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R. C. SPEED Department of Geological Sciences, Northwestern University, Evanston, Illinois 60201

Evaporite-Carbonate Rocks of the Jurassic Lovelock Formation, West Humboldt Range, Nevada

ABSTRACT

The Lovelock Formation is an assembly of late Early Jurassic or Middle Jurassic carbonate rocks and gypsum that constitute the youngest preserved sediments and, probably, the last marine deposits in successions of Jurassic rocks in the Carson Sink region of western Nevada. The formation records a set of transitional environments between open marine basinal conditions and an emergent tectonically active terrain. The current extent of the formation is probably a small fraction of its original distribution in the Carson region and, perhaps, in areas of Nevada farther west.

The Lovelock Formation occurs only in a pair of nappes in the nappe pile of the northern West Humboldt Range. Geometric relations between intranappe and internappe folds suggest that nappe emplacement and folding were coupled deformations in major Middle Jurassic tectonism. Sites of deposition of the Lovelock Formation were probably not more than a few kilometers east or west of current exposures of the formation.

The formation is comprised of three members in a maximum thickness of about 200 m. The lowest is a micrite which underwent emergence and fresh-water diagenesis before deposition of fragmental limestones of the middle member. Conglomerate of the middle member consists exclusively of intraclastic micrite pebbles from the lower member. Finer grained sedimentary breccia above the conglomerate is an accumulation of intraclasts and allochthonous particles from a variety of subenvironments on a carbonate bank. The upper member comprises gypsum and calcarenite, deposited at least in part in standing water of a barred basin. The sequence of motions of the sediment surface relative to sea level recorded in the deposits of the Lovelock Formation is conceivably due to eustatic variations, but the general temporal proximity of deposition of the formation to major tectonism suggests that such motions were probably tectonic.

Postdepositional hydrothermal recrystallization occurs sporadically in carbonate rocks of the Lovelock Formation. Such metamorphism was perhaps synchronous with local generation of solution breccias in the upper member and local calcitization of sulfate.

INTRODUCTION

Gypsum and carbonate rocks, here named the Lovelock Formation, constitute the apparently youngest marine deposits in early Mesozoic sedimentary successions exposed in the West Humboldt Range, Nevada (Fig. 1). Outcrops of the formation are limited to a pair of nappes in an area of only a few square kilometers. It is likely, however, that the preserved deposits of the Lovelock Formation are a vestige of a once more extensive lithic unit in the Carson Sink region and perhaps, in areas farther west. The rocks of the formation record paleoenvironments that were transitional from open marine basinal conditions in Lower Jurassic time to an apparently emergent, tectonically active terrain in upper Lower Jurassic or Middle Jurassic time. Thus, the Lovelock Formation and the probably correlative Boyer Ranch Formation (Speed and Jones, 1969) east of the Carson Sink were the last marine sediments of the Carson region and were deposited at the onset of or during major tectonism. This paper examines the stratigraphy and lithology of the Lovelock Formation with a view toward interpretation of its depositional and tectonic history.

Aside from its paleoenvironmental significance, the Lovelock Formation provides a key to certain lithic and structural problems of the Carson Sink region. The nappes that contain the Lovelock Formation in the northern West Humboldt Range (Gypsum Mtn., Fig. 1) occur in a pile of nappes of lower Mesozoic rocks. Nappe piles of essentially similar rocks exist farther south in the West Humboldt Range and at places in the Stillwater Range to the east across the Carson Sink. A major exception to the uniformity of the lithic assemblies of such nappe piles is that the Lovelock Formation is apparently absent from nappes of the Carson region (other than the nappe pair at Gypsum Mountain). The highly restricted occurrence of the formation has been puzzling, considering that associated early Mesozoic pelites are so widely distributed.

Nappe piles of the Carson region, however, contain a number of laterally extensive tabular bodies of carbonate breccia and marble which are apparently much like the rauhwackes[1] of the alpine chains (Leine, 1971). In the Carson region, the marble in such bodies is believed to have originated by calcitization of gypsum and the breccia by compaction and collapse of carbonate residua during aqueous dissolution of the remaining sulfate (Speed, 1974). The extent of the carbonate bodies in the Carson region indicates that precursor gypsum was widespread. There is no recognized stratigraphic interval of sulfate rocks in the Carson region other than that in the Lovelock Formation, and by correlation, it follows that the Lovelock Formation was similarly widespread. Support for the correlation is derived from the existence of small bodies of marble and breccia in the gypsum unit of the Lovelock Formation. Study of the Lovelock Formation thus provides the "initial conditions" for calcitization and brecciation in the production of the Carson rauhwackes. Description of the rauhwackes and the transforming processes is presented elsewhere (Speed, 1974; Speed and Clayton, 1974).

Earlier mention of rocks of the Lovelock Formation was made by Louderback (1904) and by Stone and others (1920), but they did not provide a correct stratigraphy because of unresolved structural complications. Wallace and Silberling (1962) give a reconnaissance cross section which includes rocks of the Lovelock Formation approximately along the same line as section AA′ of Figure 2 of this paper.

LITHIC UNITS OF THE NORTHERN WEST HUMBOLDT RANGE

The Lovelock Formation crops out entirely in the northern West Humboldt Range, Nevada, about 8 km northeast of Lovelock. It occurs in a relatively complete but structurally complicated succession of Lower Jurassic and Upper Triassic sedimentary rocks, together with minor breccia and igneous rock. The lithic units

[1] Rauhwacke: name applied in Europe, especially in the Alps, to laterally extensive tabular bodies of porous carbonate breccia or rocks in which carbonate breccia is the major constituent (Leine, 1971). *In the alpine chains, rauhwackes are frequently nappe soles.* I import the name as a convenient and general lithic descriptor. There is no genetic connotation involved.

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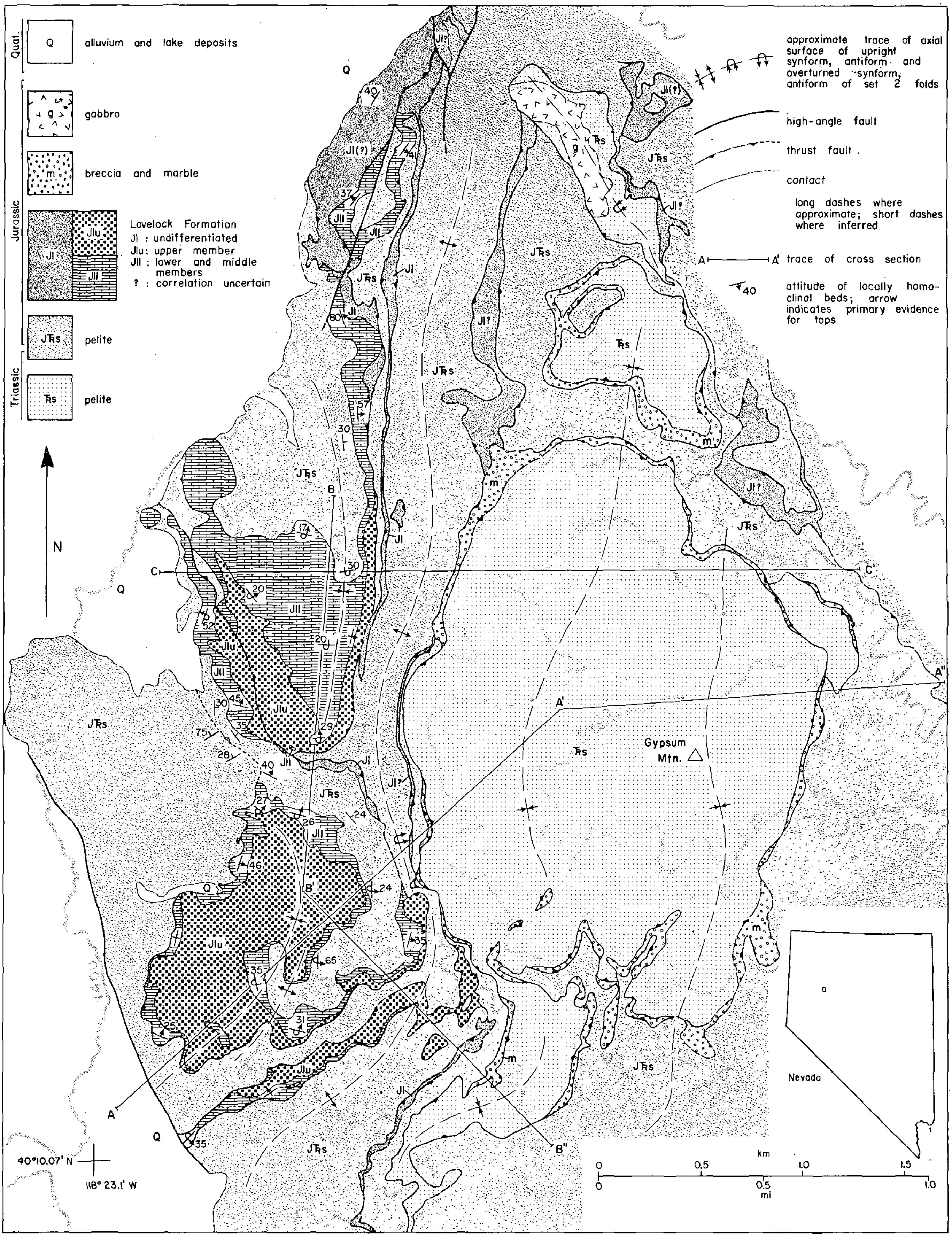

Figure 1. Geologic map of the Gypsum Mountain area, northern West Humboldt Range, Nevada, showing outcrop extent of Lovelock Formation and probable correlatives (Jl?) at the same structural level. Cross sections in Figure 2. Topography from U.S. Geological Survey Lovelock (1:62,500) quadrangle; elevations in feet.

associated with the Lovelock Formation are briefly described below, and their distributions are shown in Figure 1.

