THE JURASSIC AGE OF THE LAST GRANITOID INTRUSIVES IN THE KLAMATH MOUNTAINS AND SIERRA NEVADA, CALIFORNIA.

NORMAN E. A. HINDS.

INTRODUCTION.

In the Klamath Mountains of northern California and southern Oregon are many plutonic and hypabyssal igneous bodies intruded into the crust during the mid-Mesozoic Nevadan orogeny[1] which was responsible for the deformation of a vast area of western North America, extending, as many geologists believe, from Mexico and Lower California northward to Alaska and in the United States from eastern Utah to the Pacific Coast. The time of this deformation and associated magmatic intrusion has long been debated, and geologists have variously assigned it to the Upper Jurassic and the Lower Cretaceous. Among later writers on California geology who have discussed the problem, J. P. Smith,[2] Blackwelder,[3] Knopf,[4] Schuchert,[5] and Crickmay,[6] have given the date as Upper Jurassic. In the describing the geology of the Mother Lode system of the Sierra Nevada, Knopf writes,

"The folding to which the Mariposa rocks were subjected and the intrusion of great volumes of granite into them . . . . probably took place in late Jurassic time for the revolution was of pre-Knoxville age, and the basal portion of the Knoxville is regarded by some geologists as of late Jurassic age. The Mariposa is considered to be late though not latest Jurassic and the break between the Mariposa and Knoxville does not coincide with the dividing line between the Jurassic and Cretaceous."

Schuchert states that

"Although the intrusions may have been started in middle Jurassic time, the main injections took place at the close of the

[1] For the mid-Mesozoic deformation of the western part of the Cordilleran syncline I have recently proposed the term Nevadan, Univ. of Calif. Publ., Dept., Geol. Sci., vol. **20**, p. 378, 1932, as a modification of Nevadian applied by Blackwelder in 1914.

[2] Smith, J. P., The Geologic Formations of California, Calif. State Min. Bur., Bull. **72**, pp. 32-33, 1916.

[3] Blackwelder, E., A Summary of the Orgenic Epochs in the Geologic History of North America, Jour. Geol., vol. **22**, pp. 644-645, 1914.

[4] Knopf, A., The Mother Lode System of California, U. S. Geol. Survey, Prof. Paper **117**, p. 14, 1929.

[5] Schuchert, C., Outlines of Historical Geology, New York, 1931, p. 204.

[6] Crickmay, C. H., Jurassic History of North America, Proc. Amer. Philos. Soc., Vol. **70**, p. 88 ff., 1931.

period, extending into Lower Cretaceous time, and less significant upwellings went on even to the close of the Mesozoic era."

Crickmay believes in widespread deformation with possible intrusions of granitic magma in the early Upper Jurassic (between the Callovian and Argovian stages) followed by a second disturbance also accompanied by batholithic intrusion in the late Upper Jurassic (post-Portlandian), but in the Sierra Nevada and in the Klamath Mountains there is no evidence of a two-fold orogeny.

Lindgren,[7] Knopf in an earlier paper,[8] Lawson,[9] and Matthes[10] hold that the folding and intrusion of granitoid magma in the Sierran region occurred in early Cretaceous. Both Knopf and Matthes admit the possibility of a late Jurassic date since no definite stratigraphic evidence exists in the regions which they describe; on the maps published with their reports the batholithic rocks are listed as early Cretaceous. According to Lindgren,

"The major features of the beginning of Cretaceous history in the Sierra consisted in the plication and welding of the Mariposa formation . . . . and finally the intrusion in the foundations of the range of enormous batholiths of dioritic and granitic magma."

Lawson writes of

"The great revolution which raged throughout the western margin of the continent at the end of the Jurassic. . . . . Subsequent to the folding of the region there reached the deformed and dynamically metamorphosed rocks from below great invasions of granite magma."

The granite Lawson considers to be "post-Jurassic." The seal of approval of the United States Geological Survey is set on the Cretaceous age by Miss Wilmarth[11] who classes all of the Sierran granitoid bodies as "probably Cretaceous."

[7] Lindgren, W., The Tertiary Gravels of the Sierra Nevada of California, U. S. Geol. Surv., Prof. Paper **73**, p. 44, 1911.

