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Paleoecology of the Lowermost Part of the Jurassic Carmel Formation, San Rafael Swell, Emery County, Utah

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PALEOECOLOGY OF THE LOWERMOST PART OF THE

JURASSIC CARMEL FORMATION,

SAN RAFAEL SWELL, EMERY COUNTY, UTAH

by

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R. Joseph Dover

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ABSTRACT

Paleoecology of the lowermost Carmel Formation, San Rafael Swell, Emery County, Utah, was studied at nine localities 2 to 21 miles apart. Eight of the sections contain fossiliferous calcilutites and oölitic limestones in the basal 35 to 135 feet measured. Thickness of the fossiliferous beds ranges up to 10 feet. Beds of barren calcilutites, calcarenites, oölitic limestones, intraclastic limestones, calcareous sandstones, and bedded gypsum, separate the fossiliferous beds. A parallel-bedded, basal quartz sandstone, 0.5 to 7 feet thick, everywhere overlies the Navajo Formation.

Molluscs dominate faunal assemblages. Shells are recrystallised to calcite, but external sculpture is preserved in sufficient detail for identification. Lamellibranchs are represented by disarticulated shells in unbroken condition, oriented convex up.

Fossil assemblages constitute four main types: (1) Two widespread and heterogeneous assemblages dominated by *Camptonectes* sp.; (2) A restricted assemblage consisting only of *Trigonia* sp. in the northern Swell; and (3) A restricted assemblage consisting only of *Ophiomorpha* burrows in the southern Swell. Associated with *Camptonectes* sp. are the lamellibranchs *Vaugonia* sp., *Pronoella* sp., *Trigonia* sp., *Lima* sp., (?)*Ostraes* sp., (?)*Gryphaea* sp., and *Isognomon* sp.; the gastropods *Cossmanea* sp. and *Nerinea* sp., and the crinoid *Pentacrinus* sp..

Fossil assemblages show an imbalance; Herbivores and sediment feeders are absent, and carnivores (predators) and scavengers (selective detritus feeders) are rare. Disarticulation without great breakage suggests gradual deposition of shells and carbonate material under moderate energy conditions. On the basis of closest living relatives, the assemblages found in carbonate rocks indicate a wide tolerance of these animals to fluctuations in salinity and temperature. The well developed byssal notch of some pectinids suggests abundant vascular plant live.

Abundantly fossiliferous beds are separated by barren beds with some evaporites, a sequence suggesting a warm sea of varying but high salinity. Grain-size ranges and limestone predominance indicate, respectively, differing lateral energy levels, and a low terrigeneous clastic influx.

(73 pages)

INTRODUCTION

General Statement

This report summarizes an investigation of environmental conditions during deposition of the lowermost Carmel Formation (Jurassic) over a widespread area in central Utah. This formation overlies the Navajo Formation, a sandstone of probable eolian origin. The San Rafael Swell was chosen for study because it represents an intermediate area between nearshore sediments (Arapien Formation) in the southeast, and offshore sediments (Twin Creek Formation) in the north and west. Emphasis was placed upon occurrences and significance of fossils, and upon rock types containing them. A lesser emphasis was placed upon unfossiliferous beds. No attempt was made to analyse the entire unit; work was concentrated on only the basal 35 to 135 feet of the formation at each locality studied.

Purpose of Investigation

The purpose of this study is to cast some light upon the paleoecology and environment of deposition of the lowermost Carmel Formation in the San Rafael Swell by a study of rock types and fossils. Stratigraphic sections measured at various points around the perimeter and in the center of the Swell provided a framework for the interpretation of salinity, depth of water, current activity, distance from shore, clastic influx, cycles of transgression of the sea, and progradation of the shoreline.

Location, Accessibility, Climate, and Soils

The San Rafael Swell is doubly-plunging anticline, elongate north and south, in Emery County, Utah (Fig. 1). The northern edge is about 30 miles south of Price, Utah; the southern limit is about 15 miles north of Hanksville, Utah. The section exposed in the Swell extends from the Permian Hermosa Formation in the center of the Swell to the Cretaceous Mancos Group around the perimeter of the Swell.

The area is continental, temperate, and arid to semi-arid. As most of the formations in the San Rafael Swell are to some extent calcareous, soils that form over them are principally pedocals. Sandstones, such as the Wingate, Navajo, and Entrada Formations; occur principally as cliffs. Where structural plains are developed over them, a sandy soil forms; small, widely separated juniper trees grow in this loose soil. The Mowry Formation of the Mancos Group, is even more nearly barren of plant life. Soils that form over the Summerville Formation contain considerable amounts of gypsum and tend to support little plant life. Only two units in the entire Mesozoic section, the Jurassic Carmel Formation and the Jurassic Morrison Formation, are capable of supporting sufficient grass for grazing. Other Mesozoic formations usually support hardy plants, such as cacti and local stands of sagebrush.

Access to the area is limited. There are no paved roads in the Swell proper, though several paved roads skirt the greater part of the Swell: Utah Highway 10 in the west, Utah Highway 6-and-50 in the east, and Utah Highway 24 in the south. Three graded roads lead through the Swell. One traverses the northern portion and connects Utah Highway 10 with Utah Highway 6-and-50; another, beginning at Buckhorn Wash, proceeds

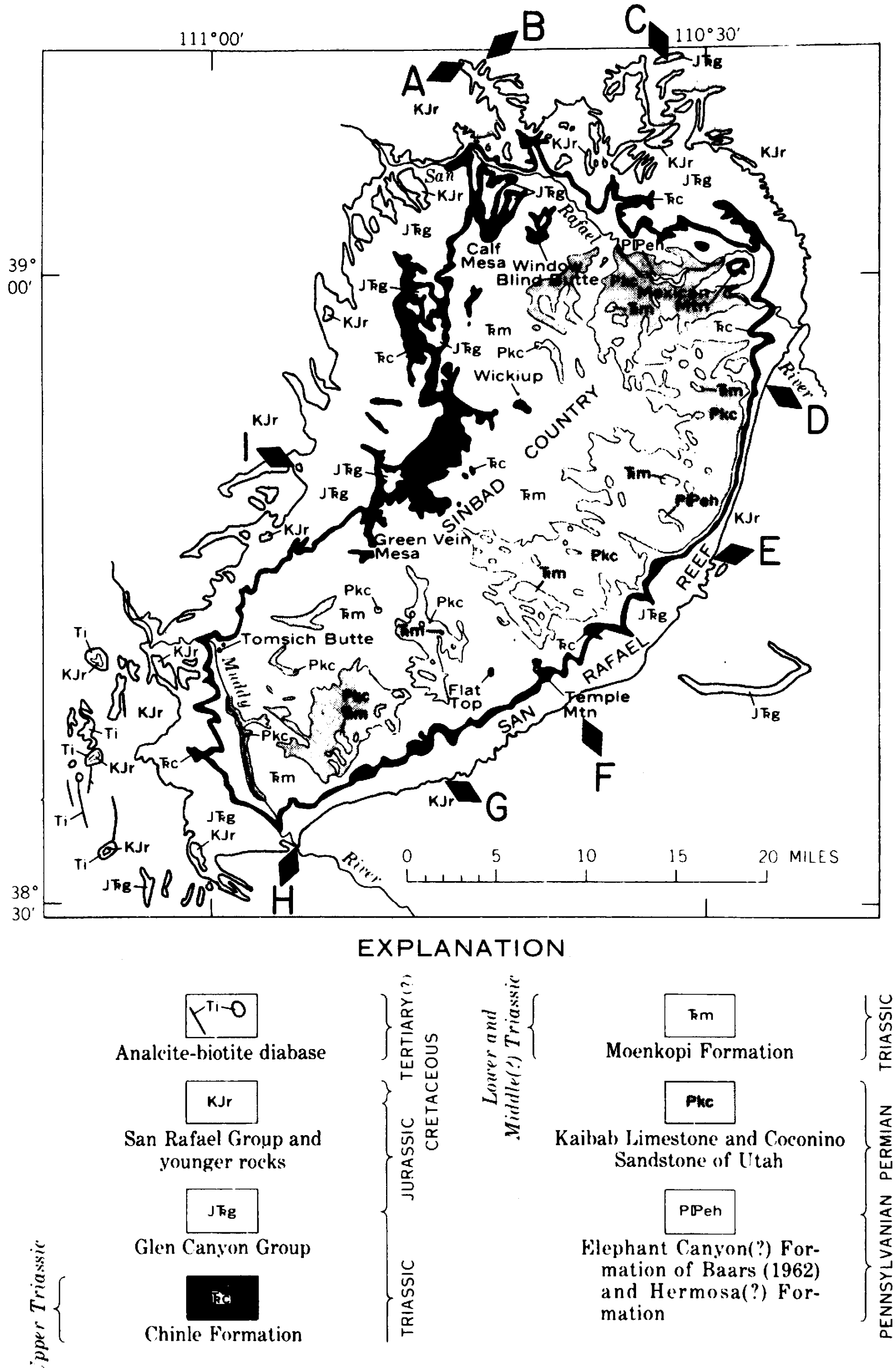

Figure 1. Generalized geologic map showing locations of sections (letters) of Carmel Formation measured along perimeter of San Rafael Swell (modified from Hawley and others, 1968).

south through the center of the Swell; it connects the northern road with Hanksville *via* Bullberry Spring, and also *via* a road at Temple Wash, paved to the edge of the Swell, 15 miles north of Hanksville. Other roads, ranging from graded roads to jeep trails are rather common. Most such roads, however, require 4-wheel drive for dependable transport. A portion of the incomplete Interstate Highway 15 permitted access to the center portion of the Swell from the west; roadcuts along this route exposed the Carmel Formation for a distance of about one mile across strike. The eastern and western ends of the Interstate Highway were not completed at the time of this writing.

The only permanent stream in the Swell is the San Rafael River; consequently, roads have no bridges except where they intersect that river. Roads are graded across the beds of intermittent streams. As a result, they are difficult and dangerous to traverse following a rain, due to flash floods and muddy conditions. Headward erosion of arroyo-shaped gullies across the roads, and subsequent erosion of ruts along the roads add to the hazards of traveling.

Field Methods and Laboratory Procedures

Field work was carried out during the summer and autumn of 1967, and constituted a total of 5 weeks. The investigation consisted of measurement of detailed sections and collection of fossils at each section. Transportation during the greater part of the study consisted of a Volkswagen sedan, and a Volkswagen squareback. A jeep was used in the southeastern and eastern parts of the Swell.

Sections were assigned letters in clockwise sequence, beginning at Buckhorn Wash and ending at Justensen flats. The closest sections (*A* and *B*) were 2 miles apart; the most distant section (H and I) were 21 miles apart (Figure 1). Samples collected were labelled with the section letter and a sequential number proceeding from bottom to top. Measurements were taken with a folding rule placed against the outcrop. Covered intervals were trenched, and steeply dipping beds were traversed with a Brunton Compass and Jacobs staff. Dr. R. Q. Oaks, Jr., aided in measuring all sections except section A.

Fossils were collected individually wherever possible, and they were labelled according to the same system used for rock samples. Beds containing very few fossils were sampled, but they were not collected extensively. Shell hashes and beds of exceedingly abundant fossils were collected as blocks due to the difficulty of collecting individual fossils. Study was made of the contact between the Navajo and Carmel Formations. Persistent beds were traced laterally as much as one-quarter mile.

Laboratory work was carried out principally during the winter and spring of 1967-1968. Morphologic and statistical analyses of the fossils were made to determine both the ecologic environments and origins of the fossil assemblages. The communities found were analyzed to determine whether they were assemblages that lived where they were found (biocoenosis), or were assemblages from which elements had been removed or admixed (mixed biocoenosis), or were assemblages composed entirely of remains washed in from elsewhere (thanatocoenosis).

Fossils were examined for density, orientation, dispersion, size frequence, relative abundance, associations, articulation, and degree of fragmentation. Fossiliferous zones were noted in the graphic version of each stratigraphic section (Figure 2). Fossils numbering more than 25 per square foot, and denser than 5 per linear inch of bed thickness, were