Pelite[2], Principally Lower Jurassic (J₨s)

The volumetrically predominant rocks of the area of Figure 1 are light colored, laminated to thin-bedded mudstone and siltstone. They contain minor thin to medium beds of calcareous sandstone and thin-bedded to massive sandy, silty, and stromatolitic dark limestone. Fossils obtained in the unit indicate Early Jurassic Hettangian, Sinemurian, and Toarcian ages. The youngest fossils (early Toarcian) are *Harpoceras* sp., identified by N. J. Silberling, which have been collected at several localities in the area of Figure 1 by Silberling and by me. The Lower Jurassic pelites exhibit no recognized stratigraphic succession of lithic variations. Thus, in the area of Figure 1 where probably all the rocks are in thrust nappes, allochthonous bodies of pelite cannot be assigned to a particular stratigraphic position in the succession by lithology. As a unit, however, the Lower Jurassic pelites are lithologically distinct from most Triassic pelitic rocks which constitute the other widespread unit of pre-Tertiary layered rocks of the Carson region.

Sulima (1970) studied an apparently continuous section of Lower Jurassic pelite in Coal Canyon 2 km north of the area shown on Figure 1. He found at least 1,000 m of Hettangian rocks which are conformable above Triassic (Norian) pelite. The Triassic rocks are largely dark slate which contrast strongly with the Jurassic pelite. An unfossiliferous interval about 100 m thick occurs above the Triassic slate in rocks lithologically similar to the Jurassic pelite. The systemic boundary could thus occur within the light-colored, more calcareous higher pelite succession; such rocks are here called J₨s, though most of them are Lower Jurassic. The Lovelock Formation lies conformably above pelite of this unit.

Triassic Pelite (₨s)

Slaty light- to dark-green mudstone and siltstone, minor micaceous sandstones, and dark limestone make up the Triassic pelite unit. Abundant *Monotis subcircularis* and other fossils indicate the unit is Norian (late Late Triassic). Triassic pelite in the area shown on Figure 1 occurs only in the youngest nappe of the pile.

Marble and Carbonate Breccia (m)

A deformed tabular layer of marble and carbonate breccia (rauhwacke) occurs as the second highest nappe (Fig. 2) in the succession of nappes in the northern West Humboldt Range. The marble is a coarse-grained tectonite; the carbonate breccia consists of marble and calcarenite clasts in a matrix of calcite-quartz sand.

Gabbroic Rocks (g)

A small body of anorthosite and anorthositic gabbro intrudes Triassic pelite of the highest nappe in the northern part of the area of Figure 1. The thrust that bases the nappe cuts both the Triassic pelite and igneous rocks, indicating that the igneous rocks are allochthonous. Jurassic pelite in the subjacent nappe, however, is slightly metamorphosed within a few meters of the igneous rocks, indicating that final cooling was essentially synchronous with emplacement of the nappe occupied by the gabbroic rocks. The gabbroic rocks are an outlier of an extensive body of gabbro farther south in the West Humboldt Range, where evidence indicates that intrusion was concurrent with emplacement of the highest nappe of the pile (Speed, in prep.). A K-Ar age of hornblende from gabbro 11 km south of the body shown in Figure 1 is 163 m.y., and there is little question that the two bodies are coeval. An age of 163 m.y. is Middle Jurassic, probably Bathonian (late Middle Jurassic; Howarth, 1964).

[2] Use of the word "pelite" as a lithic descriptor connotes a very high proportion of intercalated silicate mudstone and siltstone which may locally grade to fine-grained hornfels or tectonite.

STRUCTURE

The objectives here are to provide an understanding of macroscopic structure of the Lovelock Formation as a context for stratigraphic discussion. Space does not allow analysis of data from minor structures that indicate the deformation and transport history of the formation; the latter data will be presented elsewhere, but some conclusions are mentioned here.

All of the rocks in the area shown on Figure 1 are allochthonous, and they are contained in a vertical succession of folded nappes[3] of which there is perhaps a total of seven in the northern West Humboldt Range. Thrust boundaries of the upper four nappes are shown in Figures 1 and 2. The numbers on thrust traces in Figure 2 indicate the vertical succession of nappe boundaries and the correlation of thrusts across eroded intervals. Thrusts are easy to trace where they juxtapose different lithologies, but they are difficult to follow where they separate bodies of similar rocks, especially Jurassic pelite. Thrusts at structural levels below those shown in Figure 2 are locally recognized just north of the area of Figure 1, but their traces cannot be continued as far south as Gypsum Mountain. The implication is, however, that Jurassic pelites structurally below the Lovelock Formation are allochthonous and may comprise several nappes.

The Lovelock Formation occurs in a pair of nappes, here called the "gypsum nappes," that lie between thrusts 3 and 4 of Figure 2. The gypsum nappes contain, as well, Jurassic pelite that is stratigraphically concordant to the Lovelock Formation. Boundaries of the gypsum nappes are located with certainty except along the west side of the southern nappe (Fig. 1) where the thrust apparently occurs within Jurassic pelite. The northern gypsum nappe overlies the southern one, such that thrust 4a on Figure 2 is younger than 4b. The lateral proximity of the two gypsum nappes and their occurrence at the same general structural level in the pile of nappes at Gypsum Mountain, however, suggest that the two gypsum nappes were originally continuous and were imbricated during or after emplacement.

Relations between folds in the Gypsum Mountain area (Fig. 1) provide a basis for interpretations of the tectonic history of the Lovelock Formation. Beds of the Lovelock Formation are deformed in three sequential fold sets, of which the first (set 1) consists of intranappe folds; the others (sets 2, 3) fold both beds and nappes. Major folds occur in all sets, but minor folds are recognized only in sets 1 and 2. Axial plane foliation and lineation are well developed in gypsum of the Lovelock Formation, but they are sparsely measured owing to the paucity of exposed gypsum rock. In contrast, penetrative structures are rare in carbonate rocks of the formation.

Within the gypsum nappes, the Lovelock Formation and its substrate occur in recumbent major folds (Fig. 2). The general orientation of tops of beds in the recumbent folds is indicated by arrows in Figure 2 as determined from cross-bedding in the lower member, where it is locally homoclinal. The recumbently folded members are at places truncated by the thrusts at the nappe bottoms, and such folds were clearly formed before final nappe emplacement. Pre-emplacement folds thus constitute set 1. Amplitudes of the major folds of set 1 exceed the width of outcrop of the Lovelock Formation, and it is difficult to determine the position and direction of the trace of axial surfaces of such folds. Analysis of minor folds believed to be cogenerate with the recumbent major folds, however, indicates that the original axial traces of set 2 folds are generally northerly, and their axes are essentially horizontal.

Folds of set 2 involve both the gypsum nappes and adjacent pelite nappes and are thus clearly later than the intranappe folds of set 1.

[3] Nappe: discrete allochthonous tectonic unit of mappable size, as modified from recommended usage of Dennis (1967). There is no constraint of detachment, displacement, or nature of internal structure. Structurally continuous rocks of the upper plate of a thrust fault constitute a nappe, but upper plates of extensive master thrust faults may comprise an assembly of nappes.

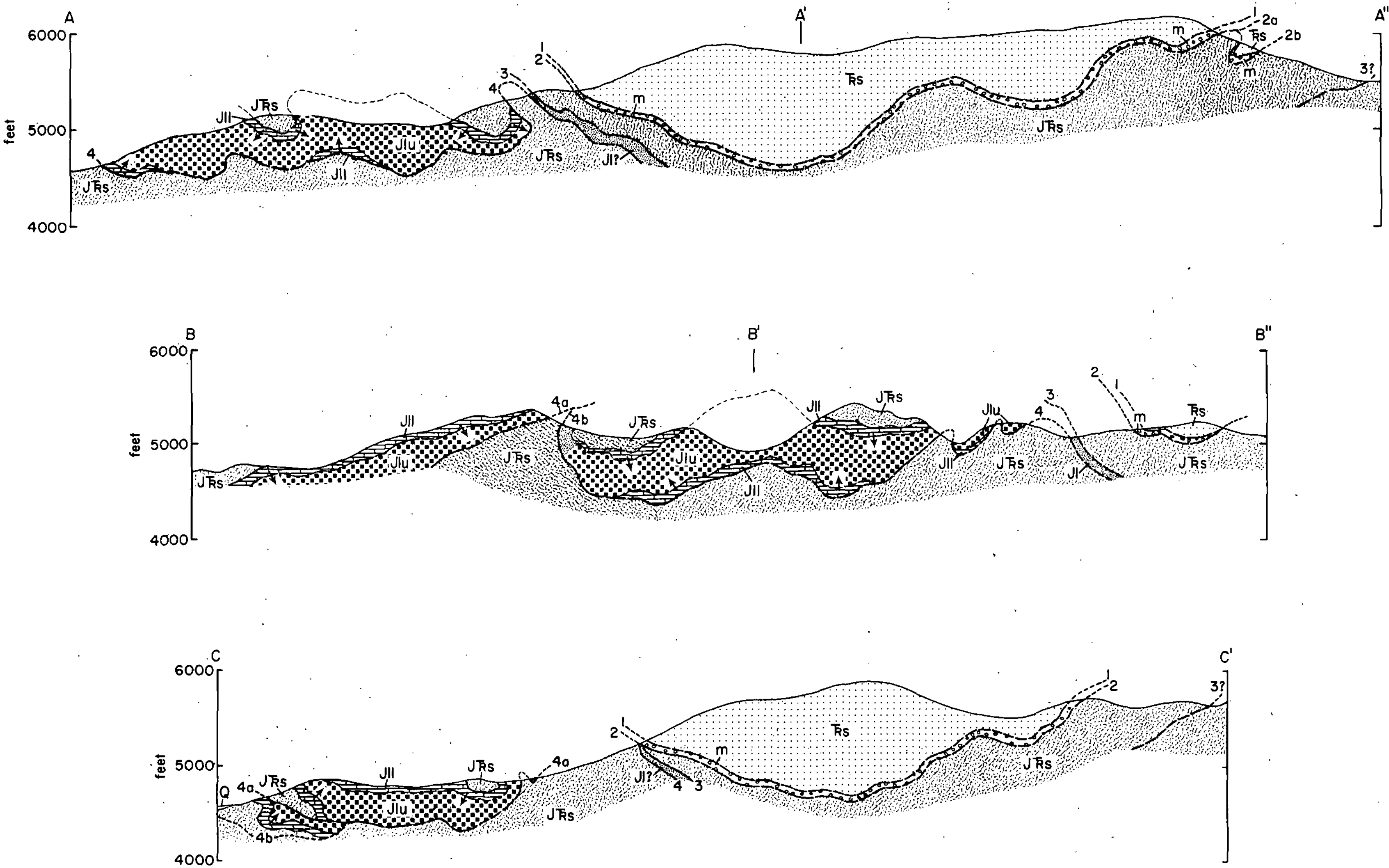

Figure 2. Geologic cross sections in the Gypsum Mountain area along traces shown in Figure 1. Symbols for lithic units and line weights for unit boundaries same as in Figure 1. Arrows in unit Jll indicate stratigraphic top in locally homoclinal segments. Numbers on thrust traces indicate generally downward sequence of nappe bottoms; 4 is bottom of gypsum nappe pair, subdivided to 4a and 4b where the separate nappes can be identified.

