LATE ORDOVICIAN–EARLY SILURIAN STRATA IN THE CENTRAL UNITED STATES AND THE HIRNANTIAN STAGE

THOMAS W. AMSDEN AND JAMES E. BARRICK

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Title Page Illustration

Sylvan Shale, Keel Formation, and Cochrane Formation at east rim of Lawrence Quarry, sec. 36, T3N, R6E, Pontotoc County, Oklahoma.

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PREFACE

This report is composed of two papers (Parts I and II) on the biostratigraphy, lithostratigraphy, and paleoenvironment of the latest Ordovician (Hirnantian) and Early Silurian strata in the southern Midcontinent region of the United States. These strata include the Keel Formation of Oklahoma, the Cason oolite of Arkansas, and the Edgewood Group of the Mississippi Valley. The sequence is composed mainly of oolitic limestones, skeletal limestones, and dolomites having a maximum thickness of about 40 feet (12 m). Fe–Mn mineralization is developed locally in south-central Oklahoma and north-central Arkansas.

Part I, by Amsden, reviews the biostratigraphy–lithofacies–biofacies of the Keel–Edgewood strata. It also discusses the paleoenvironment represented and its possible relationship to eustatic changes in sea level associated with Late Ordovician–Early Silurian glaciation. This part concludes with a review of Hirnantian faunas from other parts of the world and the paleoenvironmental implications that can be derived from these occurrences.

Part II, by Barrick, describes the taxonomy and biostratigraphy of conodonts from the Keel Formation of Oklahoma and the Cason oolite of Arkansas. These faunas are compared to those in the Edgewood Group of the Mississippi Valley.

<div align="right">T.W.A. and J.E.B.</div>

LATE ORDOVICIAN–EARLY SILURIAN STRATA IN THE CENTRAL UNITED STATES AND THE HIRNANTIAN STAGE

THOMAS W. AMSDEN[1] AND JAMES E. BARRICK[2]

PART I—PALEOENVIRONMENT OF THE KEEL–EDGEWOOD OOLITIC PROVINCE AND THE HIRNANTIAN STRATA OF EUROPE, USSR, AND CHINA

THOMAS W. AMSDEN

Abstract—This report presents a sedimentary–paleoenvironmental model for the Late Ordovician–Early Silurian calcareous oolite province in the southern Midcontinent region of the United States. The area covered extends from the Texas Panhandle across Oklahoma and Arkansas to the Mississippi River, and northward to eastern Kansas, across Missouri, into southern Illinois. The rocks studied are dominantly shallow-water oolites and oolitic skeletal limestones that grade into a silty argillaceous facies along the eastern and southeastern margins of the province. Keel–Edgewood strata are unconformably overlain by Early Silurian (late Llandoverian) strata and appear to represent a regressive sedimentary phase of impressive dimensions, possibly related to eustatic sea-level changes associated with North African glaciation. Keel–Edgewood strata bear a substantial megafauna, including a large and varied articulate-brachiopod fauna. Based on the brachiopod faunas, the Keel (lower part) and the Edgewood (Noix–Cyrene–lower Bowling Green) are correlated with the upper part of the Gamachian Stage of Anticosti Island, Quebec, and the Hirnantian Stage of Europe, the USSR, and the People's Republic of China. The region north of the Keel–Edgewood province, and extending into the Great Lakes area, is occupied by the Neda hematitic oolite. The precise age of the Neda has not been determined, but these iron-rich oolitic beds occupy the same stratigraphic position as the Keel–Edgewood, indicating that oolitic strata falling within a general Late Ordovician–Early Silurian time frame covered a large part of eastern North America.

Hirnantian strata are widely distributed across Europe, North Africa, the USSR, China, and elsewhere, where they are represented mainly by silty mudstones with a generally low-diversity total benthic fauna dominated by brachiopods and trilobites. The brachiopods from this lithofacies have affinities with those from the Keel–Edgewood carbonate facies, but they do differ in several taxonomic aspects. In parts of Europe, the USSR, and China the concentration of silt–clay in the Hirnantian beds decreases, and the strata grade into silty limestones, marlstones, and skeletal limestones, which are locally oolitic. In the more calcareous lithofacies the diversity of the benthic fauna expands sharply, and the generic and even specific affinities with the Keel–Edgewood fauna are markedly increased. It is herein suggested that the distribution of these latest Ordovician benthic faunas was controlled primarily by the paleoenvironment. During Hirnantian time the seas apparently occupied a series of shallow, tropical to subtropical, interconnected basins that permitted the free interchange of benthic organisms into all areas where compatible environments were present. Substantial quantities of fine detritus were being supplied to most of these basins, restricting the benthic faunas to those organisms that could successfully compete in an environment of high siltation. To the south the temperature of the water presumably cooled as it approached the glaciated region of North Africa, which may also have been the source of a considerable amount of the terrestrial detritus. At different times and at different places this influx of detritus abated, the seas cleared, and a much more varied benthic fauna was established; these assemblages have the closest affinities with the Keel–Edgewood faunas.