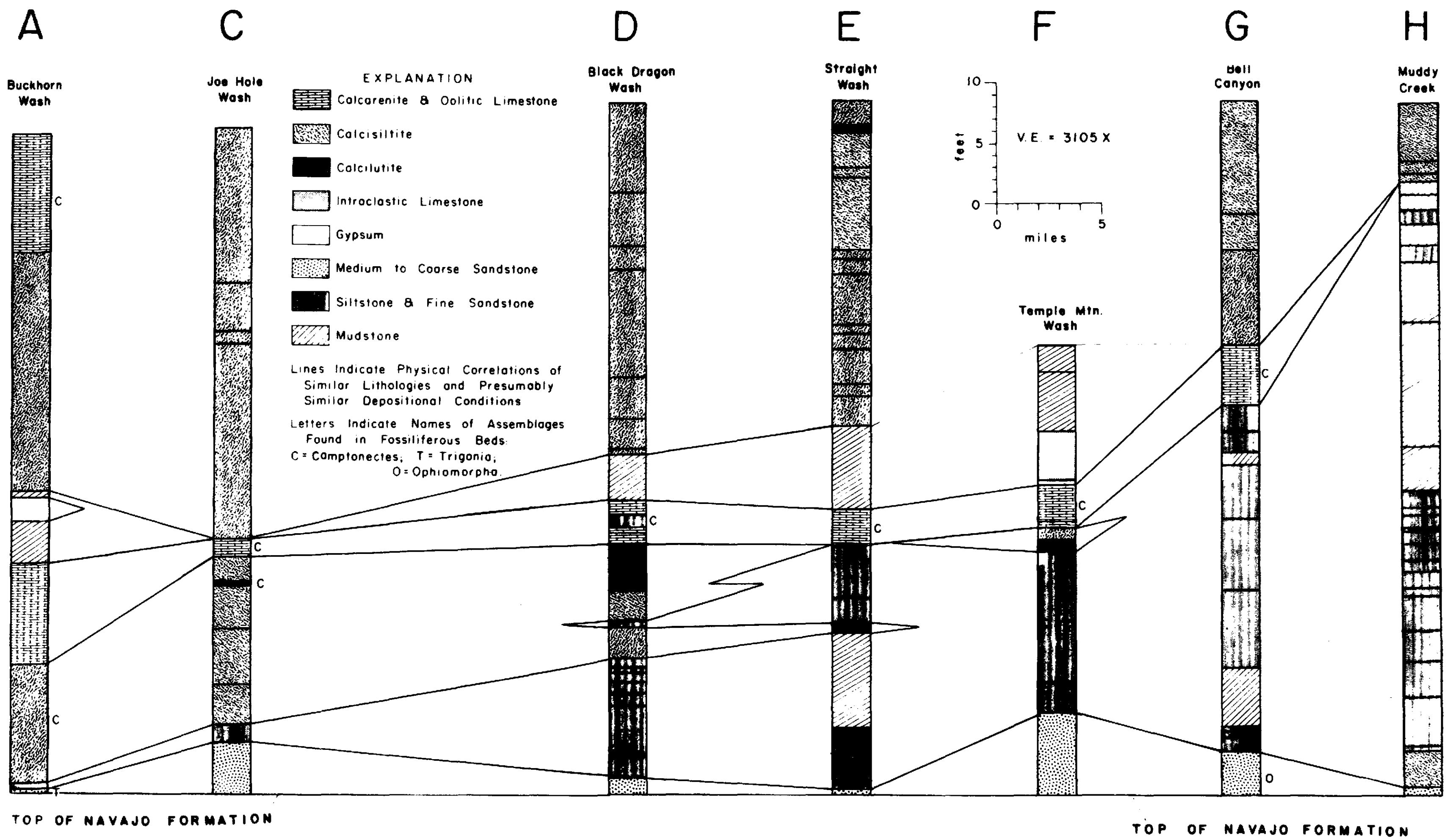

Figure 2: Geologic sections of lowermost part of Carmel Formation, San Rafael Swell, central Utah.

termed "very abundant." Fossils numbering 10 to 25 per square foot, but less than 5 per linear inch of bed thickness, were termed "abundant." Fossils numbering 5 to 10 per square foot were termed "common," whereas those between 3 and 5 per square foot were termed "uncommon." Fossils of lesser frequency were termed "rare."

Rocks were divided into the two broad classifications of clastic and nonclastic. Clastic rocks were subdivided into sandstones, siltstones, and mudstones. Nonclastic rocks were subdivided by decreasing grain size into intraclastic limestones (= rudite), calcarenite (= arenite), calcisiltite (= siltite), and calcilutite (= lutite). Oölitic limestones are approximately equivalent to calcarenites in grain size. Bedded gypsum also is present.

Rock samples gathered at each measured section were cut into slabs 0.2 inch thick, which were scrutinized with a binocular microscope for clastic content, grain size, and microfossils.

	Northern Arizona Lewis and others, 1961		San Rafael Swell Stokes and others, 1955	
Jurassic	San Rafael Group	Summerville Curtis Entrada Carmel	San Rafael Group	Summerville Curtis Entrada Carmel
Jurassic	Glen Canyon Group	Navajo	Glen Canyon Group	Navajo Kayenta
Triassic		Kayenta Moenave Wingate		Wingate

Table 1: Age assignments of the Mesozoic San Rafael and Glen Canyon Groups (after Lewis and others 1961; and Stokes and others, 1955.)

PREVIOUS WORK

General Statement

The literature on the Navajo Formation and the Carmel Formation is voluminous. In order to discuss the works of previous authors systematically, each unit will be reviewed separately in order of deposition, and according to two headings: (1) Stratigraphy; and (2) Fossils. The emphasis will be on systematics and synthesis rather than on criticism, due to the large amount of material to be reviewed.

Navajo Formation

Stratigraphy

The Navajo Formation is the youngest unit of the Glen Canyon Group (Table 1). Underlying the Navajo Formation in the San Rafael Swell, from youngest to oldest, are the Kayenta and Wingate Formations, a fluvial shale and massive sandstone, respectively (Harshbarger and others, 1957).

At Glen Canyon, Gregory and Moore (1931, p. 61) proposed the name "Glen Canyon Group" for the Navajo, Todilto, and Wingate Formations there. These formations previously had been called by Dake (1919, p.643), the "La Plata Group." The change from La Plata Group to Glen Canyon Group was made to prevent confusion with the La Plata Sandstone of Arizona.

Imlay (1952, p. 953, chart) suggested that the Navajo, Nugget, and Aztec Formations are correlatives. Stokes and others (1955, p. 2012) stated that the Navajo and Kayenta Formations intertongue, in central

Utah, and therefore are partially time equivalent. Poole (1962, p. 147) believed that the Navajo Formation is either wholly or partially equivalent to the Nugget Formation, and exactly equivalent to the Aztec Formation. Lewis and others (1961, p. 1439) favored moving the Triassic-Jurassic boundary to a point within the Navajo Formation, rather than to maintain that age boundary at the Wingate-Kayenta boundary as proposed by Stokes and others (1955, p. 2013). The view of Lewis and others is commonly accepted today.

Fossils

The Navajo Formation is largely barren of fossils; the major discovery was a theropod dinosaur found between Tuba City and Navajo Mountain, Arizona (Brady, 1935, p. 210). The remains consisted of a right hind foot, abdominal ribs, and impressions of the right femur and tibia. The dinosaur was identified as resembling *Ammosaurus major* Marsh. Another dinosaur, *Segisaurus halli* was found with hind feet drawn up under the abdomen (Harshbarger and others, 1957, p. 22). One foot was higher than the other, which suggested to those authors that the animal was trying to climb a dune. The sandstone in which the latter dinosaur was found was questionably identified as Navajo Formation.

Other fossils found in the Navajo Formation include lamellibranchs, especially *Unio* sp., remains of *Equisetum* sp., and unidentified gastropods, all of which occur in dolostone lenses in the lower portions of the Navajo Formation in Utah and New Mexico (Harshbarger and others, 1951, p. 22). The presence of *Unio* sp. indicates lacustrine conditions of some persistence (Webb, 1942, p. 127 and thereafter). The remaining rare fossils are scolithid tracks, dinosaur footprints, and a few feeding trails of unidentified creatures.

Carmel Formation

Stratigraphy

The Carmel Formation is the oldest unit of the Jurassic San Rafael Group. The other units, from oldest to youngest, are the Entrada, Curtis, and Summerville Formations (Table 1).

The name "Carmel Formation" was given to the red beds at Mount Carmel, Emery County, Utah (Gilluly, 1929, p. 100) to distinguish the marine beds (called Carmel Formation) from the non-marine beds (called Entrada, Curtis, and Summerville Formations). The group was named for the San Rafael Swell, . . . "where fine outcrops occur." (Harshbarger and others, 1957, p. 3).

The Carmel Formation consists largely of marine shales and limestones. The upper units contain appreciable amounts of gypsum. This gypsum-bearing quality is apparently characteristic of the Carmel Formation and its equivalent, the Arapien Formation. All authors that described either formation mentioned "gypsiferous beds."

Like the Navajo Formation, the Carmel Formation covers a broad area. The name "Carmel" is restricted to the area of New Mexico and central Utah. The formation thins to a feather edge near the Utah-Colorado border, and thickens to more than 1,000 feet in the San Rafael Swell. Hunt and others (1935, p. 70) noted that, as the Carmel Formation thins, it becomes less calcareous and increasingly more "earthy." Therefore, Hunt and others designated two facies of the Carmel Formation: (1) A northwestern facies of limestone and "gypsiferous beds," and (2) A southeastern facies of red-beds.

The Carmel Formation is definitely Jurassic, and ranges from Bajocian to Callovian in age (Imlay, 1957, p. 3). A definite Bajocian age was determined from the presence of the guide fossil, *Thracia weedi* Stanton.

Imlay (1952, p. 953) correlated the Carmel Formation with the Homestake Formation of the Iron Springs District, Utah, and with the Arapien Formation of the Wasatch Plateau. He correlated the upper part of the Carmel Formation with the Twin Creek Formation, and he correlated the Carmel Formation with the Lower Sundance Formation in part.

The Carmel Formation is believed to be shallow marine in origin. Its composition is described as red beds, gypsiferous beds, limestones, and mixed anhydrites. The presence of extensive beds of pure gypsum of alabaster quality, and extensive beds containing gypsum stringers has led authors to postulate a warm, hypersaline condition for the Twin Creek Sea. Harshbarger and others (1957, p. 35) noted that beds of gypsum are often contorted. Imlay (1964, p. 40) suggested that the beds were hydrated during a late Callovian transgression, and that the hydration caused the contortion. Imlay (1964, p. 4) said that the Carmel Formation and its equivalents represent the marginal environments of the Jurassic Twin Creek Sea.

Fossils

Unlike the Navajo Formation, the Carmel Formation and the Twin Creek Formation are rather fossiliferous. The fossils are not evenly distributed throughout the Carmel Formation, but tend to be more common near the base of the formation. Table 2 compares Carmel fossils found in the San Rafael Swell by Hunt and others (1953, p. 101), with those found in the course of this study. Imlay (1964, p. 1) reported that 33 genera and 44 species have been found in the Carmel Formation and its equivalents. The dominant genera he found were *Ostraea*, *Pronoella*, *Vaugonia*, *Myophorella*, and *Lima*.

Hunt and others, U.S.G.S. Prof. Paper 228	This paper (notations refer to entire individuals or entire valves found)
Camptonectes stygius White	*Camptonectes stygius* White (40 specimens)
Camptonectes extenuatus Meek and Hayden	*Camptonectes platissiformis* White (20 specimens)
Camptonectes bellistriatus Meek and Hayden	
Trigonia n. sp. *aff. Trigonia americana* Meek	*Trigonia* sp. *cf. T. americana* Meek (6 specimens)
Trigonia quadrangularis Meek	
Trigonia montanaensis Meek	
Ostraea engelmanni Meek	*(?) Ostraea* (5 specimens)
Ostraea stringelecula White	*(?) Gryphaea* sp. (3 specimens)
Plicatula n. sp.	*Isognomon perplanum* Whitfield (5 specimens)
Modiola subimbricata Meek	*Lima ziona* Imlay (2 specimens)
Pholadomya kingi Meek	*Pronoella* sp. (1 specimen)
Tancredia sp.	*Vaugonia* sp. (2 specimens)
(?) Dosinia sp.	*Nerinea* sp. (4 specimens)
(?) Tellina sp.	*Cossmanea* (3 specimens)
(?) Corbula sp.	
Dentalium subquadratum Meek	*Ophiomorpha* sp. (6 specimens)
Cardioceras cf. *C. diastans* Whitfield	*Pentacrinus* sp. *cf. P. asteriscus* (2 specimens)

Table 2: List of fossils found in Carmel Formation by Hunt and others (1953) and by the author.

He stated that fossils are most abundant in the Carmel Formation in a belt along the west side of the San Rafael Swell, and that fossils are less common elsewhere.

GEOLOGIC SETTING

The San Rafael Swell is a breached anticline that was arched upward initially during Pennsylvanian time to form the Emery Uplift. Beds in the center of the Swell are horizontal and little disturbed. In Buckhorn Wash, the horizontal succession of beds may be traced downward as far as the Permian Kaibab Formation. Rocks in the eastern perimeter of the Swell are sharply upturned to form the feature known as the San Rafael Reef. Rocks as low as the Triassic Wingate Formation are commonly found in this area. The sharpness of upturning decreases northward and southward toward the noses of the anticline.

The Navajo Formation in Buckhorn Wash and elsewhere is represented by a white to buff sandstone with sweeping cross-strata. Gilluly and Reeside (1928, p. 72) mentioned a dreikanter zone in the Navajo Formation in Buckhorn Wash, which they asserted indicates an eolian origin for the formation. The cross-strata are bottom tangent and are especially distinct and well developed near the top of the section.

Wright and Dickey (1963) described two tongues of the Carmel Formation enclosed by the Navajo Formation, one at Moab, Utah, west of the Swell, and another in the south at Glen Canyon Dam. Their interpretation of the tongue near Moab is reproduced here in Figure 3.

