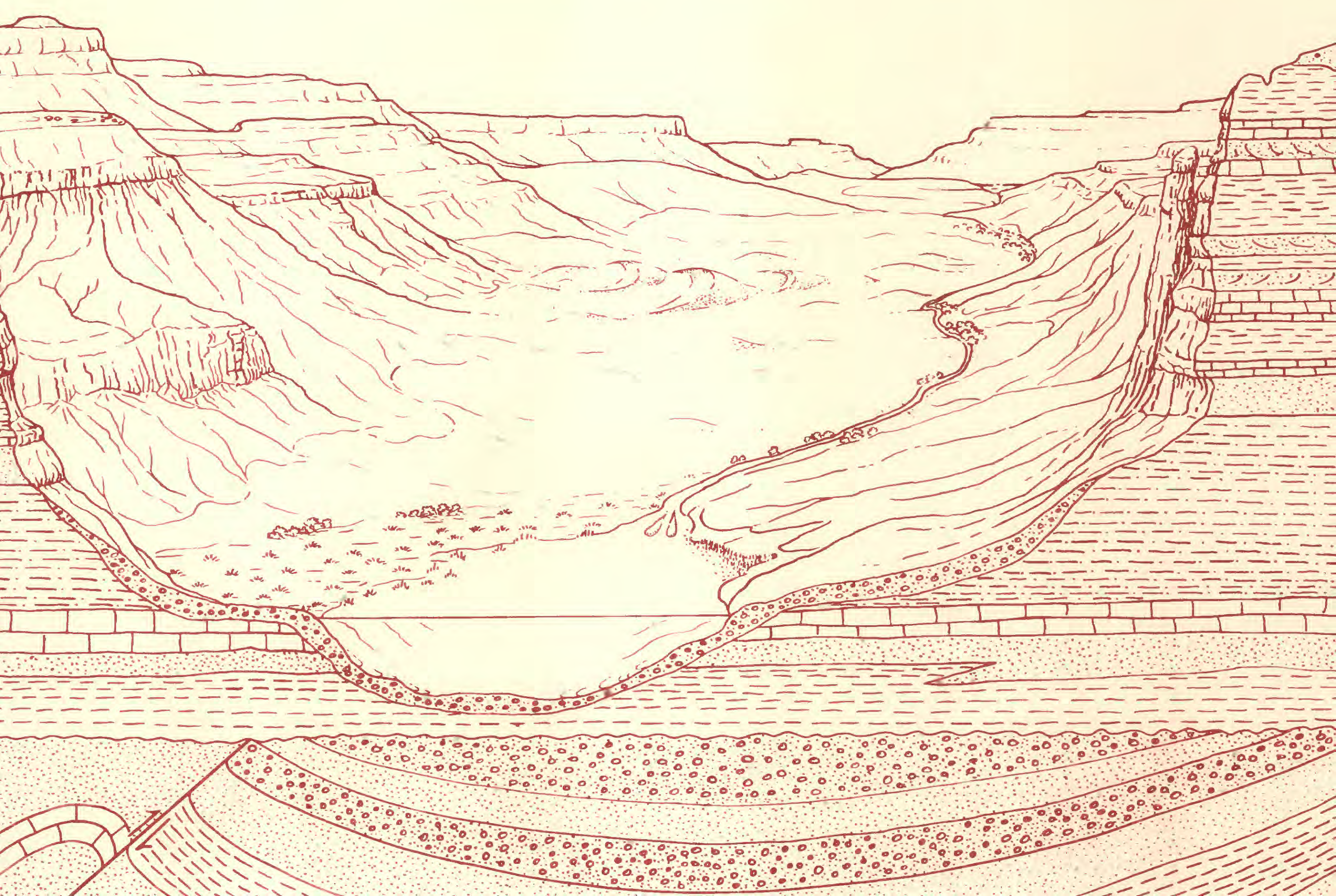
Upper Cenomanian Foraminifers from the Southern Part of the San Juan Basin, New Mexico

U.S. GEOLOGICAL SURVEY BULLETIN 1808–N



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Chapter N

Upper Cenomanian Foraminifers from the Southern Part of the San Juan Basin, New Mexico

By MARY ALICE CAREY

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1808

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1992

For sale by
Book and Open-File Report Sales
U.S. Geological Survey
Box 25425
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Carey, Mary Alice.

Upper Cenomanian foraminifers from the southern part of the San Juan Basin, New Mexico : a multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern / by Mary Alice Carey.
p. cm. — (Evolution of sedimentary basins—San Juan Basin ; ch. N)
(U.S. Geological Survey bulletin ; 1808–N)
Includes bibliographical references.
Supt. of Docs. no.: I 19.3:R1808N
1. Foraminifera, Fossil—San Juan Basin (N.M. and Colo.) 2. Paleontology—Cretaceous. I. Title. II. Series. III. Series: U.S. Geological Survey bulletin ; 1808–N.
QE75.B9 no. 1808N
[QE772]
557.35—dc20 91–42291
[563'.12'097895] CIP

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Upper Cenomanian Foraminifers from the Southern Part of the San Juan Basin, New Mexico

By Mary Alice Carey

Abstract

The Cenomanian Whitewater Arroyo Tongue of the Mancos Shale is the upper shale in an intertonguing sequence consisting of five Dakota Sandstone units and two Mancos Shale units. This sequence is best developed in the vicinity of Laguna, New Mexico, where the Whitewater Arroyo is 90 ft thick. Overlying the Whitewater Arroyo is the Twowells Tongue of the Dakota, which separates the Whitewater Arroyo from the lower member of the Mancos in the southern part of the San Juan Basin. These two tongues, the Whitewater Arroyo and the Twowells, are the most laterally extensive units of the Dakota-Mancos sequence and thus provide a basis for regional environmental interpretation.

Foraminifers recovered from six outcrops of the Whitewater Arroyo Tongue and from one outcrop of the basal part of the lower member of the Mancos Shale show that the Whitewater Arroyo represents a shallower, nearshore, better oxygenated bottom environment than does the lower member. Although both planktonic and arenaceous and calcareous benthic foraminifers were recovered from the Whitewater Arroyo, some nearshore localities in the middle Cenomanian Seboyeta bay produced only arenaceous specimens. The greatest abundance and diversity of foraminifers in the Whitewater Arroyo assemblage at the Laguna section indicate a northerly flow of southern ocean waters and an increase in vertical circulation of the sea that produced an oxygenated sea floor. In contrast, the dominance of planktonic foraminifers in the lower member of the Mancos at Laguna indicates a deeper water, open-marine environment and oxygen-reduced sea floor.

The Hartland Member–lower member of the Mancos Shale in the Chama Basin, an inferred equivalent stratigraphic unit to the Whitewater Arroyo, Twowells, and lower member of the Mancos in the San Juan Basin, produced an abundance of planktonic foraminifers dominated by *Rotalipora cushmani*, *R. greenhornensis*, and several species of *Hedbergella*, which characterize a deeper water environment and record a major incursion of the southern ocean into the Western Interior. The foraminiferal fauna of the Hartland Member–lower member of the Mancos in the Chama Basin correlates with that of the Hartland Shale Member of the Greenhorn Limestone of the Great Plains.

Differences in the foraminiferal assemblages between the Whitewater Arroyo Tongue and the lower member of the Mancos imply that a variety of bottom conditions and water-mass circulation patterns existed within the Whitewater Arroyo sea and that an abrupt change in water depth occurred at the beginning of deposition of the lower member of the Mancos, a change caused by rapid subsidence and (or) rapid sea-level rise.

INTRODUCTION

Despite considerable studies on middle and late Cenomanian foraminifers from the central, most open-marine part of the Cretaceous seaway (Eicher, 1969; Eicher and Diner, 1985; Eicher and Worstell, 1970), little work has been done to correlate these foraminiferal faunas with those of the more shoreward facies of the seaway. A complex intertonguing rock sequence of Dakota Sandstone and Mancos Shale units exposed in west-central New Mexico represents a segment of the shoreward facies and is coeval with the middle and late Cenomanian and Turonian Greenhorn Limestone of southeastern Colorado and central Kansas. The foraminifers from this intertonguing sequence document the early and ephemeral transgressive-regressive pulses of the seaway prior to the major incursion at or near the Cenomanian-Turonian boundary.

The geologic units of concern in this report are the Whitewater Arroyo Tongue of the Mancos Shale, the Twowells Tongue of the Dakota Sandstone, and the lower member at the base of the Mancos Shale, all in the southern part of the San Juan Basin of west-central New Mexico. The Whitewater Arroyo is the upper shale in an intertonguing

Manuscript approved for publication October 1, 1991.

sequence consisting of five Dakota Sandstone and two Mancos Shale units (fig. 1). Overlying the Whitewater Arroyo is the Twowells, which separates the Whitewater Arroyo from the lower member of the Mancos. These two tongues, the Whitewater Arroyo and the Twowells, are the most laterally extensive units of the Dakota-Mancos sequence in the basin and provide a basis for regional paleoenvironmental and paleogeographic interpretations.

Middle and late Cenomanian foraminiferal faunas and related microfaunas from the Whitewater Arroyo and the lower member of the Mancos provide biostratigraphic information that is useful in correlating sections characterized by marginal-marine rocks and in placing time lines through paralic paleoenvironments. Even though these faunas are limited in abundance, diversity, and preservation, they permit detailed paleogeographic reconstruction, including water depth, salinity, water-mass influence, and

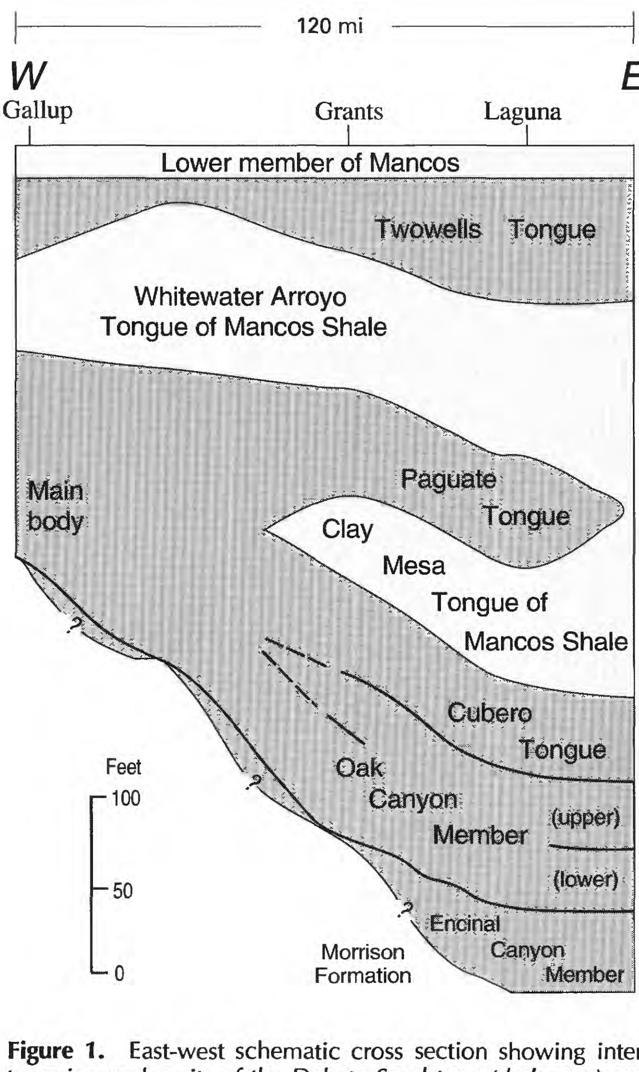

Figure 1. East-west schematic cross section showing intertonguing rock units of the Dakota Sandstone (dark gray) and Mancos Shale (light gray) in the west-central part of the San Juan Basin of New Mexico. Morrison Formation underlies Dakota Sandstone.

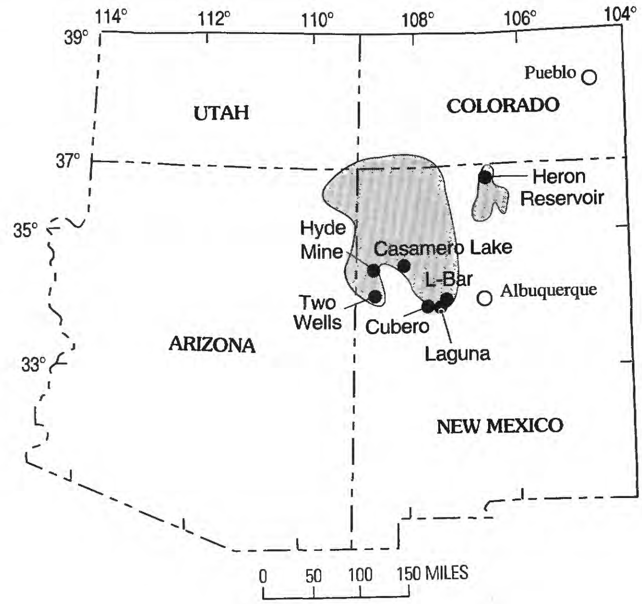

Figure 2. Sample localities in study: six localities of the Whitewater Arroyo Tongue in the San Juan Basin (large shaded area, northwestern New Mexico) and one locality of the Hartland Member–lower member of the Mancos Shale in the Chama Basin (small shaded area, Heron Reservoir east of San Juan Basin). Whitewater Arroyo type section is about 1.2 miles west of Two Wells. Description of localities given in appendix.

subfacies limits of the Cretaceous seaway in the Western Interior, and contribute evidence of proximity to the shoreline and landmass or submarine barriers.