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1

INTRODUCTION

Late Ordovician–Early Silurian Oolite Province

A Late Ordovician–Early Silurian oolite province forms a wide belt of shallow-marine sediments, perhaps locally ranging into supratidal sediments, extending from Texas to the Great Lakes (text-fig. 1). This sequence is underlain by Late Ordovician (Cincinnatian) shales and limestones and is unconformably overlain by Early Silurian (Llandoverian) strata. This oolite province appears to represent a regressive sedimentary phase of impressive dimensions, possibly related to eustatic changes in sea level associated with North African glaciation. The province can be divided into a southern part, composed almost entirely of calcareous oolite (Keel–Edgewood), and a northern part composed of hematitic oolite (Neda). The hematitic oolite occupies a stratigraphic position similar to that of the calcareous oolites; however, the precise biostratigraphic relationships of the Neda and the Edgewood are poorly understood, and the Neda is discussed only briefly in the present report.

Keel–Edgewood

The Keel–Edgewood calcareous oolites have an exclusively marine, diverse shelly fauna and a moderate conodont fauna. The Ordovician–Silurian boundary (based primarily on conodonts) falls within the Keel–Edgewood sequence. On the basis of the brachiopod fauna, the Ordovician portion is here correlated with the Hirnantian Stage of Europe and the upper part of the Gamachian Stage at Anticosti Island, Quebec. Cocks and Copper (1981, p. 1033) report a Hirnantian brachiopod fauna from the upper part of the Ellis Bay Formation on Anticosti Island; however, they note that the "brachiopods from the lower part of the Ellis Bay Formation (and therefore the lower Gamachian in Twenhofel's terms) are equivalent to those from the Rawtheyan Stage in Europe." Correlation of the Keel–Edgewood brachiopod fauna with the Hirnantian faunas of Europe is based on reasonably firm evidence. Furthermore, these Hirnantian faunas are commonly associated with graptolites, which facilitates a correlation between the North American carbonate biofacies and the Late Ordovician–Early Silurian graptolite zonation. The Keel–Edgewood conodonts also can be tied to the graptolite sequence in western Canada (see Part II), and, accordingly, usage of the term Hirnantian Stage is here preferred to that of the Gamachian Stage.

In 1974 I described the Keel–Edgewood articulate-brachiopod faunas, commented briefly on the paleoenvironment, and suggested a correlation with the European Hirnantian Stage. The objectives of the present report are (1) to provide more information on the geographic distribution, especially in the Anadarko and Arkoma Basins; (2) to furnish more detailed information on paleoenvironments; (3) to provide information on textural characteristics and stratigraphic relationships of the Fe–Mn mineralization; and (4) to discuss the age and correlatives of Keel–Edgewood strata in the light of recent studies on Hirnantian strata in other areas.

The Keel Formation crops out in the Arbuckle Mountains and Criner Hills of south-central Oklahoma, in eastern Oklahoma, and in north-central Arkansas (Cason oolite); the Edgewood strata crop out at two localities in the Mississippi Valley, in Illinois and Missouri (text-fig. 2). The brachiopods indicate that these strata are correlative throughout this region (text-fig. 3). Throughout Oklahoma and the Texas Panhandle the Keel rests with apparent conformity on the Sylvan Shale, from which Decker (1935) reported the *Dicellograptus complanatus* graptolite fauna and from which Jenkins (1970) reported a late Ashgillian chitinozoan fauna. The Keel is unconformably overlain by the Cochrane Formation (Arbuckle Mountains–Criner Hills) and the Blackgum Formation (eastern Oklahoma) of late Llandoverian age. In north-central Arkansas the Cason oolite (text-fig. 3) locally rests unconformably on the "Fernvale" Limestone, which is correlative with the upper part of the Welling Formation (Maysvillian) of Oklahoma (Amsden, *in* Amsden and Sweet, 1983, p. 40); it is overlain by the *Triplesia alata* beds of late Llandoverian age. In southeastern Missouri and southwestern Illinois, Edgewood strata rest unconformably on the Orchard Creek Shale or the Girardeau Limestone and are unconformably overlain by the Sexton Creek Formation of late Llandoverian age. In Pike County, Missouri, the Edgewood rests on the Maquoketa Shale the upper beds of which locally include some scattered oolites. In this county the Edgewood is unconformably overlain by Devonian strata, but across the Mississippi River in Calhoun County, Illinois, it is unconformably overlain by the Sexton Creek Formation of late Llandoverian age.