The Carmel Formation sharply overlies the Navajo Formation. Through most of its extent, the Carmel Formation consists of red sandy limestones or grey limestones. The contact between the two formations is sharp and distinctly flat (Figure 4). Hunt and others (1953, p. 70) characterized the contact as hummocky, with a relief not exceeding 1 foot in 100 feet. Pre-Carmel erosional scouring at the contact has not been noted. Wright and Dickey (1963, p. 65) noted that the basal Carmel beds smoothly truncate

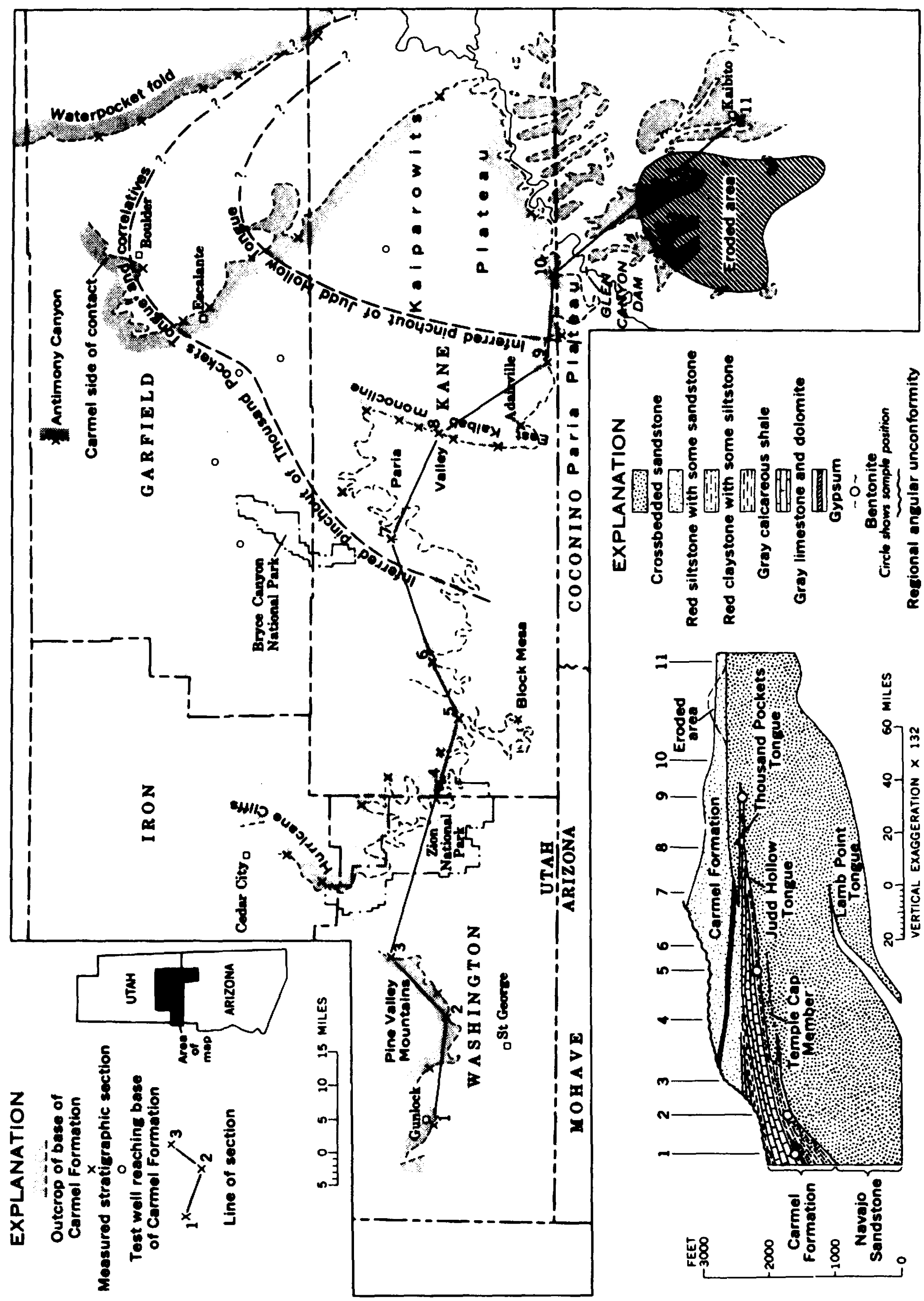

Figure 3. Map and section showing contact of Carmel and Navajo Formations, southwestern Utah and adjoining Arizona. Eroded area denotes anticline in Navajo that was beveled during deposition of Thousand Pockets Tongue (after Wright and Dickey, 1962).

cross-strata in the Navajo Formation. They also inferred that the process of planning of the Navajo-Carmel contact involved transport of Navajo sand for distances up to 70 miles. A similar flat contact was noted in each of the sections measured during the present study.

Carmel exposures vary greatly in thickness. In Buckhorn Wash, a structural plain occurs about 20 feet above the basal contact, and the remains of another, more ancient, structural plain are visible as relict portions of a resistant bed 40 feet above the current structural plain. A third structural plain is being formed on a red sandy calcisiltite whose top is only 11 feet above the contact. At other sections, structural plains occur on even less resistant beds, but none are so extensive as that at Buckhorn Wash. The thickest section was measured at Justensen Flats (section I), where no structural plain was developed.

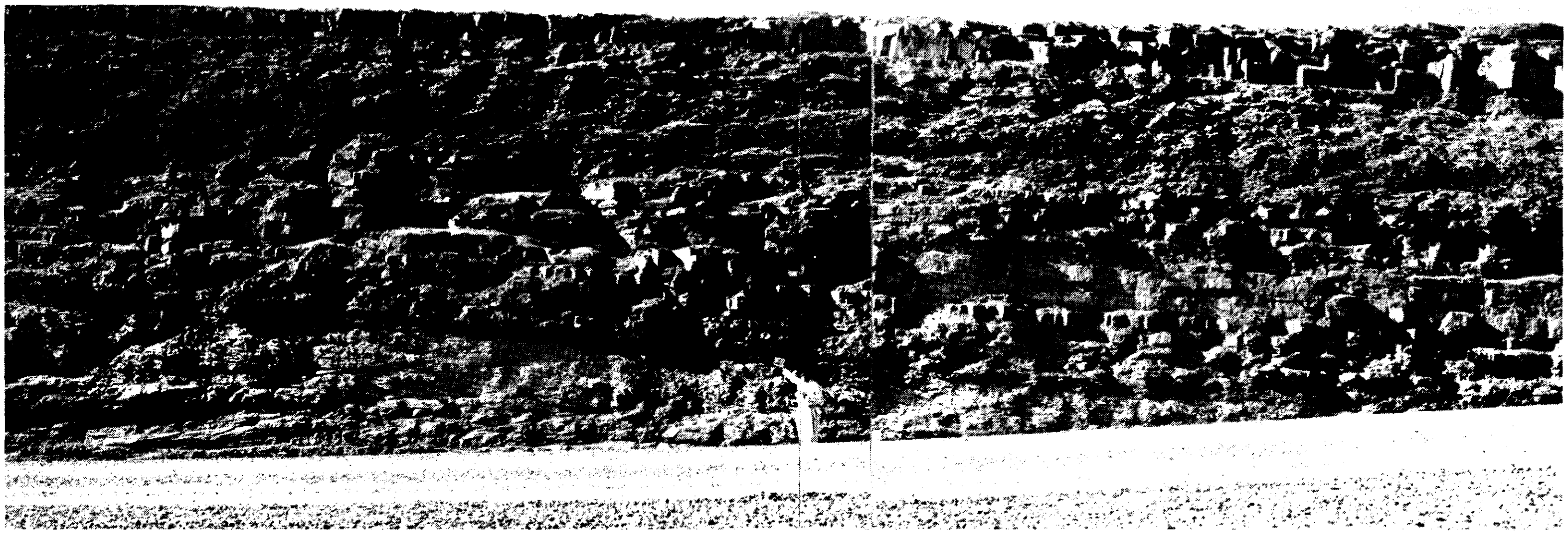

Figure 4. Photograph showing planar contact between cross-bedded Navajo Formation and overlying parallel-bedded Carmel Formation. Note sharpness of contact between formations. Justensen Flats (section I), west-central San Rafael Swell (Courtesy of Robert Oaks, Jr.).

STRATIGRAPHY

General Statement

In the sections measured, the Carmel Formation consists of a basal section of sandstone overlain by fine nearshore clastics that thicken southward, and by offshore carbonates that thicken northward (Figure 2). These in turn are overlain by a persistently fossiliferous oölitic limestone, and by a thick, nonclastic, offshore-carbonate sequence. Major bedding is parallel throughout (Figure 4). The section everywhere overlies the Navajo Formation along a sharp contact. No intertongues of the two formations were found. Section G, at Bell Canyon in the southern portion of the Swell, perhaps contained 3 to 6 feet of basal Carmel sandstone equivalent to terminal Navajo beds, but correlation is not definite. Channeling at the contact there was a possible alternative.

The Carmel Formation is not divided into members, although Imlay (1967, p. 3) subdivided the equivalent Twin Creek Formation into seven members. In the sequences measured, the basal sandstone and a persistent, fossiliferous, oölitic limestone form distinctive marker beds. The sandstone tends to be thicker in the south (0.75 to 7.0 feet) than in the north (0.25 to 4.5 feet), although differences in thickness are not systematic (Figure 2). In initial appearance, the sandstone is similar to that of the underlying Navajo Formation; however, this basal Carmel unit is parallel-bedded and contains fossils locally, whereas the Navajo Formation is cross-bedded and barren of fossils. This basal unit is interpreted as Navajo dune sand that was reworked by shoreline processes and deposited as a thin wedge of sand during transgression of the Carmel sea.

Just above the basal sand layer is a sequence of variegated siltstones, mudstones, and fine-grained sandstones. This layer is distinctly wedge-shaped, and thickens from 0.5 foot in the north to 40 feet in the south (Figure 2). The siltstones are fissile in appearance; some plates are almost 0.25 inch wide and about 0.01 inch thick. The mudstones are well consolidated, and form small steps within the siltstone slopes. Both rock types are calcareous locally. Sandstones within this clastic wedge are similar to the basal sandstone, but are finer-grained. Locally, some sandstones have cross-strata similar to those in the Navajo Formation. The contact between the basal sandstone and the immediately overlying fine clastic sequence is sharp but not abrupt. Since the fissile siltstone is a slope-former, its contact with better-consolidated beds nearly always is covered, and often is difficult to determine.

The wedge of fine clastics becomes both thicker and coarser southward, so that the northern sections contain thin beds of fissile siltstones, whereas the southern sections contain a thick section of mudstones and fine-grained sandstones, with subordinate fissile siltstones. These beds of sandstone and mudstone appear to be the nearshore lateral equivalents of the sequence of red and grey offshore carbonates that occur in the northern section between the basal sandstone and the overlying marker bed of oölitic limestone (Figure 2). The sharp contact between the basal sandstone and the fine-grained clastics above suggests that the source of sand was cut off rapidly, or that the environment of reworking and redeposition of the sand migrated rapidly over the area, and that the area of reworking lay elsewhere, though nearby, when the fine clastics were deposited.

Nature of the Beds

Unfossiliferous beds

Beds devoid of fossils include sandstones, mudstones, carbonates, and gypsum beds. Investigation under the binocular microscope shows that most sandstones are well sorted and medium- to fine-grained; only a few beds have silt mixtures. The cementing agent is calcite. Sandstone beds resemble those of the Navajo Formation in roundness, sorting, and all other aspects except average grain size and sedimentary structures.

Unfossiliferous mudstones are fine-grained and contain little or no calcite. Minor sedimentary structures are not evident in trenched sections. Unfossiliferous carbonates tend to be crystalline, with interlocking grains, and they present a sugary appearance under the binocular microscope. Most beds contain interference ripples, current ripples, and large, flat-topped ripples. No microfossils were found.

Fossiliferous beds

Beds that contain fossils are chiefly oölitic limestones, though some calcisiltites and calcarenites contain a few fossils. Three, or perhaps four, non-carbonate beds contained fossils: (1) The basal sandstone in section _A_; (2) A quartz sandstone 30 feet above the base of section _B_; (3) The basal sandstone in section _G_; and (4) A fissile siltstone bed 12 feet above the base of section _B_, that contains questionable fossils. Fossiliferous beds in sections _A_ and _B_ include a red sandy calcisiltite and a grey oölitic limestone. Section _E_ contains a fossiliferous red oölitic limestone. Abundantly fossiliferous beds in other sections are grey oölitic limestones. Southward, fossils become less abundant, so that, in section _A_, the red sandy calcisiltite, between 1 and 2 feet above the base of the section, is abundantly fossiliferous, whereas the oölitic limestone at section _G_ has only common fossils, that at section _F_ has only uncommon fossils, section _H_ has no fossiliferous beds, and section _I_ contains only a hash of fragmented fossils.

PALEOECOLOGY

Fossil Preservation and Occurrence

Preservation of fossils is chiefly by replacement. Replacement of shell material is by calcite in all cases except for *Ophiomorpha* burrows in section *G*, which are replaced by iron oxide. In all cases, replacement is of sufficient quality to permit specific or generic identification of mollusc shells. Only two beds exhibit other forms of preservation, described below.

Specimens of *Trigonia* sp. in the basal sandstone at section *A* consist of weathered casts in a matrix of coarse quartz sand, which makes determination of the original size or of the condition of the shell at deposition difficult. Preservation is sufficient to distinguish shape and ornamentation of larger fossils, especially of one individual; but preservation was insufficient to allow positive specific identification.

Preservation within a red sandy calcisiltite one foot above the base of section *A* is more problematical. The bed is a suite of three units with the following contents: (1) Abundant shells, (2) Very abundant shells, and (3) Abundant shells. Preservation of the fossils is not uniform. Fossils such as *Lima* sp., *Trigonia* sp., Nerineid gastropods, and fragments of *Pentacrinus* sp. are casts, whereas *Camptonectes* sp. and (?) *Gryphaea* sp. are replacements. The occurrence of calcite-lined vugs in the limestone suggests that the thinner shells were readily decalcified to casts, but that the thicker shells were not so easily dissolved completely, and tended instead to become recrystallized.

Most shells are unbroken. The single exception is a shell hash in section I, 12 feet above the base of the section. In this sole instance, all shells are broken in small fragments. Some specimens of Camptonectes platessiformis White, in the red calcisiltite one foot above the base of sections A and B, exhibit a broken area in the central portion of the shell. This condition seems more likely due to postdepositional compaction or to weathering of exposed fossils than to breakage at time of deposition (Fagerstrom, 1964, p. 1206). Cross-sections of fossils from the red calcisiltite show no such broken area.

Shells from the fossiliferous layers all are disarticulated, though the middle section of the red calcisiltite mentioned above yielded in cross section two specimens of probably articulated shells. One mold of a shell in articulated condition was found in the grey oölitic limestone 51 feet above the base of section A. In both cases, the shells were slightly displaced from the condition of perfect articulation, perhaps as a result of postdepositional compaction or slight current action. Penatacrinus sp. occurs only as stem fragments, and no calix plates and/or holdfasts were found. Specimens of (?) Gryphaea sp. were represented only by the smaller right valve. Both broken and unbroken gastropods were found; one Nerinea sp. occurred at the end of a scolithid trail.