[8] Knopf, A., A Geological Reconnaissance in the Inyo Range and the Eastern Slope of the Sierra Nevada, California, U. S. Geol. Surv., Prof. Paper, **110**, 1915.

[9] Lawson, A. C., The Cordilleran Shield, Proc. Third Pan-Pacific Sci. Cong., Tokyo, p. 375, 1926.

[10] Matthes, F. E., Geologic History of the Yosemite Valley, U. S. Geol. Surv., Prof. Paper **160**, 1930.

[11] Wilmarth, M. Grace, Names and Definitions of the Geologic Units of California, U. S. Geol. Surv., Bull. **826**, 1931.

Matthes,[12] in a recent publication notes that

"At least two mountain systems have in turn occupied the place on which the present Sierra fault block now stands; the first was probably developed toward the end of Carboniferous time while the second was formed either at the end of the Jurassic period or at the beginning of the Cretaceous, and it was under and into the folds of this system that the magma of the compound batholith were poured."

Ernst Cloos[13] and Knopf[14] subscribe to this opinion.

Diller[15] and Ferguson,[16] discussing the geology of the Klamath Mountains, consider that the deformation and batholithic intrusion occurred either in the late Jurassic or early Cretaceous while Graton[17] believes that these events marked the close of Jurassic history in this region. J. P. Smith[18] states that

"In the Klamath Mountains of Siskiyou, Shasta, and Del Norte counties, there are numerous batholiths of granite rocks, very like those of the Sierra Nevada, and supposed to belong to the same period. But since no fossiliferous sediments of later age than Upper Carboniferous are invaded by those rocks, no definite age can be assigned to them. And since the batholiths are isolated, we do not know that they belong to one great intrusive mass."

SOUTHERN KLAMATH MOUNTAINS.

In the southern Klamath Mountains, which suffered intense folding during the Nevadan deformation, much evidence has been secured which permits a more accurate dating of that event. In this region, the youngest formation involved in the folding is the Potem (Plate I, Jp), a thick series of marine sediments and volcanics originally classed as Liassic by Diller[19] on the basis of paleontologic studies made by Hyatt.

[12] Matthes, F. E., Geography and Geology of the Sierra Nevada, XVI International Geol. Cong., Guidebook 16-Excursion C-1, pp. 33-34, 1933.

[13] Cloos, E., Structure of the Sierra Nevada Batholith, XVI International Geol. Cong., Guidebook 16-Excursion C-1, p. 40, 1933.

[14] Knopf, A., The Mother Lode System, XVI International Geol. Cong., Guidebook 16-Excursion C-1, p. 46, 1933.

[15] Diller, J. S., The Redding Folio, U. S. Geol. Surv., No. 138, p. 8, 1906.

[16] Ferguson, H. S., Gold Lodes of the Weaverville Quadrangle, U. S. Geol. Surv., Bull. **540**, p. 27, 1914.

[17] Graton, L. C., The Occurrence of Copper in Shasta County, California, U. S. Geol. Surv., Bull. **340**, p. 85, 1914.

[18] Smith, J. P., The Geologic Formations of California, Calif. State Min. Bur. Bull. **72**, p. 40, 1916.

[19] Diller, J. S., op. cit., p. 1.

