyon to the south. The dirt road into the canyon has deteriorated and is hardly passable today. Collin’s Ranch has vanished, but was situated about a mile south of the entrance to Black Canyon.

October 2: “With Mr. F. B. Weeks measured section on north side of Black Canyon. Section broken at summit.”

Although nothing is said of field methods, in all likelihood the Jacob staff was used to measure the section. The relatively uniform dip and excellent exposures are suited for its use; Walcott (1889) published a short note on the advantages of this field tool. He had only this one day to measure a section nearly a mile thick.

October 3: “Spent the day on the east flank of Black Canyon.”

Another diary sketch, also shown in Figure 1, closely matches Figure D of Walcott (1895b) and indicates the folding seen in Black Canyon. Except in terms of this general area of the range, we cannot determine where the other cross-sections in his published paper were observed. The road into Black Canyon does not reach the summit of the range.
Walcott—Appalachian Type of Folding in California. 173

DESCRIPTION OF FIGURES.

Fig. A.—Diagrammatic section of the White Mountain range as viewed from the high ridge south of Tollgate Canyon. 2, upper limestone; 3, quartzite and shale series.

Fig. B.—Theoretical section of range south of Silver Canyon, to illustrate character of syncline. 2, upper limestone; 3, quartzite and shale series; 4, lower limestone.

Fig. C.—Syncline on the north side of Silver Canyon. 1, upper shale; 2, upper limestone; 3, quartzite and shale series.

Fig. D.—Section on the east fork of Black Canyon. 1, upper shale; 2, limestone; 3, quartzite series; 4, upper portion of the lower limestone.

Fig. E.—Anticlinal and synclinal folds occurring at x in fig. D.

Fig. F.—Outline of folding of limestone imbedded in quartzite and shales, western side of Deep Spring valley. a-b, fault.

Figure 2. Illustration from Walcott’s article, “The Appalachian type folding in the White Mountain Range of Inyo County, California,” which was published in the American Journal of Science in 1895. Compare Walcott’s figures here with the sketches from his diary in Figure 1.
October 4: “Moved camp from Collins ranch to Waucoba Canyon, 11 miles E of Big Pine. A hot days march & little result in geology.”

The canyon Walcott noted as Waucoba Canyon contains the main exposures of the Waucobi Lake Beds, which he named in 1897, and the Waucoba Road. Presently, the name Waucoba Canyon is applied to the major canyon draining east from Waucoba Mountain and into Waucoba Wash in northern Saline Valley.

October 5: “Worked on the Cambrian limestone 3 mi east of the Tollgate in Soldiers Canyon. Camped at Tollgate at night. This practically closes work for this season in the Cambrian rocks of California. Have made a beginning on the White Mountain Range.”

Cambrian limestone is present in the vicinity of Cedar Flat, which is about 5 km (3 mi) east of the site of the former toll gate.

October 6: “Examined the area near the head of Tollgate Canyon and at night camped 1/2 mile from the Alvord R. R. station in Owens valley.”

Alvord has become Zurich on present-day maps, an unlikely name for a desert town.

October 7: “Moved to Saw Mill Canyon 5 mi w. of Big Pine. Found hill of Paleozoic rocks (Lower Cam?) 2 1/2 mi W. of Big Pine.”

Walcott moved west across Owens Valley to the higher and cooler Sierra Nevada. The hill he noted is a pendant in the granite of the Sierra. His age determination is correct, even though the outcrop is metamorphosed; poorly preserved archaeocyathids occur; but it is uncertain whether Walcott saw them. This hill is the oldest pendant in the area, with the pendants en echelon becoming increasingly younger to the north.

October 8: “At noon returned to Big Pine & packed up P. M. Wrote a few letters & settled up accounts. The principal results of the two weeks work are the discovery of the Cambrian rocks in the White Mt. range and the folding of the strata in the Appalachian type.”

The next day Walcott headed north by rail and commented on the splendid view of the White Mountains. Walcott did not return to Washington until the end of October. On December 22, when administrative duties slackened, Walcott “Began working up notes on California.” Five days later, at the annual meeting of the Geological Society of America in Baltimore, Maryland, he presented two talks. On the first day of the meeting, he outlined his discoveries on structure. Although the summary of the meeting by the secretary suggests that the information on Cambrian fossils was “reported in a few words” (Yochelson, 1988), on the following day, on the meeting program itself, this is listed as a full-fledged account (Geological Society of America, 1895).

1895 PUBLICATION

This year Walcott was not in the White-Inyo range, but two short publications appeared in the American Journal of Science which recorded his work of the previous field season and gave the substance of his two talks. In February, the journal published four pages (Walcott,
1895a) devoted to the Lower Cambrian rocks and listing some of the fossils. His measured section in Black Canyon, on the west side of the White Mountains north of Tollgate Canyon, is presented, and he added a bit of detail from Silver Canyon farther north.

Regarding fossils, he found none in the basal limestone, but recorded annelid trails above and *Olenellus* still higher, in what would be the middle part of the Poleta and the Harkless formations. The Lower Cambrian corals (*Archaecyathinae* in Walcott's terminology) in the upper limestone (now Poleta Formation) were represented by at least four forms. In the younger shales of Tollgate Canyon, now the upper part of the Poleta Formation, he noted that one of the arcaheocyathids occurred with fragments of *Olenellus* and with "Cystidean plates;" these surely must have been plates of *Helicoplacus*, considered to belong to an extinct class of echinoderms (Durham and Caster, 1963).

Near the end of this short article, Walcott (1895a, p. 144) wrote: "So far as known to me, this is the oldest of the Cambrian faunas known in the western portion of the United States. Just what the relations are to the *Olenellus* fauna of central Nevada and to British Columbia are I am unable at present to state, except that I believe it to be older than the *Olenellus* fauna of central Nevada." What is now differentiated as the *Fallotaspis* zone underlying the *Olenellus* zone was thus first mentioned.

Incidentally, although Walcott's most comprehensive work in the west is his study of the fossils of the Eureka District, Nevada (Walcott, 1884), several years after that investigation he measured sections and collected Cambrian fossils in the Highland Range, about 200 km (125 mi) south of Eureka. He correlated those fossils to some collected from British Columbia (Walcott, 1888). As a result, there was a good basis for his surmise that the White Mountain trilobites were older than those to the east.

His second paper appeared in March, only six months after field work was completed and about three months after he began writing up his field notes. During Gilbert's time with the Wheeler survey, that geologist made one hurried march through the mountains and suggested a broadly synclinal structure. Although looking east from Owens Valley the range appears to be a monocline, "The first trip into Tollgate Canyon disproved this and furnished the data for the tentative conclusion that this portion of the range is a syncline of quartzite and limestones, very much broken by local folding and faulting" (Walcott, 1895b, p. 170).

Walcott then summarized the section given in his earlier published note and used the four broad stratigraphic units he had differentiated therein to discuss the structure seen in Waucoba and Tollgate canyons to the south and Black and Silver canyons to the north. The paper contains a few simple cross-sections to illustrate the folding. Although detailed mapping has shown more faults are present, in the main these sketches accurately reflect the structure where Walcott observed it. However, he was unaware of several major faults that primarily affected the lower part of the section, below the fossiliferous Montenegro Member of the Campito Formation.

Walcott concluded by mentioning the ranges traversed by the Wheeler survey and remarked "... that in the broad Paleozoic area between the Sierra Nevada on the west and
the early Paleozoic shoreline on the east (Colorado) a period of folding and thrust faulting was followed by a period of vertical faulting, which displaced the strata that had been folded and faulted in the preceding epoch. The extent and character of the disturbance can be determined only by a careful study of each of the mountain ranges for a distance of over 800 km (500 mi) east and west and probably 1,600 km (1,000 mi) north and south; and the great geologic problems will not be fully solved until the areal geology of the region between the 109th and 119th meridians shall be mapped,” (Walcott, 1895b, p. 174). During the past century, field geologists have spent thousands of man-hours in mapping at various scales, and thousands more in measuring sections and correlating, but are still not finished with the “great geologic problems” of this region.

1896 FIELD WORK

Walcott was in Reno, Nevada, in mid-September. Those who complain about jet lag should be aware of his comment, “Feeling tired after 4 3/4 days on the train.” He left his watch and $100 for safekeeping in Carson and got to Hawthorne, Nevada, the following night. However, later he gives time for several of his days in the field, so perhaps this was a particularly fine watch he left, while carrying another model with him. On the 18th he finally arrived at Silver Peak, Nevada, where the faithful Weeks “…met me 840 p.m. & we went to our camp near the spring.”

From September 19th until the 30th, the two geologists collected archaeocyathids and other fossils, explored the islands in the salt marsh, examined the gold mines in the area, and looked at a coal mine in Cretaceous rocks. Starting on the 21st Walcott recorded the distances traveled each day in miles. They are not rounded off, so one must assume that he was counting revolutions of a wagon wheel, paces of his horse, or some other comparable method. For these nine days he recorded a total of 314 km (195 mi). The party then moved down the east side of the White Mountains; mileage is given in brackets.

October 1: “Rode into Silver Peak—packed up & with outfit went to Cave spg—on road to Fish Lake Valley. Very tired at night [23].”

By traveling south on this route, Walcott was able to explore the east side of the White-Inyo range. We surmise that his immediate objective was to find the longest unbroken exposure of Cambrian rocks so that he could measure a section.

October 2: “Moved camp from Cane spg to Fish Lake Valley below Gov. Leidy’s ranch. 25 mi. Camped beside stream coming from White Mts. Examined foothills of White Mt. range. Eruptive granite etc & Cambrian quartzite & shales high up [31].”

From the distances, it appears that Walcott and Weeks ranged over the hills while the wagon traveled by road. For a team and wagon, 50 km (30 mi) was a very good day’s travel.

October 3: “Moved camp to Pipers ranch 16 mi & stopped to clean up—attend to correspondence etc.”
Walcott’s duties as Director continued to follow him into the field.

October 4: “Left Pipers [Oasis, California] at 6 40 a.m. & rode to Pigeon spg—thence to the Tule spg & back to pigeon spg—Went out on the ridge west of Tule Canyon—a long, hard day—[29].”

Pigeon Spring and Tule Spring lie southeast across the Fish Lake Valley. This was a particularly hard day, especially for a Sunday. For his trouble, Walcott probably saw little but a large expanse of poorly exposed shales of the Harkless Formation.

October 5: “Went out on ridge west of Pigeon Spg 7 mi. Returned at 12 30 & left for Pipers ranch where we camped at night [30].”

October 6: “Left Pipers ranch at 6 40 a.m. Crossed devide [sic] to Deep spg valley & camped at Lewis Payson—Antelope spg. In the afternoon went up Canyon to the north 3 mi to see Paysons silver mine [26].”

It is not clear why Walcott changed his terminology from Big Spring to Deep Spring, as the former is a more logical name. Today, Deep Spring is the name given to the geologic formation, but Deep Springs is now the official name of the valley.

October 7: “With Payson & Weeks went up Payson canyon & measured the section from the granite up to the quartzite below the mouth of the canyon—a hard days work [10].”

Insofar as we can surmise, Payson Canyon as used in the diary entries was to the north of what is presently termed Payson Canyon, which contains the road that traverses the range from Tollgate Canyon. No granite is exposed along Payson Canyon as that term is used today.

October 8: “Continued section out into foothills E of Payson’s ranch & then crossed Deep Spg. valley & went up a canyon on the west side (end). At night camped near Deep spring [23].”

In this section, Walcott would have investigated rocks from the Campito Formation up to the metamorphosed Saline Valley argillite beds before encountering the intrusive granite.

As regards the geographic setting, Deep Springs Valley is an elongate, northeast-trending structure topographically higher than Fish Lake Valley to the north and Saline Valley to the south. A small lake is in the southern end of the valley.

October 9: “Examined section S.W. of Deep spg. valley. Climbed up ridge on S.W. side of valley 3400 feet. Found all Cambrian rock but broken by faults. A hard days work with negative result. [10].”

The area on the east side of Deep Springs Valley is pervasively faulted and contains the granite contact with the Paleozoic section.

October 10: “Examined section S of Deep spg. valley. Found a broad anticlinorium much broken & folded—very little result except the finding of fossils below the archaeocyathinae limestone. Tired at night [20].”
Walcott's interpretation of the structure at the south end of Deep Springs Valley is correct; the folds in the Poleta Formation confirmed that the range was an "Appalachian" type of mountain. His discovery of fossils below the Poleta Limestone in the Montenegro Member of the Campito Formation was far more significant than he first realized.

October 11: "Rode out on the foothills east of Antelope spg. (Payson's) & up Payson canyon 7 am—to 12 45 p. m. Cldy, cool day [10]."

In contrast to the previous Sunday, this was a relatively easy day for both man and beast.

October 12: "Left Payson's at 6 30 a. m. & cross White Mt range to Alvord & and thence south 4 miles to 4 mi north Citrus station. Camped near station at 5 P. M. [34]."

Walcott summed up the daily travels he had been recording since the start of the season at Silver Peak; so far it had been 400 miles on horseback. As noted earlier, Alvord station is now Zurich; Citrus station became the metropolis of Independence, California.


This was the last day that Walcott listed the distances traversed. As mentioned under the section on recording fossils, he found Jurassic ammonites "10 mi E.N.E. of Lone Pine Inyo Co. Cal.—6 mi S. of Eclipse furnace—near summit of Inyo range."

October 14: "Rode to base of & climbed to summit of Inyo range—11200 feet by aneroid. A hard days work out 12 1/2 hrs. Camped near Eclipse Mill at night."

Walcott's pocket diary was private, and when he recorded a hard day, it was not to impress a reader.

October 15: "Took train to Alvord & stage to Big Pine. Writing letters etc. P. M. Outfit came in at 5 P. M & we camped 1 1/2 mi N.W. of Big Pine."

October 16: "All day on the road towards Saline valley a 16 mile grade rising 3600 feet kept team busy until 5 P. M. Camped 20 miles out from Big Pine. Made a study of Lake beds on way up Waucoba canyon."

Like so many of the geologists who worked in the Great Basin, Walcott was familiar with the studies of Gilbert on Lake Bonneville and the general notion concerning former Cenozoic lakes. In particular, he was aware of the work of Turner (1891) on such a former lake on the west side of the Sierra Nevada in Plumas County, California, for Turner presented a talk on his findings in Washington, and Walcott had a reprint of his paper.

October 17: "Camp moved to Waucoba Spring—15 mi. Studied section en route found limestone containing coral—apparently Silurian but may be Devonian."

This is the only reference that Walcott makes in 1896 to Paleozoic rocks younger than Lower Cambrian. The only place where Middle Paleozoic limestone-bearing corals crop out
along this general route is on both sides of Jackass Flat. The present-day road on the east side of the range is new and is west of the route on which Walcott traveled. The numerous switchbacks now seen did not exist; the old wagon road came into Saline Valley to the northeast of the present road through the canyon.

October 18: "Moved camp back to near Waucoba summit. Examined section between Deep Spg valley & Saline Valley road. There is a great thickness of deposits—Cambrian to Carboniferous. Cannot work the section this year."

Apparently the discovery of the mid-Paleozoic corals plus the great thicknesses of limestone, some repeated by faulting, mislead Walcott into guessing that younger Paleozoic strata were present on the east side of the range. October 18 was another Sunday, but the field season was ending, and camp had to be moved.

October 19: "Returned to Alvord station, collecting fossils from quaternary lake beds along Waucoba Canyon. I think the ancient lake that filled Owens Valley etc might well be called Waucoba lake. Packing up P. M. Last day in camp."

The next day Walcott left by train for Hawthorne, Nevada, where he recovered his pocket watch. Except for the time near Silver Peak, Nevada, most of the effort that field season had gone into travel and examination of areas en route. As a result, Walcott had eliminated several potential places to measure sections because of the number of faults.

1897 PUBLICATION

In the May/June issue of the Journal of Geology, Walcott published a paper on the lake beds he had observed in Waucoba Canyon; it was his third contribution in five years in that journal. In this work he used the term "Waucobi" for both the canyon and the embayment on the mountain front where they are most clearly seen. From the lake beds, Walcott had collected mollusks; they were of uncertain age, but W. H. Dall guessed they indicated Pleistocene.

"The strata of the lake beds three miles up the canyon are largely a fine calcareous deposit, with more or less arenaceous and argillaceous matter in the form of fine sand... As the beds approach the steeper side of the mountain, about ten miles above the mouth of Waucobi Canyon, the sediments become coarser and coarser, and brown arenaceous beds predominate over the drab and light gray sediments. Near the contact with the quartzites, a little below Devil's Gate, bowlders of the quartzite a foot or more in diameter occur in the coarse sediments, and the contact of the lake beds and the Cambrian quartzites is finely shown on the south side of the canyon." (Walcott, 1897, p. 342).

Walcott could describe rocks clearly without recourse to the jargon that, even then, began to appear in the literature; "bowlder," not "boulder," was the accepted spelling.

Walcott noted a dip of 3° to 5° in the lake beds, which in one place rose to 10° along with a comparable change in the slope of the canyon floor. The beds extended 914 m (3,000 ft) up the mountain front from near the east side of Owens Valley. By drawing a simple profile from the summit of the Inyo Mountains across Owens Valley to the crest of the Sierra Nevada, Walcott deduced that the range had been uplifted and tilted. Walcott also
remarked on a recent fault scarp and truncated spurs on the east side of the range; here he
was referring to Deep Springs Valley where, "... great springs flow out along the line of the
fault..." He also observed steep slopes in Saline Valley having an abrupt juncture with the
valley floor:

"I think there is sufficient evidence in the sinking of the southern margin of Deep Spring
Valley, in the phenomena observed to the south in Saline Valley, and in the position of the
Waucobi lake beds, to sustain fairly well the view that the range has been elevated to the
eastward and tilted to the westward" (Walcott, 1897, p. 346).