Faunal Assemblages

Faunal assemblages form two major groups according to the type of rock in which they occur: (1) A sand-restricted group; and (2) A carbonate group. The sand-restricted group may be further subdivided into two assemblages according to the dominant constituent: (1) An Ophiomorpha assemblage; and (2) A Trigonia assemblage. A single occurrence of Pronoella sp. in sand 32 feet above the base of section B is of uncertain importance because of the total absence of other fossils.

The Ophiomorpha assemblage consists exclusively of burrows of a single, distinctive type. The Trigonia assemblage consists of Trigonia cf. T. americana Meek, and similar fossils, preserved only as outlines, which are questionably assigned to the genus Trigonia. Both sand assemblages occur only in the basal sandstone of the Carmel Formation. The impoverishment of the assemblages suggests that Trigonia sp. and Ophiomorpha sp. lived in selective environments, and that both organisms preferred sand bottoms. Trigonia sp. occurs locally in carbonate beds as part of one Camptonectes assemblage, but in drastically reduced numbers. Ophiomorpha sp. was found only in the basal sand bed, and only in section G.

Assemblages of the carbonate group are more varied and include the following two assemblages: (1) Camptonectes platessiformis White, Trigonia americana Meek, and (?)Gryphaea sp., and Lima ziona Imlay (lamellibranchs); Cossmanea sp. and Nerinea sp. (gastropods); scolithid trails (trace fossils); and Pentacrinus sp. (crinoid); and (2) Camptonectes stygius White, (?)Ostraea sp., (?)Gryphaea sp., Isognomon sp., Pronoella sp., and Vaugonia sp. (lamellibranchs); and (?)Cossmanea sp. and (?)Nerinea sp. (gastropods). The Camptonectes platessiformis assemblage occurs only in the red calcisiltite near the base of sections A and B, whereas the Camptonectes stygius assemblage occurs in oölitic limestones, which have considerable areal extent and serve as marker beds. The red calcisiltite occurs principally in the northern San Rafael Swell, whereas oölitic beds occur principally along the eastern margin of the Swell.

The carbonate assemblages occur exclusively in carbonate beds;

only Trigonia occurs in both sandy and carbonate beds. The assemblages therefore seem to have been specific to carbonate bottoms or to sand bottoms, and especially to aerated and agitated conditions in each instance.

It should be noted that only four of the nine sections contained beds with abundant fossils. In other sections that had fossiliferous beds, specimens of Camptonectes spp. and other forms were uncommon to rare. Assemblages and beds in sections A and B were virtually identical; therefore, fossils from section B are not listed in Table 2.

Autecology

Morphology and environment

Trigonia sp.

Specimens of Trigonia sp. in the Carmel Formation are not sufficiently well preserved for extensive morphologic analysis. Information about the genus Trigonia is derived chiefly from Rogers (1906, p. 380 and thereafter), who described the modern Neotrigonia margaritacea Lamark.

The shell of Trigonia spp. is thick, small, and light. Sculpture of the shell of Trigonia americana Meek consists of raised ribs parallel to growth lines. Sculpture in Neotrigonia margaritacea Lamark consists of ribs raised normal to growth lines. Specimens of Trigonia spp. figured in Moore, Lalicker, and Fischer (1952, p. 418 and thereafter) show both concentric and normal ribs which are often ornamented with nodules.

Ligaments of modern Neotrigonia spp. are small but strong. The hinge has the form of two grooved, tightly-locking plates. The shell has subequal muscle attachments, and it lacks a pallial sinus. Neotrigonia spp. today inhabit waters more than 50 feet deep, and live specimens demonstrate powerful leaping ability.

The living Neotrigonia spp. and fossil Trigonia spp. probably are best compared to Cardium spp., which live in the littoral and sublittoral zones. The living lamellibranchs have thick shells, a rather strong ligament, equal muscle attachments, and similar sculpture, but Cardium spp. have rather weak hinges compared with the strong hinges of Neotrigonia spp. and Trigonia spp. In normal living position, Cardium spp. rest in sandy sediments with the shell exposed slightly at the siphonal margin. Because Cardium spp. lack a pallial sinus, the similar condition in Neotrigonia spp. and in Trigonia spp. is assumed to denote a similar habit of burrowing in sand to no deeper than a barely covered position. It also can be assumed, by extension, that Trigonia americana Meek of the Carmel Formation was not a deep burrower, and could even have been epifaunal.

Camptonectes spp.

Modern Pectinidae are known swimmers, and there is no reason to believe that Camptonectes spp. were otherwise, in light of the similar morphologies of both fossil and living species. All Pectinidae have only a single muscle. Both attached and actively swimming lamellibranchs show this condition. Young Pectinidae today attach to sea weeds or to other plants or animals by means of a byssus. Members of one genus, Hinnites, attach permanently to rocks. Some species of Pectinidae retain the ability to attach throughout life. The ear of the shell over the byssal orifice shows a pronounced notch. The right valve, which has a byssal notch, lies against the bottom in attached forms, and usually is more inflated than the left valve. Coarsely ribbed forms tend to occupy turbulent, nearshore environments, whereas less coarsely ribbed forms tend to occupy quieter waters (Easton, 1960, p. 348).

Two species of Camptonectes are found in the Carmel Formation: C. platessiformis White, with equal ears and a fine radiating sculpture; and C. stygius White, with a pronounced byssal notch and no sculpture. C. platessiformis White occurs only in the red calcisiltite near the base of sections A and B. The sediment and shell sculpture both suggest that it probably prefered quiet water; the lack of a byssal notch suggests that it was not attached during adult life. C. stygius White occurs in oölitic limestones, which suggests a preference for agitated waters with little clastic content. The pronounced byssal notch probably indicates retention of attachment throughout adult life.

The occurrence of Camptonectes platessiformis White with epifaunal clams such as Lima sp. (see below) that today are not tolerant of abundant vascular plant life, suggests that C. platessiformis White lived in areas of sparse plant life and consequently lost attachment ablility. The occurrence of C. stygius with Isognomen sp. (see below) suggests that both probably attached to abundant vascular plant life near or in a zone of oölites.

Lima sp.

Shells identified as Lima cf. L. ziona Imlay were found only in the red sandy calcisiltite just above the base of section A. Modern Lima spp. have a shell shape similar to Pecten spp., except that Lima spp. lack the notched ear of the latter. There is one muscle attachment, and sculpture consists of coarse, irregular, radiating ribs.

Modern Lima spp. are found on sandy bottoms and in reefs. Lima spp. today are agile, epifaunal lamellibranchs that either can attach to hard bottoms by means of a byssus, or can live free. Modern Lima spp. often allow the byssus to mat over the shell, so that bits of coral and other shells adhere to the byssus and form a crude "cave" around the shell.

Lima ziona Imlay of the Carmel Formation closely resembles the modern Lima scabra Born, which lives on shallow sandy bottoms with little plant life. The fossil species possibly inhabited a quiet, carbonate bottom similarly devoid of vascular plant life.

(?)Gryphea and (?)Ostraea

Shells identified as (?)Gryphaea sp. are flat, torted valves with a single muscle attachment. Imlay (1964, p. 483) identified both Ostraea sp. and Gryphaea sp. in the Carmel Formation. Modern Ostraea spp. are found on muddy tidal flats, and are usually solitary. Gryphaea spp. are not extant today, but also probably were mud-dwellers. Ostraea spp. attach to shell, rock, and firm mud bottoms, whereas Gryphaea spp. presumably were unattached. The latter were oriented hinge downward in the bottom (Simpson, 1949, p. 153). The red calcisiltite near the base of Section A, and a dusky yellow oölitic limestone 21 feet above the base of section D yielded shells closer in form to Gryphaea sp. than to Ostraea sp. The grey oölitic limestones yielded shells closer to Ostraea sp. than to Gryphaea sp. One specimen of a possible left valve of Gryphaea sp. was found in a grey calcilutite 12 feet above the base of section C. One possible left valve of Ostraea sp. was found in a grey oölitic limestone 40 feet above the base of section A.

Both *Gryphaea* sp. and *Ostraea* sp. were sesile filter feeders, and may be related genetically, *Gryphaea* possibly preferred quiet waters, and *Ostraea* sp. probably preferred agitated water, but definite inferences are not justified due to lack of definite identifications.

Cossmanea sp.

The gastropod *Cossmanea* sp. is represented by a few, high-spired shells that do not exceed 0.25 inch in length. They are found in the red calcisiltite just above the base of section *A*. The shells have no ornamentation, and the whorls are slightly concave in the middle. The specimens found are identified as *Cossmanea* sp. aff. *C. imlayi* Sohl (1965, pl. 4).

Cossmanea spp. are in the family Nerineidae, and they are closely related to *Nerinea* sp., which is described below. *Cossmanea* sp. appears to be restricted to the fossiliferous calcisiltite just above the base of section *A*, whereas *Nerinea* sp. occurs in oölitic limestones, and is particularly abundant in the red oölitic limestone 15 feet above the base of section *E*. Two specimens of *Nerinea* sp. were found in the red calcisiltite near the base of section *A*, one at the end of a scolithid trail.

Similar ecological niches are postulated for both *Cossmanea* sp. and *Nerinea* sp.

Nerinea sp.

The genus *Nerinea* is extinct today, but information about such epifaunal gastropods as *Siphonalia* spp. may indicate the ecological adaptation of *Nerinea*. The shells of *Nerinea* spp. are small (0.5 inch or less), smooth, and helicoidal, and have a small, upturned siphonal canal. The modern Siphonolia spp., which live on mud bottoms, also exhibit an upturned siphonal canal. The modern infaunal Terebra spp. and the epifaunal Turris spp., which are high-spired, are slow-movers. Therefore, Nerinea sp. possibly was a slow-moving, mud-dwelling carnivorous gastropod also. Whether it was a predator or a scavenger is not definitely known. The occurrence of one Nerinea sp. at the end of a scolithid trail suggests an epifaunal existence. Nerinea sp. occurs in the red calcisiltite just above the base of section A, and also in the dusky yellow oölitic limestone of section D, but is less common in the fossiliferous grey oölitic limestones.

Isognomon sp.

Only five specimens of Isognomon sp. were found. The shell is long, with a sculpture of rugae parallel to growth lines. The hinge line is straight, and set at an angle to the direction of growth. The shell resemble Mytilus sp. with its elongate ear located at the hinge line opposite the area of byssal attachment.

Modern Isognomon spp. are sessile lamellibranchs that attach firmly by a byssus to such bottom features as sea fans, branches and roots of trees tolerant of saline water, or to a firm sea bottom. Isognomon spp. are found in shallow waters from intertidal depths to the upper part of the benthic zone. Deep-water Isognomon spp. tend to be thin shelled and fragile. Intertidal Isognomon are thicker shelled. There is one muscle attachment, and the hinge attachment is weak. The byssus is extruded from an area in the middle of the hinge line.

The Jurassic Isognomon cf. I. perplanum Whitfield differs little from the modern Isognomon acutirostris Dunker. Therefore, similar life habits of both animals are inferred.

Salinity tolerances

It is difficult to infer in detail the salinity tolerances of invertebrates found in the Carmel Formation. Although gypsum and anhydrite beds are present, and beds containing gypsum stringers occur both above and below the evaporite beds, no fossils are found within 10 to 15 feet vertically of any such evaporitic sequence. It is therefore likely that none of the Jurassic animals could stand extremes of hypersalinity any better than most modern molluscs can. Imlay (1957, p. 484) believed that the presence of Ostraea sp., Mytilus sp. (not found) and Lopha sp. (not found) in the Carmel Formation indicated "normal salinity and temperature." Wilbur and Yonge (1964, p. 59) reported the salinity tolerance of the modern Crassostraea sp. ranges from 3 parts per thousand to 50 parts per thousand. The modern Isognomon spp. are found in brackish water (10-15 parts per thousand) and also in open-marine conditions (30-35 parts per thousand).

Because the corresponding Jurassic molluscs could have been as euryhaline as their closest living relatives, little definite information about salinity tolerances can be derived from their occurrences. However, salinity restrictions of modern crinoids suggest that occurrences of Pentacrinus sp. likely indicate normal marine salinities, or perhaps even slightly hypersaline conditions. Impoverishment of the assemblages may indicate imbalance of important ions rather than salinity extremes, but definite information is lacking. Evaporites, oölites, and carbonate predominance also suggest that the sea was probably of normal salinity or slightly hypersaline at all times. Further narrowing of salinity ranges without additional evidence is impossible.

Temperature tolerances

Temperature range of the Carmel Sea is equally difficult to define closely for the fossils found. Wilbur and Yonge (1964, p. 121) gave the upper thermal limit for molluscs as 45° C., and the lower limit for non-intertidal molluscs at -2°C. The thick and extensive beds of limestone with oölites, and interbedded gypsum, indicated that the sea was warm. Also, the probable desert-eolian conditions of the underlying Navajo Formation and overlying Entrada Formation make such a conclusion likely. Therefore, the animals probably were exposed to temperatures ranging from warm to hot. Imlay (1957, p. 490) suggested that the temperature of the Twin Creek-Carmel-Arapien sea was about that of the modern Borneo Sea.

Synecology

Trophic levels

Every animal requires energy to carry out its life functions. The Sun; plant life; and/or other animals provided major sources for this energy. The animals of any ecologic system therefore can be systematized according to the source of their energy, or nourishment. The source can be used to define a trophic level for each animal, wherein the level of photosynthesis is defined as the first trophic level. A herbivore would be at the second trophic level. A carnivore, (either scavenger or predator) that subsists on herbivores, or on other carnivores, would be at the third trophic level, or higher, respectively.

Trophic levels follow the second law of thermodynamics in that each trophic level supports fewer and fewer and larger and larger organisms (excluding parasites). A "food pyramid" (Odum, 1944, p. 74 and thereafter) is thus formed chiefly from plants, herbivores, and carnivores on herbivores. Such food pyramids rarely reach a seventh trophic level.