The major pattern of lithic units in the Gypsum Mountain area is largely due to set 2 folds, and folds of thrusts shown in the sections of Figure 2 are chiefly of set 2, except in the interval, BB′. Axial traces of folds of set 2, like those of set 1, are generally northerly, and axes similarly plunge shallowly. Figure 1 displays approximate axial traces of major folds of set 2, the variability of which is due to folds of set 3. Folds of set 2 comprise a spectrum of wave lengths, limb appressions (tightness), and inclinations of axial surface. The synform of the lowest harmonic recognized has a half wave length $\geqslant$ 2 km; its axial trace passes through Gypsum Mountain. The west limb of the synform exposes the lower nappes in the pile, including the gypsum nappes. Smaller wave-length folds of set 2 have axial planes that dip variably with easterly and westerly components. The variable dips indicate coaxial refolding or, possibly, remarkable divergence of the axial planes of the higher frequency folds on the limbs of the major folds[4].

Folds of set 3 consist of broad open folds with essentially easterly axial traces.

The coaxiality of the intranappe folds (set 1) and those of set 2, together with the generally similar variability of axial planes[5] of folds of the two sets, provides grounds for the proposition that the two sets were produced in a continuum of deformation rather than in tectonically discrete phases. The continuum hypothesis implies that nappe motion was adjunct to regional folding and was such that there was little rotation of set 1 axes relative to fold axes of set 2. Further, the occurrence of the Gypsum Mountain nappe pile in a major synform of set 2 implies that nappe transport was directed toward the developing synform. If the hypothesis is correct, the Gypsum Mountain synform was a nappe sink. The corollary is that nappe sources were upfolds, and if motion was generally normal to axes of folds of sets 1 and 2, such upfolds lay east and west of the northern West Humboldt Range. There is no clear interpretation of whether nappe motion was uphill or downhill, although the apparent lack of rotation of set 1 folds may be suggestive that the nappes were not detached gravity slides.

Dated gabbroic rocks (163 m.y. old) are deformed by set 2 folds and are essentially contemporaneous with emplacement of the highest nappe. Thus, deposition and deformation of the Lovelock Formation occurred during upper Lower Jurassic–Middle Jurassic time.

Evidence for the source and transport distance of the gypsum nappes is circumstantial. The hypothesis given in a previous paragraph suggests transport of the gypsum nappes either grossly east or west into a synclinal trough; the displacement would have been up to a half wave length of the major folds which regionally seems to be 4 to 9 km. The highest nappe in the West Humboldt pile probably came a few kilometers from the east or southeast, but there is no necessary association of the direction of displacement with that of the earlier gypsum nappes. Moreover, the multiplicity of nappes in the West Humboldt Range and their lithic homogeneity (chiefly Lower Jurassic rocks) suggest they had local derivation and small displacements, because rocks alien to those in the nappes and to Mesozoic rocks generally in the Carson region have not been mixed in the nappe pile. Although the arguments are not compelling, I believe the gypsum nappes were derived a few kilometers west or east of their current position and that such positions may be grossly taken as the depositional sites of the Lovelock Formation relative to the pelite substrate.

LOVELOCK FORMATION

Formation Characteristics

The Lovelock Formation comprises three informal members: a lower member of dark limestone, a middle member of limeclast conglomerate and microbreccia, and an upper member of gypsum and interbedded calcarenite. The formation is variably 25 to 200 m thick. Figure 1 shows the extent of the Lovelock Formation. It is locally differentiated in two map units, upper and lower + middle, the middle member being too thin to show separately. Elsewhere, the formation is undifferentiated either where tight folding makes the members difficult to show or where the formation consists chiefly of carbonate breccia. Such breccia is due largely to the accumulation of limestone fragments during dissolution of gypsum, as discussed later. Hence, much of the undifferentiated Lovelock Formation on Figure 1 originally consisted dominantly of the upper member. Erosionally isolated bodies of carbonate breccia and recrystallized limestone are called Jℓ? if they occur at the same structural level as the Lovelock Formation. The uncertainty in correlation is that, in principle, one or more of such bodies could represent the feather edge of some other nappe (or nappes) that lies between thrusts 3 and 4 as shown on Figure 2. The lithic similarity among breccias of the isolated bodies and that of the Lovelock Formation, however, suggests they are all evaporite solution breccias derived from the same gypsum unit whether structurally contiguous or not.

The Lovelock Formation lies conformably above Jurassic pelite. The formation top is erosional.

Age

The Lovelock Formation is undated paleontologically. Fossil material consists of pelecypod and cephalopod debris, but none is generically identifiable. Thus, age bounds are assigned to the Lovelock Formation on indirect evidence. The maximum age is Toarcian (late Early Jurassic), and the minimum is Bathonian (late Middle Jurassic).

The maximum age is based on youngest fossil ages in the Early Jurassic pelite. The pelite which lies conformably below the Lovelock Formation in the gypsum nappes has yielded no fossils, but, by lithology, it is unquestionably part of the predominantly Jurassic pelite unit (unit J$\bar{R}$s). The gypsum nappes lie above pelite with Toarcian fossils, and they are overlain by an extensive nappe which also contains Toarcian fossils. Furthermore, rocks like those of the Lovelock Formation are nowhere interbedded with pelite in the Carson region, and pelite does not lie above the Lovelock Formation. The conclusion is that the Lovelock Formation is younger than any rocks in the pelite units. The minimum age of the Lovelock Formation is equivalent to the age of the gabbroic rocks (163 m.y.) which were intruded and cooled during emplacement of the highest nappe. The gypsum nappes, having been emplaced earlier, must contain rocks older than 163 m.y.

Lower Member

The lower member of the Lovelock Formation consists of 3 to 35 m of relatively homogeneous dark limestone. The limiting thicknesses occur where the unit is tectonically attenuated or repeated; about 25 m is the average stratigraphic thickness. The limestone consists largely of calcite micrite which is widely recrystallized to microsparite. Micrite is made up of calcite grains 5μ

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[4] Wallace and Silberling (1962) published a reconnaissance structure section in the Gypsum Mountain area, approximately along section AA″ of Figure 2 of this paper. They were the first to recognize the nappe of Triassic pelite that is based by thrust 1 of my sections. They further show that strata equivalent to the Lovelock Formation are in a major fold overturned to the west. Their fold does not correspond in detail to folds delineated in Figures 1 and 2 of this paper, but it is presumably a generalized equivalent of folds of my set 2 that deform the southern gypsum nappe. They believed that the overturning indicates east to west overriding. Such motion is demonstrable at places in the West Humboldt Range, but at Gypsum Mountain, the spatial variability of inclination of axial surfaces of folds of set 2 makes difficult an interpretation of a general direction of overriding.

[5] Poles to axial planes of folds of sets 1 and 2 occupy similar great circles on equal-area plots. Such circles are spatially variable owing to rotation by set 3 folds. Set 1 poles are full circle, whereas those of set 2 occupy partial circles.

or less with an abundance of interstitial opaque material including pyrite and carbonaceous substances. In microsparite, the calcite grains are 5μ to 12μ, and they occupy a granoblastic texture which is interpreted to be of diagenetic origin. The content of opaque substances is lower in the microsparite than in the micrite. At places, micrite (or microsparite) grades to patchy sparite with calcite grain diameters of 100μ or less, generally in association with calcite spar veinlets which abundantly cut the lower member. Sparse anhedral quartz grains up to 60μ in diameter and a few platelets of white mica occur as isolated particles in the micrite and its recrystallized equivalents.

The micrite contains scattered to locally abundant laminae and thin beds of silty micrite, quartz calcsiltite, and quartz calcarenite. The coarser particles are calcite, quartz, and pyrite. Silty micrite and calcsiltite occur chiefly in plane laminae that sharply contact micrite. Calcarenite is generally in beds as much as 7 cm thick that contain sets of tangential cross-laminae whose maximum inclinations are about 15°.

The absence of fossils or skeletal debris in the lower member is noteworthy. Moreover, the existence of undisturbed plane laminae throughout the limestone indicates absence of bioturbation and suggests that benthonic faunas were lacking.

The lower member records a change, at least of local extent, in sedimentary environments from the deposition of fine silicate as represented by the Toarcian substrate to deposition chiefly of carbonate mud and only minor extraclastic components. The absence of fossils, predominance of mud, and darkness of the rocks, apparently owing to disseminated organic material, suggest a medium of largely stagnant, low-oxygen waters. The limited exposure of the Lovelock Formation prevents an understanding of the regional extent of the change of environments. The Lower Jurassic pelites, however, are characterized by their wide lithic homogeneity, implying lateral uniformity of their depositional basin. The lower member of the Lovelock Formation thus indicates either bypassing or cessation of the silicate flux and chiefly local generation of deposits.

At places, the lower member is strongly bleached and recrystallized to an average grain size of 1 mm. By its intensity and local occurrence, such recrystallization seems not to be of the same generation as the more pervasive micrite-microsparite-sparite series. The local intense recrystallization, moreover, affects the middle member (and perhaps the upper member) of the Lovelock Formation, whereas the microsparite-sparite recrystallization is at least partly earlier, apparently pre-middle member, as discussed later. Where patchy, coarse recrystallization occurs at the stratigraphic top of the lower member. Where more extensive, as at the northernmost and southernmost exposures of the Lovelock Formation, nearly the entire lower member is colorless coarse-grained meta-limestone. The absence of foliation in the coarsely recrystallized rocks implies that recrystallization was not produced by deformation of the Lovelock Formation. The distribution of such rocks suggests penetration of solutions and (or) heat downward from the top of the lower member.