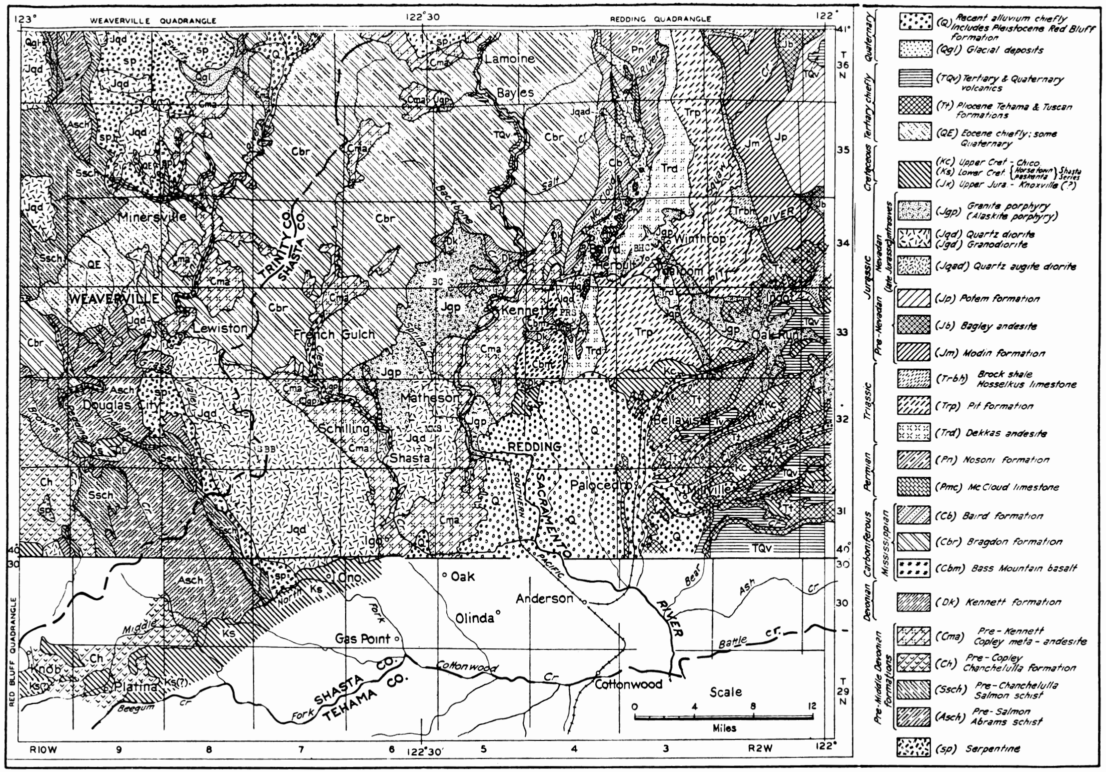

Plate I. Geologic map of the Redding and Weaverville quadrangles and the northwestern part of the Red Bluff quadrangle, northern California.

Redding quadrangle by J. S. Diller (1906), revised in part by N. E. A. Hinds and R. Dana Russell; Weaverville quadrangle by N. E. A. Hinds (1925-1930); northwestern part of Red Bluff quadrangle by N. E. A. Hinds and R. Dana Russell (1929).

Crickmay[20] has recently assigned the Potem to the Ludwigian stage of the Middle Jurassic. Later Jurassic beds may lie under the lava cap of the Cascade province which joins the Klamath Mountains on the east and which overlaps the Middle Jurassic and earlier formations. The great thickness of late Jurassic strata at the north end of the Sierra Nevada 50 miles to the south and the close relation of the Sierra Nevadan and Klamath provinces prior to the Nevadan deformation strongly suggest this. Below the Potem is a wide sequence of formations belonging to the Middle and Lower Jurassic, the Triassic, Permian, Lower Carboniferous, and Devonian; below the Devonian are at least four thick formations of unknown age. These have been described chiefly by Hershey, Diller, J. P. Smith, Ferguson, and Hinds.

The principal igneous bodies intruded into the crust in the southern Klamath region during the Nevadan orogeny are stocks, bosses and a small batholith of quartz augite diorite, a huge plutonic dike of quartz augite diorite, and two chonoliths of sodic granite porphyry. Many plutonic and hypabyssal dikes, sills and small, irregularly shaped bodies are also present. Some of these can be traced as offshoots of the larger masses; others are isolated but evidently are of the same age. Field relations show that all of these bodies, large and small, were not intruded at the same time but that they were intruded in successive stages during a single magmatic epoch. Northward in this province are other stocks, bosses, and small batholiths of quartz diorite and granodiorite very probably belonging to the Nevadan group. Older intrusives of Mesozoic and Paleozoic age, chiefly diorites and gabbros, are also present in considerable numbers, but are easily distinguishable from the Nevadan group.

The earliest of the major Nevadan intrusives is a great plutonic dike of quartz augite diorite (Plate 1, Jqad) which I have called the Redding dike[21]; this body runs through the north central part of the Redding quadrangle into the Shasta district to the north and is more than 25 miles long and a maximum of 2.5 miles wide. The offshoots and isolated bodies are numerous, especially on the west side of the dike, where they cut chiefly the pre-Middle Devonian Copley meta-ande-

[20] Crickmay, C. H., op. cit., p. 29.