This report discusses the stratigraphic distribution, significance, and interpretation of planktonic and benthic foraminifers recovered from the Whitewater Arroyo Tongue and the lower member of the Mancos at six localities in the southern part of the basin (fig. 2). The six localities represent a variety of environments within the Whitewater Arroyo, from nearshore to open ocean. An additional locality of the Hartland Member–lower member of the Mancos in the Chama Basin provides important faunal evidence for correlation and environmental interpretation between the San Juan Basin, Chama Basin, and Great Plains for middle and late Cenomanian time.

Acknowledgments.—The author thanks the following people and groups for their assistance and contributions to this report: Jennie L. Ridgley, U.S. Geological Survey (USGS) (Denver), for suggesting the initial research idea; William V. Sliter, USGS (Menlo Park), and William A. Cobban and William M. Aubrey, USGS (Denver), for their constructive reviews of the manuscript; Jean K. Dillinger, USGS (Denver), for her physical and professional field support; Douglas G. Wolfe and Don L. Eicher, University of Colorado, for specimen identification; Elisabeth M. Brouwers, USGS (Denver), for her assistance with ostracode identification; the Pueblo of Laguna Tribal Council for

permission to access, study, and collect on their land; and Farley Fleming, USGS (Denver), for his professionalism in processing rock material.

METHOD OF STUDY

Thirty-five samples were collected from seven localities in New Mexico: Whitewater Arroyo type section on the north side of Whitewater Arroyo near Two Wells, Hyde Mine, Casamero Lake, Cubero, Laguna, L-Bar, and Heron Reservoir (fig. 2, appendix). Most of the samples collected were spot samples and were taken at 5-, 10-, or 15-ft stratigraphic intervals, depending on the total thickness of the section. Complete sections of the Whitewater Arroyo Tongue, lower member, and Hartland Member–lower member were collected wherever possible.

Splits of 150 g from each shale sample were prepared for foraminiferal study using the standard kerosene technique (Kummel and Raup, 1965), which involves oven drying, a 15-hour soak in kerosene, decanting, and a 2-hour boil in Calgon and hot water. After mechanical breakdown in the kerosene process, each sample was sieved using ASTM sieves 20 and 230. The fine fraction (<62 μm) was dried and then split if necessary. The sample portion to be examined was dry sieved using sieves 20, 60, 80, and 100.

STRATIGRAPHY

Middle Cenomanian through middle Turonian stratigraphic nomenclature in the southern San Juan Basin is cumbersome due to complex facies changes in the stratigraphic sequence (figs. 1, 3). The following clear and concise statements on the stratigraphy of the San Juan Basin by Cobban and Hook (1984, p. 258–259) are followed in this report.

> In east-central New Mexico, the standard Great Plains nomenclature has long been applied: Dakota Sandstone (oldest), Graneros Shale, Greenhorn Limestone, and Carlile Shale (youngest). In recent years, a Thatcher Limestone Member has been recognized in the Graneros Shale (personal observations); the Greenhorn Limestone has been divided into Lincoln Limestone Member (oldest), Hartland Shale Member, and Bridge Creek Limestone Member (youngest); and the Carlile Shale has been divided into Fairport Member (oldest), Blue Hill Member, Codell Sandstone Member, Juana Lopez Member, and an upper unnamed shaly member***
>
> In west-central New Mexico, tongues of sandstone largely of a western source complicate the stratigraphy and necessitate a different nomenclature. The Dakota Sandstone is intertongued extensively with the Mancos Shale, and the sequence is, from oldest to youngest, [Encinal Canyon Member (of the Dakota) where present (Aubrey, 1986),] Oak Canyon Member (of the Dakota), Cubero Tongue (of the Dakota), Clay Mesa Tongue (of the Mancos), Paguate Tongue (of the Dakota), Whitewater Arroyo Tongue (of the Mancos), and Twowells Tongue (of the Dakota) (Landis *et al.*, 1973). Where the Oak Canyon, Cubero, Clay Mesa, and Paguate cannot be differentiated, the sequence consists of the main body of the Dakota overlain by the Whitewater Arroyo Tongue of the Mancos, and that in turn, by the Twowells Tongue of the Dakota (Landis *et al.*, 1973, Fig. 2); or an unnamed shale tongue of Mancos may separate the Paguate Tongue from the main body of the Dakota (Hook *et al.*, 1980, Fig. 2); or the Twowells Tongue may be separated from a basal tongue of the Dakota by a thick lower unnamed tongue of Mancos Shale.

<table>
<tr><th rowspan="2">Stage</th><th rowspan="2">Substage</th><th colspan="4">NEW MEXICO</th><th colspan="2">COLORADO</th></tr>
<tr><th colspan="2">East-west-central</th><th colspan="2">Northeast</th><th colspan="2">Southeast</th></tr>
<tr><td>Turonian (part)</td><td>Lower</td><td rowspan="3">Mancos Shale (part)</td><td rowspan="2">Bridge Creek Limestone Member (part)</td><td rowspan="5">Greenhorn Limestone (part)</td><td rowspan="2">Bridge Creek Limestone Member (part)</td><td rowspan="5">Greenhorn Limestone (part)</td><td rowspan="2">Bridge Creek Limestone Member (part)</td></tr>
<tr><td rowspan="10">Cenomanian (part)</td><td rowspan="4">Upper</td></tr>
<tr><td>Unnamed shale</td><td>Hartland Shale member</td><td>Hartland Shale Member</td></tr>
<tr><td>Dakota Sandstone</td><td>Twowells Tongue</td><td rowspan="2">Lincoln Limestone Member</td><td rowspan="2">Lincoln Limestone Member</td></tr>
<tr><td>Mancos Shale</td><td>Whitewater Arroyo Tongue</td></tr>
<tr><td rowspan="6">Middle</td><td>Dakota Sandstone</td><td>Paguate Tongue</td><td rowspan="5">Graneros Shale</td><td rowspan="2">Upper shale</td><td rowspan="5">Graneros Shale</td><td rowspan="2">Upper shale</td></tr>
<tr><td>Mancos Shale</td><td>Clay Mesa Tongue</td></tr>
<tr><td rowspan="4">Dakota Sandstone (part)</td><td>Cubero Tongue</td><td rowspan="2">Thatcher Limestone Member</td><td rowspan="2">Thatcher Limestone Member</td></tr>
<tr><td rowspan="3">Oak Canyon Member (part)</td></tr>
<tr><td>Lower shale</td><td>Lower shale</td></tr>
<tr><td colspan="2">Dakota Sandstone (part)</td><td colspan="2">Dakota Sandstone (part)</td></tr>
</table>

Figure 3. Stratigraphic nomenclature of middle Cenomanian to lower Turonian rocks in parts of New Mexico and southeastern Colorado. Modified from Cobban and Hook (1984).

The shale unit that overlies the Twowells at Laguna will be referred to in this report as the lower member of the Mancos. Dane (1948) named this unit the Graneros shale member of the Mancos, Landis and others (1973) referred to it as main body Mancos, and Cobban and Hook (1989) proposed to call it the Rio Salado Tongue of the Mancos Shale. Because of the local outcrop situation at Laguna, none of the published nomenclature is applicable to the Laguna stratigraphic section. Cobban and Hook (1984, p. 259) continued,

> Middle Cenomanian–upper Turonian rocks in eastern Colorado are included in the Graneros Shale, Greenhorn Limestone, and Carlile Shale. The sequence is best exposed and documented in the Pueblo area (Cobban and Scott, 1972). The Graneros consists of the Thatcher Limestone Member separating a lower unnamed shale member barren of molluscan fossils from an upper unnamed shale member containing molluscan fossils. The Greenhorn consists of, from oldest to youngest, Lincoln Limestone Member, Hartland Shale Member, and Bridge Creek Limestone Member.

At Heron Reservoir (fig. 2) in the Chama Basin, just east of the San Juan Basin, 63 ft of well-exposed sandstone on the south side of the dam, has been documented on the basis of ammonites as a Paguate equivalent (W.A. Cobban, U.S. Geological Survey, oral commun., 1989). At lake level and northeast of the dam (see appendix), a 25-ft-thick outcrop of medium-gray, fissile shale was assigned by Ridgley (in press) to the Hartland Member–lower member of the Mancos Shale, which occupies a stratigraphic position between the base of the Bridge Creek and the top of the Dakota Sandstone below. In the Chama Basin, this shale is 120–55 ft thick. Caution must be applied to interpretations of the strata at the reservoir because the Hartland Member–lower member shale is part of the southeast-dipping flank of the Laguna dome to the north; its lower contact is covered up slope and its upper contact is below waterline.

Sampled interval					Microfossils	
0 ft	20 ft	30 ft	40 ft	44 ft		
•	•	•	•		*Haplophragmoides* spp.	Arenaceous benthics
•	•				*Reophax* sp.	
	•	•			*Ammobaculites* spp.	
	•	•	•		*Trochammina* spp.	
•	•	•	•	•	*Lingula* sp.	
•					Bivalves	
•					Gastropod 1	
•					Gastropod 2	
	•				Gastropod 3	
	•				Spines	
	•				Gypsum	
	•	•	•	•	Leaf chitin	
			•		Resin	

Figure 4. Distribution of foraminifers and other microfossils recovered from the complete 44-ft-thick section (base=0 ft) of the Whitewater Arroyo Tongue of the Mancos Shale at the Hyde Mine locality near Gallup, New Mexico (fig. 2).

MICROPALEONTOLOGY

Whitewater Arroyo Tongue

The Whitewater Arroyo benthic foraminiferal faunas recovered from four localities—Hyde Mine, Casamero Lake, Cubero, and L-Bar—are characteristic of nearshore, inner shelf, oxygenated environs; they are low in abundance and diversity, and their preservation is poor. The faunas from the other two localities of the Whitewater Arroyo—Laguna and the type section near Two Wells—reflect a normal, open ocean, shelf environment and comprise planktonic foraminifers, though limited in diversity, and arenaceous and calcareous benthic foraminifers.

The Hyde Mine benthic fauna (fig. 4) is low in abundance and diversity and indicates very shallow, nearshore conditions. The arenaceous foraminiferal fauna is represented by species of *Haplophragmoides*, *Reophax*, *Ammobaculites*, and *Trochammina*. Casts of *Lingula*, an inarticulate brachiopod, are present throughout the Hyde Mine section and indicate quiet waters. Small bivalves, three genera of gastropods, resin, and leaf chitin are also present. The Casamero Lake fauna (fig. 5) is also entirely arenaceous benthic. Note that the Hyde Mine and Casamero Lake localities are at a similar latitude (fig. 2). Both faunas reflect a lack of influence from southern ocean waters (absence of planktonics), and the environments were probably hyposaline (Eicher and Diner, 1985). The Casamero Lake fauna has the lowest abundance and diversity of benthic foraminifers in the study, and the localitiy is probably closest to the Whitewater Arroyo shoreline. *Reophax*, *Haplophragmoides*, *Ammobaculites*, and *Trochammina* were the only genera recovered from the Casamero Lake section.

The Cubero fauna is 99 percent arenaceous and has only three calcareous benthics: one specimen each of *Palmula* sp. (pl. 1, fig. 27) and *Astacolus* sp. (pl. 2, fig. 2) from the lower part (15 ft) of the section and a questionable specimen of *Bullopora*? sp. (pl. 2, fig. 1) from the basal sample (0 ft). Figure 6, a distribution diagram of the Cubero section, shows the limited fauna recovered. The Cubero fauna has almost no calcareous benthics and probably

0 ft	10 ft	15 ft	20 ft	25 ft	Microfossils	
Sampled interval						
	●			●	*Ammobaculites fragmentarius*	Arenaceous benthics
●	●	●	●	●	*Ammobaculites* spp.	Arenaceous benthics
●	●	●	●	●	*Haplophragmoides* spp.	Arenaceous benthics
		●	●	●	*Trochammina* spp.	Arenaceous benthics
			●		*Reophax* sp.	Arenaceous benthics
●					Ostracode	
	●	●			Gypsum	
	●	●			Prisms	
				●	Gastropod (turritellid-type)	

Figure 5. Distribution of foraminifers and other microfossils recovered from the complete 28-ft-thick section (base=0 ft) of the Whitewater Arroyo Tongue of the Mancos Shale near Casamero Lake, New Mexico (fig. 2).