Walcott went on to consider the amount of change in elevation and the effect of the 1872
earthquake in Owens Valley. This venture into neotectonics whetted his appetite, for he
concluded by writing that he had a paper in preparation on faulting and tilting of
monoclinal blocks, and that his principal illustrations would be taken from faulted slabs of
limestone collected in Waucobi Canyon. On May 7, 1897, Journal of Geology editor T. C.
Chamberlin wrote him: "We shall be glad to consider your possible paper on the faulting
of the Basin Ranges. The subject is one of very great interest to me from the dynamic
standpoint." (Chamberlin Papers, Book IX, University of Chicago, Special Collections Library).

Whatever Walcott might have had in mind on this subject did not materialize in print,
for after another season in eastern California, he began to pursue the Precambrian in
Montana where the tectonic style and the basic problems of stratigraphy are different. It
would be more than a decade before the lake beds were restudied (Trowbridge, 1911).

Radiometric dates of tuffs near the top of the lake beds give a date of about 2.3 million,
so these are mainly Pliocene, not Pleistocene (Hay, 1964, p. 120; Bachman, 1978). Although
the tilting is much as Walcott described, the date of movement cannot be reliably determined.

Being a man of many parts, Walcott also presented an informal communication to the
Geological Society of Washington on the gold ore near Silver Peak, Nevada. Like all
informal communications of the society, it was not published.

1897 FIELD WORK

The summer of 1897 was a busy one. Not only was Walcott personally concerned with
the national forest reserves in South Dakota and Wyoming, the Secretary of the Interior
asked him to prepare a report on Yosemite Park. As a consequence, Walcott crossed the
Sierra Nevada on horseback, thereby arriving three times at the Inyo Range by three
different routes. On the 16th of September he was in Big Pine. The next day, Walcott

"Left Big Pine 7 45 a. m. with Weeks & rode to summit between Deep Spgs Valley and
Waucoba Canyon. Obtained a fine view of the Cambrian rocks. Will be obliged to work the
section from the south towards Saline Valley. Camped at Grahams fruit ranch."

This ranch, long abandoned, was within the boundaries of the Waucobi Lake beds. The
following day Walcott "Studied faulted beds in Waucoba Canyon & then cross Owens
Valley to Turners Range up Saw Mill canyon at the east face of the Sierra.—Camped—We
are waiting for our camp outfit."
They climbed to the summit of the Sierra Nevada thereafter, and Walcott observed, "Scenery superb. Counted 25 glacial lakes from one point." It was quite a change from the semi-desert of the Inyo Range. The geologists met their camp outfit the next day and went up Big Pine Canyon. They spent another day moving the outfit farther up the canyon. Then they climbed to 3,261 m (10,700 ft) to obtain photographs, and this was followed by another stiff climb to the divide at the head of Big Pine Canyon. On the 24th, they returned to Big Pine and rested up for the main field work to the east.

September 25: "Left Camp 7 a.m. Took breakfast at Big Pine & at 8 a.m. started for Waucoba road divide [sic]. Camped 20 miles out near N.E. base of Waucoba Mt. on Saline Valley road. 3000 feet above Alvord. Weeks. Smith & Cuddington. 8 animals."

The divide is still recognizable today where one road branches east toward Death Valley, Nevada, and the other trends southeast toward Saline Valley. We presume that a four-horse team was used, and that Walcott, Weeks, and Smith rode, with a spare saddle horse along.

September 26: "Went out on ridges east of camp & found that it was best to move camp about 7 mi S.S.E.—camped in a sagebrush valley on Saline Valley road six miles from Waucoba Spg."

From the summit of Waucoba Canyon, the road goes down into Cowhorn Valley, so named for its curved shape, and then rises again to leave the valley. The sagebrush valley mentioned must be the feature called Jackass Flats on the topographic map.

September 27: "Out all day on Saline Mts. Found them to be formed largely of Cambrian rocks—Olenellus at west base."

Walcott also noted that Weeks had gone into town with Vernon Smith, the teamster. It is a reasonable assumption that Smith also took care of the horses and that Cuddington was the cook and camp hand.

September 28: "Out all day alone N of Waucoba spg. Hills of Cambrian slates—quartz—sandy limestones—granite of Waucoba Mountain turns up & cuts off many of the lower beds."

From these comments, it would seem that Walcott rode across the Deep Spring, Reed, and Wyman formations to the base of Waucoba Mountain. The upturned strata can be seen on the west side of the present road into Saline Valley. Cutting off of the lower beds is evident at the large apophysis of granite south of Waucoba Spring.

September 29: "Worked on Cambrian section at head of Saline Valley—measured nearly 4000 feet of the Olenellus zone. Camp moved to 2 mi S.E. of Waucoba Spg."

During this time, the wagon road came down the ridge north of the mouth of Waucoba Canyon in a series of switchbacks. We presume that Walcott began his section near the road and measured eastward, downslope but up section. It seems quite unlikely that Weeks had returned and assisted in measuring the section.
September 30: "A trying day. Wind blew a gale from the south. Out until 3:20 p.m. on ridge east of Saline Valley Road. F. B. Weeks left for home on acct of illness in his family. Section badly broken by faults."

October 1: "With Vernon Smith road by trail to Willow Spg. at N.W. end of Saline Valley. Examined east side of Inyo range & returned to camp. Strata very much broken up by intrusive granite & trachyte."

About a mile southeast of Waucoba Spring a granite intrusion turns up the strata.

October 2: "Worked on the Lower Cambrian rocks E.N.E. of Waucoba Spg. Found that the fauna extended about 500 feet lower in the section - Camp moved six miles north."

These comments suggest that Walcott may have begun measuring his section within the Montenegro Member of the Campito Formation and then on this day searched for fossils lower in that member before adding the lower part of this member to his section. The move of camp back to a dryer area may have been forced by the need to curtail his investigations after Weeks left, though 1897 had already been a relatively long field season away from administrative chores piling up in Washington.

October 3: "Camp moved to Waucoba Canyon 2 1/2 mi above the Devils gate. Crossed the hill N of Waucoba Mt. Beautiful view of the Sierra & the Nevada ranges."

This was a Sunday and a relatively easy day, but travel was uphill, except for the last few miles. From the hill north of Waucoba Mountain, one can see the Sierra Nevada to the west and several block faulted ranges in Nevada to the east precisely as Walcott wrote.

October 4: "Examined the ridge of the Inyo range S.W. of Waucoba canyon - Out all day. Found all sedimentary rocks to be of Lower Cambrian age. Patrick R. Cuddington accompanied me."

On the west side of the Inyo Mountains for eight miles south of Waucoba Canyon, the complex structure exposes strata ranging form the Mule Spring Formation, near the top of the Lower Cambrian, the Bonanza King Formation of Middle to Late Cambrian age, and the Upper Cambrian Nopah Formation. October 4 effectively ended Walcott's field study of the Cambrian in the area. He moved camp to Pinto station on the railway and then to the Independence station. From there he spent three days collecting Trenton fossils and looking at the Ordovician section. He also found what he determined to be Late Silurian (Silurian of today's usage) or Devonian fossils. The last day he went to Mazourka Canyon and rode 26 km (16 mi) north.

On Sunday, the group left Mazourka Spring and camped 18 km (11 mi) south of Alvord. Walcott did make one collection of Early Cambrian fossils in Mazourka Canyon. On Monday, October 11, he "Went into Alvord. Packed up. paid men off & left for Keeler at 4 15 P. M. Took stage at Keeler 9 45 P. M.—for Mojave."

Keeler is on the east side of Owens Lake.
LATÉR PUBLICATIONS

In addition to supervising the Geological Survey, in 1897 Walcott was heavily involved in administration of national forest reserves, and from 1902 onward, the Reclamation Service. What time he could spend in the field from 1898 to 1905 was mostly devoted to the problems of paleontology and correlation of the Precambrian. It was not until leaving the Geological Survey in 1907 for the Smithsonian Institution that Walcott was able to concentrate his efforts on the Cambrian.

One of his first attempts in this direction was a summary of key sections in the Cordillera. Walcott (1908, p. 185-188) named the section on the east side of the range the Waucoba Springs section, using the plural. In the appendix herein, the currently accepted thicknesses and nomenclature are compared to Walcott's section. A geologic map covering the area where Walcott measured his section is shown in Figure A1.

Walcott (1908, pp. 188-189) also published a description of the Barrel Spring—singular—section along the road from Silver Peak to Lida (Turner, 1909, p. 239), to the north in Esmeralda County, Nevada. The Barrel Spring section was observed by Walcott and Weeks in 1896 as they rode south through Fish Lake Valley, and was measured in 1899 by Weeks who accompanied H. W. Turner that field season. This section is somewhat more complete than the one north of Waucoba Spring and it is directly connected with Walcott's investigations of Early Cambrian biostratigraphy, even if not specifically studied by him.

A few of the Early Cambrian brachiopods obtained by Walcott during his field work in the White-Inyo area were listed in his monograph (Walcott, 1912a). His final contribution to the geology of the area was a brief note wherein Walcott (1912) suggested that the term "Georgian" be abandoned, as used for the Early Cambrian and replaced by "Waucoban." In part, this was to move toward a nomenclature based on geographic names for what he called "series"—now "stages"—which were not duplicated by formational and group names. In part, however, it was also to use as a standard one of the finest Lower Cambrian sections in North America and the best in the United States that Walcott had measured.

RECORDING THE FOSSIL COLLECTIONS

In the files of the Department of Paleobiology, National Museum of Natural History, Walcott's fossil localities from 1891 through 1905 were recorded on typed sheets and numbered sequentially. Some entries are only a few lines, but others are more elaborate and include sketches made by him. There is a suggestion that those through part of 1893 were completed promptly, and then the typescript was started again at a later date; number 154 is the last 1893 locality. That would be in keeping with his receiving the Directorship in 1894 and its manifold problems.

Number 154 is followed by numbers 155, 156, 157, and 158, but these are on four small sheets approximately 3 x 5 in. The sheets are descriptions of localities, sketches, and associated comments, and they are virtually the only trace found of field notes for the White-Inyo area. From this we surmise that Walcott kept his data on fossils, and perhaps on measured sections, in such a form that he could turn appropriate pages directly over to
a typist. Somehow the Inyo Mountain notes were overlooked. The typescript begins again at 159, a locality in Georgia. The four numbers for the 1894 collections were assigned at the time the field notes were prepared, not added later.

Walcott’s 1896 localities begin with number 174 in the Silver Peak, Nevada, mining district; and many of these also read like daily comments, not simply geographic localities. Number 178 picks up again in the Inyo area, and is dated October 13, 1896. It and a following page are not typed; a few lines are worth quoting from this entry for additional information on Walcott as a field geologist. “On west slope of Inyo range—Fauna Devonian? or Carb? May be Jurassic from form of shells.” A line is drawn through the questioned Devonian or Carboniferous, and this is immediately followed by 178a recorded as Jurassic ammonites. Walcott made a sketch of the section. This locality was noted in his diary as being near the Eclipse Mill.

Another aspect to Walcott’s system is that letters were added to a particular number to indicate fossil collections from adjacent geologic units in sequence, commonly from a measured section. The numbers assigned during the 1896 season are 176 to 184. Because of letters added, actually 19 Lower Cambrian collections were recorded for that season in the White-Inyo area. In addition, there are three locality numbers for Silurian fossils and one for the material from the Waucobi lake beds.

Walcott’s system of assigning numbers to localities as they were collected, that is, in sequence during the field season and continuing the sequence from one season to the next, had its drawbacks, as indicated by a note dated October 20, 97. “By error No 187-194 were duplicated. The dates will assist in making the correction when the fossils are unpacked.” This confusion started in 1896, for the post-Cambrian localities mentioned above duplicate the numbers of some Cambrian collections. For the 1897 season, localities 191 to 193 are germane to this area. Number 191 is recorded as being collected at 10:30 A.M. on September 27, 1897, and is the only one for which a precise time is given. Walcott commented, “This is the lowest horizon of fossils yet found in this area. Same as in White Mountains further north. Did not observe Archaeocyathus.”

Because of the use of letters, actually eight collections, not three, are recorded for the 1897 season. Five of these are from the Waucoba section. For several of the collections, lists of identified fossils are given; later, Walcott wrote in “Holmia rowei W- (1910)” on one of the lists. Localities 194 to 198 are post-Cambrian, collected in the Mazourka Canyon area. A further indication that the localities were typed some years after the field work is the inclusion of another Lower Cambrian collection in 1897 at the head of Mazourka Canyon as number 176a.

Walcott’s original fossil collections are now separated into various biologic groups and it is impossible to determine how many fossils were collected. The archaeocyathids obtained in 1896 in the Silver Peak district occupy several museum drawers, and salterellids another full drawer. From this we infer that most of the White-Inyo collections must have been relatively large.
THE FIELD PHOTOGRAPHS

Walcott’s photographs are in the Photographic Library maintained by the U.S. Geological Survey at the Denver Federal Center. Among Geological Survey employees, Walcott was second only to Gilbert in the number of field pictures he took. The photographs are numbered, with letters indicating parts of a panoramic view. They are generally in order by year, though in some instances it can be demonstrated that the photographs are definitely not in daily order. For the field seasons discussed, Walcott commonly did not indicate in his diary when he took pictures.

During the 1894 season, Walcott had two cameras with him, and seemingly used them interchangeably. The collection contains 24 views with a film size of 61/2 x 81/2 inches and 15 on 5 x 7 inch size (Figure 3). He used the larger size preferentially for panorama shots and vistas. Photograph number 208c, which is part of a panorama looking east across Owens Valley, is Figure 2 of his 1897 publication. Number 226d is his Figure 5, looking east across Deep Spring Valley. (Walcott did not use the plural in his figure caption.)

These appear to be all of the 1894 photographs which have been published, with one exception. Walcott (1908, plate 18) later depicted cleavage in the Campito Formation on the east side of the range at Soldier Canyon. The illustration is cropped so that there is no obvious top or bottom, but the picture is printed correctly.
Figure 4. Lake beds, Waucoba Canyon, Inyo Range, about 8 km (5 mi) above Owens Valley, Inyo County, California. (Photo Number 300, by C. D. Walcott, 1896, courtesy of the U.S. Geological Survey. Kodak, 6 1/2 x 8 1/2 inches.)

The 1896 season in this area is represented by eleven photographs; four of which are 5 x 7 inches and the other 6 1/2 x 8 1/2 inches; five of these seven larger pictures form one panorama of the west side of the range. However, this smaller number does not indicate a lack of interest in the region, for Walcott took half a dozen pictures in the Silver Peak mining district, more in the Columbus coal field, and several panoramas of the northern part of the range as he and Weeks moved down Fish Lake Valley.

The only 1896 picture published is Number 300 (Figure 4), a view of the Waucobi lake beds. In 1991, the spot from which this was taken was reoccupied as an exercise in repeat photography. On the scale of the photograph, nothing has transpired as a result of erosion during the last century.

During his trip across the Sierra Nevada in 1897, Walcott took several photographs near Mono Pass, but apparently made no exposures in the White-Inyo Range. At one time the Geological Society of America maintained a selection of geological photographs, and several of those taken by Walcott in this area were included; nothing more is known of this selection.

SUMMARY

In three short field seasons, Walcott obtained the data for three publications. After the first season, he reported the presence of Lower Cambrian rocks (Walcott, 1895a) and contributed to the general structure of the White-Inyo Range (Walcott, 1895b). During the
second season he remarked on the Cenozoic history of the Owens Valley, with almost all of his observations made while riding horseback once up and once down Waucoba Canyon. His third season produced no papers directly, but did result in a significant measured section published later (Walcott, 1908). During all three seasons, he collected Paleozoic fossils, primarily on the Early Cambrian.

Judging from the physical evidence of photographs and fossils, Walcott concentrated on structural-stratigraphic aspects during his first field season and on stratigraphy and collecting fossils during the 1896 season. His most significant measuring of sections was in 1897. Whether this was a deliberate field strategy cannot be determined, but it seems plausible. During the latter half of the 1897 season, Walcott lacked the assistance of Weeks, and he might well have collected more fossils if Weeks had been present. There are some discrepancies between the Waucoba Springs sections and the Barrel Spring, Nevada, section, which Weeks measured in 1899. Part of the discrepancy could be a result of Weeks not participating in this aspect of the 1897 season.

In a broader context, Walcott's observation that folding preceded the normal faulting of the mountain blocks of the basin and range places him among the first generation of field geologists to note this tectonic style. Likewise, his remarks on what he judged to be post-Pleistocene tilting of former lake beds in the Owens Valley, long predated major concerns about movement in the near past on fault planes.

However, it is Walcott's efforts in Cambrian stratigraphy and paleontology and particularly the Early Cambrian, which were more important to him, and are still significant today. Four years after publication of the Waucoba Springs section, Walcott (1912) recommended that "Waucoban" be used as the name for the Early Cambrian of North America. Usage of stage names in the Cambrian has varied widely. We note that with the recent discovery of non-trilobite faunas in the early Lower Cambrian rocks of the White-Inyo Range, below those that Walcott first studied, this term seems remarkably appropriate for an even more complete section of Early Cambrian age than Walcott published.

Some of the trilobites that Walcott collected were eventually identified and described in later years, as they meshed with collections he made in the Canadian Rockies; they are his single most important paleontological legacy from this area. The brachiopod occurrences were noted in his monograph (Walcott, 1912). Most of the other fossils, particularly the archaeocyathids, went undescribed for lack of time on Walcott's part. Had they been studied, this group, which was neglected for so many years, might have been differentiated from the corals far sooner. In a drawer containing archaeocyathids from this area are sawn slabs of rock showing chevron folds, perhaps an indication of Walcott's interest in structure.

Regardless of whether Waucoban is used or not, we are impressed with just how much Walcott was able to accomplish during such a short time in the field. We are further impressed with how he was able to grasp the main elements of the complex structural geology and intrusions without even a proper topographic map to assist him. In measuring the Waucoba Springs section where he did, he went to the best possible site throughout the range.
It was not until 1912, (Knopf, 1918) that a reconnaissance geologic map of the Bishop 1° sheet was prepared. Nearly half a century more elapsed before mapping at a 15-ft scale began. Kirk (in Knopf, 1918) was the first to record the presence of Middle Cambrian in the area, and placed the base of the Cambrian at the base of the Campito Formation, an issue which Walcott had not considered; and he noted some errors in Walcott’s estimates of thickness. However, in discussing the stratigraphy, Kirk (in Knopf, 1918, p. 26) wrote, “Not until the Cambrian sections of the Inyo Range (White Mountains) had been studied by Walcott was there any definite conception of the age or approximate thickness of the Cambrian.”