[21] Hinds, N. E. A., Intrusive Rocks in the Southern Klamath Mountains, California, Bull. Geol. Soc. Amer., vol. **40**, p. 170, 1929.

site and the Mississippian Bragdon and Baird formations. On the eastern side, apophyses extend from the main body into the Permian McCloud limestone and Nosoni formation and into the Triassic Pit formation; Diller[22] reports prominent dikes of this rock cutting Middle Jurassic strata on the south slopes of Bagley Mountain in the northeast corner of the Redding quadrangle.

Of probably slightly later age are two chonoliths of sodic granite porphyry. One of these, the Balaklalla chonolith (Plate 1, BC), lies on both sides of the common boundary between the Redding and Weaverville quadrangles west of the Sacramento River; the second, the Bully Hill chonolith (Plate 1, BHC), extends from the Bully Hill mining district in the central part of the Redding Quadrangle eastward into the western part of the Lassen Peak Quadrangle. The Balaklalla porphyry cuts only Paleozoic rocks; the main part of the Bully Hill body cuts Triassic rocks, but certain offshoots and isolated masses intrude Modim strata, the lowest Jurassic of the region. The two porphyries are similar in external appearance, in texture, in mineral and chemical composition, in degree and type of weathering and in extent of hydrothermal alteration. This close resemblance indicates that they were intruded at the same time. No field evidence supports the relative dating of the Redding dike and the granite porphyries, but indirect evidence subsequently presented suggests this relation.

Closely following the rise of the granite porphyry magma came greater floods of somewhat more basic magma which solidified in the southern Klamath Mountains as quartz diorite; to this phase of the Nevadan eruptive cycle belong numerous stocks, bosses, a small batholith, and a host of plutonic and hypabyssal dikes and small irregular bodies. Farther to the north some of the plutonic intrusives are composed of granodiorite rather than quartz diorite.

One stock, the Mule Mountain (Plate 1, MMS), is in contact with the Balaklalla chonolith along its southeastern side. Apparently this contact is intrusive, but so closely did the second magma follow the first that no definite contact can be drawn between the two bodies. A zone in which the granite porphyry is more coarsely crystalline than the normal type and in which the quartz diorite is unusually quartzose, separates the

[22] Diller, J. S., The Redding Folio, U. S. Geol. Surv., Geologic Atlas of the United States, No. **138**, p. 9, 1906.

main parts of the two bodies; along this contact it might appear that the granite porphyry forms the salic roof of a huge intrusive and at depth is transitional into the somewhat more basic quartz diorite. Other evidence, however, makes certain the later intrusion of the Mule Mountain stock. To the west of this body and separated from it by a roof pendant of pre-Devonian Copley meta-andesite is the small Shasta Bally quartz diorite batholith (Plate 1, SBB), emplaced apparently at the same time as the Mule Mountain stock and probably continuous at depth with that body. Intruding the roof pendant are dikes of granite porphyry some of which can be traced as offshoots of the Balaklalla chonolith while others are separated from it. In its narrowest part, the rock of the roof pendant has been metamorphosed to chlorite schist, while to the north and south this highly metamorphosed phase passes by gradual transitions into normal, massive meta-andesite. In like manner, the granite porphyry dikes in the narrowest portion of the roof pendant have been converted into quartz sericite schist, while to the northward in the direction of the chonolith the metamorphism is less intense and gradations into the normal massive granite porphyry are present. Thus it is evident that the chonolith and its offshoots antedate both the Mule Mountain stock and the Shasta Bally batholith.

The small Pit River stock of quartz diorite (Plate 1, PRS), almost identical in physical appearance, texture, and mineralogy with the Mule Mountain stock and probably intruded at the same time, transgresses the southern end of the Redding quartz augite diorite dike. The close time relation of the granite porphyry and the quartz diorite stock and the fact that the Pit River stock cuts the Redding dike indicate that the latter body was intruded before the chonoliths.