Differences in conditions of recrystallization of micrite to microsparite and to meta-limestone are indicated by carbon- and oxygen-isotope data (Table 1). Ratios in microsparite are those of a marine limestone whose oxygen has equilibrated with light-oxygen water, as interpreted by Speed and Clayton (1974). Textures of the microsparites surely provide no suggestion that the recrystallization was at a significantly elevated temperature such that the oxygen exchange and grain reorganization in micrite ostensibly occurred during pervasion with meteoric water. In contrast, meta-limestone in the lower member contains remarkably lighter isotopic ratios than the microsparite and also textures which indeed suggest higher temperature recrystallization. Interpretations of the meta-limestone isotopic data by Speed and Clayton (1973) are that the temperature was sufficient (≥200°C) that decarbonation during recrystallization allowed concomitant lowering of δC^{13} during hydrothermal oxygen exchange. Thus, meta-limestone appears to have resulted from recrystallization due to hydrothermal fluid that entered the lower member sporadically from its top.

TABLE 1. CARBON- AND OXYGEN-ISOTOPE RATIOS OF LIMESTONES OF THE LOWER MEMBER OF THE LOVELOCK FORMATION*

Rock	δC^{13}(PDB) ‰	δC^{18}(SMOW) ‰
Microsparite	+0.6	18.2
Coarse-grained colorless meta-limestone from 0.5 m below top of lower member	-5.3	7.2

*Analyses courtesy of R. N. Clayton, University of Chicago.

Middle Member

The middle member of the Lovelock Formation is predominantly limeclast conglomerate and sedimentary breccia together with lesser amounts of calcarenite and red silicate mudstone and sandstone. The thickness of the middle member varies laterally from 3 to 20 m. The contact of the lower and middle members is largely conformable, but locally an angular unconformity exists.

The coarse-grained fragmental limestones of the middle member are of two distinctive lithic types, described below as calc-conglomerate and sedimentary calc-breccia. Conglomerate consists chiefly of a massively bedded framework of subangular to subrounded limestone clasts. A few thin lenses of calcarenite exist in the conglomerate. There is at most places a modest preferred shape orientation of clasts. The clasts are equant to ovoid; axials ratios ≤2. Maximum clast lengths are between 5 and 15 cm.

Clasts are largely micrite, laminated micrite-quartz calcarenite, and micrite variably recrystallized within the micrite-sparite spectrum. Many limeclasts contain veins which are truncated by clast margins. Clasts composed entirely of coarse-grained vein spar exist. Sparse fragments of calcarenite and pebbly calcarenite in the conglomerate are lithologically like the conglomerate matrix and are interpreted to be of synsedimentary derivation.

The calc-conglomerate matrix is fine- to medium- grained calcite-quartz–white-mica sand. The quartz content of the matrix is inversely proportional to grain size and does not exceed about 30 percent. At places, sand of the matrix grades to lensy thin beds of calcarenite or pebbly calcarenite.

Calc-conglomerate occurs chiefly at the base of the middle member and is overlain conformably by sedimentary calc-breccia which contains thin interbeds of finer grained calc-conglomerate. The clast population of the conglomerate largely contains the same lithic spectrum as does the lower member. The lithic similarity and spatial relations clearly indicate that the lower member was the pebble source. The framework structure of most of the conglomerate and quasi-equant pebble shapes and modest rounding suggest that the micrite of the lower member was at least moderately lithified by the time it was eroded.

The conglomerate is of variable thickness, and it wedges out at places. Where the conglomerate is absent, sedimentary calc-breccia lies directly on the lower member with modest angular unconformity. At such places, the lower member was variably eroded with or without uplift before deposition of the breccia. The relation indicates such places were likely sources of conglomerate pebbles. Exposure does not allow clear assessment of whether the unconformities are shallow channel bottoms or eroded surfaces of tilted micrite beds. It is thus possible that the conglomerate could be fluvial or wave-laid or both.

The second distinctive fragmental rock type in the middle member is sedimentary calc-breccia which generally lies above the conglomerate (Figs. 3, 4, 5). The breccia contains thin interbeds of

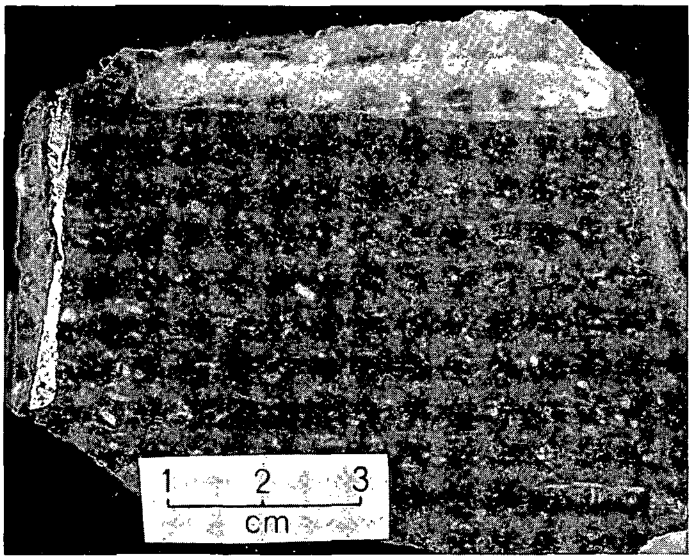

Figure 3. Calc-breccia of micrite (dark) and sparite (white) granules, outsize angular microsparite clast (at top), dark sinuous mudchips, generally dark pellets and superficial oöids. Matrix of fine-grained calcite-quartz sand. Generally unaltered hydrothermally. Polished slab.

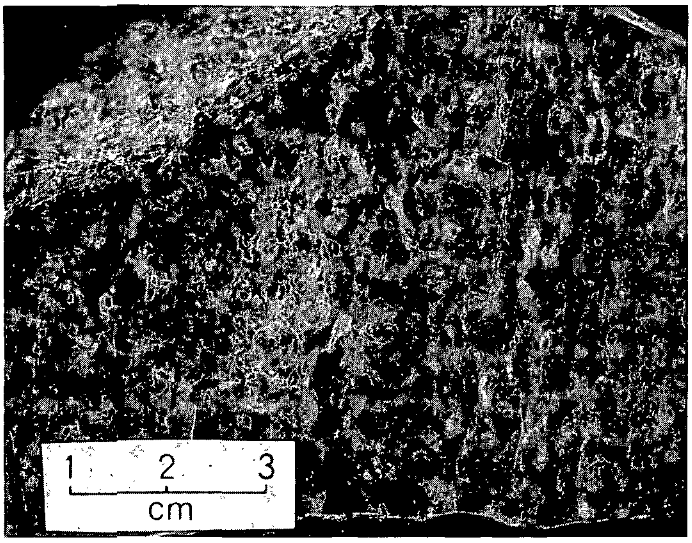

Figure 4. Moderately hydrothermally recrystallized calc-breccia with same clastic components as specimen in Figure 3. Note relict streaks of organic (dark) material perpendicular to clast elongation. Lime clasts generally more bleached than in Figure 3. Polished slab.

limestone conglomerate and calcarenite and laterally interfingers with red silicate detrital rocks. The thickness of breccia is between 0.5 and 12 m. The lithic characteristics of the sedimentary breccia are the high angularity and shape elongation of certain clastic components and the generally finer grain size than that of the conglomerate.

The sedimentary breccia comprises a framework of moderately size-sorted diverse calcitic particles in beds a few centimeters to a meter thick. The particles are chiefly granule-size micrite and sparite limeclasts and irregular platy carbonate fragments together with minor pellets, coated grains, and skeletal fragments. Particle diameters are between 0.1 mm and 2 cm.

Limeclasts consist of micrite and recrystallized and veined equivalents as in the conglomerate. Anhedral quartz silt occurs sparsely in the clasts; in the coarsest-grained fragments, chalcedony

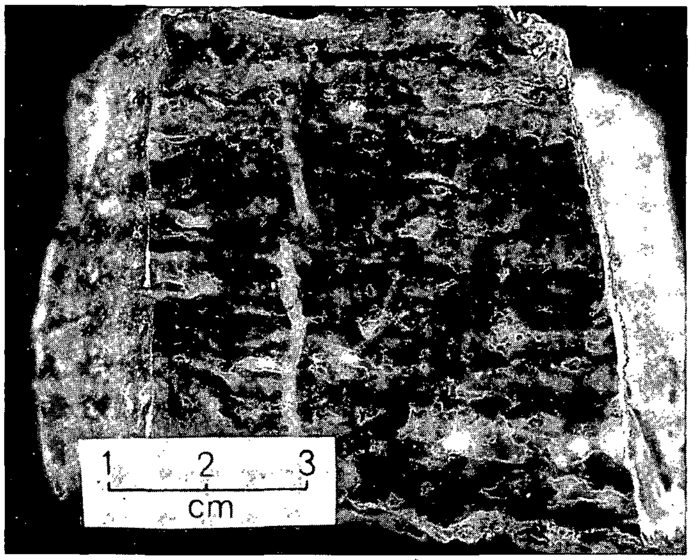

Figure 5. Well-recrystallized calc-breccia with large layers (white) of coarsely recrystallized intraclasts, pellets, and so on. Polished slab.

locally replaces calcite. The clasts are equant to ovoid and have axial ratios of <2. Each of the limeclast types occurs as both rounded and angular fragments. There is no stratigraphic differentiation of limeclasts by degree of recrystallization. It would thus appear that the conglomerate and breccia have the same limeclast source — namely, the lower member.

An apparent difference in the two clast populations, however, is that the proportion and perhaps grain size of sparite fragments is greater in the sedimentary breccia than in the conglomerate. In fact, many sparite clasts are coarser grained than rocks of the lower member except where the lower member has been coarsely hydrothermally recrystallized. Yet, it is clear that the coarse sparite clasts are depositional. The implication is that the source rocks of granule-size clasts were more highly recrystallized than the pebble source, which was probably more proximate to the preserved depositional site.