Driving in a well-powered, air-conditioned field vehicle over a maintained road today can hardly be compared with wagon and horseback travel a century ago. The more one sees of the country and the routes Walcott covered, the more one must be impressed. Walcott was an able field geologist, and anyone following in his footsteps must take very long strides.

REFERENCES


Appendix—The Waucoba Springs Section

Clemens A. Nelson

When Walcott measured the strata north of Waucoba Springs, he described more than 1,707 m (5,600 ft) of section, the upper 1,341 m (4,400 ft) of which contained olenellid trilobites. Subsequent measurement has reduced the thickness to approximately 762 m (2,500 ft). Basal beds, now known as the upper member of the Campito Formation of modern terminology, and the underlying basal member contain fragmental trilobites which extend the downward range of these fossils about 305 m (1,000 ft) lower than Walcott observed. The conformable underlying Deep Springs Formation and Reed Dolomite have yielded "small shelly fossils" unknown in the 19th century. Apart from that, the dramatic change from unfossiliferous Precambrian—not studied by Walcott—to the richly fossiliferous Cambrian strata remains much as Walcott observed it.

The comparison of the current usage of the Lower Cambrian strata of the White-Inyo Mountains to that of the section measured by Walcott is largely the result of studies by Nelson (1962; 1978) and Scott (1960). The detailed geologic map shown in Figure A1 and the bed by bed comparison is from Scott's unpublished thesis. The lines on the map indicate where Walcott most likely measured his section.

The base of Walcott's section, his unit 3d, included approximately three-quarters of the Montenegro Member of the Campito Formation. Since 1897, trilobites have been collected farther downward in the exposed lower one-quarter of the Montenegro Member, and well into the upper part of the underlying Andrews Mountain Member. Apparently, this part of the section was not examined by Walcott.

Walcott's unit 3c is equivalent to the basal archaeocyathan limestone at the base of the Poleta Formation. This is characteristically about 183 m (600 ft) thick. It is one of the most persistent units of the Cambrian section through the White-Inyo Range and eastward into Esmeralda County, Nevada.

What is now designated as the middle part of the Poleta Formation, namely the basal shales, middle limestone, and upper quartzitic sandstone, is represented by Walcott's unit 3b and the lower half of his unit 3a. In the center of unit 3a is a 15-m (50-ft) interval of pure limestone, the equivalent of the upper part of the Poleta Formation.

The overlying Harkless Formation constitutes the upper half of Walcott's unit 3a and his units 2k, 2j, 2i, and 2h in upward order. The uppermost of the Harkless Formation, a 12-m (40-ft) unit, was inexplicably missed by Walcott. As a result of a fault unseen by him, units 2g and 2f are repetitions of higher parts of the Harkless Formation.

Walcott's unit 2c constitutes what is today the lower member of the Saline Valley Formation. The upper member of the Saline Valley, an assemblage of mixed lithologies, is represented by units 2d, 2c, 2b, 2a, and unit 1d, along with the faulted repetitions that he designated as 2g and 2f.

The uppermost Lower Cambrian stratigraphic formation used today is the Mule Springs Limestone. It is a widespread "Girvanella" unit that Walcott numbered 1c, 1b, and 1a.
The thicknesses reported by Walcott agree very well with those measured by Scott, being off mainly by reason of the repeated units 2f and 2g. This fault has no obvious topographic expression. Considering that Walcott spent only parts of three days at the Waucoba Springs section, without any assistance, his accomplishment is impressive.
### SUMMARY

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### REFERENCES


Minerals of the Central White Mountains, California

Wayne A. Dollase

Abstract. Seventy different minerals have been reported in the literature or personally observed to occur in the central White Mountains of eastern central California. The present compilation lists, in addition to the chemical compositions and especially notable distinguishing characteristics of these minerals, their local geologic and geographic occurrences.

INTRODUCTION

As a result of its rich geologic history, a climate and topography which yield generally good rock exposures, and its comparative ease of access, the central White Mountains of eastern California afford a good opportunity to observe and study a wide range of minerals. The geology of this range has been well studied and good geologic maps of the region are available from the U.S. Geological Survey and/or the Geological Society of America, Map and Chart Series.

The geologic history of the White Mountains has been reviewed by Nelson, et al. (1991). In the last thirty years the geology of the central White Mountains has been mapped by Nelson (1966), Nelson and Sylvester (1971), Krauskopf (1971), Crowder and Sheridan (1972), and more recently by Ernst and Hall (1987) and by Bilodeau and Nelson (1993). To best locate and understand the occurrences mentioned in this compilation, access to a geologic map of the region is recommended. The area covered in this compilation matches that mapped by Ernst and Hall (1987).

A number of specific local geologic and mineralogic studies have also been carried out in this area including: Emerson (1966), Crawford (1972), Ulbrich (1973), Bilodeau (1981), Robigou (1984), and Hanson (1986). The Champion Mine, with its highly unusual mineralogy, falls outside the area included here, but interested readers can find a description of this renowned mineral locality in Wise (1977).

The mineral deposits of Mono County, including the White Mountains, have been summarized by Sampson (1940). Several state-wide compilations of mineralogy (Murdoch and Webb, 1966; Pemberton, 1983) report mineral occurrences in the counties that contain the White Mountains (Inyo and Mono), but contain very few references to specific locations in the central White Mountains. A recent restudy of the economic mineralogy of the this area is discussed below.

In addition to the mineralogy reported in these earlier studies and sources, this compilation includes previously unpublished studies of the author. Field and laboratory observations of the mineralogy of the White Mountains were made in conjunction with the UCLA Geology Summer Field Camp held in the White Mountains during the 1980’s. This compilation has benefited from numerous student observations and unpublished reports (including Wevik, 1982), and from field discussions with M. D. Barton, W. G. Ernst and

1Department of Earth and Space Sciences, University of California, Los Angeles, California 90024-1567.
C. A. Hall, Jr. Electron microprobe analyses of minerals reported here were obtained with the assistance of R. E. Jones.

REGIONAL MINERALOGY

Geologically, the White Mountains contain a late Precambrian through lower Paleozoic continental shelf sequence of sandstone and finer grained clastic and carbonate rocks, which have been divided into the Wyman, Reed, Deep Spring, Campito and Poleta formations in this area (Nelson, 1962). This thick pile of sedimentary rocks were later warped and intruded by Jurassic and Cretaceous granitoids (silica-rich intrusive igneous rocks). Emplacement of the granitoids resulted in several different types of alteration of the sediments.

The intrusions of the igneous rocks heated the entire region, leading to a regional low-grade alteration consisting of recrystallization, loss of water and carbon dioxide, and reactions among previously existing minerals. Such relatively weakly altered sedimentary rocks are called "metasediments" (or metaclastic and metacarbonate rocks). Very near the margins of these intrusive bodies, sediments were subjected to higher temperatures resulting in more marked and severe alteration (so-called contact metamorphism). Locally, the contact rocks show evidence of significant alteration of their chemical composition (metasomatism).

This chemical alteration involves not only loss of volatile components in the sedimentary rocks, but also addition of chemical elements either directly from the igneous bodies or indirectly as a result of flow of fluids whose origin, heat, or composition are related to the intrusions. The specific minerals produced by these sediment-metasomatic fluid interactions depend on temperature and composition of both the sediment and the fluid.

Long after sediment deposition, igneous intrusion, and metamorphism, Tertiary basalt flows poured out over the surface. Subsequent uplift and erosion has left remnants of these volcanic rocks especially at the higher elevations of the eastern edge of the area.

The geologic history of this area has produced a variety of minerals. Besides the common silicates in the granitic and basaltic igneous rocks and clastic sedimentary rocks, less common silicates formed by low-grade regional and local contact metamorphism are also present. Carbonate minerals typically associated with limestone and dolomite occur in abundance. The local metasomatism associated with igneous intrusions resulted in an additional suite of vein and replacement minerals, including minor ore minerals. The widely scattered occurrence of the latter has resulted in numerous prospects and a few small mines in the area.

There has been recent activity on the part of the United States Geological Survey and the Bureau of Mines, to survey the reserves and potential economic mineral deposits of the White Mountains. The area's mines and prospect pits have been systematically reexamined along with geochemical sampling of stream sediments. The mineral resource potential of the area has been reported by Diggles (1987). Gold and silver-bearing quartz veins were found at several of the central White Mountain mines: Moulas Mine (4 km [2.5 mi] west of Piute Mountain), Eva Belle Mine (3.5 km [2.2 mi] northeast of Piute Mountain), and the
Golden Siren Mine (1.5 km [0.9 mi] east of Campito Mountain). Silver, lead, zinc and copper sulfides and carbonates occur in carbonate contact-replacement bodies such as those at the Eva Belle Mine. Minor tungsten mineralization is observed at the north end of the Birch Creek pluton. In addition to the metals mentioned above, geochemical sampling has also indicated anomalous amounts of bismuth, arsenic, and molybdenum in the area. Potential nonmetallic deposits include barite, mica, and pumice.

FORM OF THE COMPILATION

This compilation includes, for each of the various minerals in the region covered: mineral name, simplified chemical composition, geologic occurrence within the White Mountains, any especially noteworthy identifying characteristics, and specific sample locations. Minerals are listed by major mineralogic group in the order followed by most standard reference books, such as Manual of Mineralogy (Klein and Hurlbut, 1993). Chemical compositions are necessarily somewhat idealized, but indicate the major components present. The “occurrence” describes the particular geologic and mineralogic conditions and circumstances in which the mineral occurs, specifically in the White Mountains, including, where appropriate, the specific stratigraphic formation. There are several (serially numbered) different types of occurrences for some minerals. Formation names used follow the terminology used by Nelson (1962), with areal distribution as mapped by Ernst and Hall (1987).

Most minerals in this compilation can be discerned in hand sample with the aid of a hand lens. The reader is referred to any standard mineralogy textbook for full descriptions of identifying characteristics. For completeness, minerals that are too fine grained to be identified in this manner are also included here, but are so noted. Identification of many of the minerals listed was confirmed using the techniques of thin section microscopy, X-ray powder diffraction, and electron microprobe analysis. The geographic locations listed are by no means exhaustive, but they are chosen as typical, or in some cases as noteworthy owing to especially coarse grain size or unusual color. Finally, jargon of specialists has been kept to a minimum in order to make this field guide useful to all who visit or study this mineralogically diverse area.

Abbreviations used in the mineral list are: Occ—Occurrence; ID—Identifying characteristics; Loc—Location.

NATIVE ELEMENTS

Graphite: C. Occ: Black clastic (meta)sediments, probably from the breakdown of organic material. ID: Soft, platy, lustrous metallic to dull-black grains, but here rarely coarse enough to identify in hand sample. Loc: Campito Mountain as fine, disseminated grains; Campito/Barcroft Granodiorite contact 1 km (0.6 mi) east of road as relatively coarser, platy grains to 0.5 mm diameter.
Gold: Au. Occ: As described above in the regional mineralogy, gold-bearing quartz veins are reported by Diggles (1987) from a number of mines. Several authors (listed in Pemberton, 1983, p. 24) have reported placer workings on various streams of the White Mountains.

SULFIDES
Galena: PbS. Occ: Scattered grains or in vein and veinlets, especially in carbonates and presumed related to nearby igneous activity. ID: Shiny, silvery metallic cubes with excellent cleavage. Loc: Eva Belle Mine, though mostly oxidized to cerussite, PbCO₃.


Pyrite: FeS₂. Occ: (1) Minor primary phase in granitoids; (2) Secondary mineral in carbonates; (3) Local concentration of pyrite on bedding planes of metasediments. ID: Shiny yellow metallic cubes. Loc: Crystals to 1 cm or more on edge occasionally scattered in Reed Dolomite (as in Cottonwood Meadow, Poison Creek), now altered to brown iron oxide (goethite).

Acanthite (argentite): Ag₂S. Occ: Very rare in hydrothermal sulphide-bearing veins in carbonates. ID: Occurs only in microscopic grains identified by microprobe analysis, as at the Eva Belle Mine (Wevik, 1982).

Covellite: CuS. Occ: As acanthite and similarly only identified in microscopic grains at the Eva Belle Mine (Wevik, 1982).

Tetrahedrite: (Cu₆Ag)₁₂(Sb₃As₃)₄S₁₃. Occ: Hydrothermal sulphide-bearing veins in carbonates. ID: As with other copper and silver sulfides here principally only identifiable with a microscope. Loc: Microprobe studies indicate that tetrahedrite was the major silver mineral at the Eva Belle Mine (Wevik, 1982).

OXIDES
Corundum: Al₂O₃. Occ: Rare as breakdown product of andalusite in Campito Formation. ID: Here, only identified in thin section (Robigou, 1984). Loc: Western slope of Piute Mountain.

Hematite: Fe₂O₃. Occ: Common as fine, reddish weathering stain on many different iron-bearing rock types (see also goethite). Locally as prominent red-brown stain associated with metasediment-igneous rock contact alteration.
Ilmenite: \( \text{FeTiO}_3 \). Occ: (1) Primary, but minor, igneous mineral; (2) Trace mineral in metaclastic rocks. ID: Usually small, commonly flattened, black submetallic grains, optically opaque. Loc: Campito Formation (County Line Hill north to Piute Mountain) as microscopic grains (Robigou, 1984).

Geikielite: Ideally, \( \text{MgTiO}_3 \), here about 50% geikielite, 50% ilmenite solid solution. Occ: Geikielite is a very rare mineral, occurring here as a product of contact metamorphism of dolomite. ID: Small (to 1 mm) shiny black disc-shaped grains in Reed Dolomite at igneous contacts. Loc: Large dikes of the Barcroft pluton 1 km (0.6 mi) east of Lamb Camp.

Rutile: \( \text{TiO}_2 \). Occ and ID as with ilmenite. Loc: Partially melted metasediments at the Barcroft Granodiorite contact; Campito Mountain metasedimentary rocks (in both cases identified by electron microprobe study of thin sections).

Spinel (variety pleonaste): \((\text{Mg,Fe})\text{Al}_2\text{O}_4\). Occ: High temperature reaction product of dolomite and igneous rock. ID: Tiny (to 1 mm) diameter, greenish, rounded grains in Reed Dolomite, usually associated with forsterite. Loc: Sporadically along the Reed Dolomite contact with the Beer Creek and Sage Hen Flat plutons. Relative to pure \( \text{MgAl}_2\text{O}_4 \), microprobe analyses show these spinels to have about 10% of the Mg replaced by \( \text{Fe}^2 \) and about 5% of the Al by \( \text{Fe}^3 \).

Magnetite: \( \text{Fe}_3\text{O}_4 \). Occ: (1) Primary minor mineral in plutonic and volcanic rocks; (2) Clastic sedimentary or metasedimentary mineral. ID: Black, metallic luster, attracted to magnet. Loc: Campito Formation where it is so abundant in many places that rock fragments may be picked up with a magnet. In lower grade (further from igneous contacts) Campito Formation, thin section analysis shows swarms of microscopic magnetite grains, becoming coarser and recrystallized at higher grades. Chemical analyses indicate nearly pure iron oxide though a magnetite from the southern Barcroft pluton/metasediment contact shows major Zn content indicating a gahnite, \( \text{ZnAl}_2\text{O}_4 \), component. Minor Ti, and rarely, V contents are also present in some magnetite in the Campito Formation. The chemically altered metavolcanic rocks as at White Mountain contain well-formed (euhedral) crystals of magnetite.

Goethite: \( \text{FeOOH} \). Occ: Oxidation product. ID: Goethite is a widespread dark to yellowish brown mineral, often occurring with hematite and producing a characteristic “rusty” appearance of rocks, especially on weathered surfaces. Usually goethite is too fine grained for hand-sample identification. Loc: Locally scattered in Reed Dolomite replacing pyrite cubes, as in the Poison Creek area.
FLUORIDES

Fluorite: CaF₂. Occ: Hydrothermal veins associated with igneous contacts, especially with carbonates. ID: Purple grains and masses (bleaching slowly in sunlight) commonly associated with fine white mica. Loc: Contact aureole of Reed Dolomite and Wyman carbonate-rich rocks at the northern end of the Birch Creek pluton probably resulting from metasomatizing fluids.

CARBONATES

Calcite: CaCO₃. Occ: (1) Very abundant in limestones and marbles of Wyman and Deep Spring formations; (2) As veins and contact metamorphic reaction product of dolomite; (3) Rarely in igneous dikes that cross cut carbonate rocks. ID: Relatively soft, pale colored mineral, when coarse grained shows excellent rhombohedral cleavage, fizzes with dilute HCl. Loc: Most of the prominent carbonate-rich beds of the Wyman and Deep Spring formations throughout the area.

Dolomite: CaMg(CO₃)₂. Occ: Sedimentary to metasedimentary carbonates, as in the Reed Dolomite. ID: As with calcite except that dolomite does not fizz with dilute acid.

Aragonite: CaCO₃. Occ: Rarely at igneous rock/marble contacts, probably metastable. ID: fine grained, "frothy" white seams, fizzes with dilute acid, usually requiring an X-ray pattern to distinguish from calcite. Loc: Along Barcroft Granodiorite dike-Reed Dolomite contact 1 km (0.6 mi) east of Lamb Camp.

Cerussite: PbCO₃. Occ: Hydrothermal alteration product of galena. Loc: Eva Belle Mine; found on the west slope of the White Mountains between Piute and Coldwater Canyons (Sampson, 1940).

Azurite: Cu₂CO₃(OH)₂. Occ: Oxidized copper-bearing veins, usually in carbonates. ID: Bright green, fizzes with dilute acid. Loc: Eva Belle and Moulas mines, prospect pits on west slope of Blanco Mountain.

Malachite: Cu₂CO₃(OH)₂. Occ: As with malachite, with which it usually occurs. ID: Azure-blue color, fizzes with dilute acid. Loc: As with malachite.