Other stocks, batholiths, and bosses are present throughout the Klamath Mountain province but most of them cut only Paleozoic and possibly pre-Paleozoic rocks. Certain of these bodies intrude serpentines, but, unfortunately, nothing is known regarding the age of the Klamath serpentines. Classification of these granitoid bodies as Nevadan is not positive, but is strongly indicated by the physical, chemical, and mineralogical similarity of their rocks to those of the Shasta Bally batholith and the Mule Mountain and Pit River stocks whose time of intrusion seems clear. Furthermore, the stage and type of weathering and the degree of hydrothermal alteration are the same in all of these bodies. Indirect evidence thus is strongly in favor of the assumption that they were intruded during a single magmatic epoch. Furthermore, these bodies are distinct in physical characters and mineralogical composition from a group of small granitoid bodies also widely distributed throughout the province which are probably late Paleozoic in age; these are dominantly dioritic and gabbroid and all show extensive recrystallization of their minerals.

Many dikes, sills and small irregular intrusives also belong to various stages of Nevadan intrusive epoch. Some of these intrude the Liassic Modim and the Middle Jurassic Potem beds and débris from them is found in the overlying Cretaceous strata.

Thus the field evidence shows definitely that the Redding dike, the chonoliths of granite porphyry, the Mule Mountain and Pit River stocks, and the Shasta Bally batholith were intruded during the Nevadan folding which involved the Middle Jurassic and all earlier strata in the Klamath province and that probably all of the similar large granitoid bodies throughout the province were intruded during this disturbance.

Regarding the date of orogeny and vulcanism the following evidence is presented. The youngest strata involved in the Nevadan deformation are located in southeastern part of the Klamath Mountains where the number of intrusives is least. Fortunately, however, a few bodies are present which provide highly important evidence relating to the problem. As previously noted, the Bully Hill granite porphyry chonolith intrudes Middle and Upper Triassic Pit (Muschelkalk and Karnic) strata and its apophyses and disconnected offshoots intrude the Upper Triassic (Karnic and Noric) Hosselkuss limestone, the Upper Triassic (Noric) Brock shale, and the Liassic Modim formation. Dikes, petrographically similar to the rock of the Redding quartz augite diorite dike and Nevadan dikes of other petrographic types, cut the Liassic Modim and Ludwigian Potem strata. Thus the folding and intrusion of granitoid magma are definitely post-Potem Middle Jurassic.

Overlying the deeply eroded and steeply dipping beds of this folded complex at the north end of the Sacramento Valley are Lower and Upper Cretaceous formations which are composed largely of detritus carried into advancing oceans from the Nevadan Mountains. In one place only along the contact between the Superjacent and Subjacent series do the Cretaceous strata overlie a Nevadan granitoid intrusive. From about one-half mile west of Igo (a small settlement 12 miles southwest of Redding, county seat of Shasta County) to the North Fork of Cottonwood Creek eight miles farther west, Lower Cretaceous strata were deposited over the Shasta Bally batholith (Plate 1, SBB). At the base of the Cretaceous sequence are local stretches of conglomerate in which abundant boulders of the Shasta Bally quartz diorite embedded in coarse gravel made chiefly of relatively unweathered plagioclase, quartz, and biotite evidently derived from the same body. Elsewhere are coarse arkoses and arkosic sandstones, and a few layers of conglomerate and shale, while at still higher horizons the Lower Cretaceous is dominantly shaley. Lower Cretaceous fossils present at many horizons show that the strata in contact with the batholith range from Middle Paskenta (Valanginian) on the western side to Lower Horsetown (Hauterivian) on the eastern according to information furnished me by Dr. F. M. Anderson[23] who has been making an extensive study of the Cretaceous of the northern part of the Sacramento Valley. From west to east along this contact, younger strata progressively overlap the older.

According to my field assistant, Dr. R. Dana Russell,[24] who mapped and studied the Cretaceous along the contact with the deformed bedrock series in the northwestern part of the Red Bluff quadrangle, pebbles of quartz diorite identical with those of the various Nevadan intrusives are present in various proportions along the contact from Igo to Noble Station, 22 miles to the southwest in the northwestern corner of the Sacramento Valley (Plate 1). Stratigraphically the pebbles are found from the uppermost Horsetown (Barremian) to the basal Paskenta (Infra-Valanginian), that is from the top to the base of the Lower Cretaceous. Whether the Upper Jurassic Knoxville overlies the Klamath complex in this region has not been determined; strata are present in the northwest corner of the Sacramento Valley (Plate 1, JK?) which bear close lithologic resemblance to the Knoxville of type sections farther south, but so far have yielded no fossils.

In the Weaverville quadrangle east of Igo and in the Redding quadrangle, only Upper Cretaceous strata overlie the folded complex. Detritus from Nevadan granitoid bodies, chonoliths, and dikes is abundant in these beds.