0 ft	15 ft	30 ft	45 ft	60 ft	75 ft	85 ft	Microfossils	
Sampled interval								
●	●	●	●	●	●		*Reophax* spp.	Arenaceous benthics
				●			*Reophax inordinatus*	Arenaceous benthics
●	●	●	●	●	●	●	*Trochammina* spp.	Arenaceous benthics
●		●	●	●	●		*Ammobaculites* spp.	Arenaceous benthics
		●					*A. variablis*	Arenaceous benthics
		●			●		*A. goodlandensis*	Arenaceous benthics
					●		*A. fragmentarius*	Arenaceous benthics
			●		●		*Textularia* sp.	Arenaceous benthics
				●			*Gaudryina* sp.	Arenaceous benthics
●							*Bullopora?* sp.	Calcareous benthics
	●						*Astacolus* sp.	Calcareous benthics
	●						*Palmula* sp.	Calcareous benthics
		●	●				Spines	
	●						Fish tooth	
					●		Ostracode	
				●			Gypsum	
						●	Incertae sedis	

Figure 6. Distribution of foraminifers and other microfossils recovered from the complete 85-ft-thick section (base=0 ft) of the Whitewater Arroyo Tongue of the Mancos Shale near Cubero, New Mexico (fig. 2).

represents a very shallow water environment characterized by moderately oxygenated waters and hyposaline conditions, similar to the Hyde Mine and Casamero Lake environments. Throughout the Cubero section, sediment is mostly composed of very clean, fine-grained, angular quartz; minor amounts of mica, both black and white; carbonaceous coaly material; and chitinous leaf debris. The upper half of the section contains tiny iron oxide pellets but no pyrite, and calcareous prisms were found only at the 60-ft level.

The L-Bar locality, represented by only two shale samples from the exposed upper 15 ft of the Whitewater Arroyo, is about 7 miles northeast of the Laguna locality (fig. 2). The two shale samples produced only arenaceous and calcareous benthic foraminifers. The arenaceous fauna is dominated by species of *Reophax*, *Ammobaculites*, *Trochammina*, and *Haplophragmoides* (fig. 7). *Lenticulina* was the only calcareous benthic recovered at L-Bar. Specimen preservation is extremely poor in both samples, and abundance is very low; 53 specimens were recovered in the lower sample and 19 in the upper sample. No faunal correlation can be made between the shale at L-Bar and that at Laguna because the L-Bar locality exposes the upper part of the Whitewater Arroyo and the Laguna locality the basal part. The examined part of the Whitewater Arroyo at L-Bar contains a very shallow nearshore fauna, not an unexpected fauna for a diminishing marine sedimentary environment.

The Whitewater Arroyo type section on the north side of Whitewater Arroyo near Two Wells, New Mexico (fig. 8), produced two planktonic genera—*Hedbergella* (three species) and *Globigerinelloides* (one species). Hedbergellids dominate the planktonic specimens and are well represented in the upper part of the section. Some tests of both *Hedbergella* and *Globigerinelloides* are replaced with iron oxide or are represented by iron oxide internal molds. These iron oxide tests imply that bottom conditions near Two Wells were reducing. A few calcareous benthics were also found at the 30-ft level, but the most abundant and diverse forms in the 46-ft-thick section are arenaceous. Species of *Trochammina*, *Ammobaculites*, *Reophax*, *Textularia*, and *Haplophragmoides* represent the total benthic assemblage below the 30-ft level. The planktonic fauna of the Whitewater Arroyo near Two Wells infers that this environment was deeper water than that of nearby Hyde Mine and Casamero Lake. The Two Wells area, which is south of the Hyde Mine and Casamero Lake localities, was apparently influenced by warmer southern waters of the Tethyan ocean.

At the Laguna locality, the Dakota-Mancos sequence is the most complete and well exposed of the localities studied and the Whitewater Arroyo foraminiferal fauna the most abundant and diverse. Landis and others (1973) formally named and described the Oak Canyon Member, Cubero Tongue, Clay Mesa Tongue, and Paguate Tongue (fig. 1) at this locality.

At Laguna, 5.5 miles directly east of the Cubero locality, the Whitewater Arroyo fauna changes abruptly.

Group	Microfossils	Sampled interval: 10 ft	Sampled interval: 3 ft
Arenaceous benthics	*Ammobaculites* sp.	●	
	Haplophragmoides sp.	●	●
	Reophax sp.	●	●
	Trochammina sp.	●	●
Calcareous benthics	*Lenticulina* sp.	●	
	Svenia sp.	●	
	Fish tooth		●
	Prisms		●

Figure 7. Distribution of foraminifers and other microfossils recovered from the upper 15 ft of the Whitewater Arroyo Tongue of the Mancos Shale at the L-Bar section about 3 miles east of the town of Moquino, New Mexico, and just north of the Laguna Indian Reservation (fig. 2). Top of section=0 ft.

Group	Microfossils	0 ft	10 ft	20 ft	30 ft	40 ft
Arenaceous benthics	*Haplophragmoides* spp.	●	●	●	●	●
	Reophax inordinatus			●	●	
	Reophax spp.	●	●		●	●
	Trochammina spp.	●	●	●	●	●
	Ammobaculites spp.	●	●		●	●
	Ammobaculoides mosbyensis	●				
	Textularia sp.		●		●	
Calcareous benthics	*Svenia* sp.				●	
	Lenticulina? sp.				●	
	Lenticulina sp. B				●	●
	Citharina sp.				●	
Planktonics	*Hedbergella amabilis*	●			●	●
	H. planispira				●	
	H. delrioensis				●	
	Globigerinelloides bentonensis				●	
	Ostracode				●	
	Spines	●				
	Prisms	●	●		●	●

Figure 8. Distribution of foraminifers and other microfossils recovered from the complete type section of the Whitewater Arroyo Tongue of the Mancos Shale on the north side of Whitewater Arroyo, NW¼ sec. 12, T. 12 N., R. 19 W., near Two Wells, New Mexico (fig. 2). Base=0 ft.

Planktonics, limited in diversity, are present in significant numbers and are dominated by hedbergellids. Two species of *Hedbergella* (*H. amabilis* and *H. delrioensis*), one species of *Heterohelix* (*H. moremani*), and one species of *Rotalipora* (*R. greenhornensis*) represent the planktonic fauna. The Laguna assemblage produced several planktonic and benthic foraminiferal species (fig. 9) that have also been found in the Hartland Shale Member of the Greenhorn Limestone (Eicher and Worstell, 1970) of the Great Plains near Pueblo, Colorado (285 miles to the northeast). Only two specimens of *Rotalipora greenhornensis* were recovered from the Whitewater Arroyo at the Laguna locality; however, no other deeper water planktonic forms that characterize the Great Plains fauna, such as *Praeglobotruncana*, *Schackoina*, or *Rotalipora cushmani*, were found in the Whitewater Arroyo during this study.

Lower Member of the Mancos Shale at Laguna

The fauna of the late Cenomanian lower member of the Mancos Shale at Laguna (fig. 9) reflects an abrupt environmental change at the Twowells–lower member contact. The lower member fauna implies a deeper, more normal open-marine environment than that of the Whitewater Arroyo by having a greater percentage of planktonic and calcareous benthic genera and the first and only occurrence of *Rotalipora cushmani* (one iron-oxide-replaced test) in the San Juan Basin study area. A significant decrease in arenaceous genera at the contact implies that bottom waters were less oxygenated. *Haplophragmoides coronata* is the only arenaceous benthic foraminifer in the lower member fauna; however, eight calcareous benthic genera were identified. The abundance of bivalves, the occurrence of the ostracode *Cythereis eaglefordensis*, and the increase in variety of calcareous benthic and planktonic foraminifers imply that the environment of the lower member was hospitable to calcareous organisms and highly influenced by a northerly flow of warm southern waters.

1: 20 ft above base	1: 30 ft above base	1: 60 ft, covered	2: Twowells, 74 ft	3: 0 ft above Twowells	3: 5 ft above Twowells	3: 10 ft above Twowells	Microfossils	
●							*Ammobaculites fragmentarius*	Arenaceous benthics
●							*Ammobaculites* sp.	
●							*Ammodiscus cretaceus*	
●							*Trochammina* sp.	
●							*Reophax* sp.	
●							*Textularia* sp.	
●							*Verneuilinoides perplexus*	
●							*Bimonilina reciprocata*	
					●		*Haplophragmoides coronata*	
●	●						*Lenticulina* sp.	Calcareous benthics
●				●			*Svenia* sp.	
●				●	●	●	*Citharina kochii*	
				●	●		*Citharina* sp.	
				●			*Psilocitharella* sp.	
●						●	*Gavelinella modesta*	
●						●	*Gavelinella* sp.	
					●		*Praebulimina* sp.	
					●		*Lingulogavellinella* sp.	
					●		*Ramulina aculeata*	
						●	*Neobulimina albertensis*	
●							*Rotalipora greenhornensis*	Planktonics
●				●		●	*Hedbergella amabilis*	
●						●	*H. delrioensis*	
				●			*Hedbergella* spp.	
				●			*Archaeoglobigerina* sp.	
●					●	●	*Heterohelix moremani*	
					●		*Guembelitria harrisi*	
					●		*Rotalipora cushmani*	
					●	●	*Hedbergella portsdownensis*	
●				●			*Cythereis eaglefordensis* (ostracode)	

Figure 9. Distribution of foraminifers recovered from the (1) lower 30 ft of the Whitewater Arroyo Tongue of the Mancos Shale and the (3) lower 10 ft of the lower member of the Mancos Shale near Laguna, New Mexico (fig. 2). The Twowells Tongue of the Dakota Sandstone (2) separates the shale units.

Hartland Member–Lower Member, Chama Basin

Though not within the structural boundary of the San Juan Basin, an inferred equivalent stratigraphic unit to the Whitewater Arroyo, Twowells, and lower member of the Mancos sequence is the Hartland Member–lower member of the Mancos Shale (Ridgley, in press) at the Heron Reservoir in the Chama Basin (fig. 2). The unit crops out above the reservoir at water level. Six shale samples from the upper part of the unit were collected at 5-ft intervals beginning at lake level (upper part of outcrop) (see appendix). The lower contact is covered higher in the topographic slope, and the upper contact is below the reservoir waterline. The fauna is 99 percent planktonic and is abundantly represented by *Rotalipora greenhornensis* and *R. cushmani* (fig. 10); thus the fauna is in the *Rotalipora cushmani* Zone of middle to late Cenomanian age (fig. 11) (Sliter, 1989). Several species of *Hedbergella* are present, but specific identification of many of the specimens was difficult due to moderately poor preservation and recrystallization. *Heterohelix moremani* is common in five of the six samples, but its abundance is overshadowed by the abundance of rotaliporids recovered from the Chama Basin site. Although very rare, *Globigerinelloides bentonensis* and *Clavihedbergella simplex* (pl. 3, figs. 13, 14) are present at the 5- and 15-ft levels and 0- and 10-ft levels, respectively. *Clavihedbergella simplex* is unique to this locality. Eight calcareous specimens—six *Lenticulina*, one *Svenia*, and one *Psilocitharella*—represent the benthic fauna of the section. The ostracode *Cythereis eaglefordensis* is also present but is not as abundant as at the Laguna locality (fig. 9).

Sampled interval: 25 ft	20 ft	15 ft	10 ft	5 ft	0 ft	Microfossils	
					●	*Svenia* spp.	Calcareous benthics
●	●			●		*Lenticulina* sp.	
●						*Psilocitharella* sp.	
	●	●	●	●	●	*Rotalipora greenhornensis*	Planktonics
●	●	●	●	●	●	*R. cushmani*	
●		●	●	●	●	*Heterohelix moremani*	
●	●	●	●		●	*Hedbergella delrioensis*	
●				●		*H. portsdownensis*	
●	●	●			●	*Hedbergella* spp.	
			●		●	*Clavihedbergella simplex*	
		●		●		*Globigerinelloides bentonensis*	
●	●				●	Ostracode sp. 1	
●	●			●	●	*Cythereis eaglefordensis*	
●			●	●	●	Prism	

Figure 10. Distribution of foraminifers and other microfossils recovered from an incomplete 25-ft-thick section of the Hartland Member–lower member of the Mancos Shale at the Heron Reservoir (fig. 2) near Tierra Amarilla, New Mexico, in the Chama Basin. Top of section=0 ft.