SULFATES, TUNGSTATES

Barite: BaSO₄. Occ: Local vein or pervasive replacement of carbonates. ID: Dense (specific gravity = 4.5), white to pale yellow brown massive aggregates. Loc: Gunter Canyon Mine.

Scheelite: CaWO₄. Occ: Uncommon in veins and replacement bodies in metasomatically altered metacarbonates. ID: Here rather unimpressive scattered pale prisms but markedly fluorescent with "blacklight." Loc: North contact of Birch Creek Granite with Wyman and Reed carbonate rocks.
PHOSPHATES
Apatite: \(\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F})\). Occ: Common trace component of many rock types, especially of plutonic rocks. Loc: Cottonwood Granite.

SILICATES
Silicate minerals are further subdivided on the basis of the connectivity of their component \(\text{SiO}_4\) tetrahedral groups:

ORTHOSILICATES (isolated \(\text{SiO}_4\) groups)
Olivine: \((\text{Mg,Fe})_2\text{SiO}_4\). Occ: Coarser, early formed mineral (phenocrysts) in volcanic rocks. ID: Yellowish to dark-green, rounded, glassy grains (commonly partially altered). Loc: Basalt flows east of Southfork Peak.

Forsterite: \(\text{Mg}_2\text{SiO}_4\) (magnesian end-member of olivine group). Occ: Reaction product of dolomite with igneous rocks. ID: Brown weathering, pale tan prisms to 1 cm long in dolomite. The reaction that produces the forsterite also produces calcite which can often be found surrounding the forsterite grains and masses. Loc: Sporadically along the northern and western borders of the Sage Hen Flat pluton (e.g., 0.5 km [0.3 mi] northeast of Golden Siren Mine); along the western edge of the Beer Creek pluton; along contact with large dikes of Barcroft pluton east of Lamb Camp. Microprobe analyses show about 5% of Mg has been replaced by Fe in these samples of forsterite.

Clinohumite: \((\text{Mg,Fe})_9\text{Si}_4\text{O}_{16}(\text{F},\text{OH})_2\). Occ: Reaction of dolomite with F-bearing solutions at igneous contacts. ID: Similar to forsterite, requires microscope observations to differentiate. Loc: Reed/Cottonwood Granodiorite contact in Cottonwood Meadow; northern Birch Creek contact aureole. Chemical analyses indicate these clinohumites are near the Mg-end member with approximately equal proportions of F and OH.

Garnet: \(\text{Ca}_3(\text{Al,Fe})_2\text{Si}_3\text{O}_{12}\) (grossular-andradite solid solution). Occ: Carbonate/igneous contacts especially as a product of metasomatic reactions. ID: Commonly red-brown with bright vitreous luster, isolated rounded grains and masses. Loc: Limestone bed in Wyman Formation near the cave southeast of the WMRS Crooked Creek facilities shows prominent garnets zoned from dark red-brown rims to lighter tan cores; along southern Barcroft Granodiorite/metasediment contact; between McCloud Camp and Crooked Creek Canyon road in metasomatized Wyman Formation limestone bed. Microprobe analyses show these garnets to vary between the aluminum (grossular) and iron (andradite) varieties.

Zircon: \(\text{ZrSiO}_4\). Occ: Common fine-grained trace component, especially of igneous rocks. ID: Under the microscope, small, high relief, high birefringent grains. Loc: Such as the Cottonwood (Beer Creek) Granite; Campito Formation at Piute Mountain.
Andalusite: \( \text{Al}_2\text{SiO}_5 \). Occ: (1) Medium-grade regional, to large-scale contact, metamorphism of aluminous sediments; (2) Quartz, feldspar-rich partially melted metasedimentary rocks (migmatites) close to igneous contacts. ID: Small ovoid to large (to 2 cm) rectangular crystals in a fine-grained matrix in Al-rich metasediments, found several kilometers from igneous contacts. The “chiastolite” variety of andalusite, found here only rarely, shows a characteristic cross-shaped pattern of inclusions. Note: At least some of the prominent dark, ovoid to rectangular “spots” of the spotted schists in this area are (or once were) andalusite. Most of these so called “porphyroblasts,” however, have been altered to (randomly oriented) white mica and other fine-grained phases (demonstrating that the alteration postdates the schistosity). Some “spots” likely represent (altered) cordierite or other minerals. Loc: Campito Formation from Piute Creek northwards to Piute Mountain.

In the second occurrence, andalusite occurs in “clots” of fine-grained minerals surrounded by quartz-feldspar veinlets in migmatite. Associated minerals include sillimanite. This occurrence of andalusite is difficult to identify in hand sample owing to its fine grain size and is best identified in thin section. This occurrence of andalusite commonly shows a weak, pinkish pleochroism probably due to minor manganese replacement.

Sillimanite: \( \text{Al}_2\text{SiO}_5 \). Occ: High temperature contact metamorphism of aluminous metasediments, close to igneous contacts. ID: Tiny (to 2 mm) white prisms or very fine needles (“fibrolite” variety). Loc: South of contact of Barcroft pluton in partially melted metasediments as scattered grains; abundant in aluminous metasedimentary block (Campito Formation?) included in the Barcroft pluton near its southern edge. Chemical analysis reveals this specimen of sillimanite to be unusual with up to 3% of the Al replaced by vanadium.

Sphene: \( \text{CaTiSiO}_5 \). Occ: Common minor component of plutonic rocks, less common in metamorphics. ID: Small, usually rounded cinnamon-colored grains. Loc: Sage Hen Flat pluton; southern Barcroft pluton/metasediment contact.

Chloritoid: \( (\text{Fe, Mg})\text{Al}_2\text{SiO}_5(\text{OH})_2 \). Occurrence: Low-grade contact metamorphism of Fe-rich sedimentary rocks. ID: Relatively rare in area, few fine grains observed in thin section from Sage Hen Flat pluton contact aureole. Chloritoid is chlorite like in appearance and is known from the contact aureoles of the Joshua Flat pluton (Warner, 1971) and the Papoose Flat rock unit/Harkless Formation contact aureole 30 km (19 mi) to the south (Sylvester, 1966).

PYROSILICATES (\( \text{Si}_2\text{O}_7 \) or \( \text{Si}_2\text{O}_7 + \text{SiO}_4 \) groups)

Hemimorphite: \( \text{Zn}_4\text{Si}_2\text{O}_7(\text{OH})_2\cdot\text{H}_2\text{O} \). Occ: Vein mineral in carbonates associated with Cu mineralization, such as at the Eva Belle Mine (Wvik, 1982).
Epidote: Ca$_2$(Al,Fe)$_3$Si$_3$O$_{12}$OH. Occ: (1) Scattered component of low grade (or contact metamorphosed) calcareous sediments; (2) Veins or pervasive replacement of entire sedimentary beds as a result of hydrothermal solutions; (3) Oxidative alteration product of iron-bearing igneous minerals. ID: Characteristic yellow-green color, elongated sheaths of darker green crystals when coarse grained. Loc: Southern part of Barcroft Granodiorite/metasediment contact; north Birch Creek Granite, contact metasomatic veins show the sequence: (i) dolomite + forsterite + calcite + spinel, (ii) forsterite + calcite, (iii) talc + chlorite + diopside, (iv) quartz + epidote (or pink clinozoisite) ± feldspar.

Clinozoisite: Ca$_2$Al$_3$Si$_3$O$_{12}$OH (Fe-free end-member of epidote group). Occ: Contact of dikes of the Barcroft Granodiorite and Reed Dolomite. ID: Clinozoisite appears as pale, pink layers in the contact sequence: granodiorite-clinozoisite-diopside-dolomite. The color, which probably reflects a minor Mn content, stands out next to the green diopside. Loc: Upper Cottonwood Creek about 1 km (0.6 mi) east of the road.


Piemontite: Ca$_2$(Al,Mn)$_3$Si$_3$O$_{12}$OH (manganese-bearing variety of epidote). Occ: Hydrothermal veins associated with contact metamorphism. ID: Characteristically pink to red and yellow to red in transmitted light. Loc: Pinkish, transparent gem-quality prismatic crystals of piemontite to half-cm length have been found in the contact aureole on the northern edge of the Birch Creek pluton, in fluorite-muscovite veins.

Idocrase: F,OH-bearing garnet-like composition. Occ: High-grade metacarbonate/igneous contacts usually indicating metasomatism. ID: Usually greenish masses to coarse, square cross-section prisms. Loc: 0.8 km (0.5 mi) east of the WMRS Crooked Creek facilities along the road in metasomatized carbonate bed; southern part of Barcroft pluton contact west of the road.

CYCLOSILICATES (rings of corner-shared SiO$_4$ tetrahedra)

Cordierite: (Mg,Fe)$_2$Al$_4$Si$_5$O$_{18}$. Occ: Low to intermediate grade contact metamorphism of Al-rich metasediments. ID: Cordierite is not very distinctive in hand sample, appearing as colorless to grey, rounded, glassy grains, up to about 3 mm diameter. On weathered surfaces, the grains show a yellow-brown surface alteration. Loc: Campito Formation within about 0.5 km (0.3 mi) of the Barcroft pluton, e.g., near Lamb Camp. Chemical analyses indicate this cordierite is intermediate between Mg and Fe end-members; cordierite is locally altered to chlorite and mica. (Note: If both AlO$_4$ and SiO$_4$ tetrahedra are considered, cordierite can be classified as a tectosilicate.)
Tourmaline: Complex boro-silica te. Occ: (1) Igneous rocks, especially in pegmatitic veins; (2) Persistent in clastic sediments; (3) Newly formed mineral in metasedimentary rocks. ID: Where coarse crystals, usually dark to black, elongated striated prisms, some with characteristic triangular cross section. Loc: Especially common in this area's sedimentary rocks and pegmatites. An unusual occurrence is as scattered round brownish-red aggregates to 2-cm diameter in the “roof pendent” (included sedimentary block) near the southern part of the Barcroft Granodiorite border where it occurs with sillimanite.

Beryl: Be$_3$Al$_2$Si$_6$O$_{18}$. Occ: Rare in hydrothermal (metasomatic) veins. ID: Pale green elongated crystals with hexagonal cross section. Loc: North end of Birch Creek pluton.

CHAIN SILICATES (chains of corner-sharing SiO$_4$ groups)

Pyroxene: Three pyroxenes (diopside, hedenbergite and augite) occur in this area.

Diopside: CaMgSi$_2$O$_6$. Occ: Metadolomite at igneous contacts. ID: Dull, stubby greenish prisms but commonly too fine grained to distinguish individual grains. Loc: Barcroft dike/Reed dolomite contact 1 km (0.6 mi) east of Lamb Camp.

Hedenbergite: CaFeSi$_2$O$_6$. Occ: Contact metamorphism and fluid alteration of metacarbonates. ID: Darker green to brown, dull prisms usually showing some solid solution towards diopside. Loc: Southern Barcroft Granodiorite 1 km (0.6 mi) west of Southfork Peak.

Augite: Ca(Mg,Fe)Si$_2$O$_6$ (also commonly shows some replacement of Ca by Mg,Fe). Occ: Primary igneous mineral, especially in rocks less silica-rich than granite. ID: Very dark green to black prisms, usually intergrown here with amphibole in clots. Loc: Barcroft Granodiorite; Tertiary basalt flows, but mostly too fine to discern.

Wollastonite: CaSiO$_3$. Occ: Limestone/igneous contacts of Sage Hen Flat and Birch Creek plutons reported by Ulbrich (1973) but not seen by this author. The occurrence of calcite as a reaction product in the contact metamorphism of dolomite, and the widespread occurrence of scapolite in this area suggest that CO$_2$ partial pressure was high and therefore wollastonite would not be expected.

Amphibole: Three chemically different varieties (tremolite, actinolite and hornblende) may be easily differentiated in the central White Mountains.

Tremolite: Ca$_2$Mg$_5$Si$_8$O$_{22}$(OH)$_2$. Occ: Metacarbonates, commonly in metadolomite. ID: Elongated to acicular (to 2 cm), white to tan crystals with a diamond-shaped cross section, commonly occurring in radiating clusters of crystals scattered in marble and metadolomite in the vicinity of igneous contacts. Loc: Reed Formation near Patriarch Grove, and neighboring Deep Spring Formation; Big Prospector Meadow near Sage Hen Flat pluton.
**Actinolite**: Similar to tremolite in occurrence and ID except color is medium to dark green due to partial replacement of Mg by Fe. **Loc**: Above road to Patriarch Grove.

**Hornblende**: (Composition similar to actinolite but with additional substitutions mostly involving Al and to a lesser extent, Na). **Occ**: (1) Several of the plutonic rocks and igneous dikes of the area; (2) Ca-rich metaclastic rocks, such as the Wyman Formation; (3) Carbonate metasomatism. **Loc**: Cottonwood, Sage Hen Flat, and Barcroft plutons (Occ 1); Campito Formation west of Piute Mountain (Occ 2); 0.8 km (0.5 mi) northeast of Blanco Mountain (Occ 3).

**SHEET SILICATES** (layers of corner-sharing tetrahedra with composition Si$_2$O$_5$.)

- **Serpentine**: Mg$_3$Si$_2$O$_5$(OH)$_4$. **Occ**: Greenish to yellow, soft vein mineral in metadolomite or forming from chemical alteration of contact metamorphic forsterite. **Loc**: Contact aureoles of Barcroft, Cottonwood, Birch Creek, and Sage Hen Flat plutons with Reed Dolomite; as Barcroft dike contacts with Reed Dolomite 1 km east of Lamb Camp and along road 1 km (0.6 mi) south east of Lamb Camp. About 0.5 km (0.3 mi) north of WMRS Crooked Creek facilities the Reed/Sage Hen Flat Granite contact shows a sequence of mineral reactions: dolomite, calcite, serpentine (minor amounts of phlogopite can be present), chlorite, diopside + clinozoisite.

- **Talc**: Mg$_3$Si$_4$O$_{10}$(OH)$_2$. **Occ**: Dolomite/igneous contacts. **ID**: Silvery white to pale greenish, soft, flaky masses and individual soft plates. **Loc**: Locally talc occurs in minor amounts at the contact of the Reed Dolomite and the Barcroft, Sage Hen Flat, or Cottonwood plutons, but is not a common mineral in this area (found, for example, in small excavation on east flank of Blanco Mountain). However, some 15 km (9.3 mi) to the southeast, the contact aureole between the Joshua Flat pluton and the Lead Gulch Formation contains minable quantities of talc (Warner, 1971).

- **Pyrophyllite**: Al$_2$Si$_4$O$_{10}$(OH)$_2$. **Occ**: Low grade metamorphism of Al-rich sedimentary rocks. **ID**: Soft micaceous or talc like platy white to greenish masses. **Loc**: Several deposits of pyrophyllite were mined along the western flank of the White Mountains, including the Benton Pit near the mouth of Milner Canyon and the Pacific Mine just south of the mouth of Piute Creek Canyon.

- **Muscovite**: KAl$_2$Si$_3$AlO$_{10}$(OH)$_2$. **Occ**: (1) Primary igneous mineral as in Birch Creek pluton; (2) Pegmatitic veins as in Barcroft Granodiorite, common around southern margin, (3) Metaclastic rocks as metamorphic mineral; (4) Hydrothermal alteration of earlier formed minerals such as andalusite. **ID**: Silvery white mica. Microprobe analyses of Ulbrich (1973) indicate relatively high Fe$^3+$ for Al substitution.

- **Biotite**: K(Mg,Fe)$_3$(Si,Al)$_4$O$_{10}$(OH)$_2$. **Occ**: (1) Common primary sheet silicate in all plutonic rocks of this area; (2) Common product of low-grade regional metamorphism in nearly all
clastic sedimentary rocks of this area; (3) Hydrothermal alteration of earlier formed minerals such as cordierite. ID: Shiny, black mica. Microprobe analyses of Ulbrich (1973) show approximately equal Mg and Fe² contents. Robigou (1984) reports an increase in the Ti-contents of Campito Formation biotite as one approaches the Barcroft Granodiorite contact.

**Phlogopite:** KMg₃Si₃AlO₁₀(OH)₂. Occ: Metadolomite at igneous contacts. ID: Mostly fine, pale brown to colorless mica flakes. Loc: Phlogopite is one of the most widespread contact metamorphic minerals in the metadolomite of this area but it is commonly present in only very minor amounts. Reed Dolomite/Cottonwood Granite contact in Cottonwood meadow; Reed Dolomite/Sage Hen Flat contact north of WMRS Crooked Creek facilities.

**Chlorite:** Mg,Fe-bearing layered-aluminosilicate. Occ: (1) Abundant metamorphic mineral in low-grade metaclastic rocks; (2) Metadolomite at contacts with igneous rocks. ID: Soft, scaly masses, layers and veins, less “flaky” than the micas, typically dark green, but in the second occurrence reported it is also very pale to white. Loc: Wyman Formation throughout area (Occ 1); Barcroft dike/Reed Dolomite contact between Piute Mountain and Lamb Camp (Occ 2).

**Prehnite:** Ca₂Al₂Si₃O₁₀(OH)₂. Occ: Uncommon vein mineral at carbonate/igneous contacts. ID: Stubby, pale greenish tan transparent crystals 0.5 to 1.0 cm, commonly with gently curved crystal faces. Loc: Southern Barcroft pluton-metasediment contact area. A museum quality sample of prehnite was found by M. Pope near Southfork Peak.

**TECTOSILICATES** (3D frameworks of corner sharing (Si,Al)O₄ tetrahedra.)

**Quartz:** SiO₂. Occ: Igneous, metamorphic, and sedimentary rocks, nearly ubiquitous. ID: Mostly white to colorless, hard vitreous rounded grains and masses. Loc: Present in nearly all White Mountain rock units except for Reed Dolomite and the olivine basalts.

Several significant varieties can be differentiated:

**Smokey quartz.** Occ: Rare in veins in plutonic rocks. ID: Irregularly grey colored transparent to translucent elongated hexagonal prisms. Loc: Beer Creek pluton 2 km (1.2 mi) east of Eva Belle Mine.