Thus field evidence proves that, before the invasion of the

[23] Anderson, F. M., Personal communication.
[24] Russell, R. Dana, Personal communication.

earliest Cretaceous seas and subsequent to the Middle Jurassic Potem epoch, the crust in the Klamath region had been folded, intruded by floods of granitoid magma, and deeply enough eroded to expose considerable portions of certain of the granitoid bodies. If strata of Knoxville age overlie the Subjacent Complex, then the deformation occurred between the Middle Jurassic Potem and the late Upper Jurassic Knoxville epoch. Detailed field studies are needed to determine this important point. Certain is the fact that the folding and associated intrusion occurred in late Jurassic time in the Klamath region and that it was accomplished during a single epoch. There is no evidence of two Jurassic deformations such as Crickmay[25] has sought to establish. Unconformities separate the various members of the Jurassic in the southeastern Klamath, but these unconformities are erosional and not angular. Volcanic activity occurred in Liassic Modim time and twice during the Middle Jurassic (Bagley and Potem epochs), but is distinct from that associated with the great orogeny. The dominant magma erupted during the pre-Nevadan Jurassic crystallized as pyroxene andesite and basalt, while the Nevadan magma produced chiefly quartz diorite, granodiorite, and granite porphyry. The Potem and earlier Jurassic volcanics show a considerable amount of recrystallization while the Nevadan rocks exhibit practically none. Also the earlier Jurassic activity produced great volumes of extrusive rocks, while none have been identified as of Nevadan age.

The data above presented have an important bearing on the age of the granitoid rocks in the nearby Sierra Nevada. Though the Klamath and Sierra Nevada provinces are now separated by an area blanketed with relatively undeformed Cretaceous and later deposits, much of the region during epochs of pre-Nevadan time formed a continuous basin of deposition for either marine, continental, or volcanic deposits. The similarity of many Paleozoic and Mesozoic formations in the Redding district of the southern Klamath and in the Taylorsville district of the northern Sierra Nevada was long ago demonstrated by Diller.[26] The entire region apparently was folded into mountains during the Nevadan deformation. Where the folded trends of the southeastern Klamath pass

[25] Crickmay, C. H., Jurassic History of North America, Proc. Amer. Philos. Soc., vol. **70**, pp. 88 ff., 1931.

[26] Diller, J. S., Geology of the Taylorsville District, California, U. S. Geol. Surv., Bull. **353**, 1908.

under the mantle of later rocks, they have approximately the same orientation as those of the northwestern Sierra Nevada where they in turn disappear beneath the southern margin of this mantle. It thus appears that, at the close of the Nevadan orogeny, a continuous belt of mountains extended from Oregon and northern California into the present Sierra Nevada region. These mountains wasted away rapidly, but certain sections were rejuvenated in Cretaceous time. During this period a portion of the belt became a basin of marine deposition, and, in the Tertiary and Quarternary, was further covered by continental sediments and volcanics. Thus was the continuity of the folded belt destroyed, and the Klamath Mountains were isolated from the Sierra Nevada.

During this orogeny, granitoid magmas were intruded on a vast scale into the Sierra Nevadan section of the folded crust, and their solidified equivalents have been extensively exposed by subsequent erosion. In a few places granitoid intrusives cut Upper Jurassic Mariposa beds; as previously noted, the Mariposa is late but not latest Jurassic in age. Cretaceous rocks overlie the Nevadan bodies at various localities, but nowhere is this Cretaceous older than the Chico. It thus appears that the folding and igneous invasion in the Sierran Nevada postdates the Mariposa deposition and antedates the submergence beneath Chico seas. Reasoning from the relations previously described from the Klamath Mountains, both events took place before the opening of Cretaceous time.

Since this manuscript was written, N. L. Taliaferro has informed me that his detailed studies of many sections of the Mesozoic formations in the southern Sierra Nevada show that in places the Upper Jurassic Mariposa formation was deposited on moderately flexed beds of probably early Jurassic age. Neither the extent of the folding nor the exact age of the latest strata involved in the deformation have been determined; from evidence now at hand Taliaferro does not consider the folding to have been widespread.

University of California,
Department of Geological Sciences,
Berkeley, California.