The ecologic systems represented by the two major *Camptonectes* assemblages in the Carmel Formation are distinctive in two ways: (1) Genera are many, but species are few; and (2) Trophic levels, as defined above, never reach beyond the fourth trophic level. Representatives of the first and second trophic levels (plants and micro-organisms) are not preserved because of their delicacy. Larger herbivores and omnivores at the second and third trophic levels commonly are preserved, and the presence of lower trophic levels may be inferred from the presence of higher ones.

The sand-bottom assemblage is strikingly impoverished. The basal sandstone contains specimens of *Trigonia* cf. *T. americana* Meek in small local areas in the northern portion of the Swell. The basal sandstone in the south, in section *G*, contains specimens of *Ophiomorpha* sp. No mixing of the animals was observed; competitive exclusion is possible, although not likely. If *Ophiomorpha* spp. can be compared to the Modern *Callianassa* spp. (an uncertain comparison) then Ophiomorpha represents the burrows of a scavenger, or selective detritus feeder (Hedgpeth, 1957, p. 721). *Trigonia* sp. is inferred to be a filter-feeder (Rogers, 1906, p. 357). These animals, while occupying separate niches, represent the second, or possibly the third, trophic level. Lower trophic levels are inferred, but evidence of higher levels is absent in the basal sandstone.

The absence of higher levels of the food chain may be attributed to several factors, or combinations thereof: (1) Ionic impoverishment or severe physical conditions could limit the biomass of the third level to a number insufficient to support a significant number of predators; or (2) The biomass of the lower levels was unusually small due to the short time of existence of the ecological conditions set up by a rapidly transgressing sea; or (3) Physical barriers prevented the ingress of predators into the area; or (4) Predators had few hard parts and/or were unlikely to be preserved, or were in insufficient numbers to be statistically significant for fossils to actually occur.

Conditions of the basal sandstone probably represent a combination of the above factors. Dolomite veins occurring in local patches of anastomosing veins suggests unusual physical conditions, perhaps periodic drying and cracking. These veins extend up to two feet into the Navajo Formation, and tend to lack typical mud-crack features. However, they are not observed elsewhere in the Carmel Formation. Further, a general lack of dolomite in the Carmel Formation (Imlay, 1957, p. 502) except as noted suggests that the Carmel-Twin Creek Sea may have been impoverished in the magnesium ion (important to most marine animals), and thus a barrier of osmosis could be set up. The small numbers of fossils found, and the thinness of the basal and stone in the north suggests both that the environment was ephermeral (in contrast to the oölitic limestone environment), and may represented a seral stage of community development, rather than a climax community. Further, Imlay (1957, p. 485) suggested the existence of ephemeral islands and bars that could have set up barriers to circulation and/or migration of predators, thus setting up both physical and ionic barriers. Or, the basal sandstone represented water too shallow for most predators, and/or the predators that were able to live in the environment may have been too few for the probability of fossilisation to be significant. Thus, all four factors may have acted in concert, or in other combinations to produce the observed community.

The Camptonectes assemblages present a more varied grouping, but the problem of the small number of higher trophic levels is thereby only more perplexing. Species of each assemblage are analysed in Table 3 according to their relation to the bottom and their mode of feeding. Genera of anisomyarian (one-muscled) lamellibranchs outnumber genera of isomyarian (two-muscled) ones. Further, the epifaunal animals are represented by more genera than infaunal one. The highest trophic level is the fourth, and the biomass of this level is rather small.

The unbalanced isomyarian-anisomyarian ratio is principally a function of the niches available to animals on a current-washed mobil substrate, and not a function of trophic levels. The epifaunal-infaunal ratio could result from the same considerations, or from unfavorable pH (acidity) or Eh (oxidation-reduction) conditions below the depositional interface. Or this latter ratio may be a function of high water temperature (Thorson, 1957, p. 464), rather than a function of food chains. However, none of these restraints sufficiently explains the small biomass of the highest trcphic level.

The principal constituents of the carbonate assemblages are filter-feeders, except Nerinea sp. (and Cossmanea sp.), so that only one trophic level is well-represented in the carbonate assemblages. Nerinea sp., as was noted in the section on autecology, was probably a carnivore. However the disproportionate biomass of the snail in comparison with the clams under it in the food chain suggests that Nerinea sp. was not a predator, but a scavenger. Although the niche of the animal is uncertain, a scavenger niche seems consistent with its morphology, which consideration would explain its small biomass in an oxidising environment.

Interpretation

Although the assemblages under discussion present similar aspects, the reasons for their similarity are very different. It is necessary to analyze the communities in terms of three parameters: (1) Bottom types, (2) Energy levels, and (3) Comparative maturity.

Bottom types ranged from clastic to nonclastic, based on the dominant materials surrounding the fossils. The clastic bottoms where organisms lived consist now only of quartz sand grains with calcite cement. The transitional and nonclastic bottoms where organisms lived included three varieties, sandy calcisiltite, oölitic limestone, and calcarenite composed of shell hash. Of the nonclastic bottoms, only the first two were quantitatively significant in fossil content. Animals in the third case were not identifiable, and hence were not readily analyzed.

High-, medium-, and low-energy levels were represented by various fossiliferous beds. Grain size tends to increase proportionately with evergy level, so that, in a sequence not appreciably altered diagentically, a fine grain size generally indicated low energy, and a coarse grain size, high energy. Only the high-energy level is represented by the fossiliferous clastic bottoms, whereas all three energy levels are represented by the fossiliferous nonclastic and transitional bottoms.

Assemblages therefore can be classified as follows:

	Clastic Assemblages	Transitional Assemblages	Nonclastic Assemblages
High Energy	*Ophiomorpha* *Trigonia*	None	Shell hash
Medium Energy	None	None	*Camptonectes stygius*
Low Energy	None	*C. platessiformis*	None

For comparison, members of each assemblage are classified below on the basis of bottom type:

Clastic (Quartz Sandstone)	Transitional (Sandy Calcisiltite)	Nonclastic (Oölitic Limestone)
Ophiomorpho sp.	*C. platessiformis*	*Camptonectes stygius*
Trigonia sp.	*Trigonia* sp.	*Vaugonis* sp.
	Lima sp.	*Isognomon* sp.
	Cossmanea sp.	(?)*Cossmanea* sp.
	Nerinea sp.	(?)*Nerinea* sp.
	(?)*Gryphaea* sp.	(?)*Gryphaea* sp.
	Pentacrinus sp.	(?)*Ostraea* sp.
		Pronoella sp.

Most animals, such as *Isognomon* sp., were specific to a single bottom type and to only one energy level, whereas a few, such as *Trigonia* sp., apparently were tolerant of different bottom types and energy levels.

Relative maturity of the communities is a matter not so easily determined. As mentioned before, the sand (clastic) groups occur only in the thin basal sand. The lack of numerous genera of animals suggests that the sand groups could be a community in a relative early stage of establishment. The small biomass of the communities supports this hypothesis, although severity of the environment and/or subsequent diagenesis also could be explanations.

The carbonate assemblages occur in thicker beds of as much as 10 feet, and have more genera. They appear to represent more or less well established communities. The change in biomass, from abundant to very abundant in the center of the sandy calcisiltite bed near the base of sections A and B, with no change in the animals present, suggests that the community was well established, but subject to change in ion balance, nutrients, or other physical or chemical factors.

The environment represented by the basal sandstone of the Carmel Formation is probably one of a shoreline area with plentiful clastic supply. The lack of abundant life suggests that the environment supported few animals, possibly due to the extremely short duration and high-energy condition of the environment. Hardy animals such as Trigonia sp. and Ophiomorpha sp. probably were among the few animals able to survive coastal conditions of the earliest invasion.

A deepening of the water was accompanied by deposition of a red sandy calcisiltite in the northern Swell, while fine sand and mudstone were deposited in the south. The calcisiltite represents a marked decrease of energy and a noticeable decrease in clastic supply. The water probably was not deep, nor was the clastic supply far removed, yet marine conditions had become sufficiently established to support large numbers of Camptonectes platessiformis White, and subordinate numbers of Lima ziona Imlay and Trigonia americana Meek. The lack of rain-drop impressions, mud cracks, or other signs of dessication suggests that the calcisitite was rarely, if ever, exposed. The disarticulated convex-up condition of the weak-hinged shells of Camptonectes spp. suggests that weak or moderate underwater currents probably were present. Larger shells such as _Trigonia_ sp. and _Lima_ sp. are preserved only as casts, and articulation therefore could not be determined. Ripple marks are difficult to detect where fossil shells are abundant. The presence of _Lima_ sp. and pectinid without a pronounced byssal notch suggests that vascular plants were not abundant. Lack of diversity of ranges in shell size suggest that currents in the water were sufficient to remove the small, light _Camptonectes_ shells, disarticulate larger shells, and possibly wash in small (?)_Gryphaea_ shells as much as one inch in diameter.

The oölitic limestones represent a second carbonate-bottom environment populated by yet another community. Members of the transitional assemblage that either tolerated or required a sandy bottom are absent. _Vaugonia_ sp. is found in place of _Trigonia_ sp., and _Isognomon_ sp. is present, whereas _Lima_ sp. is absent. Communities in oölitic limestones at all localities are nearly identical. The red oölitic limestone in section _E_ contains (?)_Gryphaea_ sp., whereas the grey oölitic limestone in section _A_ contains (?)_Ostraea_ sp. Specimens of _Isognomon_ sp. are more common (4 specimens) in a grey oölitic bed 40 feet above contact in section _A_ than in the marker bed in other sections (1 specimen). The grey oölitic limestone in section _A_ has definite rain-drop impressions at one horizon, whereas the other oölitic beds are not distinctly marked.

The environment represented by the oölitic limestones probably was a carbonate shoal or tidal flat somewhat above wave base, possibly exposed periodically, but not highly turbulent. During spring tides, with offshore winds, the area could have been exposed, so that rain could leave an impression locally.

Specimens of _Camptonectes_ spp. fall into two size categories: 1 inch to 1.5 inches (96% of the population) and 1.75 to 2.0 inches (4% of the population). Smaller specimens were not found. Three possible alternatives are posited for this situation: (1) Agitation of the water removed young members of the community, while at the same time disarticulating the remaining shells; or (2) Water temperatures inhibited reproduction during the warmest Jurassic Seasons; or (3) The community represents an early sere of evolution of the ecotopic community, and that the shells were washed in from elsewhere.

Of the alternatives, the third is the least likely. The large biomass of Camptonectes spp., together with the thickness of the oölitic beds, suggests that the community was a climax one in a well-established ecotome. Further, shells from the oölitic limestones exhibit no breakage, which suggests that any transport undergone by the shells was very little. The finding of a slightly disarticulated cast of a Camptonectes in the oölitic limestone __ feet above the base of section A supports this idea.

Alternative (2) is harder to evaluate. Pectinidae are found in all seas today. Other animals, such as Isognomon perplanum Whitfield, (?)Ostraea sp., Vaugonia sp., and Nerinea sp., which are unrelated to Camptonectes stygius White, and therefore have different reproductive habits, also show a selective size range; i.e., usually only one size is represented. Quite probably, temperature was not a factor inhibiting reproduction. If reproduction of such a diverse community was indeed inhibited, then a factor such as ion imblance or salinity fluctuations must be invoked. The lack of significant dolostone (Imlay, 1964, p. 462) suggests that magnesium (required of most molluscs) may have been periodically impoverished. However, lack of knowledge of the formation of dolomite, or of ion indicators in ancient seas precludes any firm inference.

Alternative (1) is the most supportable hypothesis. Shells are oriented as per the Model II community of Johnson (1960, p. 1078 and thereafter). The shells show no sign of wear, or of transportation over any great distance. Therefore, the communities in the oölitic limestones are inferred to be living communities with small, light, and young members removed by current action (compare Sohl, 1965, p. 6).

The fossils of the carbonate assemblage show the same size range as those in the red calcisiltite at section A. The shells perhaps were transported a sufficient distance to cause disarticulation, but not enough to break the shells. Adequate wave agitation of the water or gentle bottom currents are present in modern nearshore environments. Small shells could be removed in this manner, leaving behind larger shells, or larger shells could have been concentrated by storm waves.

The presence of *Camptonectes stygius* White, with its pronounced byssal notch, implies abundant vascular plants, though none were preserved. Oxidation probably destroyed many remains. Therefore, during deposition of the oölitic limestones, the water probably was warm, agitated sufficiently to form oölites with at least a single, clearly marked rind, and sufficiently oxygenated to support abundant animals and vascular plants.

In most cases, depositional conditions of the fossiliferous zones were terminated by a sudden influx of fine-grained clastics. A bed of fine-grained, fissile siltstone overlies the basal *Trigonia*-*Ophiomorpha* sandstone. The red calcisiltite of the northern Swell has a similar siltstone above it. The oölitic limestones in sections along the eastern border of the Swell are sharply overlain by mudstone beds, except in section C, where the fossiliferous oölitic limestone is overlain by a thick calcisiltite sequence with little clastic content. In all cases, the transition from coarse-grained clastics or carbonates to fine-grained clastics or calcisiltite is sharp, but not abrupt. Transitions from fine-grained clastics to overlying coarse-grained beds are more gradational. In conclusion, the influx of fine-grained material apparently smothered the fossiliferous zones, and brought living conditions for the existing communities to an end. (Table 3)

Mode of Life / Relation to Bottom		Herbivores	Filter Feeders	Sediment-Feeders	Carnivores and Scavengers
Epifaunal	Mobile		*Camptonectes stygius* *C. platessiformis* *Lima ziona* (rare)		*Nerinea* sp. *Cossmanea* sp.
Epifaunal	Attached		*Isognomon perplanum* *Pentacrinus asteriscus* ?*Gryphaea* sp. ?*Ostraea* sp.		
Infaunal	Burrowing in Unconsolidated Sediment		*Pronella* sp. *Trigonia americana* *Vaugonia* sp. (rare)		*Ophiomorpha* sp.
Infaunal	Boring				

Table 3: Fossil invertebrates of the lowermost Carmel Formation, arranged according to type of bottom and mode of feeding (after McAlester, 1968).