**Milky quartz.** Occ: Late veins cutting metasediments. ID: Hard, bright white, massive vein fillings. Loc: Near Barcroft contact, about 1 km (0.6 mi) west of road.

**Feldspars:** Potassic-feldspars (microcline and orthoclase), sodic-feldspar (albite), intergrowths of these two feldspars (perthite), calcic-feldspar (anorthite), and plagioclase (a solid solution between albite and anorthite) all occur in this region.
Microcline, orthoclase: $\text{KAlSi}_3\text{O}_8$ (these varieties differ only in the distribution of Al and Si, making distinction between them difficult and normally requiring microscope observation). Occ: (1) Primary igneous mineral in most of the White Mountain granitic rocks and granodiorites where it commonly occurs both as coarse (phenocryst) grains and as grains similar in size to the other igneous minerals; (2) Metasedimentary, metaclastic rocks. ID: Generally coarse, grayish white to pinkish, elongated, angular prisms up to several cm in length. Broken grains show two prominent cleavage planes; simple twinning is commonly visible at the outcrop. Loc: Contact metamorphic microcline-sillimanite, and microcline-cordierite zones just south of Barcroft Granodiorite margin.

Perthite: A common lamellar intergrowth of a potassic and a sodic feldspar. Occ: As with microcline and orthoclase. ID: Distinguishing the presence of two feldspars usually requires microscopic aid. Loc: The white, ovoid feldspar “phenocrysts” found in partially-melted (migmatitic) metasedimentary rocks near the southern Barcroft margin are particularly perthitic.

Plagioclase: $(\text{Na,Ca})(\text{Al,Si})_4\text{O}_8$. Composition is commonly expressed as the proportion of the calcium end-member, anorthite. The An-content can be determined by examination under the microscope. Occ: (1) Primary, medium-grained igneous mineral with low An-content in granitoids and higher An-contents in basalt; (2) Metasedimentary rocks as metamorphic mineral (low to intermediate An-content). ID: Here generally pale grey, ovoid to slightly elongated prismatic grains with two fair cleavages. Grain size is mostly fine and only rarely coarse. Loc: Cottonwood, Sage Hen Flat, Barcroft, and Birch Creek granitoids. Common low- to medium-grade mineral in metasedimentary rocks, e.g., Campito Formation. With increasing grade, the An-content is seen to increase (Robigou, 1984). Found as coarse white porphyroblasts in Deep Spring Formation west of Eva Belle Mine.

Anorthite (plagioclase calcic end-member): $\text{CaAl}_2\text{Si}_2\text{O}_8$. Occ: Metacarbonates near igneous contacts. ID: As with plagioclase, hard pale grey grains usually overlooked in these rocks. Loc: Deep Spring Formation northwest of Golden Siren Mine; 2 km (1.2 mi) southeast of WMRS Barcroft facilities at granodiorite-carbonate contact.

Scapolite: $(\text{Ca,Na})_4(\text{Si,Al})_{12}\text{O}_{24}(\text{CO}_3,\text{Cl})$. Occ: Metacarbonate-rich rocks, especially meta-limestone (marble), and Ca-containing metaclastic rocks. ID: Elongated (to 5 mm), pale tan crystals with characteristic square cross section scattered in marble, commonly “weathering out” on surfaces. Loc: Deep Spring Formation just east of road east of Campito Mountain (contact with Sage Hen Flat pluton about 1 km (0.6 mi) distant); small scattered exposures of Wyman Formation in upper Cottonwood Creek, near the Barcroft pluton include bluish metacarbonate layers containing the unusual assemblage: scapolite-diopside. Scapolite is particularly widespread in this area but it is commonly too fine grained to identify without a microscope. Chemical analyses of both occurrences listed here fall near the middle of the $\text{Na,Cl}$ (marialite)-$\text{Ca,CO}_3$ (meionite) solid solution.
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Metamorphic Petrology of Noncalcareous Uppermost Precambrian and Lower Cambrian Strata in the Crooked Creek Area, Southern White Mountains, Eastern California

W. G. Ernst

Abstract. Superjacent strata of the north-northwest-trending White Mountain anticlinorium have been metamorphosed by contact with calc-alkaline arc plutons intruded episodically over the approximate interval 80 to 180 Ma. Strongly retrograded andalusite ± sillimanite ± cordierite-bearing metapelitic assemblages and diopside plus grossular-bearing calc-silicate skarns in wall rocks at contacts with the granitoids testify to thermal maxima approaching 500 to 600°C in the inner aureoles and xenoliths. Biotite isopleths have been documented for several stratigraphic units, the Wyman meta-argillites, Deep Spring and Andrews Mountain metaquartzites, and Montenegro phyllites. Metamorphic grade west of the White Mountain Range crest is chlorite zone of the greenschist facies (characterized by temperatures of about 300 to 350°C), but rises abruptly on the extreme north adjacent to the Barcroft Granodiorite, and gradually increases eastward towards the Beer Creek/Cottonwood pluton. Lithostatic pressures accompanying thermally induced recrystallization are poorly constrained, but were on the order of 3±1 kbar, with fluid pressures less than $P_{\text{total}}$ in these fractured rocks.

Most of the middle- to late Mesozoic intrusive igneous bodies in this area crosscut the regional fold pattern of the country rocks. The anticlinorial structure is manifested in strata ranging in age from latest Precambrian to at least as young as mid-Paleozoic. Background low-grade regional dynamothermal metamorphism could have been produced synkinematic with deformation, and therefore might be substantially older than the middle- to late-Mesozoic time of arc intrusion. In any case, the progressive metamorphic mineral parageneses reported here do not represent a synchronous thermal event, but instead constitute a composite of more local recrystallization episodes attending calc-alkaline granitoid emplacement, perhaps overprinting a pervasive but feeble, chloritic metamorphism coeval with earlier folding.

INTRODUCTION

The Crooked Creek area lies astride the White Mountain anticlinorium (Nelson, 1966a, b). This north-northwest-trending structure is cored by the uppermost Precambrian Wyman Formation, which in turn is overlain successively by the Lower Cambrian Reed Dolomite, Deep Spring Formation, Campito Formation, and Poleta Formation (Nelson, 1962). This platform sequence of argillites, pelites, carbonates, and fine-grained feld-
spathic quartzite beds are intruded in the Crooked Creek area by the northern margin of the 144 to 145 Ma Sage Hen Flat Granite (Bilodeau and Nelson, 1993), and by the much larger 162 to 180 Ma Beer Creek/Cottonwood Granodiorite body on the east. The rather mafic 161 to 166 Ma Barcroft Granodiorite lies about 8 km (5 mi) north along the northern margin of the study area, and the more felsic 79 to 82 Ma Birch Creek Granodiorite invades the Cambrian-Precambrian section about 12 km (8 mi) to the south along the southern margin of the White Mountains.

The metasedimentary section was thermally recrystallized during episodic emplacement of these plutons over the time period from Middle Jurassic to Late Cretaceous—an interval approaching 100 m.y. In general, granitoids, such as the Sage Hen Flat pluton, appear to have truncated pre-existing large-scale folds, and the Barcroft Granodiorite evidently was emplaced along a profound, range-crossing structural break (Krauskopf, 1971; Crowder and Sheridan, 1972; Dunne et al., 1978; Sylvester et al., 1978). In the southern White Mountains, only the small Birch Creek granitoid seems to have shouldered aside its wall rocks. Thus, to a large extent, regional deformation may have preceded magma injection in this area. Although contact metamorphism clearly accompanied calc-alkaline pluton emplacement (see Nelson and Ernst, 1994 [this volume], for a list of neoblastic minerals in the wall rocks), a feeble pre-intrusion regional greenschist facies metamorphism seems to have accompanied development of the major structure—the White Mountain anticlinorium. This hypothesized deformation, and possible associated background synkinematic recrystallization, could be as young as Early Jurassic or as old as Middle Paleozoic (Ernst et al., 1993).

Regional geologic relationships in the southern White Mountains are illustrated in Figure 1. An allochthonous slide block consisting of Andrews Mountain and Deep Spring quartzites situated on the northwest margin of Deep Springs Valley (Nelson, 1991) is ignored for simplicity of presentation.

METAMORPHISM OF CARBONATE-POOR LAYERED ROCKS IN THE VICINITY OF CROOKED CREEK

General Statement

Recrystallization of the uppermost Precambrian and lower Paleozoic strata of the southern White Mountains took place in response to periods of advective heating, reflecting the temporally distinct intrusion of the several granitic plutons. Early metamorphic mineral assemblages were overprinted and partly to completely replaced by successor assemblages produced by later heating events. Thus, observed mineral assemblages represent composite growth and transformation at different times, the highest temperature phases and associations generally being at least partially preserved (Barton et al., 1988; Hanson and Barton, 1989; Stüwe et al., 1993). However, on cooling, pervasive retrograde reactions thoroughly converted cordierite and andalusite(? porphyroblasts in pelitic meta-

sedimentary rocks adjacent most of the granitoids to chlorite + white mica ± biotite intergrowths.
Figure 1. Regional geology of the Crooked Creek area, southern White Mountains, after Ernst et al. (1993).
The superjacent rocks are typified by a regional development of greenchist facies minerals; common phases in recrystallized stratified rocks include quartz, sodic plagioclase, microcline, white mica, chlorite, biotite, epidote, pyrite, and magnetite. Thermal annealing reflects more intense baking occasioned by the emplacement of calc-alkaline plutons of various Middle Jurassic to Late Cretaceous ages. Most plutons have produced distinct contact metamorphic zonations in the surrounding strata, indicated by the formation of new, higher temperature minerals such as garnet, cordierite, tremolite, tourmaline, fluorite, scapolite, andalusite, and calcic plagioclase close to the igneous contacts; a few quartzite xenoliths in the plutons contain sillimanite. In spite of the imposition of local metamorphic aureoles encircling the Mesozoic granitoid bodies, a gradual increase in grade from chlorite zone rocks near the southern limit of the mapped area around the Birch Creek Granodiorite and on the west side of the crest of the White Mountains, to biotite zone on the east, approaching the Barcroft and Beer Creek/Cottonwood plutons, is evident. Studied mineral parageneses combined with published experimental phase equilibrium investigations allow the provisional assignment of pressure and temperature values for the composite, polystage metamorphism: regional metamorphic conditions reached approximately 300 to 350°C and 3 ± 1 kbar total pressure, with local isobaric upgrading at calc-alkaline plutonic contacts to approximately 500 to 600°C (Ernst et al., 1993). The abundance of fracture fillings suggests that fluid pressure was less than the lithostatic load.

Petrographic Data

Microscopically estimated volume percentages of phases present in the metamorphosed uppermost Precambrian and Lower Cambrian layered strata as well as in later metamafic dikes and sills have been presented by Ernst et al. (1993). Beds consisting dominantly of carbonates were studied petrographically, but because of the paucity of metamorphic index minerals and their sporadic occurrences, assemblage data for such units were not utilized in the investigation of regional parageneses. Dollase (1994 [this volume]) presents an account of the new minerals which have grown in the marbles. The following lithologically distinct bulk-rock compositions were studied in the present work: noncalcareous and mildly calcareous meta-argillite beds of the Wyman Formation; iron-rich quartzite beds of the Andrews Mountain Member of the Campito and Deep Spring formations; and micaceous phyllites beds of the Montenegro Member of the Campito Formation.

Mineral Parageneses

In all investigated units, the modal abundances of chlorite versus prograde hornblende, clinopyroxene, biotite, and garnet appear to be inversely proportional—compatible with textures suggesting both consumption of chlorite produced by the weak regional metamorphism, and partial back reaction (chloritization) of the higher grade contact-metamorphic phase assemblages. Thus, chlorite is both a prograde and a retrograde phase. White mica is an essential mineral in almost all of the investigated metamorphic rocks, and is distributed
ubiquitously throughout the terrane; its abundance does not appear to be systematically related to the progressive metamorphism, but like the chlorite, white mica seems to have been generated both during increasing and decreasing intensity of recrystallization. More detailed conclusions must await the results of ongoing electron microprobe analyses of this widespread phase. Traces of newly grown tourmaline and apatite are also scattered throughout the mapped area, but presence or absence of these phases does not seem to be related to metamorphic grade, distance from the calc-alkaline plutons, or the nature of other mineral parageneses. In spotted metapelitic and quartzofeldspathic units, original cordierite and/or andalusite porphyroblasts have been almost totally converted to intergrowths of layer silicates ± quartz. Indistinct, penetrative, axial plane foliation is pervasive but feebly developed in the more micaceous beds of the Wyman, Deep Spring, and Montenegro metamorphosed units. Most quartzofeldspathic Andrews Mountain lithologies do not appear to contain strain markers, so the extent of deformation is difficult to evaluate except where pytgmatic folding is present.

Mineral parageneses in Wyman meta-argillite beds include the scattered, but rare, development of K-feldspar, calcic plagioclase, diopside-hedenbergite, grossular-andradite, scapolite, and/or cordierite adjacent to the Sage Hen Flat, Beer Creek/Cottonwood, and Birch Creek plutons. Epidote is virtually ubiquitous. Neoblastic hornblende is confined to eastern parts of the northern Wyman Formation outcrop area, and is especially abundant adjacent to the granitic intrusions. Metamorphic biotite is present in modest proportions throughout the Wyman section, where it seems to be vaguely related to the fold structures.

In the ferruginous Andrews Mountain and Deep Spring metaquartzite units, K-feldspar, garnet, hornblende, cordierite, and andalusite are rare, but scattered occurrences of one or more of these phases characterize sections adjoining the Barcroft and Beer Creek/ Cottonwood plutons. Minor K-feldspar grains occur in the higher grade metamorphic culmination defined by the northern Wyman argillite parageneses. In general, mineral assemblages of the Deep Spring and Andrews Mountain lithologies mimic the recrystallization sequence described for the Wyman Formation, with units containing substantial amounts of magnetite plus biotite abundant in the northern area, and grade increasing eastward; west of the crest of the southern White Mountains, weakly recrystallized magnetite plus chlorite-rich metaquartzites predominate.

The Montenegro Member of the Campito Formation also displays highly chloritic, biotite-absent assemblages to the west of the crest of the White Mountains, with the progressive development of rather small amounts of biotite eastward, and especially in the north, adjacent to the Barcroft Granodiorite.

Areal relationships

Structural features in the general neighborhood of the Crooked Creek area are presented in Figure 2. Also shown are the proportions of biotite in the three studied noncalcareous metasedimentary lithologies. For the argillaceous Montenegro phyllite beds, the zero percent isopleth for biotite is illustrated; this micaceous, chloritic unit is devoid of biotite
along and west of the crest of the White Mountains. The underlying magnetite-rich albitic quartzites of the Andrews Mountain and Deep Spring units are much richer in biotite, and this phase is present in amounts exceeding 10 volume percent over most of the central and eastern portions of the mapped area; it also is abundant along the contact with the Barcroft Granodiorite. North of the Sage Hen Flat pluton, noncalcareous Wyman meta-argillites carry 5 to 10 volume percent biotite, but in the southern part of the investigated region, between the Birch Creek and Sage Hen Flat plutons, biotite exceeding five modal percent inexplicably seems to be confined to tracts characterized by synclines and basinal folds. The reason for this apparent structural correlation is unclear, but may reflect stratigraphic bulk-rock compositional differences within an essentially conformable sequence (e.g., see Gomez, 1993). Because the eastern Wyman, and the overlying Deep Spring and Campito formations exhibit a systematic eastward and northward increase in metamorphic grade throughout the area, structurally upward increasing intensity of recrystallization (i.e., upside-down metamorphism) of the Wyman meta-argillites is not likely.

As another measure of the regional development of metamorphic minerals, an east-west transect across the superjacent section through upper Silver Canyon and Wyman

Figure 3. Modal proportions of chlorite (x-symbols and dashed line) and biotite (filled dots and solid line) in an east-west traverse across the White Mountain anticlinorium, through upper Silver Canyon on the west and Wyman Canyon on the east, showing eastward increase in metamorphic grade. Modal data are from Ernst et al. (1993). Formational abbreviations are as follows: R = Reed Dolomite; A-D = Andrews Mountain Member, Campito Formation and Deep Spring Formation.
Canyon is presented as Figure 3. In spite of wide scatter in estimated mineral proportions, the gradual eastward increase in metamorphic grade is apparent. The influence of bulk-rock composition evidently is as important as physical conditions of recrystallization in determining the proportions of neoblastic phases.

SUMMARY

The WMRS Crooked Creek facilities are located directly west of the White Mountain anticlinorium structural culmination just within the northern border of the Sage Hen Flat Granite. Surrounding sedimentary strata have been baked by the igneous intrusion, but the overall metamorphic grade increases imperceptibly eastward. West of the topographic crest of the range, chloritic Montenegro phyllites are devoid of biotite at this latitude. In contrast, the magnetite-bearing quartzites of the Andrews Mountain and Deep Spring units cropping out towards the east carry more than 10 percent biotite and correspondingly lesser amounts of chlorite. The same relative phase proportions of layer silicates occur in the Wyman meta-argillites exposed between the Sage Hen Flat and Beer Creek/Cottonwood plutons; in addition, these noncalcareous metamorphic rocks contain variable but eastward-increasing amounts of epidote ± hornblende.

Metamorphism in the region around Crooked Creek evidently took place as a series of discrete recrystallization events. Assemblages characteristic of the biotite zone of the greenschist facies, and most especially those of higher grades, are confined to rocks adjacent igneous contacts, and undoubtedly formed accompanying the emplacement of granitoids. The ages of consolidation of these calc-alkaline plutons range from about 80 to 180 Ma. The several geographically distinct thermal upgradings may have been superimposed on a feeble background regional metamorphism, chlorite zone of the greenschist facies. This ubiquitous but weak recrystallization developed during the Middle Jurassic or earlier main-stage folding, which produced the White Mountain anticlinorium. Although many details remain to be elucidated, the Crooked Creek area constitutes an excellent, well-exposed example of polymetamorphism, reflecting the interplay between regional deformation/recrystallization and sporadic granitoid intrusion accompanying construction and thermal metamorphism of a Middle- to Late-Mesozoic calc-alkaline arc.