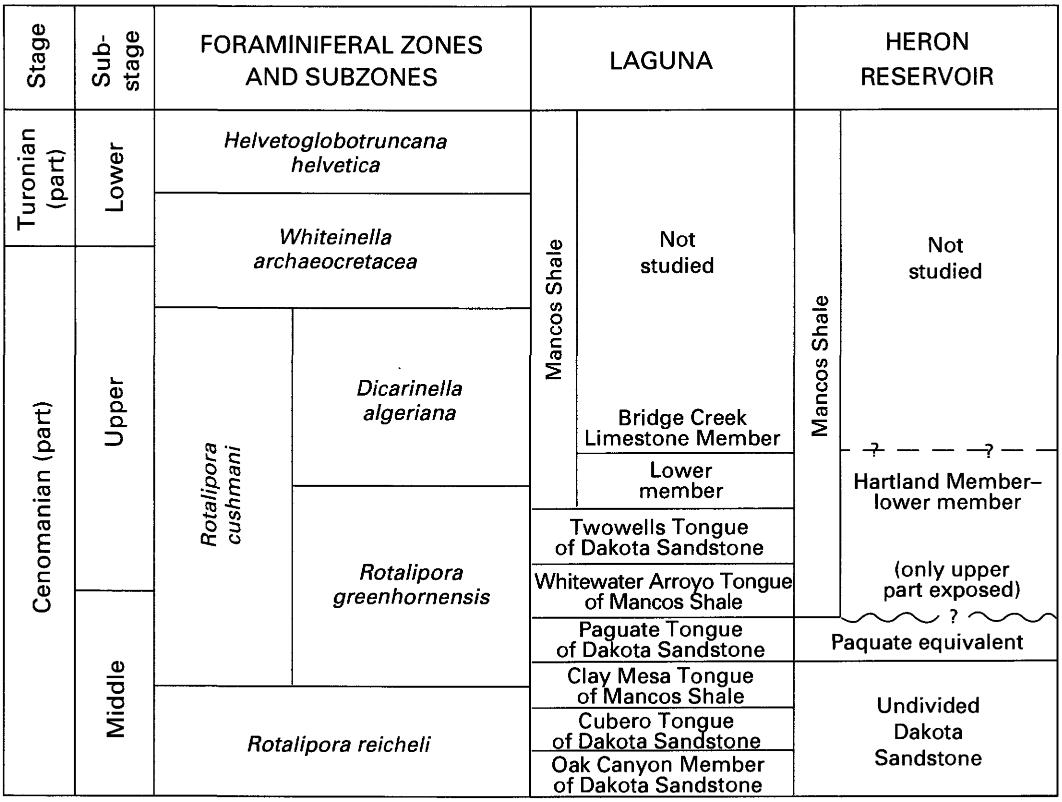

Figure 11. Foraminiferal zones and subzones (Sliter, 1989) and stratigraphic nomenclature in the southern San Juan Basin (modified from Cobban and Hook, 1989) as related to the Laguna and Heron Reservoir localities of this study. (Only the lower 20 ft of the lower member of the Mancos Shale is exposed at Laguna.)

The overwhelming abundance of rotaliporids in the Hartland Member–lower member at the Heron Reservoir locality is certainly unique to this study and yet characteristic of the late Cenomanian sea. Eicher and Diner (1985) stated that *Rotalipora* was a distinctive, widespread, rapidly evolving genus at this time; however, the rotaliporid assemblage was not present at the studied localities of the Whitewater Arroyo in the San Juan Basin.

SIGNIFICANCE OF PLANKTONIC FORAMINIFERS

Modern planktonic foraminifers are rare in the nearshore environment of the continental shelf and increase in abundance, diversity, and size with increasing water depth toward the open sea. They are generally restricted to open-marine environments of normal oceanic salinity and clear water. Spinose symbiont (algae)-bearing species require sunlit, near-surface waters, whereas nonspinose symbiont-barren species occupy deeper waters (Leckie, 1987) that support their full life cycles.

The application of modern and established foraminiferal distribution patterns is useful in the reconstruction of Cretaceous paleoenvironments. For example, in the Western Interior of the United States Eicher (1969) and Eicher and Worstell (1970) showed that the globular morphotypes (*Hedbergella* and *Heterohelix*) were the first planktonics to appear during transgression of the Cretaceous (Cenomanian and Turonian) epicontinental sea and the last to disappear during regression. Sliter (1972), in a study of planktonic foraminifers from the eastern Pacific margin, proposed that the increase in eurytopic hedbergellid and heterohelicid abundance and diversity in shallow waters implies that these types are opportunistic, mostly epipelagic species that dominate adverse environments of shelf waters. Leckie (1987) observed planktonic species distribution in modern shelf environments and applied the distribution patterns to mid-Cretaceous planktonic assemblages to derive consistent stratigraphic indicators of generalized paleowater depths. His criteria were based on test morphology: inflated, globose, spinose morphotypes inhabited near-surface waters, whereas flatter keeled forms occupied deeper habitats. Leckie (1987) believed that the nonspinose globorotaliid morphotypes (*Rotalipora* and *Praeglobotruncana*) keeled genera were the deepest dwelling of the mid-Cretaceous planktonic foraminifers.

Leckie (1987) proposed three faunal groups containing characteristic genera.

1. Epicontinental sea fauna (ESF): shallow epeiric or marginal sea (<300 ft); fauna probably inhabited near-surface waters. Characteristic globose genera, *Gubkinella*, *Guembelitria*, and *Heterohelix*, are present in greatly reduced abundance in open-ocean pelagic sections. Large proportions of small specimens of *Hedbergella* spp. and *Globigerinelloides* spp. are also associated with epicontinental sea fauna. This faunal assemblage is believed to have had the widest and highest tolerance to the environment in the mid-Cretaceous.

2. Shallow-water fauna (SWF): shallow water, open marine, pelagic (<300 ft). Major generic components are *Hedbergella* and *Globigerinelloides*. Associated genera include species of *Clavihedbergella*, *Schackoina*, and *Ticinella*.

3. Deep-water fauna: deep water, open marine, (>300 ft). Believed to be the most sensitive to the environment in the mid-Cretaceous. Characteristic genera are keeled forms such as species of *Planomalina*, *Rotalipora*, and *Praeglobotruncana*.

Applying Leckie's (1987) generic characteristics to the Whitewater Arroyo Tongue, lower member of the Mancos Shale, and Hartland Member–lower member faunas, the Laguna assemblage is a shallow-water fauna in which *Hedbergella amabilis*, *H. delrioensis*, and *Heterohelix moremani* are the dominant planktonic forms. The Laguna fauna, characterized by arenaceous and calcareous benthics and planktonics, reflects a mid- to outer-shelf, hospitable, open-marine environment and water depths of less than 300 ft. The lower member faunal assemblage at Laguna, in which planktonic genera, specimen abundance, and calcareous benthics increase, indicates a warmer water mass and sufficiently oxygenated bottom waters to support both arenaceous and calcareous benthics. Water depth is still less than 300 ft and represents the mid- to outer-shelf. The dominance of rotaliporids in the Hartland Member–lower member of the Mancos Shale in the Chama Basin reflects a water depth of probably greater than 300 ft.

FAUNAL AND ENVIRONMENTAL INTERPRETATIONS

Faunal data recovered from the Whitewater Arroyo Tongue of the Mancos Shale in the southern San Juan Basin provide a basis for limited regional environmental interpretations. The faunal assemblages from the northern localities of Hyde Mine and Casamero Lake represent a very shallow water, nearshore environment characterized by moderately oxygenated waters and low salinity; the shoreline probably was nearby and to the north. The faunal assemblage from Cubero contains very little calcareous material; three calcareous foraminifers and *Inoceramus* prisms from one sample comprise the entire calcareous contribution. The Cubero environment probably was a protected shallow-water realm close to shore as evidenced by coaly material and chitinous leaf remains that are present throughout the section. Moderately oxygenated waters and hyposaline conditions persisted at Cubero. The limited faunal assemblage from L-Bar, dominated by arenaceous foraminifers, represents a very shallow nearshore environment transitional into the regressive sandstone environment of the overlying Twowells Tongue.

The locality of the Whitewater Arroyo Tongue near Two Wells, south of the Hyde Mine and Casamero Lake localities, probably was influenced by northerly flowing warm waters of the Tethyan ocean and slightly deeper waters than the two northern localities. Planktonics are present in the upper part of the Two Wells section, and no evidence of terrestrial influence such as leaf chitin or resin was found.

The abrupt change in the Whitewater Arroyo fauna between the Cubero and Laguna localities is interpreted as an abrupt environmental change. At Laguna, 5.5 miles east of Cubero, the fauna reflects a normal marine foraminiferal assemblage of the mid-shelf. The presence of both arenaceous and calcareous benthics and three genera of planktonics suggests that the mid-shelf sea floor was well oxygenated and that warm southern waters of the Tethyan ocean flowed northward and brought the planktonics to Laguna.

The ostracode, *Cythereis eaglefordensis* Alexander (pl. 2, fig. 13), is common in both the Whitewater Arroyo Tongue and the lower member of the Mancos Shale at the Laguna locality. It is common and widespread in the Gulf Coastal Plain and Western Interior of the United States. Hazel (1969) used it as a guide fossil for the latest Cenomanian and placed it at the "top of the Cenomanian in the *Rotalipora cushmani–R. greenhornensis* zone" (Hazel followed Pessagno's 1967 zonation), which is approximately equal to the *Rotalipora cushmani* Zone of Sliter (1989). (The "top" of the Cenomanian is in the *Whiteinella archaeocretacea* Zone (Sliter, 1989) (fig. 11).) Because the ostracode *Cythereis eaglefordensis* and the foraminifer *R. greenhornensis* are the only age-diagnostic species in the Whitewater Arroyo, the Whitewater Arroyo fauna is placed in the *R. cushmani* Zone of middle and late Cenomanian age (Sliter, 1989) (fig. 11). Based on morphology, E.M. Brouwers (U.S. Geological Survey, written commun., 1989) stated that the species is "deeper water-neritic but not inner shelf." The ostracode data support the environment suggested by the foraminiferal data, mid-to outer-shelf and normal open marine water less than 300 ft deep.

The Laguna fauna exhibits the greatest diversity of the six Whitewater Arroyo sections and therefore is used for comparison with the coeval Great Plains faunas. The Whitewater Arroyo and the Twowells together are generally accepted as coeval with the Lincoln Member (late middle to early late Cenomanian) of the Greenhorn Limestone of the

Great Plains. Eicher and Worstell (1970) and Eicher and Diner (1985) reported that no benthics were recovered from the Lincoln Member. Eicher and Diner (1985, p. 63) stated that,

> In the uppermost sample of the Graneros and lowest samples of the Lincoln Member, the foraminifera consist only of tiny specimens of the ubiquitous genera, *Hedbergella* and *Heterohelix.*

The foraminiferal distribution charts of Eicher and Worstell (1970) illustrate that little faunal change occurred between deposition of the lowest samples and the upper sample of the Lincoln Member, except for a few rare additions of planktonic genera. The Laguna Whitewater Arroyo planktonic foraminifers consist only of the same two genera, *Hedbergella* and *Heterohelix* (fig. 9); the only exception is the two specimens of *Rotalipora greenhornensis.* The Whitewater Arroyo also contains both arenaceous and calcareous benthics, and this major difference between the two coeval middle to late Cenomanian age assemblages can be explained by the geographic locations of the two faunas within the seaway. The Whitewater Arroyo is in the shallower "mixed" benthic biofacies of the western margin, and the Lincoln is in the "no benthics facies" in the deeper central part of the seaway to the east, as proposed by Eicher and Diner (1985) (fig. 12). The data of Eicher and Worstell (1970) and Eicher and Diner (1985) are for localities much farther to the east and north of San Juan Basin (Pueblo and Fort Collins, Colorado, and western Kansas), where deeper and warmer waters contributed to a hospitable planktonic environment.

The next significant faunal change observed by Eicher and Worstell (1970) and Eicher and Diner (1985) is first recorded in the upper part of the Lincoln Member and continues through the Hartland Shale Member, which overlies the Lincoln Member. Eicher and Diner (1985, p. 63) stated that,

> In the upper Lincoln and Hartland these [*Hedbergella* and *Heterohelix*] are joined successively by larger species of *Hedbergella* and species of *Globigerinelloides, Rotalipora, Praeglobotruncana, Schackoina, Clavihedbergella, Guembelitria* and *Anaticinella.****The foramininferal fauna of the Lincoln and Hartland Members of the Greenhorn Formation [Limestone] consists solely of abundant planktonic specimens and contrasts markedly with the comparatively scanty, arenaceous benthic fauna that dominates the underlying Graneros.