Principal framework components in much of the sedimentary breccia are dark irregular platy calcareous fragments, hereafter called "chips," whose squarish broad faces vary from 0.5 to 1 cm on a side. Chip thickness is 1.5 mm or less, generally in proportion to their diameter, and their profiles are variably undulous and planar (Figs. 3 through 6). Some have curled ends or are convolute with the matrix. Chips may locally constitute as much as 70 percent of the breccia.

The mean size of the chips is proportional to the size of associated limeclasts within different beds of the breccia. The chips, moreover, are discrete (unattached to other grains), and their broad faces are moderately well aligned in the bedding plane. The observations strongly indicate that the chips are detrital and that they were cosorted with the limeclasts. Some chips partially conform to the surface of a limeclast which, together with the curled ends and local convolutions, implies the chips were nonrigid on deposition. Others, however, have angular, rectangular ends, suggesting they are fragments of once larger grains.

The chips are composed of granoblastic sparry calcite in the grain size range of 10μ to 100μ. Some are homogeneously coarse or fine; others have microspar at the margins grading inward to coarser spar. Chips are rich in organic matter relative to lithic clasts and hence are darker (Figs. 3 through 6). Coarser grained chips are clearer, but they generally contain relict organic matter in columns perpendicular to chip lengths (Fig. 4). Replacement chalcedony occurs in a few.

L. C. Gerhard kindly examined specimens of the calc-breccias to assess a suggestion that the chips are algal. He finds no morphologic evidence or internal structure in the chips to establish the presence of algae (notably chlorophytes) which could, in principle, contribute coarse skeletal debris. Moreover, Gerhard reports (1973, written commun.) that no Jurassic chlorophytes are known which bear morphologic resemblance to the chips. The well-aligned, vaguely bounded columns of dark organic material in chips are not skeletal structures, because parallel columns exist in partly recrystallized micrite clasts (Fig. 5).

Because the chips are evidently nonskeletal, they must be presumed to be organic-rich micrite laminae or equivalently, carbonate mudchips. Evidence of flexibility during deposition indicates that at least some chips were soft and incompletely lithified. Moreover, their apparently fragile character and angularity suggest the chips were not transported a great distance. The chips are evidently intraclasts, and the most likely origin of such mudchips, as suggested by L. C. Gerhard, was as dessication clasts. The steady production, erosion, and marine deposition of the mudchips apparently required an intertidal environment. The mud surface was ostensibly a seal to atmospheric oyxgen such that organic matter was at least partly unoxidized in the mudchips. There is no relict internal structure in the mudchips suggestive of original algal binding agents.

Sparser clastic framework components in the breccia are pellets and various coated particles with diameters between 0.1 and 0.6 mm. Pellets are homogeneously micrite; no algal components have been resolved. Some pellets have a single very thin concentric rim. Many with or without rims have drusy rim cement. Superficial oöids or multicoated pellets have as many as four coatings; such particles are less abundant than pellets, and oöids are yet more scarce. Coarse calcite crystals of probable skeletal origin occur within single or multi-coatings. A few veined pelletal aggregates exist. It is important to note that the pellets and coated grains are largely spherical, thus unstrained, in locally planar segments of the middle member. It is thus clear that the fabric of the sedimentary breccia is not tectonitic.

L. C. Gerhard (1973 written commun.) observed sparse and poorly preserved fossil fragments in the calc-breccia. He found pelecypod and cephalopod debris, and possible ostracodes. Such fragments indicate that the calc-breccia is marine. The shell fragments as places have micritic coatings and algal(?) borings as described by Bathhurst (1966).

The coarser components of the sedimentary breccia form a compact framework whose interstitial volume is less than 10 percent. The close packing is obviously due to the subparallel stacking of the carbonate mudchips and their draping around limeclasts. The interstices contain variably calcite mud and sand-size calcite-quartz-pyrite. The sand matrix is distinguished by its higher quartz proportion and abundant pyrite.

Red silicate mudstone and sandstone and pebbly equivalents occur in a generally discrete subunit in the middle member of the northern gypsum nappe; such rocks are absent in the southern gypsum nappe. The silicate rocks are bounded by conformable contacts with sedimentary breccia which, moreover, occurs as laterally tapered fingers and isolated depositional lenses in the silicate rocks. The silicate rocks have a maximum thickness of about 5 m; their thickness is proportional to the thickness of the member. The rocks are predominantly kaolinite mud containing various proportions of quartz silt or sand, detrital coarse white mica flakes, and finely disseminated iron oxides. Sorting is generally poor, and where it can be resolved, bedding is plane.

At places, the silicate rocks are pebbly mudstone or sandstone; the clasts are commonly rounded, ill-sorted, and as coarse as 1 m in diameter. The most abundant clasts are dark micrite and variably recrystallized equivalents as in the fragmental carbonate rocks.

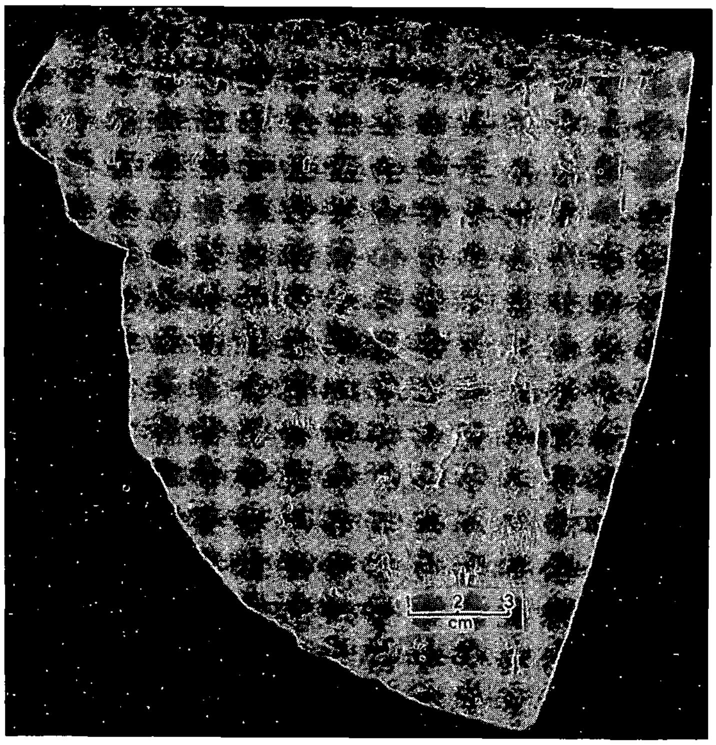

Figure 6. Laminated gypsum-calcarenite; right side of specimen is a polished surface where darker bands are gypsum rich, and white bands are more calcitic.

In both the calc-conglomerate and calc-breccia of the middle member, two phases of recrystallization in the intraclasts can be recognized. The earlier phase corresponds to the production of microsparite and sparite in the lower member and is at least partly pre-middle member. The later phase involved strong hydrothermal recrystallization, and by the proportionate degrees of such alteration in the lower and middle members, the hydrothermal event was post-middle member.

The temporal relations of the first recrystallization and deposition of the middle member are interpreted from the juxtaposition of micrite and sparite clasts and the existence within clasts of veins cut by clast boundaries in conglomerate and breccia at places where effects of the later recrystallization are apparently absent. Further, in such rocks, the matrix contacts lithic clasts sharply and matrix carbonate is not evidently texturally different whether it contacts micrite or sparite clasts, implying the variable recrystallization within lithic fragments is pre-clast. The relations thus support evidence from the morphology of clasts derived from the lower member that they were lithified before erosion.

The recrystallization history of the carbonate mudchips in the calc-breccia is more uncertain than that of the lithic clasts. The microsparite and sparite of the mudchips are zoned in many chips such that the coarsest grains are in the chip center. The zoning indicates recrystallization after fragmentation. Boundaries of chips, however, are sharp with respect to the matrix, suggesting that recrystallization occurred prior to deposition. Thus, it is possible that the mudchips recrystallized during dessication and transport, possibly having started as aragonitic mud. On the other hand, aragonitic mudchips could conceivably have been deposited and then recrystallized to calcite without interaction with the calcite sand of the matrix.

The later phase of hydrothermal recrystallization is patchy in the middle member, as is also the case in the lower member except at the northern and southern ends of the outcrop area of the Lovelock

Formation. There, a high degree of recrystallization pervades the formation and at places makes the fragmental character of the middle member difficult to recognize. Figures 3, 4, and 5 illustrate the creation of lensy patches of colorless coarse calcite (meta-limestone) from clasts, mudchips, and matrix in calc-breccias during progressive alteration. The dark organic material in the mudchips is preferentially retained relative to that in the limeclasts, but the ultimate product is a completely bleached rock. The organic carbon removed during hydrothermal recrystallization of the lower and middle members may play an important role in generation of light-carbon marble in the upper member and rauhwackes of the Carson region (Speed and Clayton, 1974).

Sedimentology of the Middle Member

The middle member of the Lovelock Formation consists almost entirely of deposits of allochthonous abraded and accretionary or aggregational carbonate particles. In-place biogenic components are absent. The abraded particles are largely coarse lithic particles, mudchips, and fine-grained calcite-quartz sand. Accretionary and aggregational grains are coarse sand-size pellets, oöids, and skeletal particles. The member also contains minor extrabasinal silicate and quartz sand of presumed terrigenous origin.

Perhaps 50 percent or more of the middle member consists of limeclasts of micrite and variably recrystallized equivalents. Coarse clasts are in the calc-conglomerate, the granule fraction is in the calc-breccia, and the full size range occurs in the red siltstone. The limeclast population constitutes a homogeneous and continuous lithic spectrum that corresponds closely to the spectrum of limestones of the lower member. The conclusion is that limeclasts of the middle member were derived solely from the subjacent member.

Dark limestones that exist sparsely in Jurassic pelites below the Lovelock Formation could in principle have served as a limeclast source. Such limestones, however, are sandy and abundantly stromatolitic and are not easily confused with the limestone of the lower member of the Lovelock Formation. Moreover, it is difficult to conceive of the limestone of the pelite sequence as a source for the limeclasts of the middle member because of the absence of clasts of resistant sandstone and siltstone which volumetrically predominate over dark limestone in the Jurassic part of the pelite sequence.