Acknowledgments. This work was initiated in 1978, employing the facilities of the White Mountain Research Station, at which time the author served as a faculty member with UCLA colleagues C. A. Hall, Jr., C. A. Nelson, and W. A. Dollase. We studied the geology of the Crooked Creek area and contiguous regions while conducting the geologic summer field camp for undergraduate UCLA students. I have continued these scientific investigations since moving to Stanford in 1989. My research has been supported most recently by the National Aeronautics and Space Administration through grant NAGW-1918, as well as by the White Mountain Research Station. This paper has been reviewed by the UCLA colleagues named above. I thank these institutions and colleagues for their help.
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Weathering of the Reed Dolomite as a Function of Elevation, White-Inyo Range: Evidence from an Infrared Spectral Study

Paraluman Russell

Ronald J. P. Lyon

W. G. Ernst

Abstract. Two aircraft flight lines of Geoscan multi-spectral imagery, covering approximately 500 sq km (200 sq mi), and approximately two hundred samples were examined by infrared reflectance measurements, in order to identify characteristics of the Reed Dolomite over a wide range in elevation. Previous workers (Ernst and Paylor, 1993) experienced difficulty in mapping sections of stratigraphy within the Reed, even using multispectral satellite imagery. This study was undertaken in order to further detail spectral characteristics of the Reed Dolomite as an aid in geologic mapping in the White-Inyo Range, and in the remote sensing of dolomites elsewhere. Laboratory spectra of fresh and weathered surfaces were analyzed in conjunction with reflectance-corrected image data to determine what effect the weathered surfaces had on the spectral signature at various study sites. X-ray diffraction, SEM, and thin-section analyses were performed to aid in interpreting the multispectral imagery.

The low-elevation study sites (up to 2,200 m [7,300 ft]) are characterized by excellent exposures of massive, unmetamorphosed upper (cream to buff) and lower (dark gray) Reed Dolomite members. Chemical weathering dominates at these low elevations, and a thin, tan-colored dolomite coating has developed on the outer surfaces of exposures. The lower Reed Dolomite exhibits quenched (low-contrast) spectra on fresh surfaces; however, the coating on the uppermost surfaces enhances the spectral signature of these rocks. Multispectral scanner imagery displayed using band-difference treatments reveals distinct member boundaries and the differentiation between limestone (of other formations) and dolomite.

At high elevations (up to 3,350 m [11,000 ft]), the Reed Dolomite is recrystallized, appears stark-white, and contains scattered calcilicate minerals. Upper and lower members are not distinguishable in these outcrops. Coatings do not occur on these rocks, and spectra of the uppermost and fresh surfaces are nearly identical, both exhibiting strong dolomite absorptions. Multispectral scanner imagery shows that although the Reed is identifiable in some areas as a dolomite (using the difference treatments employed at lower elevations), results are inconsistent, probably due to lack of extensive exposures. At these altitudes, outcrops apparently break up by frost action, carpeting the area with flat fragments, interspersed with a clay-rich, carbonate-free soil, probably of aeolian origin. Inasmuch as the rock-to-soil ratio is usually about 0.5, this effectively "dilutes" the carbonate airborne signatures.

1,2,3School of Earth Sciences, Stanford University, Stanford, California 94305-2210.
GEOLOGIC INTRODUCTION

The Problem

This study is part of a detailed mapping effort in the White-Inyo Range of the Waucoba Mountain, Blanco Mountain, and Mount Barcroft 1:62,500 quadrangles in central eastern California. Conventional mapping techniques have been applied to this area since the late 1800's, after the discovery of mineral resources.

The use of airborne multispectral scanning systems to aid in identifying mineralogically-distinct lithologies has been recognized and established (Goetz et al., 1985). The Geoscan system principally used in this research measures 24 channels with 22 to 73 nm bandwidths. The narrower bandwidths of these newer systems have greatly aided mineral identification and differentiation.

Initial cursory examination of the Geoscan data indicated that the spectral character of the Reed Dolomite changes N-S along the flight line. The purpose of this study is to utilize high-resolution (6-m [20-ft] pixels) multispectral remote sensing and laboratory spectral data to characterize this unit, especially as a function of elevation. The initial hypothesis was that the Reed Dolomite developed an elevation- and climate-controlled coating which influences the remotely sensed spectra. Outcrops of the Reed Dolomite rise from 1,500 m (5,000 ft) in the south to 3,350 m (11,000 ft) in the north; systematic changes in spectral effects could go hand-in-hand with increasing altitude.

General Geology

The White-Inyo Range is approximately 175 km (110 mi) long and is the westernmost block of the Basin and Range province. The range is dominated by the north-south doubly-plunging White Mountain anticlinorium and the northwest-southeast trending Inyo anticlinorium (Nelson, 1981). The structure is flanked by overturned synclines in the northwest and folds in the east. To the west, the White Mountains dextral-slip shear zone truncates the range, whereas to the east it is bounded by granites; isolated Middle and Late Mesozoic plutons occur throughout the range. Folding and faulting preceded and accompanied the emplacement of these plutons, as is evidenced by deflected structures and stratigraphic thinning (Sylvester et al., 1978). Mio-Pliocene plateau basalts and Plio-Pleistocene lake beds (Bachman, 1978) reveal the eastward tilting of the White Mountain block and westward tilting of the Inyo block within the past several million years.

U.S. Geological Survey topographic maps at a scale of 1:24,000 for the Mount Barcroft, Blanco Mountain, Westgarth Pass, Deep Springs Lake, and Uhlmeyer Spring quadrangles were utilized in the present study. Detailed geologic maps by Nelson (1966a, b), Krauskopf (1971), Ernst and Hall (1987), Nelson et al., (1991) and Ernst et al. (1993) provide a framework by which to check the new remote sensing results. For descriptions of the instrumentation, image processing, and the near and short-wave infrared spectra of carbonates, see Russell (1993).
Description of the Reed Dolomite

The uppermost Proterozoic-Lower Cambrian Reed Dolomite is approximately 650 m (2,140 ft) thick and ranges from coarse-grained gray to buff, locally oolitic dolomite in the lower members, to fine-grained, light gray to cream in upper members. The southern and eastern portions contain a calcareous, cross-bedded quartz arenite named the Hines Tongue by Nelson (1962). This unit divides the massive Reed Dolomite into upper and lower carbonate members. These members have been further divided by Ernst and Paylor (1993) into six sub-units listed in Table 1.

Table 1. The six subunits of the Reed Dolomite as defined by Ernst and Paylor (1993), employing space-borne imaging spectrometer data.

<table>
<thead>
<tr>
<th>Subunit</th>
<th>Description</th>
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<tbody>
<tr>
<td>1</td>
<td>Very coarse-grained, gray, pisolithic, blocky dolomite</td>
</tr>
<tr>
<td>2</td>
<td>Medium-grained, white, oolitic, massive dolomite</td>
</tr>
<tr>
<td>3</td>
<td>Coarse-grained, gray, oolitic, massive, crystalline dolomite, and rare interbedded rusty quartzite arenite</td>
</tr>
<tr>
<td>4</td>
<td>Medium-grained, cross-stratified, locally limonitic interlayered siltstone, quartz arenite, and sandy dolomite</td>
</tr>
<tr>
<td>5</td>
<td>Fine-grained, thin-bedded, sparsely oolitic, buff dolomite</td>
</tr>
<tr>
<td>6</td>
<td>Fine-grained, fissile, dull-white dolomite</td>
</tr>
</tbody>
</table>

Study Areas

Five main and three minor areas at different elevations and locations throughout the range were chosen for study. Selection was based on lithologies, accessibility, altitude (plant zonation), and availability of high-resolution Geoscan image data. Plant zones defined by altitude (Spira, 1991) were used. Table 2 lists the study areas and their elevations; Figure 1 locates each by number.

Table 2. Study areas, elevations, and plant zones used in this study. Numbers correspond to locations on Figure 1.

<table>
<thead>
<tr>
<th>Site #</th>
<th>Name</th>
<th>Elevation</th>
<th>Plant Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Marble Canyon</td>
<td>1,590</td>
<td>(5,100)</td>
</tr>
<tr>
<td>2</td>
<td>Soldier Canyon</td>
<td>1,950</td>
<td>(6,400)</td>
</tr>
<tr>
<td>3</td>
<td>Waucobi Embayment</td>
<td>2,200</td>
<td>(7,220)</td>
</tr>
<tr>
<td>4</td>
<td>Mollie Gibson Mine area</td>
<td>2,440</td>
<td>(8,000)</td>
</tr>
<tr>
<td>5</td>
<td>Patriarch Grove area</td>
<td>3,350</td>
<td>(11,000)</td>
</tr>
<tr>
<td>6</td>
<td>Grandview Mine area</td>
<td>2,500</td>
<td>(8,200)</td>
</tr>
<tr>
<td>7</td>
<td>Barcroft Gate area</td>
<td>3,500</td>
<td>(11,480)</td>
</tr>
<tr>
<td>8</td>
<td>Birch Creek contact zone</td>
<td>2,440</td>
<td>(8,000)</td>
</tr>
</tbody>
</table>
Figure 1. Location map of Reed Dolomite outcrops (brick pattern) with outlines of the approximate flightlines. Study areas are notated with numbers: 1=Marble Canyon, 2=Soldier Canyon, 3=Waucobi Embayment (TM data), 4=Mollie Gibson Mine area, 5=Patriarch Grove, 6=Grandview Mine area, 7=Barcroft Gate (Lamb Camp), 8=Birch Creek contact zone. Granitoid plutons are outlined and labeled, but unpatterned.
Marble Canyon and Soldier Canyon are steep-walled, with extensive exposures of Reed Dolomite on either side. The Desert Scrub zone contains grayish, small-leaved shrubs less than 1 m (3 ft) in height. Common species of sagebrush in this area are: Bud Sagebrush (Artemisia spinescens) and Basin Sagebrush (A. tridentata). Low rainfall in this area (less than 2.5 cm/yr [1.0 inch/yr]) inhibits tree growth.

Waucobi Embayment and Mollie Gibson Mine areas are in the Pinyon-Juniper Woodland zone. As the name implies, the dominant vegetation consists of Pinyon Pine (Pinus monophylla) and Utah Juniper (Juniperus osteosperma). Trees are typically widely spaced (10 to 20 m [30 to 60 ft] apart) and under 6 m (18 ft) tall. In drier areas such as Waucobi Embayment, trees are less common, and shrubs (Artemisia nova and A. tridentata) dominate the landscape. The Waucobi Embayment lies on the transition zone between the Desert Scrub zone and the Pinyon-Juniper Woodland zone, and as such, it contains characteristic vegetation of both areas.

The Subalpine zone site, Patriarch Grove is dominated by Bristlecone Pine (Pinus longaeva). These trees, the oldest living terrestrial organisms, preferentially grow on Reed Dolomite substrate, and are the chief form of vegetation encountered at this altitude. Other common vegetation found in the Subalpine zone include the low, ground-hugging sagebrush (Artemisia sp.), Limber Pine (Pinus flexilis), and Quaking Aspen (Populus tremuloides).

WEATHERED SURFACES
General Statement

The importance of weathered surfaces to what is sensed remotely is commonly overlooked by the geologist interested in the “fresh” rock for primary mineral identification and geochemical analysis. In remote sensing, however, the commonly altered outer surface (upper few microns) of a sample contains the most pertinent information inasmuch as this is the material that the airborne scanner or laboratory spectrometer detects.

Weathering is defined by Elliott-Fisk (1991) as the “chemical decomposition and mechanical disintegration of rock materials.” These two processes, mechanical and chemical, are evident throughout the White-Inyo Range, and vary as a function of microclimate. Chemical weathering is a function of temperature and presence or absence of liquid water, whereas mechanical weathering usually requires pronounced temperature and moisture fluctuations. Owing to the overall aridity, chemical weathering is considered to be a relatively slow process in the White Mountains (LaMarche, 1968). The rate of mechanical erosion for Sage Hen Flat was calculated by Marchand (1971) to be approximately 1.7 to 2.1 cm (0.7 to 0.9 in) per 1,000 years. The weathering rate is more rapid at higher elevations due to the coupling of an increase in precipitation and the mechanical work of agents such as freezing-thawing, glacial flow, and mass wastage.

Conclusions of a study conducted by LaMarche (1967) on weathering characteristics of the Reed Dolomite and limestone of the Wyman Formation indicate that thermally metamorphosed and recrystallized carbonates near intrusions tend to weather spheroidally, whereas unmetamorphosed carbonates weather into fragments with greater angularity.
At low elevations, caliche (CaCO₃) occurs on the underside of rocks, indicating chemical precipitation of calcium carbonate from downward-percolating vadose waters. Unless caliche forms on the upper surfaces of rock outcrops, this alteration is not of concern to the remote sensor.

Types of Surfaces
The outer surface of rocks in the central White-Inyo Range varies significantly. Samples pictured in Figure 2 show examples of Reed Dolomite variation: a thin tan coating on a dark, lower Reed Dolomite sample (a); caliche coating on underside of sample (b); angularly weathered surface with small amounts of lichen (c); and no visible surface coating (d). In general, rocks present at lower elevations such as Waucobi Embayment, Soldier Canyon, Mollie Gibson Mine area, and Marble Canyon exhibit a thin, fine-grained, tan coating, whereas samples from Patriarch Grove and near the Barcroft Gate do not have a discernible coating. (For elevations, see Table 2)

One of the most common weathering products in arid and semi-arid environments is clay- and manganese-rich desert varnish (Adams et al., 1982; Lyon, 1990; Rivard et al., 1992). The Reed Dolomite does not develop such surfaces. Adams (1982) noted that the varnish

![Figure 2](image-url)

Figure 2. Examples of the wide range of Reed Dolomite samples collected: (a) dark gray lower Reed (M522-1) with tan coating; (b) upper Reed Dolomite (L801-7) with caliche (underneath-side up); (c) angularly weathered upper Reed Dolomite (MS22-10); (d) metamorphosed upper Reed Dolomite (L923-31) with no visible coating.
is not chemically or mineralogically related to the substrate on which it forms; it accumulates discontinuously and requires a specimen that is stable for thousands of years. If denudation rates found by Marchand (1971) are accurate for the high-altitude Reed Dolomite locations, then the weathering rate is too high to accommodate such surface alteration.

Laboratory Spectral Measurements

Laboratory infrared studies indicate that the type and amount of iron (Fe$^{2+}$) detected in some dolomite samples is different between fresh and weathered surfaces. A broad iron absorption band near 1.1 μm due to the presence of the ferrous ion is described by Hunt and Salisbury (1971). They attribute all bands near the 1.0 μm region to ferrous iron, either as the principal cation or as an impurity. They found that as little as 0.03 weight percent iron (as Fe) is needed to detect this broad ferrous absorption. Gaffey (1985, Figure 13) showed that this broad minimum increases in depth as Fe increases from 0.5 to 3.3 percent, but in a non-linear manner. Absorptions due to the ferric (Fe$^{3+}$) ion are found at shorter wavelengths and vary according to iron-oxide mineral. Absorptions for goethite are found to be between 0.896 and 0.932 μm (e.g., Townsend, 1987; Windeler and Lyon, 1991).

Examination of 29 pairs of spectra from outermost coatings and associated fresh rock interiors show the following pertinent facts: (1) fresh rock in 60 percent of the pairs exhibits a broad absorption between 1.0 and 1.1 μm attributable to Fe$^{2+}$ substituting for Mg$^{2+}$ in the dolomite structure; (2) associated coatings show that this minimum is no longer present or has shifted to shorter wavelengths near 0.9 μm, attributable to the oxidation of Fe$^{2+}$ to Fe$^{3+}$; (3) 14 percent show no change in position or strength of the Fe$^{2+}$ absorption at 1.0 to 1.1μm; (4) 20 percent show a change in the absorption from 0.9 μm (Fe$^{3+}$) to zero absorption effect (iron-leached); and (5) 83 percent of the spectra of coatings show a rapid rise in reflectance from 0.9 μm. This is usually considered to be an effect caused by fine-grain-size materials. Similar spectra shapes have been found on caliche (CaCO$_3$) surfaces.

Specific Localities

Because we were interested in the effect of surface coatings on the airborne scanner data, laboratory spectra of fresh and original outer surfaces of each specimen were obtained when possible. Characteristics of each locality, from south to north, are discussed in the following sections. Figures for all spectra in this section display the weathered surfaces above fresh surfaces combined in one graph. The spectra, offset for clarity, are displayed at 10 percent increments on the y-axis. Reflectance relative to Halon (percent) values at 1.30 μm are noted for reference. Russell (1993) provides all 200 spectra measured in this study.

Marble Canyon (1,590 m [5,220 ft]). Spectra in Marble Canyon (Figure 3) are both of bright, upper Reed specimens. No dark outcrops of Reed were visible at this location. The samples from Marble Canyon show little difference between the fresh and weathered surfaces, aside from a slight increase in reflectance and a finer-grained outer surface. All four dolomite
Figure 3. Spectra of weathered and fresh surfaces from Marble Canyon (Site 1). Reflectance values at 1.3 μm are noted for reference. Top curve corresponds to the upper surface, lower curve to fresh rock.

R= the "ramp" at the blue end of the spectrum; "Fe++" is the absorption due to ferrous iron. Vertical dotted lines correspond to the band-centers of the narrow-band Geoscan filters.

absorptions from these samples are very strong. Sample M523-2 shows a strong ferrous oxide absorption near 1.0 μm. A weak Fe$^{2+}$ absorption near 1.00 μm in M523-2 is found on the fresh surface, but has shifted to slightly shorter wavelengths on the coating. Sample M523-5 shows a similar shift on the coating.