At Laguna, at the conformable contact between the Twowells Tongue of the Dakota and the overlying lower member of the Mancos, an abrupt faunal change is observed in the lower member. The faunal change, noted by an increase in calcareous benthic and planktonic generic diversities and a decrease in arenaceous benthic diversity (fig. 9), records the appearance of many of the same species (both planktonics and calcareous benthics) that are present in the uppermost Hartland. The Hartland fauna of the Great Plains (except the uppermost part) consists only of planktonic foraminifers as does that of the Lincoln. According to Eicher and Worstell (1970) and Eicher and Diner (1985), only two faunal differences are observed between the Lincoln and the Hartland. (1) *Rotalipora* is present near the top of the Lincoln and continues through the Hartland, and (2) *Schackoina* and *Praeglobotruncana* are present about midway through the Hartland and continue across the Cenomanian-Turonian boundary.

Based on the presence of *Rotalipora, Hedbergella, Heterohelix, Archaeoglobigerina,* and *Guembelitria,* the lower member of the Mancos at Laguna is considered coeval with the uppermost Lincoln and lower Hartland of the Great Plains. Other than the presence of *Rotalipora* and calcareous benthic species (also in the uppermost Hartland) in the Graneros fauna of the Great Plains, no finer distinction can be made regarding the assignment of this fauna. The lower member of the Mancos occupied the shallower part of the seaway to the west and is a time-equivalent stratigraphic unit to the Hartland Shale Member of the Greenhorn Limestone, which occupied the deeper part of the seaway to the east (fig. 12).

The foraminiferal fauna of the Hartland Member–lower member in the Chama Basin consists solely of planktonics and calcareous benthics (fig. 10). *Rotalipora cushmani* and *R. greenhornensis* overwhelmingly dominate the assemblage. *Hedbergella* spp. abundances decrease and *Clavihedbergella simplex* is unique to this locality in this study. The presence of *C. simplex, Heterohelix moremani,* and *Globigerinelloides bentonensis* places the fauna in the upper *R. cushmani* Zone (Sliter, 1989). Because none of the distinctive genera characteristic of the *Dicarinella algeriana* Subzone of late Cenomanian age is present, the author is reluctant to assign the fauna to the subzone. Benthics are rare, which indicates poorly oxygenated bottom waters in the Western Interior in Lincoln and Hartland time as reported by Eicher and Diner (1985). Applying Leckie's (1987) criteria based on test morphology, the Hartland Member–lower member of the Mancos assemblage at the Heron Reservoir locality in the Chama Basin represents a sensitive, open-marine fauna and a water depth probably greater than 300 ft.

The dominance and abundance of rotaliporid species and the presence of *Clavihedbergella simplex* indicate that the Hartland Member–lower member of the Mancos in the Chama Basin probably is time equivalent to the Hartland Shale Member of the Greenhorn Limestone of the Great Plains and to the lower planktonic zone of Eicher and Worstell (1970) recovered at Pueblo, Colorado, 145 miles to the northeast. On species content, it is in closer association with the Hartland fauna at Pueblo than with the lower member fauna at Laguna, 140 miles to the southwest. The geographic distances between the localities of Pueblo, Heron Reservoir, and Laguna and the distribution of foraminifers in the middle Hartland sea as proposed by

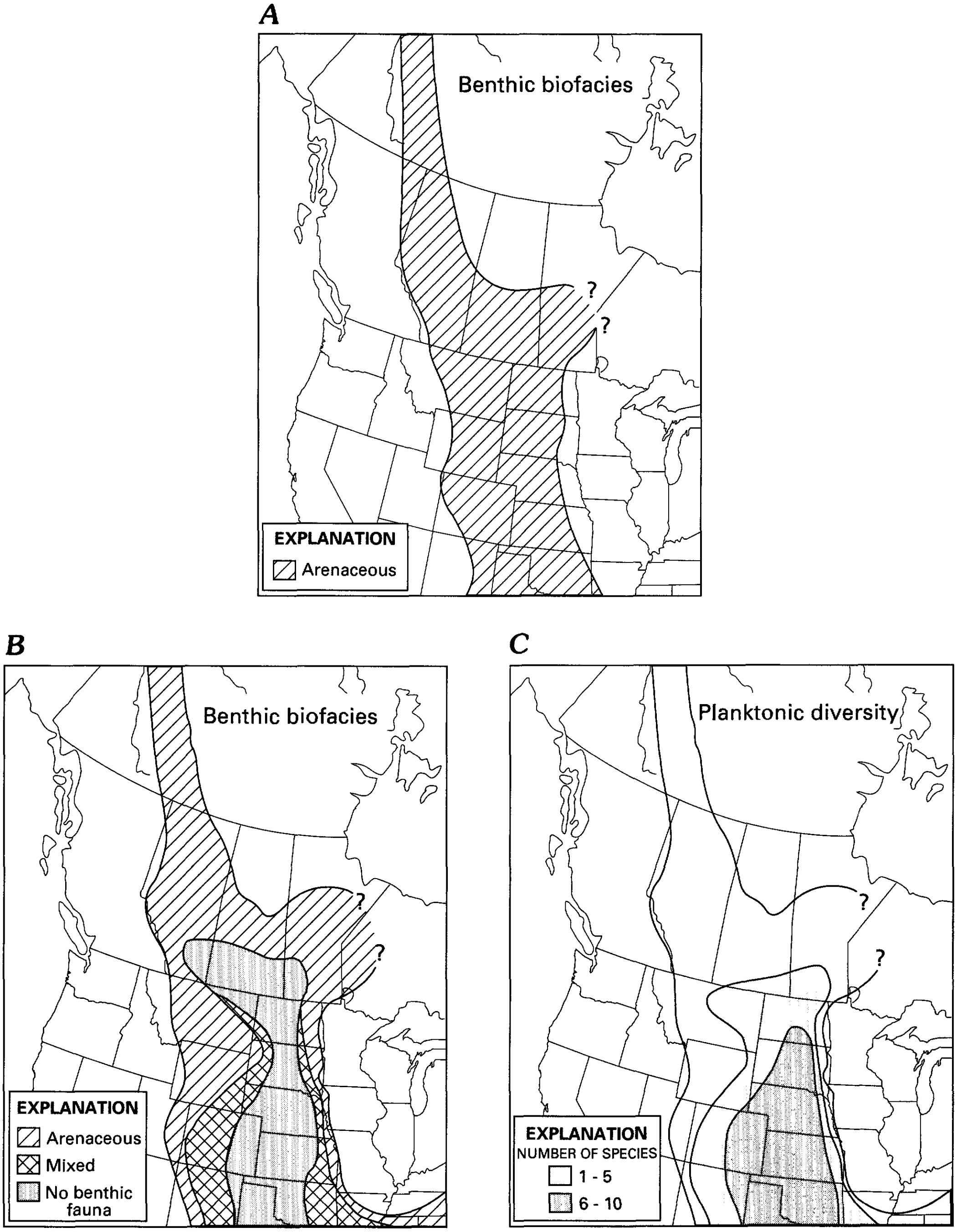

Figure 12. Distribution of foraminifers in the Western Interior during (*A*) latest Graneros time and (*B* and (*C*) middle Hartland time. Modified from Eicher and Diner (1985).

Eicher and Diner (1985) in figure 12 imply that the fauna of the lower member at Laguna inhabited a shallower biofacies than did the Hartland faunas at Pueblo and Heron Reservoir.

PALEOGEOGRAPHIC THEORIES

New theories and paleogeographic models have been proposed since the work of Landis and others (1973) on the Dakota and Mancos sequence at Laguna. Noon (1980) proposed a deltaic Four Corners Headland (fig. 13) that would serve as the source for the fluvial facies of the Dakota Sandstone in the Four Corners area as well as for the offshore sands of the Twowells Tongue of the Dakota. The deltaic model supports generally accepted concepts concerning the Whitewater Arroyo Tongue of the Mancos Shale and the Twowells Tongue: (1) the shoreline positions of Cobban and Hook (1984) (fig. 14) for the Whitewater Arroyo and Twowells; (2) the time-transgressive nature of the top of the Twowells, which is younger to the southwest (in San Juan Basin) (Hook and others, 1980; Esterly, 1985; D.G. Wolfe, University of Colorado, oral commun., 1989); and (3) a southwest source area for the Twowells as proposed by Landis and others (1973). Assuming that the Four Corners protodeltaic headland existed in early Cenomanian time (Encinal Canyon time), it could have contributed to the landmass in the area of southwestern Colorado and northwestern New Mexico (fig. 15). As the seaway transgressed westward, it encroached the headland as defined by Noon (1980) (fig. 13). In early late Cenomanian time (middle to late Whitewater Arroyo time), a barrier may have existed along the Colorado–New Mexico State line that formed the northern boundary of Seboyeta bay and maintained a nearshore, marginal-marine foraminiferal environment in northwestern New Mexico. Perhaps a submarine remnant of Seboyeta bay, which was established in middle Cenomanian time (Oak Canyon and Cubero time) (Cobban and Hook, 1984), existed even though the actual surface configuration of the bay had disappeared by Whitewater Arroyo time and the shoreline was far to the west (fig. 14).

Wolter (1987) built part of his sedimentation theory of the Twowells on the Four Corners Headland model of Noon (1980) and coined a sedimentary structural term, the "Acoma ridge," for a structure in the Acoma Basin between Grants and Acoma and from Interstate Highway I-40 south for more than 25 miles (fig. 13). As further defined by Wolter, the Acoma ridge trends north-south, is 6 miles wide, and has a maximum thickness of 105 ft. During the early and middle Cenomanian, the Acoma ridge in Seboyeta bay was protected from the southward-flowing tidal currents of the open shelf by the Four Corners Headland. Wolter (1987) stated that the funneling effect of the bay, the open tidal communication with the proto-Gulf of Mexico, and the shallow, wide shelf all enhanced tidal currents of the bay and deposition of the Acoma ridge (Twowells) in a north-south-trending erosional low.

Faunal evidence implies that the Laguna area was at the eastern edge of Seboyeta bay in its late phase and was greatly influenced by southward-flowing currents (Wolter, 1987) coming off the eastern promontory of a deltaic headland (Noon, 1980) along the Colorado-New Mexico State line and by the northerly flowing waters from the Tethyan ocean. These southward-flowing currents carried large amounts of sediment, nutrients, and species of foraminifers from a deeper carbonate realm to the east (fig. 12).

The 6-mile width of the Acoma ridge is remarkably close to the 5.5-mile distance between the Cubero and Laguna sections, and the ridge would have formed an excellent barrier if it existed in the pre-Twowells Seboyeta bay. Conversely, the Cubero locality is 8.5 miles east of the Acoma ridge and north of Interstate Highway I–40 as plotted by Wolter. Hence, present-day geographic distances between Cubero, Laguna, and the Acoma ridge do not provide evidence to explain the faunal differences between the Cubero and Laguna Whitewater Arroyo.

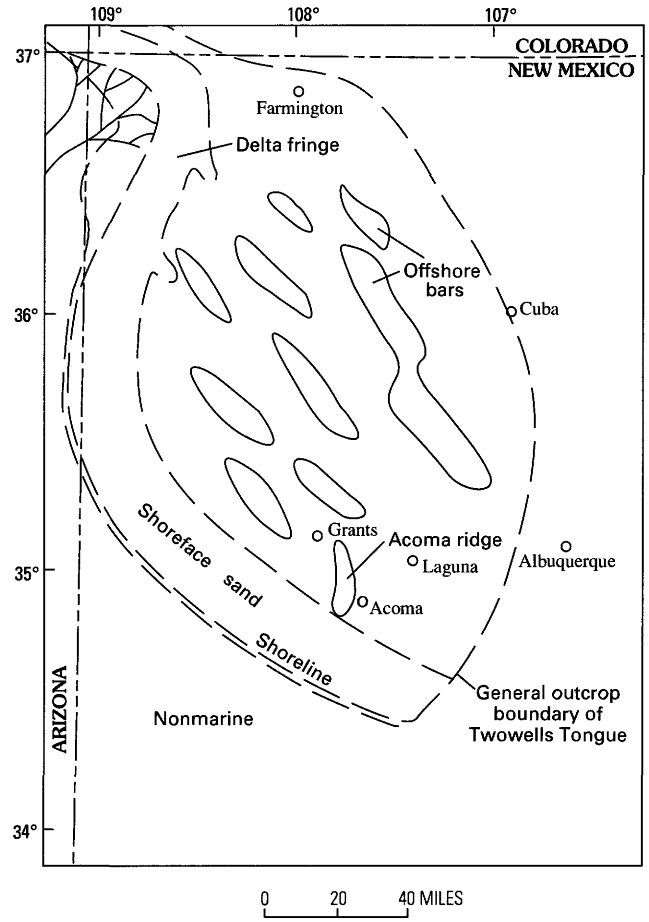

Figure 13. Sketch showing deltaic Four Corners Headland model of Noon (1980, from D.E. Owen, 1979, unpublished sketch), location of Acoma ridge, and general outcrop boundary of the Twowells Tongue of the Dakota Sandstone (Wolter, 1980). The headland served as a source for the offshore bars and shoreface sands of the Twowells. The same river system that supplied sediments for the headland probably provided the fluvial facies of the Dakota Sandstone in northwestern New Mexico.