Evidence is lacking for dating the hiatus between the lower and middle members within the age limits of the formation. Broadly considered, however, the events which changed the environment from silicate to micrite deposition at the base of the Lovelock Formation were likely to have been related to those which ultimately provided conditions for gypsum (or anhydrite) saturation in marine waters and deposition of the upper member. Given such continuity, the clastic middle member was surely related to the same events, and the limeclasts would be truly intraclastic (Folk, 1959; Wolf, 1960).

Clast morphology and textural relations with the conglomerate matrix indicate that the limeclasts were at least moderately lithified before transport. Lithification was presumably concurrent with the recrystallization of micrite in the lower member to microsparite and sparite. The question arises as to how such recrystallization could have occurred in a scheme of quasi-continuous evolution of the Lovelock Formation. Because the early recrystallization of micrite in the lower member apparently involved oxygen-isotope exchange between calcite and meteoric water, there must have occurred partial or total emergence of the micrite after deposition. The early recrystallization was thus a fresh-water diagenesis. Moreover, it follows that emergence provided the local sources of lithified limeclasts for deposition as calc-conglomerate of the middle member.

Limeclasts in the conglomerate and breccia of the middle member underwent modest lateral motion as indicated by their sorting, rounding, and packing. The lithic homogeneity of the pebble population, the spatial coupling of the conglomerate to its clast source, and the variability of thickness of the conglomerate argue effectively, however, that pebble transport was short and that extrabasinal input to the conglomerate was nil. I envision that after exposure and diagenesis of the micrite sediments of the lower member, wave and (or) fluvial erosion dissected such rocks and created an irregular terrain. Fluvial erosion may have been important in local clast transport, but postulated streams were surely not connected to major terrestrial drainage systems that would have contributed extraclastic debris.

The transition in the middle member from conglomerate to calc-breccia records the deposition of granule-size intraclasts and near exclusion of pebble and coarser sizes. The transition implies lateral and (or) vertical erosional retreat of the irregular limestone terrain and a change to a lower flow regime. Such changes were concurrent with the first recognized deposition of carbonate mudchips, coated grains, pellets, and skeletal particles. This particle assembly was derived from subenvironments that are common to shallow carbonate banks with laterally variable flow regimes. Mudchips were ostensibly dessication clasts on intertidal flats, oöids were probably generated at places of strong tidal flow or wave motion, and pellets were more generally lagoonal (Sanders and Friedman, 1967). Deposition of the calc-breccia thus reflects either the construction of a carbonate bank or perhaps the first preservation of allochthonous bank-generated particles. I postulate that erosion of the exposed, initially irregular micrite terrain, coupled with deposition of the calc-conglomerate, smoothed the surface and created a lower relief littoral environment with much enhanced particle circulation. The flow regime during deposition of the calc-breccia was reasonably strong, however, because of the thorough mixing of various particles and the absence of autochthonous micrite laminae whose presence would indicate flows locally too weak to rip off bottom mud.

Fine-grained, calcite-quartz sand occurs in the middle member as generally discrete calcarenite beds or as the matrix of the coarse fragmental rocks. Such sand thus appears to have existed throughout the deposition of the middle member. The calcite fraction consists entirely of abraded particles, apparently of lithic origin. It is reasonable to assume that during deposition of the conglomerate, lithic carbonate sand accumulated in quieter waters, perhaps offshore of the eroding terrain. The quartz component could have been partly derived from the micrite and, perhaps as well, by longshore transport. The suggestion is that such sands formed the bank margin once the micrite platform was smoothed by erosion.

Beds of red mudstone and sandstone and quartz silt and sand in the matrix of fragmental carbonate rocks and calcarenite beds indicate a terrigenous input into the postulated carbonate bank environment. Matrix quartz is ubiquitous and implies a steady but small influx. The red silicate rocks, however, have characteristics which suggest emplacement as a single pulse. The rocks are poorly sorted except where they grade into sedimentary breccia; they occupy a single stratigraphic interval in a restricted area (northern nappe only). Lastly, they contain a wide spectrum of sizes of matrix-supported clasts, some of which are intraclastic and some extrabasinal. Pickup and transport of the clasts would seem to require significant velocity and density of the fluid. The characteristics suggest that the red silicate rocks were emplaced as a mudflow into the depositional site of the sedimentary breccia. Local reworking produced some bedded silicate rocks and interfingering silicate and carbonate layers along the margins of the mudflow. Regardless of mode of emplacement, the red silicate beds indicate breachment of a barrier (solid or fluid) which had apparently prevented large terrigenous input during preceding deposition of the middle member.

Upper Member

The upper member of the Lovelock Formation is made up of gypsum and quartz calcarenite which are interlayered on various scales from lamination to homogeneous beds 2 to 3 m thick. The member also locally contains bodies of calcarenite breccia and of very coarse grained tectonitic marble. The contact of the upper and middle members is placed at the top of the sedimentary breccia; the basal rocks of the upper member are conformable fine-grained thin-bedded calcarenite. The boundary is thus a sharp change from coarse fragmental carbonate rocks to carbonate sandstone; because calcarenite occurs in the middle member as matrix and as sparse discrete beds, the transition essentially records the cessation of deposition of coarse particles. The top of the upper member is apparently erosional, and it is inferred that beds of the upper member are the last marine deposits of their stratigraphic succession.

The upper member presents difficulties in stratigraphic and structural analysis because thick surficial efflorescent gypsum coats much of the surface underlain by the member. A qualitative appreciation of the nature of the unit can be gained from mine faces and trenches, but spatial variability is impossible to determine at the surface. Beds of the upper member are in isoclinal folds of set 1. Axial planes of the isoclines are minor-folded on northerly axial traces in harmony with the megascopic refolding of the major recumbent folds in the nappes (Fig. 2). Calcarenite beds in fold limbs occur commonly in boudinage.

The original stratigraphic thickness of the upper member is unknown. The preserved thickness is uncertain but is perhaps of the order of 100 m.

Layered rocks of the upper member are various assemblages of gypsum-calcite-quartz-white mica. Laminated rocks are abundant, and they occupy stratigraphic intervals as much as several meters thick. The laminae are 0.1 to 5 mm thick (Fig. 6). They are alternately homogeneous gypsum in anhedral mosaics and gypsum-calcite-quartz-mica. Calcite and quartz occur in generally discrete equant grains between 0.1 and 0.2 mm in diameter at a relatively constant ratio (calcite-quartz grains) of 30. White mica is in trace quantities. Very thin calcite-quartz laminae are essentially monoparticle layers of which gypsum is perhaps 50 percent. As the thickness of the calcite-quartz laminae increases the proportion of gypsum diminishes, and the calcite and quartz grains are slightly coarser. Thin-bedded rocks are apparently more plentiful than the laminated ones. Here, gypsum containing disseminated granular calcite occurs in beds a few centimeters to a few tens of centimeters thick. The gypsum beds alternate with calcite framework quartz-calcarenite beds 1.5 cm thick which contain little or no gypsum. Still thicker beds are exposed locally; they consist of homogeneous coarse-grained gypsum up to 3 m thick and cross-bedded calcarenite or calcitic quartz sandstone over intervals 5 m thick.

Thick-bedded calcarenite occurs at the base of the upper member, but there appears to be no other preferred stratigraphic succession among the layered rocks of the upper member. Discrete calcarenite beds are estimated to constitute about 25 percent of the upper member. Inclusion of calcite and quartz in laminae and disseminated in gypsum would increase the nonsulfate quantity another 10 to 15 percent.

Gypsum associated with calcite-quartz in laminae or thin beds occurs in a mosaic of anhedral grains averaging about 50μ in diameter. In more homogeneous gypsum layers, however, abundant euhedral gypsum grains up to 5 mm in length occur with smaller anhedral grains. Some coarse gypsum rocks are nearly panidiomorphic. A few coarse gypsum euhedra intersect laminae of calcite-quartz-mica and include the nonsulfate grains of the lamination without modification. As indicated below, calcite, quartz, and mica are believed to be clastic particles. The textures suggest that the coarse gypsum grains have grown at the expense of former finer grained anhedral gypsum which commonly is associated with the nonsulfates. Moreover, there is a preferred orientation of (001) of coarse gypsum grains which parallels axial planes of minor folds as well as a grain-shape lineation. The coarse gypsum thus appears to be postdepositional and probably is synkinematic with first deformation, ostensibly during the creation of the major recumbent folds before or during nappe transport.

One would predict that sulfate in a tectonic and hydrothermal environment like that of the Lovelock Formation would have undergone multiple dehydrations and hydrations in its history. It thus may be questionable whether recrystallization fabrics should reasonably be assigned to deformation early in the formation's history. Anhydrite, however, is currently unrecognized in surface rocks of the Lovelock Formation, and to my knowledge, it has not been found by drilling. Textures provide no evidence for replacement of anhydrite by gypsum or the former existence of nodular anhydrite.

The calcite-quartz-mica laminae and calcarenite beds are well-sorted deposits of fine-grained and very fine grained sand. The interpretation is based on the occurrence of discrete, equant grains in laminae, the similar size of quartz and calcite, and the low-angle cross-bedding. Biogenic, pelletal, or oölitic grains are apparently absent in these rocks.

Gypsum and calcarenite of the upper member were deposited conformably and in probable temporal continuity with fragmental rocks of the middle member. The concomitant disappearance of mudchips and coated and skeletal particles from the section with the onset of evaporite deposition suggests deepening and decrease in circulation coupled with increased salinity. Such changes may have been in conjunction with landward transgression of the environments represented by the middle member. The accumulation of locally thick pure sulfate implies precipitation in standing water and the existence of a barred basin. Alternation of gypsum with calcarenite that includes quartz of ostensible terrigenous origin indicates, however, some degree of particle transport. The laminated rocks (Fig. 6) surely indicate periodicity, tidal or diurnal, of deposition; thin-bedded rocks might similarly represent lower frequency periods. The rocks are not dune accumulations, judging from the absence of appropriate structures; the evaporite is not supratidal, because it forms the rock framework and does not apparently disrupt calcite-quartz beds (Kinsman, 1969). The deposition of evaporites over littoral deposits of the middle member indicates subsidence of at least 100 m of the evaporite basin relative to its marine barrier.