Soldier Canyon (1,950 m [6,400 ft]). There are two distinct classes of spectra from Soldier Canyon—those from the upper and the lower Reed Dolomite samples (Figure 4). Spectra from darker, lower Reed Dolomite are apparently "quenched," showing decreased contrast
in carbonate absorptions and overall lower reflectance values. Outer surfaces of all samples exhibit strong dolomite absorptions. Some include hydroxyl absorptions at 1.4 μm and 1.9 μm typical of Al-clays, samples M522-11 and M522-2 being the strongest. These would be typical of desert varnishes formed from airborne silicate dusts. Loss of Fe$^{2+}$ in the outer surface coating is seen at about 1.02 μm in the spectra of M522-11; M522-2 shows Fe$^{2+}$ in the fresh surface, with a shift to ferric iron with an absorption at 0.70 μm in the coating.

Figure 4. Spectra of weathered and fresh surfaces from Soldier Canyon (Site 2). Reflectance values at 1.3 μm are noted for reference. Top curve corresponds to the upper surface, lower curve to fresh rock. R= the “ramp” at the blue end of the spectrum; “Fe$^{2+}$” is the absorption due to ferrous iron.
WEATHERING OF THE REED DOLOMITE AS A FUNCTION OF ELEVATION—71

Figure 5. Spectra of weathered and fresh surfaces from Waucoibi Embayment (Site 3). Reflectance values at 1.3 μm are noted for reference. Top curve corresponds to the upper surface; lower curve to fresh rock.

Waucoibi Embayment (2,200 m [7,220 ft]). Spectra from Waucoibi Embayment to the south (Figure 5) show typical dolomite absorptions at 2.320 μm. Generally, the weathered surfaces have higher reflectance values than fresh surfaces. Sample WM-625 (upper Reed Dolomite) shows a fresh surface with a 61 percent reflectance versus the weathered surface of 44 percent. Spectra of the weathered surface of samples in this area mimic those of the fresh surfaces, except for a small portion of the visible in L412-23.

The steadily increasing “ramp” (indicated by “R”) of reflectance increasing with wavelength is typical of fine-grained rock samples (i.e. well below 100 μm particle size; Crowley, 1986), but does not appear to affect the actual carbonate spectra at wavelengths less than 0.8 μm. Sample L412-23 appears to have most of the carbonate absorptions described by Hunt and Salisbury (1971) resolved (four would be expected in this region).

Sample WM-625 exhibits strong O-H absorption at 1.9 μm, masking the carbonate absorptions in this region of the spectrum. Iron in the coating of WM-627 shows a shift to shorter wavelength (0.929 μm) from the ferrous coating at approximately 1.020 μm. Samples L412-23 and WM-625 show similar iron absorptions for both outer and fresh surfaces (~1.0 to 1.02 μm).
Figure 6. Spectra of weathered and fresh surfaces from Mollie Gibson Mine area (Site 4). Reflectance values at $1.3 \mu m$ are noted for reference. Top curve corresponds to the upper surface; lower curve to fresh rock.

Mollie Gibson Mine area (2,440 m [8,000 ft]). The one lower Reed Dolomite fresh rock sample (M522-20) from Mollie Gibson Mine shows a "quenched" spectra (Figure 6). The outer rind of this sample also exhibits weak carbonate absorptions. The other two samples from the area show a trend not found consistently at the other study sites; the fresh surface has very strong dolomite absorption, whereas the weathered surface only displays a weak dolomite absorption near $2.320 \mu m$, and a weak hydroxyl absorption near $1.9 \mu m$. Both possibly have an aluminous clay coating, but neither show the accompanying $1.4 \mu m$ absorption. Iron absorptions for coatings of M522-22 and M522-23 are again shifted to shorter wavelengths compared to fresh surfaces.

Patriarch Grove (3350 m [11,000 ft]). Samples from Patriarch Grove show no detectable weathered surface (Figure 7); in fact, it is difficult to distinguish between weathered outer and fresh inner surfaces without referring to annotations on the sample! There are strong ferrous oxide absorptions in spectra from all samples, but the fresh and outer surfaces of L918-100 and L918-32 have similar iron absorptions. However, L923-21 has a shorter wavelength iron absorption. Reflectance values for weathered and fresh surfaces are similar. Dolomite absorptions are well-defined and high in contrast. Sharp absorption at
just below 1.4 μm probably is due to the presence of the metamorphic mineral tremolite, a calcisilicate which is widespread in this area.

Thin-section and XRD Measurements

Optically investigated samples display either unimodal or bimodal grain sizes, with the bimodal distribution due to presence of oolites. Results show that the smallest (fresh-rock) grain size detected was 43 μm. The ramps on the laboratory infrared spectra indicate that coatings on the outer surfaces are less than 2 μm (clay sized). Thus the inner (fresh) surface is always coarser grained than the coatings.

X-Ray diffraction results of powders drilled from the outer surfaces of Reed Dolomite show that most of the surfaces are dolomitic, with minor occurrences of calcite, quartz and clays. In general, the XRD results demonstrate that the surface coatings on rocks from all areas is predominantly dolomitic. The presence of calcite in some specimens collected at higher elevations may be caliche contamination.

SEM Results

SEM analysis was performed on three samples. The photographs were all taken at approximately the same magnification (~x400) to facilitate comparison. Soldier Canyon samples M522-1 and M522-11 (Figures 8 and 9) were chosen to compare the characteristics
Figure 8. SEM photographs of weathered (a) and fresh (b) surfaces of lower Reed (M522-1) collected in Soldier Canyon. Scale bar is 100 μm, magnification is 363 and 476 times for (a) and (b), respectively.
Figure 9. SEM photographs of weathered (a) and fresh (b) surfaces of upper Reed (MS22-11) collected in Soldier Canyon. Scale bar is 100 μm, magnification is 400 and 388 times for (a) and (b), respectively.
of upper and lower Reed (see Figure 4 for spectra of these weathered and fresh surfaces). For both samples, the weathered rinds consisted of platy, chiefly discontinuous surfaces, physically (but not chemically) similar to, but not as well-developed as those found by Adams et al. (1982) on desert varnished surfaces in arid regions. The fresh surfaces of both samples also appear similar, with no visible structure or planar surfaces. Grains do not appear to be oriented. Patriarch Grove sample L918-100 (Figure 10) was selected because it lacked any visible weathering rind. The outer surface does not possess the platy, layered features of samples at lower elevations; in fact it appears to be quite similar to the fresh surface of M522-1. Grain boundaries are rounded. The smoothness of the grains may be due to metamorphic history of the rock, and, in the case of the outer surface, mechanical degradation and aeolian etching.

SEM analysis illustrated that the samples which show a visible coating possess a surface of thin, platy material which is distinctly different from the inner fresh surfaces. Laboratory infrared spectra suggest that the grains which form this platy surface should be a composite of ~2 μm-sized particles. The sample from Patriarch Grove is similar on both fresh and weathered surfaces, except for slightly rounded grain boundaries on the outer surface.

OTHER FACTORS INFLUENCING SPECTRAL SIGNATURES

Although research described in this report emphasizes the relationship between weathered and fresh surfaces, other factors also may affect airborne spectral signatures. Some, germane to this study, are discussed below.

Soil Cover and Nature of Outcrop

The complex relationship between soil cover, microclimate, and weathering processes has not yet been resolved. Inasmuch as it is difficult to hold influential factors in soil development (erosion, slope wash, and vegetation) constant throughout such an elevational gradient, Elliott-Fisk (1991) concluded that at this stage in our knowledge, it may be inappropriate to quantify soil development as a function principally of climate in the White Mountains.

Soil samples collected at low-, mid-, and high-elevations resting on Reed Dolomite outcrops show weak, if any, carbonate features (Figure 11); only strong hydroxyl absorptions typical of clay minerals are found (Hunt et al., 1973; Crowley and Vergo, 1988). Further, the spectra do not show any significant change in spectral shape with altitude; only the sample from the Grandview Mine area has a slightly stronger ferrous iron absorption at about 0.9 μm. These results suggest that soils from various locations are quite uniform throughout the White-Inyo Range. It is probable that, due to extreme elevations and high winds acting as dust transporting agents, the White-Inyo Range simply may not be well-suited for such genetic analysis relating the soils to the local bedrock.

Marchand (1970) studied lithosols of Reed Dolomite at elevations from 3,000 to 3,600 m near Sage Hen Flat. He found that soils in that area were probably contaminated by as much as 30 percent by windblown rhyolitic ash from the volcanic Mono Craters or Mono Glass
Figure 10. SEM photographs of weathered (a) and fresh (b) surfaces of metamorphosed Reed Dolomite (L918-100) collected at Patriarch Grove. Scale bar is 100 μm, magnification is 472 and 400 times for (a) and (b), respectively.
Mountain eruptions approximately 80 km (50 mi) to the northwest, and up to 50 percent net aeolian contamination from nearby sources such as the local granitoid terrain. Patterns of strong winds noted by Powell and Klieforth (1991) are consistent with these data. Fieldwork by one of us (R. J. P. L.) indicates that such aeolian-derived surface soils are common in the eastern California/western Nevada regions where they are known as vesicular, frothy layers.

Given the poor correlation between soils and underlying bedrock, sites which have the least soil cover will obviously yield the highest quality imagery for carbonates in this area. At relatively flat localities such as Patriarch Grove, soils have accumulated to form a thin superficial layer, obscuring most of the outcrop. Comparatively steep canyons with extensive exposures such as Soldier and Marble canyons tend to have high rock-to-soil ratios, and can easily be distinguished as dolomitic on imagery. While canyons provide large exposures of rock with minimum soil and vegetative cover, steep walls also tend to produce shadows. The image quality is thus greatly enhanced by data acquisition during mid-day.

Contact Metamorphism

Mesozoic mafic granodiorite to granitic plutons (Krauskopf, 1968) of various sizes and ages (185 to 75 Ma., Nelson, 1981) are found throughout the White-Inyo Range. These plutons have been the subject of many other studies including Emerson (1966), Nelson and...
Sylvester (1971), Crowder *et al.* (1973), Barton (1987), and Bilodeau and Nelson (1993). The effects of thermal metamorphism of the wall rocks, and modification of infrared spectra of associated carbonates are relevant to this study. Hunt and Salisbury (1976) found that common metamorphic minerals such as amphibole, chlorite, and biotite significantly alter the spectra of host rocks. An especially common mineral found in the metamorphosed Reed Dolomite is tremolite; spectra of dolomite samples from Patriarch Grove and Birch Creek (discussed below) have been modified by its presence.

The Birch Creek pluton is almost entirely enveloped by Reed Dolomite. Most of the Reed Dolomite within the contact aureole has been metasomatically altered, decarbonated and recrystallized into a coarse grained, sugary dolomite. Sprays of tremolite and distinct veining are apparent. Spectra of different sections of a vein (Figure 12) illustrate the effects of metamorphism (see also Zenger, 1976).

The dominant mineral in the lower spectra is tremolite, with a very sharp absorption at 1.4 μm, and smoother bands at 2.2 μm and 2.3 μm, due to combination tones of the O-H stretch (Hunt and Salisbury, 1970). The spectra of dolomite and tremolite retains the absorptions at 1.4 μm, 2.3 μm and 2.4 μm. In addition, there is a sharp increase in the ferrous ion absorption at 1.0 μm and a strong band at 1.9 μm, probably due to the presence of water (as fluid inclusions?). Similar neoblastic minerals in spectra of metamorphosed samples were observed at Patriarch Grove (*i.e.* L918-32 and L923-21 of Figure 7).
Trace Impurities and Inclusions

Various trace impurities found in carbonate rocks can greatly alter their spectra. Crowley (1986) found that very small amounts (<0.1 percent) of finely disseminated organic material may quench the spectra of a carbonate sample. This phenomenon lowers the overall brightness of the sample and produces spectra with low absorption contrast. O-H bonds in clays and water do not typically mask the main carbonate absorption at 2.320 μm if it is strong, but O-H absorptions (due to vibrational overtone features of hydroxyl groups at 1.4 μm and 1.9 μm) in some cases may conceal carbonate absorptions (i.e. Figure 4, samples M522-11, M522-2). The presence of the 1.9 μm band indicates that molecular water is present in the sample, whereas the absence of a 1.9 μm absorption but presence of a 1.4 μm band indicates that only OH is present (Clark et al., 1990). Similarly, fluid inclusions in carbonate samples may cause absorptions between 1.6 and 2.0 μm (Gaffey, 1985; Hunt and Salisbury, 1971), but usually will not obscure the main carbonate absorption. These absorptions do not occur within the Geoscan spectral bands, the position of which are shown as vertical lines on each spectral figure.

SUMMARY AND CONCLUSIONS

Lower Elevation: 1,590 to 2,440 m (5,220 to 8,000 ft) (Southern Area)

• The outermost surface of most of the southern Reed Dolomite (upper and lower stratigraphic units) has a ramped spectrum typical of a fine-grained surface with an effective grain size below 2 μm. The reflectance of these outer surfaces is usually higher than that of the inner, fresh rock. The fine-grained nature of the coating enhances (brightens) the total albedo of darker, unmetamorphosed samples.

• Spectra of the fresh surfaces of lower Reed formation are strongly quenched (i.e. have low albedo and little or no spectral contrast), probably due to small amounts of finely disseminated organic impurities. The tan coating, which shows a rapid increase in reflection in the visible green, was found to be primarily dolomite. The coating appears to enhance the main carbonate absorption near 2.320 μm of the dark gray (lower Reed Dolomite) dolomite beds, facilitating identification from airborne scanners.

• The oxidation state of iron is different in the outermost surface compared to the fresh rock. A significant number of samples in which the fresh rock spectra exhibit a ferrous iron absorption near 1.0 μm display it shifted to shorter wavelengths (~0.9 μm; ferric iron) or do not show an iron absorption at all on the weathered surface. This suggests that the ferrous iron found in the fresh rock may be oxidized to ferric oxide (or removed) when the finer-grained coatings form.

• The best laboratory spectra of the lower Reed Dolomite were obtained where the dolomite has developed a surface coating. Southern study areas show better airborne spectra due to the near absence of soils, presence of large exposures in canyons, and strong development of coatings.
• Calcite (caliche) sometimes appears as a weathering product on the underside of rock fragments, but it does not significantly cover the upper surface of the dolomite, and hence is not detected by the scanner.

High Elevation: Above 3,350 m (11,000 ft) (Patriarch Grove)
• Laboratory spectra for samples from high elevations exhibit nearly identical spectra of uppermost and fresh surfaces, with high contrast and typical dolomite absorptions. Some laboratory spectra indicate the additional presence of calcisolicates.

• Samples at high elevations have been exposed to freezing conditions in winter, and exist in a climate where mechanical weathering dominates over chemical weathering. Physical disaggregation does not allow sufficient time for chemical reaction to develop coatings. In most weathered surface/fresh rock spectra pairs, ferrous iron effects appear at 1.1 to 1.2 \mu m unchanged.

• The Reed Dolomite at Patriarch Grove has been thermally metamorphosed by the intrusion of the Barcroft and Cottonwood plutons. Metasomatic fluids have removed any visible impurities, leaving a stark, white rock. However, windblown soils and glacial till tend to cover most of the Reed directly north of Sage Hen Flat Granite, obscuring the sparse outcrops of dolomite from the airborne scanner. This phenomenon is not observed at lower elevations due to the precipitous slopes, hence extensive outcrops in canyons and higher rock-to-soil ratios.

Metamorphic Influences
• Samples obtained from the Birch Creek pluton illustrate the effects of metamorphism on dolomites. The recrystallized lower Reed at the contact of the intrusion is bleached white, is coarse grained, and contains other neoblastic minerals such as tremolite and calcite. Metamorphosed wall rock samples from Birch Creek have spectra with combinations of dolomite, tremolite and O-H or H-O-H bonds. The metamorphism has effectively "bleached" the dolomite, but has also introduced calcisolicates which slightly alter the spectra. Samples from the Patriarch Grove area are similarly affected by the intrusion of the Barcroft and Cottonwood plutons.

Analytic Results
• XRD analysis of powders shows that the upper surfaces of most samples are primarily dolomite. Some samples (i.e. L801-7, L412-21) also contain quartz, calcite, and clays in their outer coatings. This may be a chemical residual which forms from solution of the original carbonate rocks, or it may be a form of desert varnish.

• SEM analysis indicates that, at lower elevations, the weathered surface has a thin, patina-like coating similar in character to desert varnish. The fine-grained "plates" are probably made up of many grains of dolomite; grain sizes of less that 2 \mu m are deduced from the
ramping of their infrared spectra. Weathered surfaces of high-elevation, metamorphosed Reed are difficult to distinguish from fresh surfaces in SEM photographs.

Role of Soils

- The spectra of soils over the Reed Dolomite from three different elevations (near Barcroft Gate, the Grandview Mine area, and Waucobi Embayment) are very similar. This result illustrates that either the weathering products of the parent rocks are essentially the same, or the soil represents an aeolian deposit from a Sierra Nevada source west or northwest, rather than being locally derived. We favor the latter interpretation. Sites with high rock (outcrop) -to-soil ratios, such as canyons, thus will yield the highest quality imagery.

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WEATHERING OF THE REED DOLOMITE AS A FUNCTION OF ELEVATION—83


WEATHERING OF THE REED DOLOMITE AS A FUNCTION OF ELEVATION—85


Abstract. Multispectral scanning of the Reed Dolomite in the Waucoba Mountain, Blanco Mountain, and Mount Barcroft quadrangles, has allowed elucidation of stratigraphic and structural relations for this extremely massive unit. Six discrete bedding units have now been recognized in exposures of this formation:

(6) Fine-grained, fissile, dull-white dolomite;  
(5) Fine-grained, thin-bedded, sparsely oolitic, buff dolomite;  
(4) Medium-fine-grained, cross-stratified, locally limonitic interlayered siltstone, quartz arenite, and sandy dolomite;  
(3) Fine- to coarse-grained, light-gray, oolitic, massive, crystalline dolomite and rare interbedded rusty quartz arenite;  
(2) Medium-grained, white, oolitic, massive dolomite;  
(1) Very coarse-grained, gray, pisolitic, blocky dolomite.