LATE CENOMANIAN STRATIGRAPHY AND AMMONITE ZONES

Middle Cenomanian geography of the San Juan Basin, particularly Seboyeta bay, played a major role in forming the depositional geometry of upper Cenomanian strata, the upper part of the Whitewater Arroyo Tongue of the Mancos Shale, the Twowells Tongue of the Dakota Sandstone, and the lower member of the Mancos Shale.

During early middle Cenomanian time, the Oak Canyon Member and Cubero Tongue of the Dakota Sandstone were deposited in Seboyeta bay (Hook and

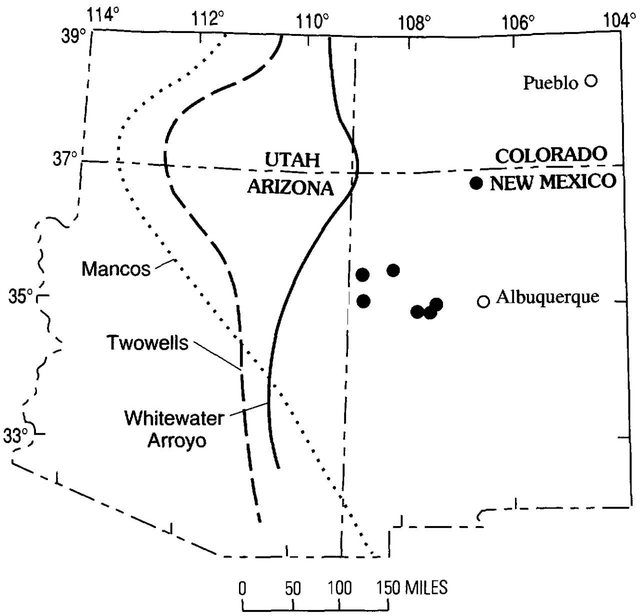

Figure 14. General position of late Cenomanian shorelines during deposition of the upper part of the Whitewater Arroyo Tongue of the Mancos Shale, the Twowells Tongue of the Dakota Sandstone, and the main body of the Mancos Shale as defined by the geographic distribution of zone indicator ammonite species in the San Juan Basin. Modified from Cobban and Hook (1984). Solid circles indicate sample localities (fig. 2).

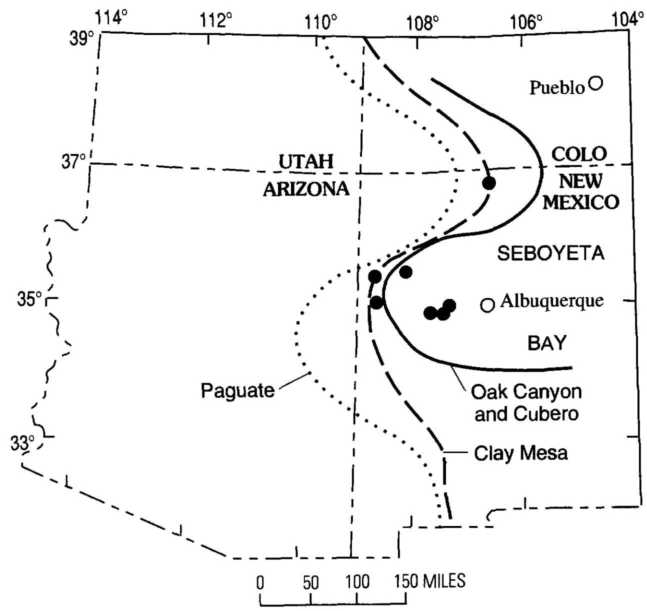

Figure 15. General position of middle Cenomanian shoreline during deposition of the Oak Canyon Member and Cubero and Paguate Tongues of the Dakota Sandstone and the Clay Mesa Tongue of the Mancos Shale as defined by the geographic distribution of zone indicator ammonite species. Modified from Cobban and Hook (1984). Solid circles indicate sample localities (fig. 2).

others, 1980) (fig. 1). The molluscan fauna of these two units is in the ammonite zone of *Conlinoceras tarrantense* (fig. 16). Deposition of the Clay Mesa Tongue in the middle middle Cenomanian shows a considerable southward transgression of the sea to El Paso, Texas, and reveals that Seboyeta bay still existed but with little southern boundary. In the study area, the Clay Mesa Tongue is in the ammonite zone of *Acanthoceras amphibolum*. Cobban and Hook (1989) reported that ammonites are uncommon and list only three species in the Clay Mesa. A third transgression to the west in late middle Cenomanian deposited the Whitewater Arroyo Tongue. Fossil molluscs are abundant and in great variety in shallow-water sandstones such as the Paguate Tongue of the Dakota Sandstone in Seboyeta bay (Cobban, 1977). The molluscan fauna in the Paguate at Laguna places the sandstone in the ammonite zone of *Plesiacanthoceras wyomingense* (Cobban and Hook, 1989). Ammonites from the Whitewater Arroyo Tongue reveal that it ranges in age from the late middle Cenomanian zone of *P. wyomingense* into the early late Cenomanian zone of *Calycoceras canitaurinum* (Cobban and Hook, 1989). Shoreline positions of the middle Cenomanian changed the least in the Casamero Lake area, and encroachment was minor in the Four Corners area. Figure 15 shows the general position of middle Cenomanian shorelines based on the occurrences of ammonite species (Cobban and Hook, 1984).

In the late Cenomanian the sea continued to transgress to the west and encroached the Four Corners area for the first time during this stage. During early late Cenomanian the sea flooded the areas of southwestern Colorado and northwestern New Mexico, removed the northern boundary of the Seboyeta bay, and deposited the upper part of the Whitewater Arroyo and Twowells Tongues. The Twowells molluscan fauna is in the zones of *Calycoceras canitaurinum* and *Metoicoceras mosbyense* of early late Cenomanian age. The lower member of the Mancos at Laguna, which immediately overlies the Twowells, marks the beginning of a major advance of the Greenhorn sea into southeastern Utah and northeastern Arizona. Foraminifers from this basal unit imply that water depth changed abruptly and document a large-scale incursion of the Greenhorn sea. The oyster *Pycnodonte newberryi* (Stanton) paves the ground as float on top of the Two wells at its contact with the lower member of the Mancos. These molluscs may be weathering out of the Bridge Creek Limestone Member, which is about 15 ft above the contact. At Laguna, the Bridge Creek Limestone Member marks the base of the *Sciponoceras gracile* ammonite zone of middle late Cenomanian age (Cobban and Hook, 1989) (fig. 16).

CONCLUSIONS

The Whitewater Arroyo Tongue of the Mancos Shale in the southern San Juan Basin is latest middle to early late

Stage	Sub-stage	FORAMINIFERAL ZONES AND SUBZONES		LAGUNA		AMMONITE ZONE
Turonian (part)	Lower	*Helvetoglobotruncana helvetica*		Mancos Shale	Not studied	*Vascoceras birchbyi*
		Whiteinella archaeocretacea				*Pseudaspidoceras flexuosum*
Cenomanian (part)	Upper					*Neocardioceras juddii*
		Rotalipora cushmani	*Dicarinella algeriana*			*Burroceras clydense*
					Bridge Creek Limestone Member	*Sciponoceras gracile*
			Rotalipora greenhornensis		Lower member	*Metoicoceras mosbyense*
				Twowells Tongue of Dakota Sandstone		*Calycoceras canitaurinum*
				Whitewater Arroyo Tongue of Mancos Shale		
	Middle			Paguate Tongue of Dakota Sandstone		*Plesiacanthoceras wyomingense*
		Rotalipora reicheli		Clay Mesa Tongue of Mancos Shale		*Acanthoceras amphibolum*
				Cubero Tongue of Dakota Sandstone		
				Oak Canyon Member of Dakota Sandstone		*Conlinoceras tarrantense*

Figure 16. Foraminiferal zones and subzones (Sliter, 1989), stratigraphic nomenclature (Cobban and Hook, 1989), and ammonite zones (Cobban and Hook, 1989) in the southern San Juan Basin as related to the study area. (Only the lower 20 ft of the lower member of the Mancos Shale is exposed at Laguna.)

Cenomanian age. Foraminifers in the northwestern part of Seboyeta bay of the Cretaceous seaway represent a shallow, nearshore, marginal-marine environment influenced somewhat by the Tethyan ocean to the south. The fauna reflects the existence of a land barrier to the north, in about the position of the Colorado–New Mexico State line. The foraminifers at Laguna characterize an open-ocean, normal-marine, mid- to outer-shelf environment that implies a diminishing influence of the northern land barrier on the foraminiferal environment. The Twowells Tongue of the Dakota Sandstone is early late Cenomanian in age, and the lower member of the Mancos at Laguna is middle late Cenomanian in age. The foraminifers of the lower member reflect an abrupt change in water depth (deeper and transgressive) and environment (reduced oxygen bottom waters) at the base of the unit, possibly caused by rapid subsidence or rapid sea-level rise.

The fauna from the Hartland Member–lower member in the Chama Basin characterizes much deeper, open-marine conditions than the Whitewater Arroyo fauna and shows little association in species duplication and environmental elements with the Whitewater Arroyo fauna. The assignment of the Hartland Member–lower member fauna at the Heron Reservoir as coeval with the Hartland Shale Member fauna of the Greenhorn Limestone of the Great Plains implies that the Lincoln-equivalent fauna probably exists up flank (above the 25-ft sample) of the Hartland Member–lower member and that the Bridge Creek–equivalent fauna is probably present in the shale below the reservoir waterline.

TAXONOMIC NOTES ON SELECTED SPECIES

Bimonilina reciprocata Loeblich and Tappan

(Plate 2, figure 10)

A single specimen of this form was recovered from the Whitewater Arroyo Tongue of the Mancos Shale at the 20-ft level of the Laguna locality. Identification remains in question because the aperture of *Bimonilina* is described as "slitlike." Specimen is magnificent.

Heterohelix moremani (Cushman)

(Plate 3, figure 1)

This small species consisting of globular chambers represents a major planktonic constituent of the lower member of the Mancos at the Laguna locality. It has less lobate chambers than *Heterohelix globulosa*, the Campanian to Maastrichtian species (Pessagno, 1967) that Eicher and Worstell (1970) stated is present in the Cenomanian

Great Plains fauna. *Heterohelix moremani* is also present in the Hartland Member–lower member of the Mancos at the Heron Reservoir locality but cannot compete in dominance with *Rotalipora* spp.

Guembelitria harrisi Tappan

(Plate 3, figure 2)

All specimens of this rare and extremely small species are damaged. It is present only in the lower member of the Mancos in the sample from the 5-ft level of the Laguna locality.

Hedbergella amabilis Loeblich and Tappan

(Plate 3, figure 3)

The illustrated specimen, beautifully preserved as an internal mold, shows the globose periphery of the chambers and the rapid increase of chamber size, both of which differentiate this species from *H. delrioensis*. It is a common species at most localities where planktonic foraminifers are present.

Hedbergella portsdownensis (Williams-Mitchell)

(Plate 3, figures 4–6)

This species is recognized by its lobate periphery, 5–6 chambers in the final whorl, and the distinctive overhang of the last chamber onto the umbilical side. It is most common in the lower member of the Mancos at the Laguna locality but also is present in the Hartland Member–lower member of the Mancos at the Heron Reservoir locality.

Considerable discussion surrounds this genus and species. Some foraminiferal researchers regard *Hedbergella portsdownensis* to be synonymous with *Whiteinella brittonensis*. Eicher and Worstell (1970) wrote that "both Hermes (1969, p. 50–51) and Pessagno (1967, p. 282) have pointed out the close similarity of *H. portsdownensis* [from Germany]***and *H. brittonensis*" [from Texas]. Later in the same discussion, Eicher reported that he "has seen numerous specimens from the Cenomanian of northern Europe [that are referred to as] *H. portsdownensis* and these appear to be identical to the numerous representatives of *H. brittonensis* from the Greenhorn." Eicher and Worstell used *Hedbergella portsdownensis* in their systematic paleontology. Pessagno (1967), in his systematic remarks, wrote that "*Hedbergella brittonensis* Loeblich and Tappan*** seems suspiciously similar to *Hedbergella portsdownensis* (William-Mitchell, 1948) and may be a junior synonym of this latter specie****Hedbergella brittonensis* appears to have been derived from a *Hedbergella delrioensis* stock."