GEOLOGIC HISTORY AND PALEOGEOGRAPHY

Transgression of the sea from north to south is recorded by the lowermost part of the Jurassic Carmel Formation; however, the details of the transgression are complex.

The eolian origin of the Navajo Formation, below the Carmel Formation, suggests that the Carmel Sea transgressed over a dry and warm or hot area. High temperatures also are inferred from chemical and paleontologic evidence in the Carmel Formation itself. The transgression of the sea undoubtedly increased humidity and reduced temperature extremes without radically changing the average temperature.

Imlay (1957, p. 470) suggested that invasion of the Carmel-Twin Creek Sea resulted from tectonic downwarping of the Laramide trough, and that subsequent tectonic movements caused the sea to be divided into several subsidiary basins and shallow submerged areas (Figure 5). Thereafter, upwarping presumably caused extensive beds of gypsum to be deposited locally under restricted, hypersalin conditions.

The contact of the lowermost Carmel Formation with the underlying Navajo Formation is sharp and flat, and shows no small-scale warping. Thinness of the basal Carmel sandstone and stratigraphic relations of overlying facies suggest that this sandstone is essentially equivalent in time, in a geologic sense, throughout its extent. The basal sandstone thickens slightly southward, and the relations of clastic and carbonate wedges above it suggest that the unit of basal sandstone represents a single, rapid transgression from north to south that overran the entire area of the present San Rafael Swell. Then a pause in the transgression

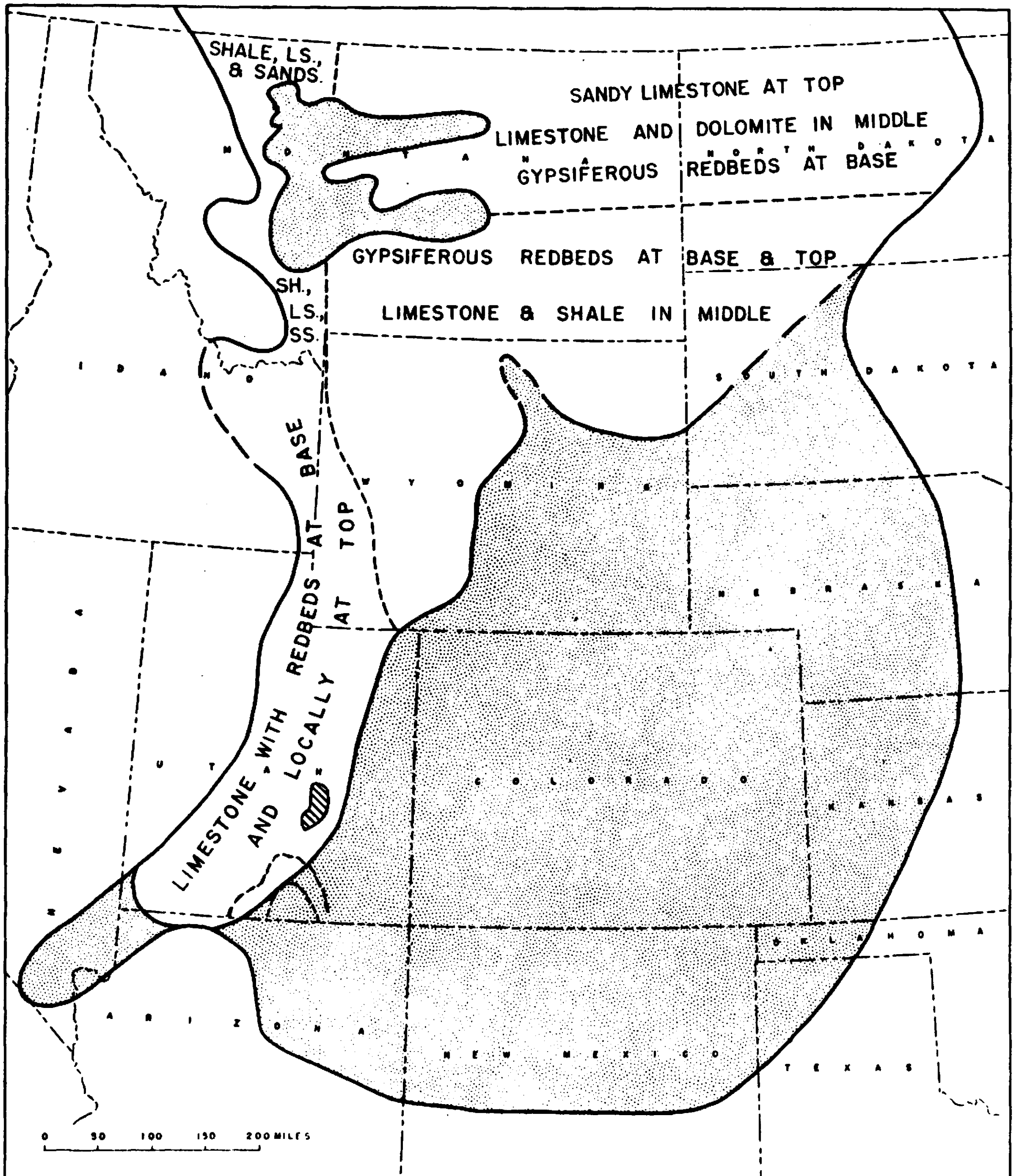

Figure 5. Distribution of marine (clear) and non-marine (stippled) deposits of middle Jurassic age (Bajocian), after initial transgressive phases of Carmel-Twin Creek Sea. Position of San Rafael Swell shown by ruled lines; extents of Judd Hollow Tongue and Thousand Pockets Tongue shown by dashed lines. Outer line designates present limits of Jurassic sediments. (Modified from Imlay, 1957).

resulted in shoreline deposition for a short period at Muddy Creek and possibly at Bell Canyon (sections G and H respectively).

At the end of the major transgression, a shoreline at the southern edge of the Swell was formed. This shoreline probably trended northeast-southwest. In the southern portion of the Swell, a clastic wedge was deposited, while brief deposition of clastics in the northern Swell was quickly succeeded by deposition of a carbonate sequence that thickened northward.

A later broad tectonic movement, or a possible differential deposition of carbonate material, caused an oölitic shoal to form just offshore. In Buckhorn Wash, a bar or island forming there caused a barren, ripple-marked calcarenite to form. A thriving, but impoverished community developed widely on the oölite shoal, probably from migrations from farther north where the Twin Creek Formation was being deposited, as shown by the similarity of faunas (Sohl, 1965, p. 13).

A slight subsequent regression of the sea (or progradation of the beach) caused mudstones to be deposited in the southern Swell, covering oölitic limestones as far north as section D.

Another major transgression of the sea moved the shoreline much farther south (possibly to the Utah Border), and caused thick sequences of calcisiltite to be deposited in the Swell. In section A, an oölitic shoal formed, and persisted for some time. Restriction of circulation due to bars, islands, or reflux conditions caused gypsum to be deposited locally. The sequence above the oölite shoal (excluding the one at Buckhorn Wash) is thought to be equivalent to the lowermost beds of the Judd Hollow Tongue of Wright and Dickey (1963).

There is no well known modern equivalent of the Carmel sea. Imlay

(1957, p. 501) compared the upper Carmel Formation to the Florida-Bahama region for depositional characteristics, and compared the whole Carmel sea to the Java Sea and the southern portion of the South China Sea for shallowness. However, there are few known places today with a shallow carbonate sea surrounded by extensive low-relief deserts. An analog of the Carmel sea would be produced if the Mediterranean Sea transgressed over the Sahara desert. The reworked dune sands of the desert would supply a basal sheet of sand overlain by thin, fine-grained clastics, and then by carbonate sediments.

CONCLUSIONS

Several conclusions based on the present study of the lowermost Carmel Formation seem justified:

(1) The initial Carmel-Twin Creek transgression was swift, but neither abrupt nor catastrophic. Imlay (1957, p. 474) stated that the earliest invasion of the Jurassic sea proceeded south from Alaska to a point near Fernie, British Columbia, near the end of Navajo time. Thereafter, within a short period, the sea transgressed southward from British Columbia to Arizona. Furthermore, churned beds and large marine scours are missing along the planar top of the Navajo Formation, so that the shoreline probably did not remain long in any one place.

(2) The Carmel sea was warm. Thick beds of carbonate deposition, oölites, and evaporites occur only in warm, shallow seas today. The ratio of epifaunal animals to infaunal animals (Thorson, 1957, p. 464) further suggests a tropical sea, although other factors also can control this ratio.

(3) The fossiliferous zones represent energy environments that range from high to low. The basal sandstone is coarse grained, and represents high-energy conditions. The red calcisiltite of the northern Swell is fine-grained, and probably represents low-energy conditions. The oölitic limestones imply a shoal somewhat above wave base, and therefore, medium-energy conditions.

(4) Communities show progressive diversity with time. The first assemblages, of Trigonia and Ophiomorpha, were characterised by lack of diversity on both generic and specific levels. The small biomass of

fossils, and the position in the top of the basal sandstone, suggest that these were communities just established before they were extinguished.

The Camptonectes platessiformis assemblage shows more diversity of genera, but a small number of species. The large biomass of C. platessiformis White with other, subordinate, elements suggests a community better established than the sand assemblages, but with few predators or vascular plants present.

The Camptonectes stygius assemblage shows approximately the same diversity as the C. platessiformis community, except that subordinate elements are more common. The C. platessiformis assemblage probably represents quiet water near or below wave base, whereas the C. stygius assemblage probably represents a well established community in shoal conditions, perhaps far from shore, with abundant plants, and with occasional exposure to air.

(5) The fossils in the communities were transported short distances. The lack of diversity of size ranges in all the communities, and disarticulation of shells suggest that currents or wave agitation removed smaller, lighter members of the communities, leaving larger or heavier members. Or, the same physical agents may have washed the larger elements in from elsewhere. However, lack of breakage shows that transportation was not far. Conversely, uniform size ranges could indicate cyclic spawning periods.

This study of the Carmel Formation defines some of the environmental parameters of an epeiric sea in an arid area. Other such studies, and closer study of the Carmel and Twin Creek Formations can only uncover even more interesting and useful facts about shallow, interior seas of the past.

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APPENDIX

Measured Geologic Sections

The nine sections measured are designated by letters from A to I, beginning clockwise from Buckhorn Wash in the north of the San Rafael Swell, and ending at Justensen Flats in the west. Sections were measured up to thick monotonous calcisiltite sequences, or up to the top of the exposed section. Thicknesses thus range from 37 to 133 feet. Measurements were made with a folding rule marked in inches and tenths. Covered intervals were trenched; such intervals and slumped sequences were traversed by means of a Jacobs staff and Brunton Compass. Color notations are those of the Munsell Rock Color Chart. Exposures of all measured sections were in good condition in the autumn of 1967.

Carmel Formation: Section A, exposure in north side of Buckhorn Wash, 0.25 mile east of road intersection at upstream entrance to Wash; Lat. 39°9'30"N, Long. 110°44'58"W; SW/4, NE/4, Sec. 13, RIOE, T19S.

		Thickness (Feet)
	Erosional top of section	
10.	Oölitic limestone, light gray(N7), raindrop impressions, parallel bedding 4 to 6 inches thick, fossiliferous: chiefly *Camptonectes stygius* White.	10.0
9.	Calcisiltite, gray green (5G 6/1), fissile, contains colored silicate nodules, becomes nodular at upper contact; slope-former	21.0
8.	Anhydrite, abundant gypsum stringers, very dark red (5R 2/6)	0.25
7.	Gypsum, white (N9), weathers very light gray (N8), fissile, forms small step.	3.0
6.	Anhydrite, abundant gypsum stringers, very dark red (5R 2/6)	4.5
5.	Calcarenite, moderate brown (5YR 5/4), gypsum stringers in upper 2 feet, fissile, current ripples on bedding surfaces, casts with appearance of fossils; cliff-former.	10.0
4.	Siltstone, unconsolidated, gray green (5G 6/1), fissile, plates average 0.25 inch wide, .01 inch thick; plates of sand, 0.5 inch thick, 3.0 inches wide contain casts with appearance of fossil	0.25
3.	Calcisiltite, sandy, moderate red (5R 5/4), locally medium gray (N5), calcitic vugs, bedding obscure, abundant *Camptonectes platessiformis* White in upper and lower portions, very abundant in middle portion, gradational base	11.25
2.	Siltstone, fine sandy, gray green (5G 6/1), ripples, fissile at top	0.5
1.	Sandstone, quartzose, medium-grained, calcite cement and some dolomite veins that extend into underlying Navajo Formation; grayish orange (10YR 7/4) to pale yellowish orange (10YR 8/6), parallel laminae and bedding; rare *Trigonia*	0.25
Total	. . . .	61.0

Navajo Formation

Carmel Formation: <u>Section B</u>, exposure in west wall of small, south-draining tributary of Buckhorn Wash, next to east-west road across north part of Swell; Lat. 39°10'24"N, Long. 110°43'45"W; NW/4, NW/4, Sec. 17, R11E, T19S.