Calcarenite of the upper member is similar in composition and grain size to that in subjacent members except for a possibly finer mean size. The implication is that calcite-quartz sands were continuously generated during the history of the Lovelock Formation. If such sands constituted a bank margin at the onset of deposition of the middle member, they may have contributed to the barrier that existed during evaporite precipitation.

Marble in the Upper Member

The upper member contains bodies of calcite marble which are clearly postdepositional. The existence of marble in the Lovelock Formation is an important link in the interpretation of the origin of rauhwackes in the Carson region.

Marble consists of coarse-grained (1 to 5 mm) calcite with a granoblastic texture, and at places, a megascopic grain-shape foliation and lineation. Colorless marble at places contains interlayers of gray to black finer grained crystalline calcite rock which gives strong emission of H_2S when broken. Where layered, isoclinal folds are evident in the marble. Rocks classed as marble are clearly coarser in grain size than the sparites, and they are both coarser grained and far more uniformly granoblastic than the hydrothermally altered meta-limestone below the upper member.

Bodies of marble occur in the upper member in the northern and southern nappes. An extensive but thin (0.5 to 5 m) body of tectonitic marble lies along the thrust contact of the upper member and rocks of the pelite sequence over a distance of about 1 km in the northern nappe. Here, a zone of breccia separates gypsum from the marble. The position of this marble body is suggestive that its origin may be connected with thrusting. Another body of marble of outcrop dimensions 30 m on a side is surrounded by gypsum. Marble is brecciated at the contact, and gypsum fills the cracks. A third body of marble, about 100 m long, occurs at the base of the upper member. The body is about 20 m thick and is apparently overlain by gypsum. The marble contains intercalated cross-bedded calcarenite in layers which parallel the top of the middle member. The relations suggest that gypsum was removed and coarse calcite was emplaced. The calcarenite and adjacent carbonate rocks of the middle and lower members are not recrystallized to grain sizes comparable to those of the marble, and the origin of the marble is problematic. Similar rocks occur in the rauhwackes of the Carson region, and an origin by calcitization of gypsum is proposed on structural and isotopic grounds (Speed and Clayton, 1974).

Breccia in the Upper Member

Stone and others (1920) observed in underground workings that breccia was abundant near the base of the gypsum. Carbonate breccia is in fact widespread in the upper member of the Lovelock Formation in sporadic bodies which are topographically (not stratigraphically) below gypsum-bearing sections.

The simplest breccias are monolithologic calcarenite bodies. They consist variably of intervals 1 m thick of undisrupted folded thin-bedded fine-grained calcarenite which grades to fragmented but unrotated calcarenite beds to framework breccia of rotated fragments and (or) to pebbly sandstone. The matrix of the fragmental rocks is well-sorted fine-grained calcite and quartz sand; the same sand-size components constitute the framework of the pebbly sandstone. This type of breccia clearly has correlative degrees of fragmentation and of sand to lithic clast ratio.

The prevalent monolithologic calcarenite breccia within the spectrum is a framework of co-oriented bed segments without size sorting and with calcite-quartz sand matrix. Intervals as much as 1 m thick of clast framework may alternate with matrix-rich layers.

Calcarenite clasts in breccias have the same grain-size spectrum (very fine grained to nearly medium grained) and bed thickness range as does calcarenite in place in the upper member. The breccias are unquestionably accumulations of such rocks. Where calcarenite is interbedded with gypsum in the upper member, breccia is absent, thus implying that intraclastic sedimentary breccias were not a normal mode of calcarenite deposition. Conversely, the absence of gypsum in calcarenite breccias and the similarity of calcarenite breccia clasts to calcarenite in the gypsum section strongly indicate that the breccia originated by solution of sulfate and gravitational accumulation of the undissolved fraction. Solution of sulfate in the laminated and thin-bedded rocks which contain largely discrete calcite and quartz sand grains would provide free sand for the breccia matrix and unbedded pebbly sandstone. The preservation of segments of continuous calcarenite alternating with fragmented but well-oriented calcarenite and with pebbly sandstone indicates a steady uniform withdrawal of sulfate from the rocks and concomitant compaction of the insolubles. The final compacted products reflect their initial sulfate content. That is, in the absence of sulfate, no breccia is developed; interbeds of sulfate and calcarenite yield calcarenite breccia; and where calcarenite beds were lacking, only disseminated calcite-quartz sand accumulates. Compaction solution breccias are clearly different from collapse breccias in that motions are nonaccelerative such that original stratigraphic ordering is better reflected in the compacted products. Moreover, cavities would not be created in steady compaction, and lateral sorting and transport by subsurface streams would, in principle, be absent. Stanton (1966) found evidence that certain solution breccias in Montana accumulated by compaction rather than collapse.

Large masses of polymict breccia occur in the upper member in apparent association with certain structures. The clasts are largely calcarenite, as in the monolithologic breccia, but they are mixed with clasts of other lithologies along the borders of the breccia body.

The largest body of polymict breccia occurs in the northernmost outcrops of the Lovelock Formation, and together with a coextensive belt of marble, it comprises the upper member for about 1 km south of the northern margin of Figure 1. Gypsum is absent over this interval. Here, marble forms the margin of the formation, and the east side of the marble belt is the thrust which begins the overturned Lovelock Formation over Jurassic pelite. Breccia occupies the 10- to 20-m-thick zone between marble and the middle member. The breccia is chiefly calcarenite with calcite-quartz sand matrix, but isolated angular blocks of marble as much as 1 m across occur sporadically in the breccia. Within a meter of the contact of breccia and marble, the breccia consists largely of marble clasts, but it contains the same sand matrix as in calcarenite breccia. In the vicinity of some major fold hinges, probably of set 2 folds, the breccia has highly stretched clasts ostensibly indicating that the breccia is pre–set 2. South from the sulfate-free zone, the breccia grades to bedded gypsum and calcarenite except at the formation top, here upside down. A thin marginal belt of marble and marble-calcarenite breccia and calcarenite breccia totaling about 3 m thick continues south between the thrust on the east side and the gypsum-calcarenite of the upper member for about ½ km.

The marble was clearly formed before the breccia. In the gradational zone, however, the thickness of the breccia and the frequency of marble clasts are proportional to the thickness of the marble, possibly suggesting a genetic connection of marble and breccia. The thickness of the breccia is also inversely proportional to the thickness of the gypsum, and significantly, to the thickness of the formation as a whole. The latter relations together with the similarity of calcarenite clasts and sand of the polymict and monolithologic breccias surely indicate that the polybreccias are also of solution origin. The problem is—how did large fragments of marble get into the calcarenite breccias?

A possible solution to the postulated transfer of marble clasts during breccia formation is that cavities and subsurface flows existed in the particular polybreccia under discussion. Evidence for open spaces is that some of the finer grained calcarenite breccia is size sorted, and the sand of associated pebbly sandstone is modestly bedded. The polybreccia thus differs from the monolithologic type which exhibits no recognized sorting. The polybreccias in general, however, have characteristics better explained by compaction than collapse. In particular, there are no assemblies of large mixed fragments including a concentration of marble clasts as might be predicted from the collapse of a cavern roof. I think that mechanical transfer is an unlikely origin for the marble clasts.

A preferred origin is that the marble blocks are more or less in place, and they simply compacted during sulfate solution, along with calcarenite. The implication is that calcitization of gypsum, as referred to earlier, occurred within the upper member as well as at its margin. The calcitization, moreover, was earlier than dissolution of sulfate. Support for internal calcitization obtains from the occurrence of a large marble body, previously described, completely surrounded by gypsum. Conceptually, dissolution of gypsum and precipitation of calcite could have been concomitant as a replacement process. Calcite precipitation was perhaps then arrested by change of solution composition, but sulfate continued to be dissolved, thus producing breccias with marble fragments. The covariant thicknesses of the breccia and continuous marble as well as the other proportionalities support the idea.

Another type of polymict breccia occurs in the upper member, chiefly in the hinge regions of major folds. As with the first type, monolithologic calcarenite breccia is predominant, but near the contact of the upper and middle members, clasts of carbonate rocks from the middle member are mixed with the calcarenite clasts in a zone a few meters thick. A few clasts of highly altered microdiorite were observed in these polymict breccias. Such breccias are largely massive and lack preferred fragment orientation; the matrix is sandy calcite-quartz-pyrite. The massive breccia, however, locally grades laterally to unbedded pebbly sandstone with good pebble-preferred orientation. The lateral gradation of breccia to sandstone suggests at least local collapse and lateral transport of finer particles by waters flowing through a cavity network.

The association of breccias containing clasts of the upper and lower members and fold hinges is suggestive of tectonic brecciation as a factor. One hypothesis is that hingeward flow of sulfate and its associated bedded and disseminated carbonate occurred during major isoclinal folding. The more competent middle member fractured during flexure, and materials of the upper member invaded the fractures. Subsequent solution of sulfate rendered a zone of mixed carbonate clasts in the vicinity of the contact of the upper and middle members.

If correct, the hypothesis indicates that solution brecciation was post–set 1 folds. The occurrence of other breccia bodies in the upper member topographically below gypsum but independent of any stratigraphic control strongly supports the development of recumbent major folds before breccia formation. The existence of fragments of igneous rocks indicates a period of intrusion which is postgypsum but prebreccia. The age of the solution breccias is thus not certain, but if the postulated calcitization of sulfate and dissolution of sulfate were in fact penecontemporaneous, the solution breccias were formed during or shortly after emplacement of the nappes in which the Lovelock Formation occurs. The reasoning is that elsewhere in the West Humboldt Range, extensive marbles (which are believed to be calcitized sulfate) and calcarenite breccias are intruded by gabbroic rocks of Middle Jurassic age. It is probable that the upper member of the Lovelock Formation was the precursor to all of these marbles and breccias.