Loeblich and Tappan (1988, p. 462) stated that, at the generic level, *Hedbergella* has an "***umbilical-extraumbilical arch with a narrow lip or flap [and *Whiteinella* has the same arch but is] bordered by a wide apertural flap or porticus that extends into the umbilicus***."

Because the specimens recovered from the lower member of the Mancos at the Laguna locality and from the Hartland Member–lower member of the Mancos at the Heron Reservoir locality appear to be identical to those in photomicrographs in Eicher and Worstell (1970), the same systematics are retained herein.

Hedbergella delrioensis (Carsey)

(Plate 3, figures 7–9, 11, 12)

This is a common species in both the Whitewater Arroyo and the lower member at the Laguna locality and in the Hartland Member–lower member at the Heron Reservoir locality. Both localities represent open-ocean areas. Chambers are less lobate and increase in chamber size is less pronounced than in *Hedbergella amabilis*. Recrystallized specimens from the Heron Reservoir locality prevent examination of details.

Clavihedbergella simplex (Morrow)

(Plate 3, figures 13, 14)

This species is rare and limited to the Hartland Member–lower member of the Mancos at the Heron Reservoir locality. The few small specimens recovered have 4–5 chambers in final whorl.

Archaeoglobigerina

(Plate 3, figure 15)

The aperture location and hispid texture of the test characterize this genus. It is confined to the base of the lower member of the Mancos at the Laguna locality.

Rotalipora cushmani (Morrow)

(Plate 3, figures 16–19)

Figure 16 of plate 3 is the single iron-oxide-replaced representative of this species from the San Juan Basin. Although the species is abundant at the Heron Reservoir locality in the Hartland Member–lower member, the specimens are recrystallized and details are obscured. Species variation exists between the San Juan Basin (lower member at Laguna) specimen and the Chama Basin (Heron Reservoir) specimens (pl. 3, figs. 17–19), but no conclusion can be drawn from a single specimen for comparative purposes.

Rotalipora greenhornensis (Morrow)

(Plate 3, figures 21–23)

This distinctive species is the most abundant form in the Hartland Member–lower member of the Mancos at the Heron Reservoir locality in the Chama Basin. Two specimens were also recovered from the 20-ft interval of the Whitewater Arroyo Tongue at the Laguna locality.

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APPENDIX—DESCRIPTION OF LOCALITIES

[Localities shown in figure 2]

San Juan Basin

Whitewater Arroyo type section.—NE¼ sec. 17, T. 12 N., R. 19 W., Vanderwagen 7½-minute quadrangle, McKinley County, New Mexico. About 1.2 miles west of Two Wells, New Mexico. The entire section of the Whitewater Arroyo Tongue of the Mancos Shale is well exposed and accessible. It is overlain by 30 ft of the Twowells Tongue of the Dakota Sandstone. Owen (1966) described an 80-ft-thick type section, and Dane and others (1971) measured a 46-ft-thick section at this same locale from which five shale samples were collected. The upper 6 ft of the latter section is sandy and transitional and was not collected for this study.

Hyde Mine.—NE¼NW¼ sec. 12, T. 15 N., R. 18 W., Gallup East 7½-minute quadrangle, McKinley County, New Mexico. About 1.5 miles due north of I-40 at the Hogback; actual road distance from I-40 is 3 miles. The entire section of the Whitewater Arroyo is nicely exposed and easily accessed. The Whitewater Arroyo is 54 ft thick; the upper 10 ft of the section is a transition zone with the Twowells and was not collected. Five shale samples cover the sampled section, although eleven were collected.

Casamero Lake.—NE¼ sec. 30, T. 15 N., R. 11 W., Casamero Lake 7½-minute quadrangle, McKinley County, New Mexico. Though not a prominent outcrop, a complete section (28 ft) of the Whitewater Arroyo is well exposed and is overlain by 15 ft of Twowells. A thin, 2-in.-thick, dark-brown, iron-stained, fossiliferous bed caps the top of the Twowells. The Mancos above the Twowells has been eroded from the valley floor. Five samples were collected from this locality.

Cubero.—SE¼SW¼ sec. 21, T. 10 N., R. 6 W., Laguna 7½-minute quadrangle, Cibola County (formerly included in Valencia County), New Mexico, on the Laguna Indian Reservation. The 85-ft-thick outcrop of the Whitewater Arroyo is excellent and complete. A 20-ft-thick transition zone is between the medium-gray shale of the Whitewater Arroyo and the weathered yellowish-gray of the 48-ft-thick cliff-forming Twowells. The transition zone is light to medium gray and increases upward in silt content. It has the same cliff-face habit as the Twowells above. Mancos is eroded on top of the Twowells. Seven samples were studied from this locality, although nineteen were collected.

Laguna.—NE¼SE¼ sec. 20, SW¼NW¼ sec. 21, T. 10 N., R. 5 W., Laguna 7½-minute quadrangle, Cibola County (formerly included in Valencia County), New Mexico, on the Laguna Indian Reservation. Access is time consuming but not difficult through section 29 to the south. Of the 90 ft of the Whitewater Arroyo measured by Landis and others (1973), 55 ft is covered by very large slope debris from the overlying Twowells, which is 74 ft thick. The Whitewater Arroyo at Laguna is represented by the lower 31 ft of exposed shale. The remaining 4 ft of Landis and others' section is bentonite and siltstone. The lower 20 ft of the lower member of the Mancos is well exposed and was sampled. The top of the section is incomplete at this locality. The Laguna locality is the best exposure of the intertonguing sequence of the Dakota and Mancos. Landis and others (1973) stated that "the Dakota-Mancos rock sequence***is developed to its fullest degree and is well exposed in the area***of Laguna." It is the type section for several of the units in the Dakota and Mancos sequence described by Landis and others (1973).

L-Bar.—SE¼SW¼ sec. 24, T. 11 N., R. 5 W., Moquino 7½-minute quadrangle, Cibola County (formerly included in Valencia County), New Mexico, just north of the Laguna Indian Reservation. Access is excellent but only the upper few feet of the Whitewater Arroyo are exposed below a very steep cliff face of 79 ft of Twowells. Because L-Bar is not a complete section, it is a check point and not a reference section. Only the upper 15 ft of the Whitewater Arroyo are represented by two shale samples.

Chama Basin

Heron Reservoir.—No township and range are on the map. Heron Reservoir 7½-minute quadrangle, Arriba County, New Mexico. Approximately lat 36°42′50″N.; long 106°38′52″W. Outcrop is at lake level on a small peninsula. Six shale samples were collected from about 25 ft of section, from the upper part (lake level) toward the base of the section. The upper contact is below water and the lower contact is covered above. Ridgley (in press) assigned this unit to the Hartland Member–lower member of the Mancos Shale. Caution must be applied to interpretations of the strata at the reservoir because the Hartland Member–lower member is part of the southeast-dipping flank of Laguna dome to the north.

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PLATES 1–3

Contact prints of the plates in this report are available, at cost, from U.S. Geological Survey Photographic Library, Federal Center, Denver, Colorado 80225

PLATE 1

[All figures are scanning electron microscope photomicrographs. Bar scale for each specimen is 200 μm unless otherwise noted; all specimens are from the Whitewater Arroyo Tongue of the Mancos Shale unless otherwise noted. Distance above base of section is given]

FIGURE 1. *Gaudryina* sp. Cubero section, 60 ft.

2, 3. *Reophax inordinatus* Young.
- 2. Type section, 20 ft.
- 3. Cubero section, 60 ft.

4, 8, 15. *Ammobaculites fragmentarius* Cushman.
- 4. Casamero Lake section, 10 ft. a, Side view. b, Apertural view, 40 μm.
- 8. Cubero section, 75 ft.
- 15. Laguna section, 20 ft.

5. *Ammodiscus cretaceous* (Reuss). Laguna section, 20 ft, 100 μm.

6. *Ammobaculites variablis* Tappan. Cubero section, 30 ft.

7. *Ammobaculites* sp. Casamero Lake section, 0 ft.

9, 10. *Ammobaculites goodlandensis* Cushman and Alexander.
- 9. Cubero section, 30 ft.
- 10. Cubero section, 75 ft.

11. *Ammobaculoides mosbyensis* Eicher. Type section, 0 ft. Damaged aperture, 100 μm.

12, 13. *Textularia* spp.
- 12. Cubero section, 75 ft.
- 13. Type section, 10 ft, 100 μm.

14, 16, 18. *Haplophragmoides coronata* (Brady).
- 14, 16. Lower member of the Mancos Shale, Laguna section, 5 ft.
- 18. Type section, 40 ft. a, Side view, 100 μm. b, Reverse side view with light-colored piece of debris, 100 μm.

17. *Verneuilinoides perplexus* (Loeblich). Laguna section, 20 ft, 100 μm.

19. *Ramulina aculeata* (d'Orbigny). Lower member of the Mancos Shale, Laguna section, 5 ft, 100 μm.

20. *Citharina* sp. Lower member of the Mancos Shale, Laguna section, 5 ft.

21. *Psilocitharella* sp. Lower member of the Mancos Shale, Laguna section, 0 ft.

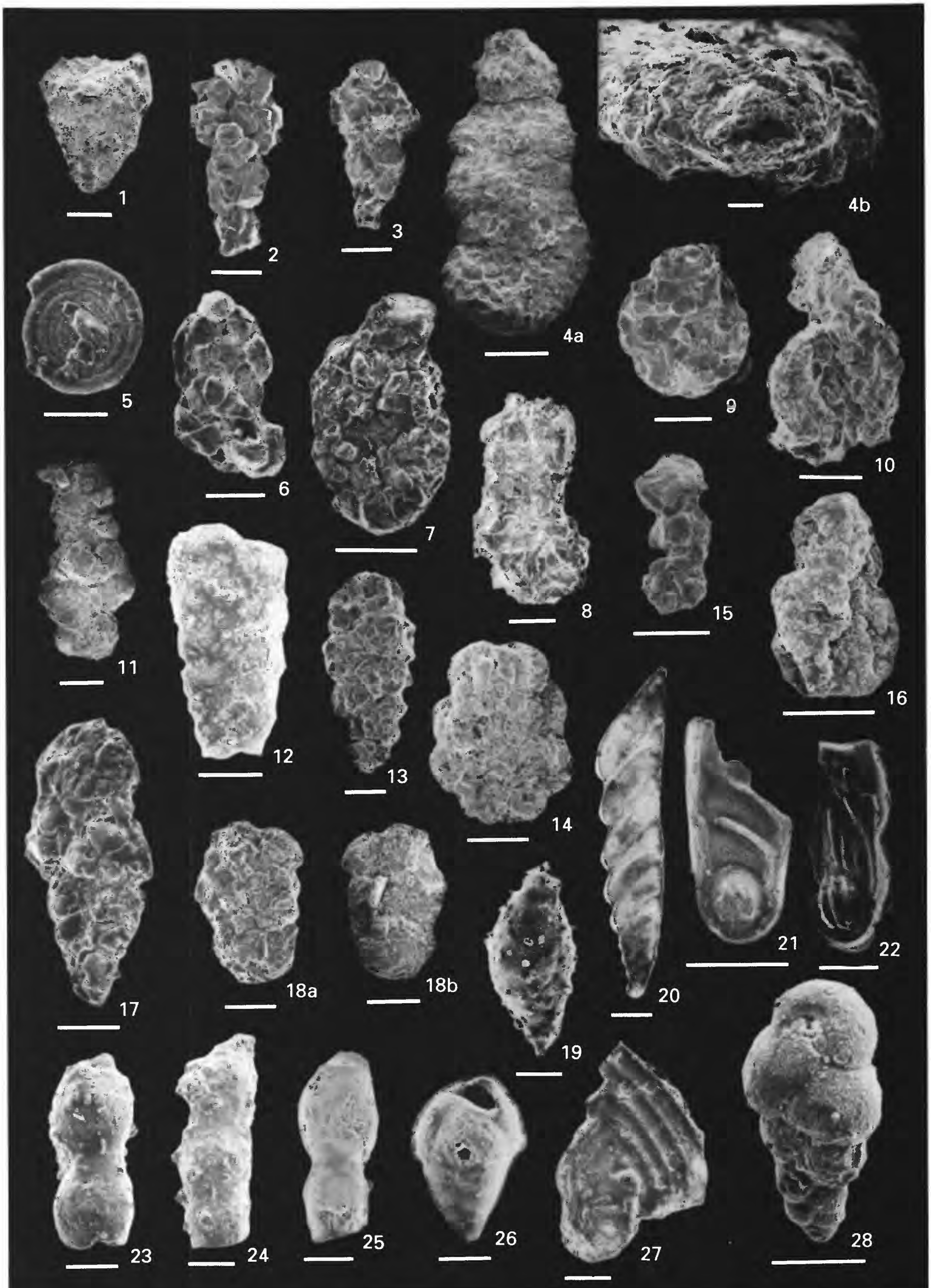
22. *Citharina kochii* (Roemer). Type section, 30 ft, 100 μm.