		Thickness (Feet)
	Covered interval to crest of hill.	4.0
18.	Calcisiltite, light gray (N-7), parallel bedding 4 to 6 inches thick, interference ripples.	8.0
17.	Calcisitite, with clay admixture, grayish orange (10YR 7/4)	13.75
16.	Calcarenite, light brownish gray, (5YR 7/6), parallel bedding 4 inches to 1 foot thick, interference ripples; cliff-former	8.0
15.	Calcisiltite, oölitic, medium gray (N-5), blocky, parallel bedding, ripple marks with oölites on ripple crests; cliff-former	6.25
14.	Calcilutite, medium gray (N-5), parallel bedding; slope-former.	1.25
13.	Oölitic limestone, rounded clasts of carbonate material, broken fossils common; light olive gray (5Y 6/1); slope-former.	2.25
12.	Calcilutite, dense, medium gray (N-5); slope-former	0.5
11.	Calcisiltite, light olive gray (5Y 6/1), blocky, uncommon <u>Pronoella</u>; slope-former.	1.25
10.	Oölitic limestone, light gray (N7), bedding obscure, common <u>Camptonectes stygius</u> White; cliff-former	10.0
9.	Sandstone, quartzose, medium-grained, dark yellowish green (10GY 4/4), bedding obscure, local cross-strata, rare <u>Pronoella</u>	21.0
8.	Anhydrite with gypsum stringers, very dark red (5R 2/6), locally white; slope-former.	0.25
7.	Gypsum, white, (N9), locally gray (N8), fissile; slope-former.	3.0
6.	Anhydrite with gypsum stringers, very dark red (5R 2/6); slope-former	4.5

<u>Section B</u> (continued)	Thickness (Feet)
5. Calcarenite, rare gypsum stringers in upper portion: moderate brown (5YR 5/4), fissile, ripples; cliff-former.	10.0
4. Siltstone, gray green (5G 6/1), plates of sand contain casts with appearance of fossils. . . .	0.25
3. Calcisiltite, moderate red (5R 5/4), calcite-lined vugs, abundant *Camptonectes platessiformis* White in middle portion, gradational base.	11.0
2. Siltstone, minor sand, fissile at top, gray green (5G 6/1)	0.5
1. Sandstone, quartzose, medium-grained, parallel bedding, calcite cement, dolomite veins, grayish orange (10YR 7/4), pale yellowish orange (10YR 8/6).	0.25
Total	106.0

Navajo Formation

Carmel Formation: Section C, exposure in north side of east-flowing tributary to Joe Hole Wash, 750 feet north of east-west road across north part of Swell; Lat. 39°10' 36"N, Long. 110°31'25"W; SW/4, SW/4, Sec. 12, R12E, T19S.

		Thickness (Feet)
	Erosional top of section	
12.	Calcilutite with calcisiltite, light brownish gray (5YR6/1), parallel bedding local ripples, fissile, rare fossil-like casts	14.0
11.	Calcisiltite, grayish orange (10YR7/4) parallel bedding, parallel laminae weather into plates; slope-former	4.0
10.	Calcisiltite, minor clay greenish gray (5G6/1), thinly laminated	1.0
9.	Calcisiltite, light brownish gray (5YR6/1), very thinly laminated, fissile to platy; slope-former	16.5
8.	Oölitic limestone, light gray (N-7), common *Camptonectes stygius* White; cliff-former	1.5
7.	Calcisiltite, light gray (N-7), thin parallel bedding and laminae, rare fossils, worn and weathered *Camptonectes* spp.; slope-former	2.0
6.	Calcilutite, medium light gray (N-6), common fossils; cliff-former	.5
5.	Calcisiltite, light olive gray (5Y6/1), parallel bedding; cliff-former	3.5
4.	Calcisiltite, light brownish gray (5YR6/1), interference ripples, rare *Pronoella* sp.; cliff-former	4.5
3.	Calcisiltite, dusky red (5R3/4), parallel bedding and laminae; slope-former	4.5
2.	Calcisiltite, grayish orange (10YR7/4), and dusky red (5R3/4), thin bedding and laminae, granular appearance; slope-former	3.25
1.	Sandstone, quartzose, medium-to fine-grained, calcite cement, dark yellowish orange (10YR6/6), parallel bedding, nearly paralled laminae, cliff-former . . .	4.5
Total	. . . .	60.25
	Navajo Formation	

Carmel Formation: Section D, exposure in north side of Black Dragon Wash, 100 feet north of graded road, Lat. 38°51'14"N, Long. 110°27'07"W; NE/4, NE/4, Sec. 6, T22S, R14E.

		Thickness (Feet)
	Erosional top of section	
26.	Calcarenite, fine-grained, grayish orange (10YR7/4), thin bedding, laminae wavy parallel; some burrows in basal portion	7.5
25.	Calcisiltite, grayish orange (10YR7/4), churned; gypsum stringers perpendicular to bedding	4.5
24.	Siltstone, calcareous; yellowish gray (5Y7/2), with pale brown streaks (5YR5/2); slope-former	2.0
23.	Siltstone, fine sandy, grayish orange (10-1R74), wavy parallel to wavy non-parallel bedding, shallow scours, ripples; slope-former	0.5
22.	Siltstone, dusky yellow (5Y6/4), thin bedding, wavy parallel laminae; cliff-former	9.25
21.	Calcisiltite, local gypsum stringers parallel to bedding; grayish orange (10YR7/4) wavy parallel bedding, thin laminae	6.0
20.	Calcisiltite, grayish orange (10YR7/4), wavy parallel bedding; cliff-former	0.5
19.	Siltstone, locally oölitic, grayish orange (10YR7/4); Slope-former	4.0
18.	Oölitic limestone, dusky yellow (5Y6/4), massive; cliff-former	1.25
17.	Silt, unconsolidated, dusky yellow (5Y6/4), churned; slope-former	1.0
16.	Oölitic limestone, dusky yellow (5Y6/4), churned, uncommon Camptonectes sp.; cliff-former	0.5
15.	Oölitic limestone, dusky yellow (5Y6/4), unfossiliferous; slope-former	0.75
14.	Calcilutite, light gray (N7), parallel to nonparallel bedding 0.25 to 0.75 foot thick, unidentifiable fossils in upper part, interference ripples	3.0

Section D (continued)

		Thickness (Feet)
13.	Calcilutite, silty yellowish gray (5Y7/2), stylotites at upper contact with overlying bed; cliff-former	1.0
12.	Silt, find sandy, calcareous; yellowish gray (5Y7/2), wavy parallel bedding with interference ripples; slope-former	0.25
11.	Siltstone, very calcareous, light brown (5YR6/4), wavy parallel to nonparallel bedding, flat-topped ripples; cliff-former	2.5
10.	Silt, fine sandy, calcareous, grayish orange (10YR7/4), wavy parallel bedding; slope-former	0.5
9.	Calcarenite, fine-grained, fine sandy siltstone at base, very sandy throughout, dusky red (5R3/4); slope-former	2.5
8.	Siltstone, unconsolidated, fissile, plates 0.01 inch thick, 0.5 inch wide, variegated, dusky red (5R3/4) and grayish orange (10YR7/4); slope-former	0.75
7.	Sandstone, quartzose, fine - to medium-grained; light olive brown (5Y5/6); slope-former	0.5
6.	Sandstone, quartzose, fine - to medium-grained; poorly consolidated, grayish orange (10YR7/4); slope-former	0.75
5.	Silt, variegated medium dark gray (N4), light olive (5Y5/6), and brown and dusky red (5R3/4), unconsolidated; slope-former	1.0
4.	Sandstone, quartzose, fine-grained, moderate olive brown (5Y4/4), wavy parallel bedding; cliff-former	1.0
3.	Silt and sand; poorly consolidated; medium dark gray (N4), light olive brown (5Y5/6) and dusky red (5R3/4); slope-former	3.5

Section D (continued)

		Thickness (Feet)
2.	Sand, quartzose, fine-grained, unconsolidated, bluish white (5B9/1); slope-former	0.25
1.	Silt and sand, poorly consolidated, bluish white (5B9/1); some clay admixture	2.5
Total		57.75

Navajo Formation

Carmel Formation: Section E, exposure in south side of Straight Wash, 0.25 mile south of stream bed, on jeep trail; Lat. 38°45'44"N, long. 110° 29'47"W; SW/4, NW/4, Sec. 35, R13E, T23S.

		Thickness (Feet)
	Erosional top of section	
24.	Calcisiltite, greenish gray (5GY6/1), parallel bedding; slope-former	2.0
23.	Calcilutite, pale red (10R6/2), parallel bedding and laminae, irregular base; cliff-former	0.5
22.	Calcisiltite, some silt and clay, pale red (10R6/2); slope-former	2.75
21.	Calcisiltite, moderate red (5R5/4), parallel bedding, interference ripples; cliff-former	0.75
20.	Calcisiltite, pale red (10R6/2), poorly consolidated; slope-former	6.0
19.	Calcisiltite, grayish red (5R4/2), bedding obscure, rare Camptonectes sp.; cliff-former	0.75
18.	Calcisiltite, medium light gray (N-6), parallel bedding, interference ripples; cliff-former	1.25
17.	Calcisiltite, moderate red (5R5/4), wavy parallel bedding and laminae; rare Camptonectes and Vaugonia; cliff-former	3.0
16.	Calcisiltite, some silt and clay, moderate reddish orange (10R6/6), moderately consolidated	1.0
15.	Calcisiltite, mudstone-calcilutite interbeds and lenses light red (5R6/6), parallel bedding, interference ripples; cliff-former	2.5
14.	Calcisiltite, moderate red (5R5/4), parallel bedding and laminae; cliff-former	3.0
13.	Calcisiltite, light red (5R6/6), parallel bedding; cliff-former	1.0
12.	Calcisiltite, light gray (N7), very hard parallel bedding, interference ripples; cliff-former	2.5
11.	Mudstone, moderate red (5R5/4), parallel bedding, unit slumped and rotated northwards, well consolidated but not a cliff-former	7.0

Section E (continued)

		Thickness (Feet)
10.	Oölitic limestone, moderate red (5R5/4), interference ripples, common, Camptonectes stygius White; cliff-former	2.75
9.	Sandstone, quartzose, medium-grained, calcite cement; grayish orange (10YR7/4), churned; cliff-former	4.5
8.	Sandstone, quartzose, fine-to medium-grained, calcareous, grayish orange (10YR7/4), irregular bedding, churned, cliff-former	2.5
7.	Calcilutite, yellowish gray (5Y7/2), parallel bedding; cliff-former	1.0
6.	Mudstone, calcareous, yellowish gray (5Y7/2), parallel bedding; slope-former	1.0
5.	Mixed siltstone, fine-grained sandstone, and mudstone; calcareous, dark yellowish orange (10YR6/6), more friable, unconsolidated, and calcareous upward; slope-former	2.25
4.	Sandstone, quartzose, fine-to medium-grained, dark yellowish orange (10YR6/6), irregular bedding; slope-former	0.75
3.	Sandstone, quartzose, fine-grained, calcareous, dark yellowish orange (10YR6/6), wavy parallel bedding, ripples and cross strata indistinctly present; slope-former	0.75
2.	Sandstone, quartzose, fine-grained, dark yellowish orange (10YR6/6), wavy parallel bedding; slope-former	1.5
1.	Sandstone, quartzose, fine-to coarse-grained, grayish orange (10YR7/4), parallel bedding sand reworked from underlying Navajo Formation	0.5
Total		51.5

Navajo Formation

Carmel Formation: Section F, exposure in east side of wash just north of Temple Mountain Wash, Lat. 38°39'31"N, Long. 110°38'13"W; SE/4 SE/4, Sec. 1, R11E, T25S, 125 feet south of graded road through wash.

		Thickness (Feet)
	Erosional top of section	
11.	Mudstone, grayish orange pink (5YR7/2), thin parallel bedding, interference ripples; cliff-former	2.25
10.	Mudstone, grayish orange pink (5YR7/2), parallel bedding and thin parallel laminae; slope-former	5.0
9.	Intraclastic limestone, clasts abundant in basal portion but less abundant upward, light brown (5YR6/4), basal section has low-angle cross-strata near base, parallel bedding in upper portion.	4.0
8.	Intraclastic limestone, minor clay and silt, bedding obscure, medium dark gray (N4); slope-former	0.5
7.	Oölitic limestone, stylolites at base, grayish orange (10YR7/4), interference ripples	3.0
6.	Oölitic limestone, light gray (N7), thin bedding, uncommon *Camptonectes* sp., ripples	0.5
5.	Calcisiltite, light gray (N7), parallel bedding; cliff-former	0.75
4.	Calcilutite, dense, light red (5R6/6), interference ripple; cliff-former	1.0
3.	Sandstone, quartzose, fine-grained, calcareous, minor clay and silt, dusky yellow green (5GY5/2); slope-former	11.0
2.	Sandstone and siltstone, non-calcareous, grayish yellow green (5GY7/2) and very pale blue (5B8/2), bedding obscure; slope-former	2.5
1.	Sandstone, quartzose, medium - to fine-grained, grayish orange (10YR7/4), parallel bedding and laminae, locally churned	7.0
Total	. . . .	37.5
	Navajo Formation	

Carmel Formation: Section G, exposure in east side of canyon just east of Bell Canyon, 0.75 mile north of road; Lat. 38°35'23"N, Long. 110°47'55"W; R10E, T25S, 7 miles north of Emery - Wayne County line.