Diagenetic and Epigenetic Events

Each of the members of the Lovelock Formation is affected by one or more stages of textural reorganization, the conditions of which are important in interpretations of the evolution of the formation.

An early stage of recrystallization of micrite of the lower member occurred before deposition of intraclastic fragmental rocks of the middle member. Providing the temperature was 100°C or less, the isotopic ratios of microsparite indicate oxygen exchange of an initial marine calcite with fresh water. There is surely no indication by grain size of the products microsparite and sparite that the temperature of such recrystallization was elevated significantly. Thus, I interpret the early recrystallization of the micrite to have been a fresh-water diagenesis that occurred in the micrite after it was exposed, either tectonically or eustatically. Erosion of the lower member to provide clasts for the middle member surely required the lower member to have been raised above wave base. It is thus reasonable to ally exposure and lithification of the carbonate mud by fresh-water diagenesis as concomitant events.

Carbonate rocks in the lower and middle members have locally undergone more intensive recrystallization due to hydrothermal fluids. Isotopic evidence suggests (Speed and Clayton, 1973) that the temperature of such recrystallization was ⩾200°C. The metalimestones of the hydrothermal phase are most abundant in the middle member and at the stratigraphic top of the lower member. The distribution suggests fluid transport through zones in or above the middle member and local penetration stratigraphically downward into the lower member. Such flow paths are entirely reasonable because of the large permeability contrast that probably existed between the lower and middle members.

Where the hydrothermal phase is most intensive in the middle and lower members, extensive solution breccia occurs in the upper member. The relation suggests that dissolution of sulfate and recrystallization of some adjacent carbonate rocks were concomitant. Further, if it is correct that calcitization of gypsum was continuous with dissolution of gypsum, calcitization was thus penecontemporaneous with the later recrystallization of the carbonate rocks.

The hydrothermal recrystallization of the limestones and calcitization and solution in the upper member are clearly postdepositional and occurred apparently during or after folds of set 1 and nappe transport. Such events thus are epigenetic.

Summary and Sequence of Events

Deposition of fine-grainted silicate sediments together with less abundant carbonate occurred with lateral uniformity in shallow seas of the Carson region during the Early Jurassic, from the systemic boundary to early Toarcian or later. Between early Toarcian and Bathonian time, the influx of silicate mud and silt ceased at the site in which the Lovelock Formation was to be deposited, and deposition of carbonate mud and sparse terrigenous sand followed conformably in a probably euxinic environment. Thus, the changes recorded by the deposition of sediments of the lower member of the Lovelock Formation are principally the effacement of the silicate mud source or bypassing of the silicate mud influx.

Succeeding events involving the Lovelock Formation up to the deformation forming fold set 2 are also in the interval, early Toarcian-Bathonian. The next event after micrite deposition was subaerial exposure and fresh-water diagenesis followed by fluvial or littoral erosion. Competent intraclasts derived from the lithified micrite were laid down in close proximity to their source as the gravels of the conglomerate of the middle member. Succeeding deposits of the calc-breccia are accumulations of particles from a number of subenvironments of the littoral zone. These deposits ostensibly represent significantly greater lateral transport and mixing than do those of the calc-conglomerate and deposition in a lower flow regime. Progressive erosion wore down the pebble sources, smoothed the terrain, lengthened particle transport paths, and provided a general change to a low-relief carbonate bank environment. The excellent mixing and stratification of the diverse particles of the calc-breccia indicate, however, that circulation and turbulence of marine waters on the bank were significant. A possible mudflow of silicate, intraclastic, and extraclastic detritus is envisaged as entering the littoral zone, implying nearby inland relief of at least modest degree.

Deposition of 100 m or more of sulfate and calcarenite followed conformably above the calc-breccia. The sulfate rocks formed at least in part by direct precipitation from standing water, implying growth of a barred basin. Onset of sulfate deposition was synchronous with local effacement of the earlier carbonate bank environment, due either to deepening or landward transgression of the bank environment represented by the middle member.

The nature and sequence of events associated with cessation of deposition of the Lovelock Formation are not certain. One possibility is uplift and marine withdrawal, then folding and nappe transport. Another possibility is that folding was actually commensurate with deposition of the middle and upper members; that is, they were deposited in a synclinal trough. Increased deformation, nappe motion, and perhaps, regional uplift finally obliterated the marine basin.

The Lovelock Formation in the gypsum nappes was folded recumbently before or during nappe emplacement. Calcitization of sulfate occurred at places, chiefly where sulfate was at the base of the nappe. Thus, calcitization is probably postrecumbent folding. Dissolution of sulfate, formation of solution breccia by compaction and, sparsely, by collapse, and intensive hydrothermal recrystallization of limestones were postrecumbent-folding events in the Lovelock Formation that were possibly penecontemporaneous with calcitization.

The piling-up of nappes was completed by about 163 m.y. ago, approximately Bathonian or earlier time. Structural relations suggest that the nappes were emplaced in a major syncline which continued to fold on a northerly axial trace and then, to be refolded on an easterly axial trace.

Tectonism during Deposition

The occurrence of tectonism as manifested by folds and nappes in the Carson region and the deposition of the Lovelock Formation were closely spaced in time, in the Toarcian-Bathonian interval. The Lovelock Formation apparently contains the youngest deposits in the Mesozoic succession in the area, and its sediments represent an abrupt lithic change from the relatively uniform subjacent Jurassic pelite. The question thus arises whether the deposition of all or part of the Lovelock Formation records the onset of tectonism, such that deposition was syntectonic. The alternative is that the Lovelock Formation is pretectonic, and its lithic succession is owing only to lateral motion of depositional regimes, perhaps coupled with eustatic sea-level changes.

Each lithic subunit of the Lovelock Formation could have formed in a tectonically stable littoral-neritic complex. The lower member could have been lagoonal, provided that the silicate influx was low. The conglomerate may represent beach gravel eroded and deposited during rapid lowering of sea level. The breccia is an accumulation of allochthonous particles from shallow bank environments. The evaporite-calcarenite sequence was perhaps deposited in a marginal basin during a sea-level rise in which the basin barrier grew vertically at just the right rate to adjust the normal marine inflow for gypsum saturation within the basin.

In their vertical succession, however, the subunits of the Lovelock Formation cannot have been produced solely by laterally propagating environments as is occurring, for example, in the Persian Gulf (Kinsman, 1969). Oscillation in water depth with time seems required by the following observations:

1. The basal micrite was deposited in a euxinic environment; it was then uplifted as indicated by probable fresh-water diagenesis and certainly by its wave and (or) fluvial erosion.

2. The existence in the middle member of skeletal-oöpelletal-intraclastic calc-breccia above calc-conglomerate indicates significant mixing of particles from a variety of marine subenvironments over wave or fluvial gravels, hence probable slight submergence.

3. The accumulation of perhaps 100 m of evaporite and associated carbonate of the upper member over clearly littoral deposits of the middle member indicates subsidence of at least 100 m between the terrestrial shoreline and the evaporite basin barrier. The subsidence indicated here was likely coupled to the submergence noted above.

Each of the bottom motions could have been eustatic or tectonic. For example, sudden rise in sea level after deposition of calc-breccia, coupled with construction of a barrier bar at the former bank margin, could in principle have produced the barred evaporite basin. The distinction between eustatic and tectonic changes of sea level is clearly difficult because the small lateral exposure of the Lovelock Formation precludes analysis of its lateral differentiation. More broadly, however, the demonstrable temporal proximity of deposition of the Lovelock Formation and folding and nappe emplacement surely favor tectonic effects and acceptance of the proposition that the Lovelock Formation is syntectonic. The corollary is that the sequence of paleoenvironments indicated by the Lovelock Formation represents the transition in surface conditions from initial open marine silicate deposition to that of an emergent tectonically active terrain.

STRATIGRAPHIC CORRELATIONS

Within the northern Carson Sink region (north of 48° N.), the Lovelock Formation appears to be the only vestige of originally widespread gypsum-carbonate deposits that are now represented by bodies of carbonate breccia and marble, the rauhwackes (Speed, 1974). Thirty km south of Gypsum Mountain in the Mopung Hills at the southern tip of the West Humboldt Range, however, a nappe contains an undated assembly of gypsum, calcarenite, dark micrite, breccia, and quartz arenite. The strong lithic resemblance of the Mopung Hills rocks and those of the Lovelock Formation and their similar associations with Jurassic pelite are sufficient to indicate probable correlation. As in the case of the Lovelock Formation, the Mopung Hills rocks can also be interpreted to be an isolated remnant of evaporite deposits that escaped complete conversion to rauhwacke. It should be noted that the Mopung Hills deposits contain significant volumes of quartz arenite, whereas discrete quartz sandstone deposits are rare in the Lovelock Formation.

In the Dixie Valley region east of the Carson Sink, Speed and Jones (1969) found that syntectonic quartz arenite of the Boyer Ranch Formation was deposited in the same duration that is here given for the Lovelock Formation. Later studies indicate that the westernmost Boyer Ranch Formation in the Stillwater Range (Speed, 1974) contains rauhwacke such that it is inferred that gypsum-carbonate units originally existed in the Boyer Ranch Formation. The lithic and temporal relations allow correlation of the Lovelock and Boyer Ranch Formations. The existence of gypsum-quartz arenite-limestone in the Mopung Hills clearly supports the contemporaneity of evaporite and quartz sand deposition in the Carson region in Jurassic time. The paleogeographic evolution as it relates to Middle Jurassic tectonism will be expanded in another paper.

A large undated deposit of gypsum occurs with carbonate rocks in the vicinity of Gerlach, Nevada, 80 km northwest of Gypsum Mountain (Fig. 1). Layered rocks that crop out in the intervening distance are Triassic and Jurassic pelites (Tatlock, 1966) which are similar to those of the Carson region. Because evaporite deposits are unknown in the pelites, it is reasonable to suggest that the Gerlach sulfate deposits are correlatives of the Lovelock Formation or, more generally, that they are postpelite. If such long-range correlations are correct, evaporite deposits of Toarcian-Bathonian age may have extended over a large terrain west of the Carson Sink. Judging from the history of the Lovelock Formation, evaporite deposition seems more likely in a series of tectonically barred basins than in a single continuous sea.

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