23–25. *Svenia* spp.
- 23, 24. Hartland Member–lower member of the Mancos Shale, Heron Reservoir section, top of section, 100 μm.
- 25. Type section, 30 ft, 100 μm.

26. *Praebulimina* sp. Lower member of the Mancos Shale, Laguna section, 5 ft, 40 μm.

27. *Palmula* sp. Cubero section, 15 ft.

28. *Neobulimina albertensis* (Stelch and Wall). Lower member of the Mancos Shale, Laguna section, 10 ft, 100 μm.



SELECTED SPECIMENS FROM STUDY AREA

PLATE 2

[All figures are scanning electron microscope photomicrographs. Bar scale for each specimen is 100 µm unless otherwise noted; all specimens are from the Whitewater Arroyo Tongue of the Mancos Shale unless otherwise noted. Distance above base of section is given]

FIGURE 1. *Bullopora*? sp. Cubero section, 0 ft.

2. *Astacolus* sp. Cubero section, 15 ft.

3. Unknown foraminifer. Cubero section, 45 ft.

4. *Lenticulina* sp. A. Type section, 30 ft. a, Side view. b, Edge view.

5–8. *Gavelinella* sp.

- 5, 7, 8. Lower member of the Mancos Shale, Laguna section, 10 ft.
  - 5, 7. Umbilical view.
  - 8. Spiral view.
- 6. Lower member of the Mancos Shale, Laguna section, 5 ft. Spiral view.

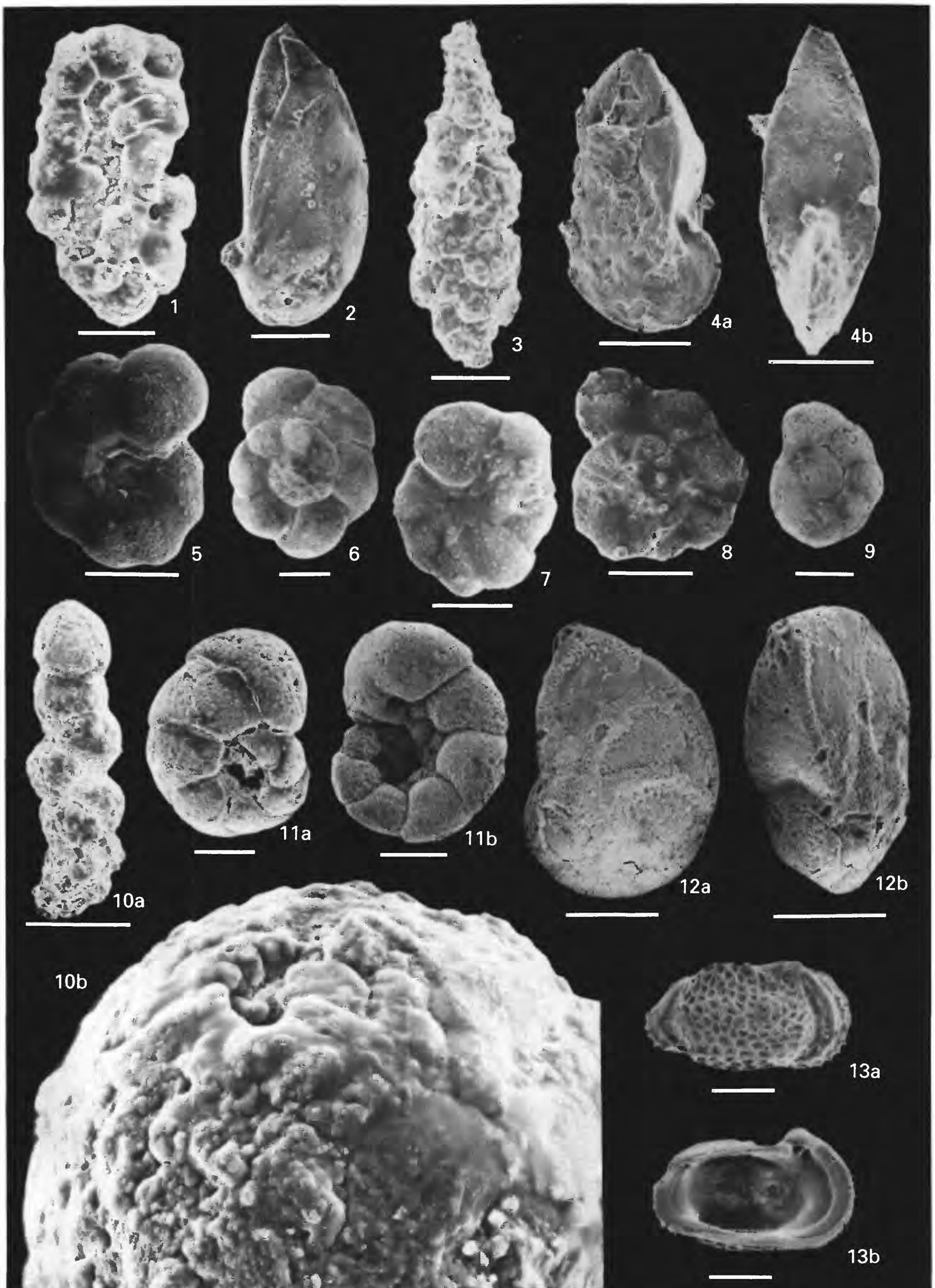
9. *Gavelinella modesta* Eicher and Worstell. Laguna section, 20 ft.

10. *Bimonilina reciprocata* Loeblich and Tappan. Laguna section, 20 ft. a, Side view, 200 µm. b, Enlargement of aperture, 20 µm.

11. *Lingulogavelinella* sp. Internal mold. Lower member of the Mancos Shale, Laguna section, 5 ft. a, Spiral view. b, Umbilical view.

12. *Lenticulina* sp. B. Type section, 40 ft. a, Side view. b, Oblique view of aperture and side.

13. *Cythereis eaglefordensis* Alexander. Ostracode. Lower member of the Mancos Shale, Laguna section, 0 ft. a, Exterior view, 200 µm. b, Interior view, 200 µm.



SELECTED FORAMINIFERS FROM STUDY AREA

PLATE 3

[All figures are scanning electron microscope photomicrographs. Bar scale for each specimen is 100 μm unless otherwise noted. Distance above base of section given except for Heron Reservoir samples, which are described by distance below top of section]

FIGURE 1. *Heterohelix moremani* (Cushman). Lower member of the Mancos Shale, Laguna section, 5 ft.

2. *Guembelitria harrisi* Tappan. Lower member of the Mancos Shale, Laguna section, 5 ft, 40 μm.

3. *Hedbergella amabilis* Loeblich and Tappan. Internal mold. Whitewater Arroyo Tongue, type section, 30 ft.

4–6. *Hedbergella portsdownensis* (Williams-Mitchell).
- 4. Lower member of the Mancos Shale, Laguna section, 5 ft, 40 μm.
- 5, 6. Lower member of the Mancos Shale, Laguna section, 10 ft.

7–9, 11, 12. *Hedbergella delrioensis* (Carsey).
- 7–9, 12. Lower member of the Mancos Shale, Laguna section, 10 ft.
- 11. Hartland Member–lower member of the Mancos Shale, Heron Reservoir section, 0 ft (below top).

10. *Hedbergella* sp. Lower member of the Mancos Shale, Laguna section, 0 ft.

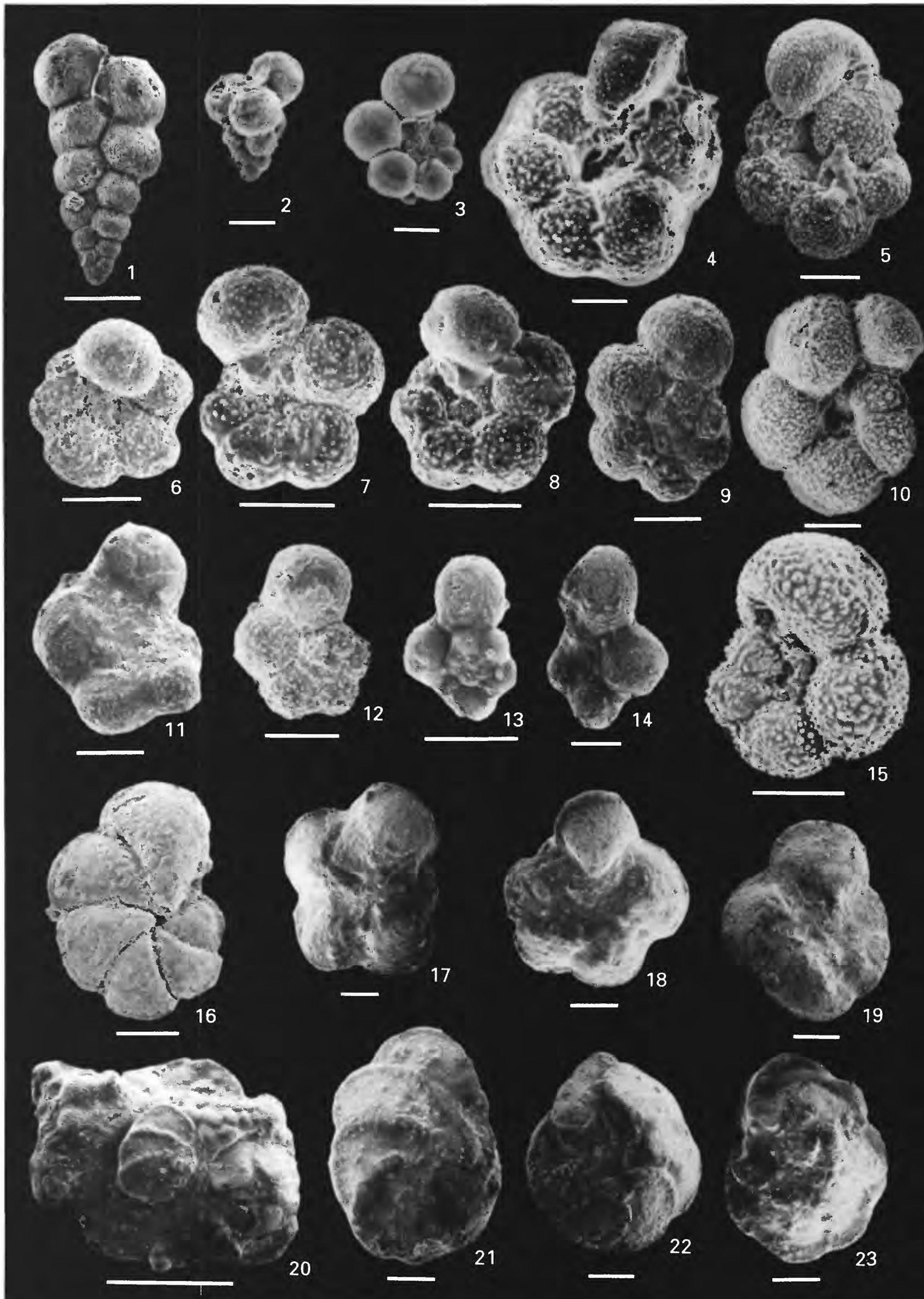
13, 14. *Clavihedbergella simplex* (Morrow).
- 13. Hartland Member–lower member of the Mancos Shale, Heron Reservoir section, 0 ft (below top).
- 14. Hartland Member–lower member of the Mancos Shale, Heron Reservoir section, 10 ft (below top).

15. *Archaeoglobigerina* sp. Lower member of the Mancos Shale, Laguna section, 0 ft.

16–19. *Rotalipora cushmani* (Morrow).
- 16. Lower member of the Mancos Shale, Laguna section, 5 ft.
- 17–19. Hartland Member–lower member of the Mancos Shale, Heron Reservoir section, 0 ft (below top).

20. Small cluster of sample taxa from Hartland Member–lower member of the Mancos Shale, Heron Reservoir section, 10 ft (below top). Note both spiral and umbilical views of *Rotalipora greenhornensis* (Morrow) and *Heterohelix moremani* (Cushman), 400 μm.

21–23. *Rotalipora greenhornensis* (Morrow). All specimens are from Hartland Member–lower member of the Mancos Shale, Heron Reservoir section, 10 ft (below top).
- 21. Spiral view.
- 22, 23. Umbilical view.



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Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations; as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that maybe cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales, they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. The series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; the principal scale is 1:24,000, and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Books and Open-File Reports Sales, Box 25286, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879-1961" may be purchased by mail and over the counter in paperback book form and as a set microfiche.

"Publications of the Geological Survey, 1962-1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971-1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only.

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March 3, 1849