Subunit (4) and underlying subunit (3) appear to be genetically related, with (4) representing the more proximal facies; in the southeast corner of the mapped area, (4) is present whereas (3) is absent, with the situation reversed along the western and northern portions of the range. Subunit (5) thins to a feather edge on the north near the Barcroft Granodiorite. Thickness variations of the different stratigraphic entities in the Reed Dolomite in the eastern and northern White-Inyo Range appear to reflect attenuation accompanying granitoid intrusion, as well as original stratigraphic variations. The broad exposure of Reed Dolomite directly northeast of the Sage Hen Flat pluton reflects the presence of north-south-trending folds. Details of the White-Inyo anticlinorium are better resolved in the central portion of the range where previously undetected folds, faults and homoclinal sections within the Reed Dolomite have been detected in the macroscopically featureless dolomite. Thickness trends and facies boundaries for the newly recognized Reed Dolomite subunits possess north-south or north-northeast orientations throughout the studied area, locally reflecting a gentle west-northwest paleoslope of the continental shelf at ~560 Ma, at least as far to the southeast as Death Valley.
INTRODUCTION

The areal setting of the White-Inyo Range is shown on the index map (Figure 1). The general geology of the range, extending from the northeast-southwest-trending Barcroft pluton on the north in the White Mountains, through Westgard Pass to the east-west-trending Papoose Flat pluton on the south in the Inyo Mountains, has been studied intensively over the past 25 years. Consequently, detailed maps at scales of 1:24,000 and 1:62,500 are available for the entire area (Nelson, 1966a,b; Nelson et al., 1991; Krauskopf,
The regional structure consists of a south-southeast-trending anticlinorium flanked by marginal synclinoria. Intense folding, faulting, and scattered Middle and Late Mesozoic granitoid plutons characterize the area. Outcrop patterns of the various stratified superjacent units support deduced structural relationships. Uncertainties, however, reflect the presence of several thick, monotonous sedimentary units with variable outcrop belt widths, especially the Wyman, Reed, and Campito formations. Such variations can result from primary depositional patterns, structural complexities, and/or thermal attenuation; however, the exact nature of these variations cannot be ascertained easily because of lack of detailed stratigraphic control. The most massive unit is the Reed Dolomite, hence this formation was selected for an in-depth investigation using remote-sensing techniques in the hope of elucidating an internal, throughgoing stratigraphy, the lateral extent of which would provide constraints for a more complete structural interpretation (Ernst and Paylor, in review). This paper reports the geologic conclusions of the multispectral work.

GENERAL DESCRIPTION OF THE SUPERJACENT UNITS

Rocks of the uppermost Proterozoic-Lower Cambrian stratified section were laid down along the western edge of an Atlantic-type continental margin as a succession of shallow carbonate bank deposits (Nelson et al., 1991). The low-standing nature of the adjacent North American platform is attested to by the paucity and multicycle nature of associated clastic debris. After a long hiatus, reflecting sporadic Late Paleozoic mountain building (Burchfiel and Davis, 1975), a north-northwest trending Mesozoic igneous arc was initiated, as reflected by a series of volcanics and volcanogenic sedimentary rocks, as well as by predominantly later subjacent granitic plutons. A brief description of the depositional units follows. For reference, a generalized pre-Mesozoic stratigraphic column after Mount and Signor (1991) is presented as Figure 2.

Wyman Formation. The uppermost Proterozoic Wyman Formation consists mainly of calcareous and siliceous argillite interlayered with widespread, thin, discontinuous lenses of blue-gray limestone and rare calcareous sandstone. A minimum thickness for the Wyman of 2,750 m (9,023 ft) has been estimated by Nelson (1962); the base of the formation is not exposed in the study area. The argillite is dark brown, fractures into platy slabs, and commonly possesses a phyllitic texture. Primary lamination, cross-stratification, ripple marks, and mud cracks occur locally. An indistinct angular unconformity or disconformity separates the Wyman Formation from the overlying strata. In the southern portion of the mapped area, some limestones in the Wyman Formation have been partly dolomitized and are virtually indistinguishable from the main Reed Dolomite (Zenger, 1976).
Figure 2. Composite stratigraphic column of the superjacent uppermost Proterozoic-Lower Cambrian section, southwestern Great Basin (after Mount and Signor [1991] Figure 2).
Reed Dolomite. The uppermost Proterozoic-Lower Cambrian Reed Dolomite comprises approximately 650 m (2,133 ft) of massive, white to buff-colored, fine- to coarse-grained dolomite (Nelson, 1962; Mount and Signor, 1991). Bedding is generally difficult to discern even though oolitic horizons and/or algal stromatolites are present locally. The rock weathers to form dull-white, angular to spheroidal, erosion-resistant outcrops riven by joints. Small, diffuse patches, stringers, and pods of calc-silicate minerals occur sporadically. The Reed Dolomite has been subdivided locally by Nelson (1966a, b) into three members; upper, Hines Tongue, and lower (see Figure 2). The Hines Tongue Member crops out in the southern and eastern parts of the mapped area and is a calcareous, crossbedded quartz arenite.

Deep Spring Formation. The Lower Cambrian Deep Spring Formation consists of about 400 to 570 m (1,312 to 1,870 ft) of interbedded limestone, dolomite, quartzite, sandstone, and siltstone. Nelson (1962) divided it into three members (see Loomis and Hall, 1991, for a more detailed description). The lower member, about 100 m (328 ft) thick, comprises a bioturbated and locally stromatolitic sequence from bottom to top of finely laminated marl, gray dolomite, pale-blue limestone, and buff-colored, coarse-grained dolomite. The middle member is approximately 230 m (755 ft) thick. The lower portion consists chiefly of fine-grained, white and orange, cross-stratified orthoquartzite; this unit increases to a local maximum nearly 80 m (263 ft) thick in the northern Blanco Mountain quadrangle (Emi and Hall, 1987). The quartz arenite is overlain by dark-brown, fine- to very fine-grained sandstone and bedded blue-gray limestone, which in turn is overlain by a buff-colored dolomitic sandstone. The upper member, about 75 m (245 ft) thick, is composed of dark-brown to black, fine-grained, Campito-like quartzitic sandstone at the base, capped by a massive but discontinuous, gray, fine-grained dolomite.

Campito Formation. The Lower Cambrian Campito Formation is composed of two members (Nelson, 1962; Mount, 1985) and is characterized by abundant trace fossils. The Andrews Mountain Member consists of approximately 850 m (2,790 ft) of very dark-brown to greenish-black, fine-grained, blocky, and quartzitic sandstone. It forms craggy cliffs and sheds abundant blocky, angular debris which builds enormous talus cones. Magnetite-ilmenite averages around five volume percent of the rock (Robigou, 1986). Cross-stratification and worm tracks are common; trilobite remains are rare. The overlying Montenegro Member is of variable thickness, but reaches a maximum of about 300 m (785 ft) west of the range crest. It consists of argillaceous, gray-green, thinly laminated siltstone and very fine-grained quartzite. The Montenegro Member weathers to more subdued prominences, and provides substantial amounts of green, slabby talus. Layer silicates are abundant, imparting a phyllitic, micaceous aspect to this lithologic unit.

Preliminary bulk-rock carbon isotope chemostratigraphic data (Corsetti, 1993) suggest the possibility that the Proterozoic-Cambrian boundary may reside within the overlying Deep Spring Formation rather than within the Reed Dolomite as presumed here. Others (e.g., Mount and Signor, 1991) place the Proterozoic-Cambrian boundary at the base of the Reed Dolomite.
Poleta and Harkless formations, and younger Cambrian units. The Poleta Formation consists of rhythmically interbedded buff and blue limestone beds, interstratified with green or olive-drab, fissile shale and fine-grained quartzite beds. Archaeocyathans are locally present. The Harkless Formation is chiefly green and gray slaty siltstone, argillite, and fine-grained quartzite. Superjacent Cambrian units, including the Saline Valley and Mule Spring formations, constitute a conformable stratigraphic package, and consist chiefly of carbonate rocks, interlayered thin siltstone beds, and quartz arenite (Nelson, 1966a,b).

Overlying Paleozoic strata. Similar to the units below, this section is represented predominantly by platform carbonate-rich rocks and fine-grained orthoquartzite, siltstone, and shale beds (Nelson, 1966b).

White Mountain Peak metavolcanic and metasedimentary rocks. An approximately 3-km-thick sequence of intercalated volcanic and volcaniclastic units crops out directly northwest of the Barcroft pluton (Hanson, 1986). A similar assemblage of volcanic and volcanogenic sedimentary rocks of Middle and Late Jurassic age crops out farther south in the Inyo Mountains (Dunne and Walker, 1993). Flows range from mafic andesite to rhyodacite; the sequence also includes ash-flow tuffs and hypabyssal dikes and sills. Volcanogenic metasedimentary units overlie the extrusives and include volcanic breccias, tuffs, sandstones, siltstones, and conglomerates. Although the underlying mafic and felsic flows have been intruded by the Barcroft Granodiorite of Middle Jurassic age (Krauskopf, 1971), zircons in an upper ash-flow tuff interstratified with the White Mountain Peak metasedimentary rocks have a U/Pb crystallization age of about 154 Ma (Hanson et al., 1987); an analyzed associated hypabyssal rock appears to be even younger (137 Ma). The deposition of the White Mountain metavolcanic and metasedimentary section of rock evidently overlapped the time of emplacement and final crystallization of the Barcroft pluton.

Cenozoic surficial units. Younger geologic units include olivine basalt, lake beds, unconsolidated landslide and glacial deposits, and alluvium. Tableland olivine basalt flows are Miocene-Pliocene in age (10.8 Ma or younger) according to K/Ar bulk-rock analyses (Dalrymple, 1963; Robinson et al., 1968). Confined principally to the White Mountains east of the range crest, they dip gently eastward. Plio-Pleistocene (2.3 Ma) lake beds in the Waucobi Embayment area crop out on the east side of Owens Valley, and dip about 6° to the west (Bachman, 1978). Moraines and small glacial lake beds are present east of the White Mountain Range crest, but only at elevations exceeding approximately 3,100 m (10,170 ft) (Ernst and Hall, 1987).

GENERAL DESCRIPTION OF THE SUBJACENT UNITS
Calc-alkaline granitoid plutons invaded the terrane in Middle and Late Mesozoic time. Most range in composition from mafic granodiorite and diorite to ternary granite. Descri-
tions have been provided by Kistler et al. (1971), Crowder et al. (1973), Stern et al. (1981), and Ernst et al. (1993), among others. The Jurassic granitic intrusions tend towards metaluminous, I-type compositions, and are hornblende ± clinopyroxene-rich, whereas the muscovite-bearing Cretaceous bodies in general have peraluminous S-type bulk-rock chemistries. Judging from their compositions, the Jurassic plutons seem to have been derived from deep-crustal or shallow upper-mantle protoliths, whereas the Cretaceous granites probably represent remobilized metasedimentary units.

STRUCTURE OF THE RANGE

The mountain block, elongated in a north-northwest direction, is cored by uppermost Proterozoic argillites of the Wyman Formation and uppermost Proterozoic-Lower Cambrian carbonate beds of the Reed Dolomite in the gently doubly plunging, north-south-trending White Mountain anticlinorium north of Westgard Pass, and in the gently southeast-plunging Inyo anticlinorium south of this topographic/structural saddle. The flanks of the White-Inyo Range contain the limbs of marginal synclinia and, along with an east-west-trending syncline in the vicinity of Westgard Pass, expose Lower Cambrian strata of the Campito, Poleta, Harkless, and overlying formations. The western margin of the White-Inyo Range is truncated by the dextral-slip White Mountains shear zone; the eastern border is extensively invaded by Middle or Late Jurassic calc-alkaline granitoids. On the north, the melanocratic, Middle Jurassic Barcroft Granodiorite occupies a profound northeast-trending structural disjuncture—the Barcroft break—across which down-dropped superjacent Mesozoic White Mountain Peak volcanogenic arc rocks are exposed (Crowder et al., 1973; Ernst and Hall, 1987). Progressing southward, the Upper Jurassic Sage Hen Flat Granite appears to have risen through the Wyman-Campito strata largely by passive stoping (Bilodeau and Nelson, 1993), whereas the yet more southerly, mid-Cretaceous, leucocratic granodiorites/granites of Birch Creek (Nelson and Sylvester, 1971) and Papoose Flat (Sylvester et al., 1978) evidently have significantly deformed their wall rocks.

Folding and faulting both preceded and accompanied emplacement of the Mesozoic plutons (Dunne et al., 1978), as indicated by locally deflected structural alignments and thermally induced stratigraphic thinning of the wall rocks (Paterson et al., 1991). Pleistocene-Holocene eastward tilting of the White Mountain block and westward tilting of the Inyo block are reflected by dipping piles of Mio-Pliocene plateau basalt and Plio-Pleistocene lake beds, respectively. The locus of the structural twist in the White-Inyo Range seems to coincide with the east-west crossfold near Westgard Pass. Glacial deposits are restricted to present high elevations. The mountains were thus low lying during Miocene basaltic extrusion, but uplifted by the time of Pleistocene alpine glaciation.

REMOTE SENSING STUDY

We employed satellite-borne Landsat Thematic Mapper (TM) and SPOT panchromatic data, airborne NS-001, and aerial photographs in our study of the Reed Dolomite (Ernst and Paylor, in review). Ground investigations included conventional geological mapping and
sample collection to check interpretations of remotely-obtained image data. Mineralogic and spectroscopic analyses of field samples were also conducted to better understand the lithologic significance of image interpretations. Descriptions of instruments and techniques utilized in this study and discussions of their geologic utility can be found in Ernst and Paylor (in review) as well as in Russell et al. (1994 [this volume]).

STRUCTURAL AND STRATIGRAPHIC INTERPRETATION

Based on integrated field mapping and multispectral scanning studies (Ernst and Paylor, in review), the lithostratigraphic succession involves six more-or-less laterally continuous units. From top down these are:

<table>
<thead>
<tr>
<th>Unit</th>
<th>New Stratigraphy</th>
<th>Old Designation</th>
</tr>
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<tbody>
<tr>
<td>6</td>
<td>Fine-grained, fissile, dull-white dolomite;</td>
<td>upper Reed Dolomite</td>
</tr>
<tr>
<td>5</td>
<td>Fine-grained, thin-bedded, sparsely oolitic buff dolomite;</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Medium-fine grained, cross-stratified, locally ochrous brown,</td>
<td>Hines Tongue Member</td>
</tr>
<tr>
<td></td>
<td>interlayered quartz arenite, tan siltstone, and sandy dolomite;</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Fine- to coarse-grained, light-gray, oolitic, massive crystalline dolomite and</td>
<td>lower Reed Dolomite</td>
</tr>
<tr>
<td></td>
<td>rare interbedded rusty quartz arenite;</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Medium-grained, white, oolitic, massive dolomite;</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Very coarse-grained, granular, gray, pisolitic, blocky dolomite.</td>
<td></td>
</tr>
</tbody>
</table>

The subunits described above have been investigated as far north as the southern border of the Barcroft Granodiorite, and as far south as the northern margin of the Papoose Flat Granite. Recognition of this stratigraphic sequence employing various techniques, as well as further field study, permitted us to differentiate extensive tracts of Reed Dolomite formerly regarded as featureless.

Conclusions newly obtained through our remote-sensing investigations are as follows:
(a) Monoclinal sections on the south side of Waucobi Embayment in the Waucoba Mountain quadrangle are confirmed as mapped previously by Nelson (1966b). (b) Massive “fingers” of Reed Dolomite, as mapped in the central Blanco Mountain quadrangle by Nelson (1966a) and Ernst and Hall (1987), are, in fact, more complex. The southernmost “finger” is a homoclinal, north-dipping section faulted on its northern margin. The next “finger” to the north consists of a faulted anticline/syncline pair. The northernmost “finger” is a syncline. (c) Other Reed units near Blanco Mountain and at the eastern limit of the Ernst and Hall (1987) map are homoclinal successions as previously concluded. (d) The variable, but great width of exposure of the Reed Dolomite northwest of the Sage Hen Flat Granite appears to reflect the presence of a north-south-trending anticlinal fold and more easterly syncline paralleling the regional strike of the various formations. This structure extends as a progressively more intensively compressed feature to the Barcroft break. (e) The discon-
Figure 3. Lateral extent of stratigraphic subunits of the Reed Dolomite, and map locations of the investigated stratigraphic columns of Figure 4 (western and eastern, north-south traverses).
Continuous limestone layers interbedded with the argillite beds in the Wyman Formation seem to be conformable with newly recognized stratigraphic subunits in the overlying basal Reed Dolomite, hence an angular unconformity at the contact between the formations appears to be unlikely.

The apparent northern limit of subunit (5), the western pinchout of the Hines Tongue (4), and the eastern limit of subunit (3) are shown in Figure 3; this illustration also indicates the map locations for the diagrammatic stratigraphic sections presented as Figure 4, in which thicknesses and lateral continuity of the newly recognized subunits are summarized. Several conclusions may be drawn from the areal variations in thicknesses for the six subdivisions of the Reed Dolomite (Figures 3 and 4). For instance, subunit (4), limonitic quartz arenite of the Hines Tongue, and underlying subunit (3), coarse-grained oolitic dolomite containing rusty quartz arenite interbeds, appear to be related, with (4) representing the more proximal facies. Provided that the correlation of Reed Dolomite with Stirling Quartzite is correct (Mount and Signor, 1991), relationships in Death Valley support this eastward increase in multicyle terrigenous material. Subunit (5), fine-grained oolitic buff dolomite directly below the capping, dull-white subunit (6), appears to thin to a feather edge.
in the northern White-Inyo Range just south of the Barcroft Granodiorite. The stratigraphic thinning observed in columnar sections H, I, J, and K, along the eastern and northern portions of the mapped area, at least in part is probably due to attenuation accompanying granitoid pluton emplacement. Thickness trends of the newly recognized stratigraphic units and facies boundaries for the Reed Dolomite and its subunits appear to strike north-south or north-northeast across the central White-Inyo Range. We interpret these trends to reflect the subdued west-northwest paleoslope inclination of the latest Precambrian-Early Cambrian shelf and continental margin (Burchfiel and Davis, 1975); in contrast, the Mesozoic structural grain strikes north-northwest (Nelson et al., 1991), providing a probable west-southwest dipping continental shelf/rise.

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