		Thickness (Feet)
	Erosional top of section	
19.	Calcilutite, yellowish gray (5Y7/2), irregular parallel bedding, large ripples, possible scours; cliff-former	3.75
18.	Calcilutite, yellowish gray (5Y7/2), thinly laminated, interference ripples, wavy parallel bedding; cliff-former	0.75
17.	Calcisiltite, light brown (5YR6/4), parallel bedding; cliff-former	1.5
16.	Calcisiltite, moderate reddish brown (10R4/6), bedding obscure, churned; cliff-former	6.5
15.	Calcisiltite, local coarse-grained calcarenite, very light gray (N8), thin wavy parallel bedding; cliff-former	13.0
14.	Calcisiltite, minor sand, pale reddish brown (10R5/4), shallow scours; cliff-former	3.0
13.	Calcisiltite, pale reddish brown (10R5/4), parallel bedding; slope-former	8.0
12.	Oölitic limestone, silty in upper portion, medium light gray (N6), weathers light olive gray (5Y6/1), common Camptonectes sp.; cliff-former	5.0
11.	Siltstone, fine sandy, grayish orange (10YR7/4), poorly consolidated; slope-former	2.0
10.	Sandstone, quartzose, fine-grained, silty, grayish orange (10YR7/4), wavy parallel laminae, ripples, friable; cliff-former	1.75
9.	Mudstone, calcium carbonate along some bedding surfaces, grayish orange (10YR7/4), thin parallel laminae; slope-former	0.75
8.	Siltstone, minor clay, carbonate cement, grayish orange (10YR7/4), moderate reddish brown (10R4/6) at base, parallel bedding, flat-topped ripples, grades into fine sand at top; cliff-former	4.5

Section G, (continued)

		Thickness (Feet)
7.	Siltstone, minor clay, moderate reddish brown (10R4/6), wavy parallel and locally irregular bedding, ripples; slope-former	6.0
6.	Siltstone, minor clay, pale reddish brown (10R5/4), wavy parallel and locally irregular bedding; cliff-former	6.5
5.	Mudstone, moderate reddish brown (10R4/6), parallel bedding, thin parallel laminae, calcite stringers parallel to bedding planes; slope-former	4.75
4.	Siltstone, dark yellowish orange (10YR6/6), friable, parallel bedding; slope-former	0.5
3.	Silt, moderate yellowish brown (10YR5/4), loose, gypsum stringers 0.25 inch thick; slope-former	0.5
2.	Siltstone, variegated, grayish orange (10YR7/4), and dark yellowish orange (10YR6/6), friable, bedding obscure; slope-former	1.25
1.	Sandstone, quartzose, coarse-grained, light brown (5YR6/4), weathers dark yellowish orange (10YR6/6), bedding irregular and discontinuous but locally parallel, churned locally, iron concretions and Ophiomorpha burrows present	3.5
Total	. . . .	73.5

Navajo Formation

Carmel Formation: Section H, exposure in east side of canyon cut by Muddy Creek, 1 mile south of Hidden Splendor Uranium Mine; Lat. 38°32'30"N, Long. 110°56'10"W; R9E, T26S, 3 miles north of Emery - Wayne County line.

		Thickness (Feet)
	Top of measured section; nearly vertical rock face limited further measurement at this locality.	
34.	Oölitic limestone, moderate reddish brown (10R4/6), parallel bedding; cliff-former	2.5
33.	Siltstone, moderate reddish brown (10R4/6), bedding obscure; cliff-former	1.25
32.	Siltstone, varigated grayish yellow (5Y8/4) and pale red (10R6/2), bedding obscure; slope-former	3.0
31.	Mudstone, grayish yellow (5Y8/4), parallel bedding; slope-former	0.75
30.	Mudstone, moderate yellow green (5GY7/4), flat-tipped fipples; cliff-former	2.75
29.	Mudstone, moderate greenish yellow (10Y7/4), parallel bedding and laminae, interference ripples; slope-former	6.25
28.	Mudstone, moderate greenish yellow (10Y7/4), weathers into nodules, interference ripples; cliff-former	5.25
27.	Mudstone, light gray (N7), bedding obscure; slope-former	4.5
26.	Mudstone, medium light gray (N6), parallel bedding; slope-former	4.5
25.	Mudstone, medium light gray (N6); slope former	1.0
24.	Calcisiltite, light gray (N7), dense, interference ripples; cliff-former	0.5
23.	Mudstone, greenish gray (5GY6/1), parallel bedding and laminae; cliff-former	1.0
22.	Mudstone, greenish gray (5GY6/1), parallel laminae and steep cross laminae; slope-former	1.25
21.	Sandstone, quartzose, very fine-grained, bluish white (5B9/1), parallel bedding, wavy parallel laminae; increasingly calcareous upward, stylolites at contact with overlying bed; slope-former	1.25

Section H, (continued)

		Thickness (Feet)
20.	Sandstone and siltstone, inter-layered, light bluish gray (5B7/1), parallel bedding, interference ripples; slope-former	1.75
19.	Sandstone, quartzose, fine-grained, light bluish gray (5B7/1), parallel bedding, interference ripples, some parallel laminae; slope-former	1.5
18.	Siltstone, pale red (5R6/2), parallel bedding and laminae; slope-former	4.75
17.	Siltstone, pale blue (5PB7/2), bedding obscure, (parallel ?); slope former	10.5
16.	Siltstone, light red (5R6/6), parallel bedding; slope-former	3.5
15.	Sandstone, quartzose, fine-grained, light brown (5YR6/4), parallel bedding, cross-strata possibly present; cliff-former	1.25
14.	Sandstone, quartzose, fine-grained, light brown (5YR6/4), scours; cliff-former	0.75
13.	Sandstone, quartzose, fine - to medium-grained, light brown (5YR6/4), parallel bedding and laminae	1.0
12.	Sandstone, quartzose, very fine-grained, pale blue green (5B67/2), bedding obscure; cliff-former	0.25
11.	Sandstone, quartzose, fine-grained, light brown (5YR6/4), parallel bedding, cross-strata dip steeply southward; cliff-former	1.25
10.	Sandstone, quartzose, fine-grained to very fine-grained, light brown (5YR6/4), parallel bedding and laminae; cliff-former	1.25
9.	Sandstone, quartzose, fine - to very fine-grained, silty admixture, light brown (5YR6/4), parallel bedding, steep bottom-tangent cross-strata; cliff-former	2.25
8.	Sandstone and siltstone, interlayered, grayish red (10R4/2), parallel bedding, interference ripples; cliff-former	0.75

Section H, (continued)

		Thickness (Feet)
7.	Siltstone and sandstone, quartzose, fine-grained, interlayered, moderate reddish brown (10R5/4), contorted laminae, sand injected up to 6 inches into overlying bed; slope-former	3.25
6.	Siltstone and sandstone, quartzose, very fine-grained, interlayered, pale reddish brown (10R5/4), laminae possibly contorted, parallel bedding; slope-former	2.5
5.	Sandstone, quartzose, fine-grained, pale reddish brown (10R5/4), interference ripples, increasingly calcareous upward; slope-former	2.75
4.	Sandstone and siltstone, pale reddish brown (10R5/4), steep cross-laminae, some sand injections; slope-former	4.0
3.	Mudstone, dark reddish brown (10R3/4), contorted; slope-former	0.75
2.	Calcisiltite, light red (5G6/6), local gypsum and calcite; parallel bedding, laminae obscure; slope-former	2.5
1.	Sandstone, quartzose, medium-grained, moderate reddish brown (10YR5/4), bedding obscure; slope-former	0.75
Total	. . . .	83.0

Navajo Formation

Carmel Formation: Section I, exposure in road cut for Interstate I-15, Justensen Flats, Lat. (approx.) 36°50'35"N, Long. (approx.) 110°53'40"W; NE/4, NW/4, Sec. 3, R9E, T23S.

		Thickness (Feet)
	Top of measured section; thick monotonous sequence of calcisiltite lies above unit 24 at this locality.	
24.	Calcisiltite, light blue (5B7/6), weathers yellowish gray (5Y7/2), calcilutite interbeds, wavy parallel bedding; cliff-former	36.5
23.	Calcisiltite, light blue (5B7/6), parallel bedding; slope-former	1.75
22.	Mudstone, calcareous, grayish orange (10YR7/4), locally grayish green (10G4/2), parallel bedding, thick laminae; slope-former	16.75
21.	Calcisiltite, variegated grayish orange (10YR7/4), grayish yellow (5Y8/4), and moderate red (5R5/4), parallel bedding; cliff-former	1.5
20.	Anhydrite, very light gray (N8), streaks of dusky red (5R3/4); slope-former	1.0
19.	Gypsum, very light gray (N8), contorted, calcilutite clasts, veinlets extend into underlying bed	8.0
18.	Calcisiltite, gypsum stringer, contorted, light gray (N7); cliff-former	2.5
17.	Calcisiltite, dusky red (5R3/4), parallel bedding, gypsum stringers parallel to bedding planes, irregular contact with underlying and overlying beds	3.5
16.	Calcisiltite, pale reddish brown (10R5/4), thin gypsum veinlets approximately parallel bedding, calcite along joints, load casts at base; cliff-former	15.0
15.	Calcisiltite, medium light gray (n6) and light olive gray (5Y5/2), with red partings, deformed at top; parallel beds, thin laminae, some low-angle bottom0tangent cross-strata that dip eastward, calcite vugs near top	12.0
14.	Shale and calcisiltite, interlayered, medium gray (N5), fissile, ripplemarked calcisiltite dominates upwards	9.5

Carmel Formation: Section I, exposure in road cut for Interstate I-15, Justensen Flats, Lat (approx.) 36°50'35"N, Long, (approx.) 110°53'40"W; NE/4, NW/4, Sec. 3, R9E, T23S.

		Thickness (Feet)
	Top of measured section; thick monotonous sequence of calcisiltite lies above unit 24 at this locality.	
24.	Calcisiltite, lt. blue (5B7/6), weathers yellowish gray (5Y7/2), calcilutite interbeds, wavy parallel bedding; cliff-former	36.5
23.	Calcisiltite, lt. blue (5B7/6), parallel bedding; slope-former	1.75
22.	Mudstone, calcareous, grayish orange (10YR7/4), locally grayish green (10G4/2), parallel bedding, thick laminae; slope-former	16.75
21.	Calcisiltite, variegated grayish orange (10YR7/4), grayish yellow (5Y8/4), and moderate red (5R5/4), parallel bedding; cliff-former	1.5
20.	Anhydrite, very lt. gray (N8), streaks of dusky red (5R3/4); slope-former	1.0
19.	Gypsum, very lt. gray (N8), contorted, calcilutite clasts, veinlets extend into underlying bed	8.0
18.	Calcisiltite, gypsum stringer, contorted, lt. gray (N7); cliff-former	2.5
17.	Calcisiltite, dusky red (5R3/4), parallel bedding, gypsum stringers parallel to bedding planes, irregular contact with underlying and overlying beds.	3.5
16.	Calcisiltite, pale reddish brown (10R5/4), thin gypsum veinlets approximately parallel bedding, calcite along joints, load casts at base; cliff-former	15.0
15.	Calcisiltite, med. lt. gray (N6) and lt. olive gray (5Y5/2), with red partings, deformed at top; parallel beds, thin laminae, some low-angle bottom-tangent cross-strata that dip eastward, calcite vugs near top	12.0
14.	Shale and calcisiltite, interlayered, med. gray (N5), fissile, ripplemarked calcisiltite dominates upwards	9.5

Section I, (continued)

		Thickness (Feet)
13.	Calcilutite, dusky red (5R3/6), wavy parallel bedding, rare Trigonia sp., some vugs; slope-former	1.25
12.	Shale, dusky red (5R3/6), bedding obscure; slope-former	0.25
11.	Shell-hash, calcarenite matrix, pale green (10G6/2) and medium light gray (N6), probable cross-strata; slope-former	11.0
10.	Mudstone, light gray (N7), fissile, slope-forming interbeds alternate with cliff-forming interbeds	1.5
9.	Mudstone, light gray (N7), dense, flat, parallel laminae; cliff-former	0.5
8.	Siltstone, medium light gray (N6), rare unidentified fossils; cliff-forming interbeds alternate with thin slope-forming interbeds	3.5
7.	Siltstone, greenish gray (5G6/1), fissile, obscure bedding; slope-former	0.5
6.	Calcarenite and calcisiltite, interlayered, dark yellowish orange (10YR6/6), parallel bedding, rare and broken fossils	0.75
5.	Siltstone, pale green (10G6/2), thin parallel laminae	0.5
4.	Calcarenite, light gray (N7), thin laminae; slope-former	1.5
3.	Sandstone, quartzose, fine-grained at base, siltstone with some fine sand at top, parallel bedding, calcitic lenses and intraclasts, dark yellowish orange (10YR6/6); slope-former	2.75
2.	Siltstone, pale green (5G6/2), wavy parallel bedding, flat-topped ripples near top of bed	0.75
1.	Sandstone, quartzose, fine-grained, pale yellowish orange (10YR8/6), local lenses and green plates of siltstone; slope-former	0.25
Total		133.00

Navajo Formation

Section I, (continued)

		Thickness (Feet)
13.	Calcilutite, dusky red (5R3/6), wavy parallel bedding, rare *Trigonia* sp., some vugs; slope-former	1.25
12.	Shale, dusky red (5R3/6), bedding obscure; slope-former . .	0.25
11.	Shell-hash, calcarenite matrix, pale green (10G6/2) and med. lt. gray (N6), probable cross-strata; slope-former	11.0
10.	Mudstone, lt. gray (N7), fissile, slope-forming interbeds alternate with cliff-forming interbeds	1.5
9.	Mudstone, lt. gray (N7), dense, flat, parallel laminae; cliff-former	0.5
8.	Siltstone, med. lt. gray (N6), rare unidentified fossils, cliff-forming interbeds alternate with thin slope-forming interbeds	3.5
7.	Siltstone, greenish gray (5G6/1), fissile, obscure bedding; slope-former	0.5
6.	Calcarenite and calcisiltite, interlayered, dark yellowish orange (10YR6/6), parallel bedding, rare and broken fossils	0.75
5.	Siltstone, pale green (10G6/2), thin parallel laminae	0.5
4.	Calcarenite, lt. gray (N7), thin laminae; slope-former	1.5
3.	Sandstone, quartzose, fine-grained at base, siltstone with some fine sand at top, parallel bedding, calcitic lenses and intraclasts, dark yellowish orange (10YR6/6), slope-former	2.75
2.	Siltstone, pale green (5G6/2), wavy parallel bedding, flat-topped ripples near top of bed	0.75
1.	Sandstone, quartzose, fine-grained, pale yellowish orange (10YR8/6), local lenses and green plates of siltstone; slope-former	0.25
Total	. . . .	133.0

Navajo Formation

VITA

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