Keel–Edgewood strata are dominantly oolites and oolitic skeletal limestones. In Oklahoma and the northern Mississippi Valley, exposures of the oolites include little terrigenous detritus and commonly average only about 1 percent HCl-insoluble residues. However, in the southeastern area, extending from north-central Arkansas to southeastern Missouri, the terrigenous detritus increases sharply; and in southwestern Illinois, Edgewood strata are represented by argillaceous
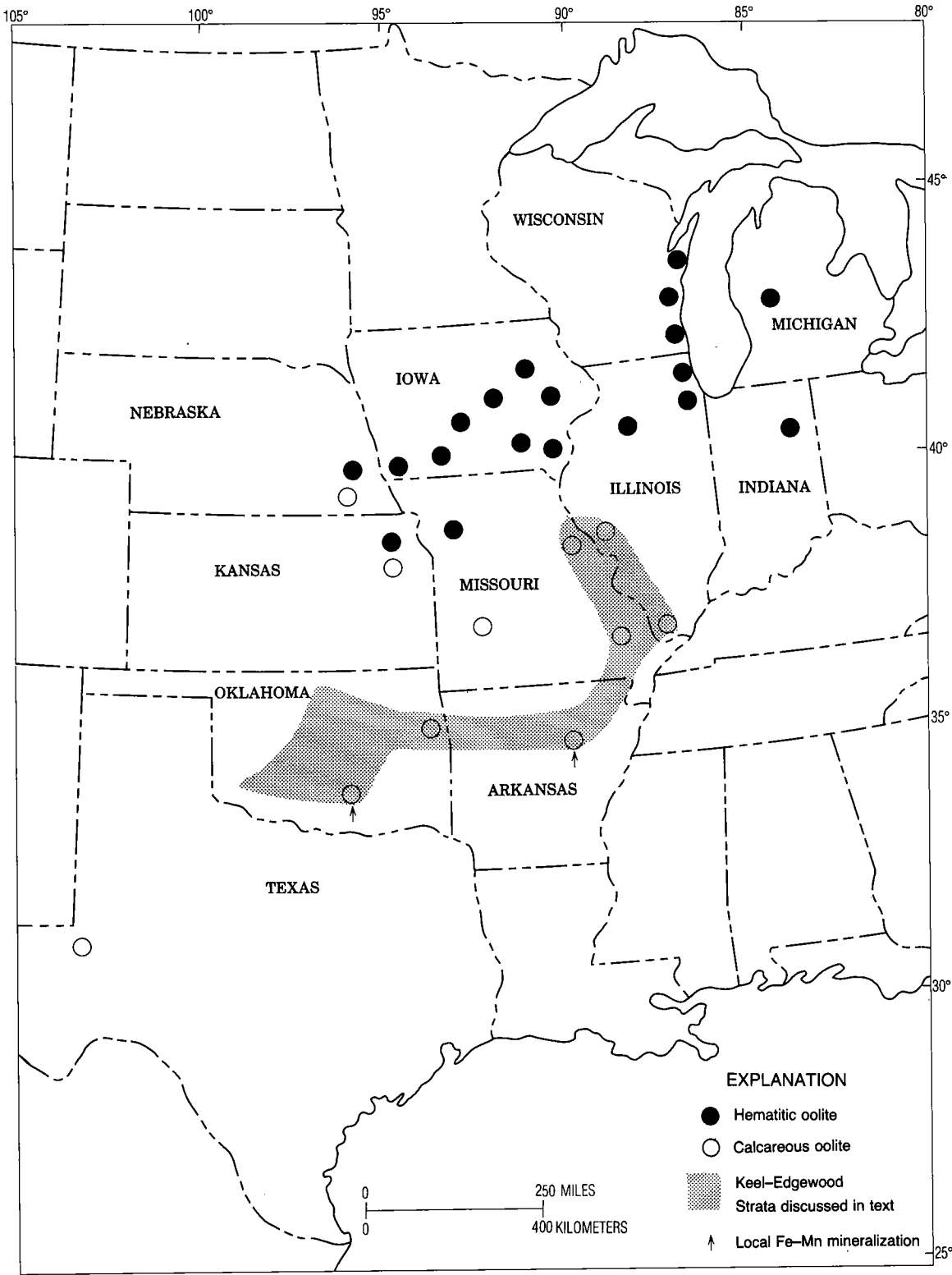
Text-figure 1. Map showing distribution of oolitic strata in central United States. The hematitic oolite (Neda) is in the same stratigraphic position as the calcareous oolites (Keel–Edgewood), although the age of the Neda is uncertain; oolitic strata from this stratigraphic position have been reported from West Texas. (Neda information from Mikulic and Kluessendorf, 1983, fig. 3.)
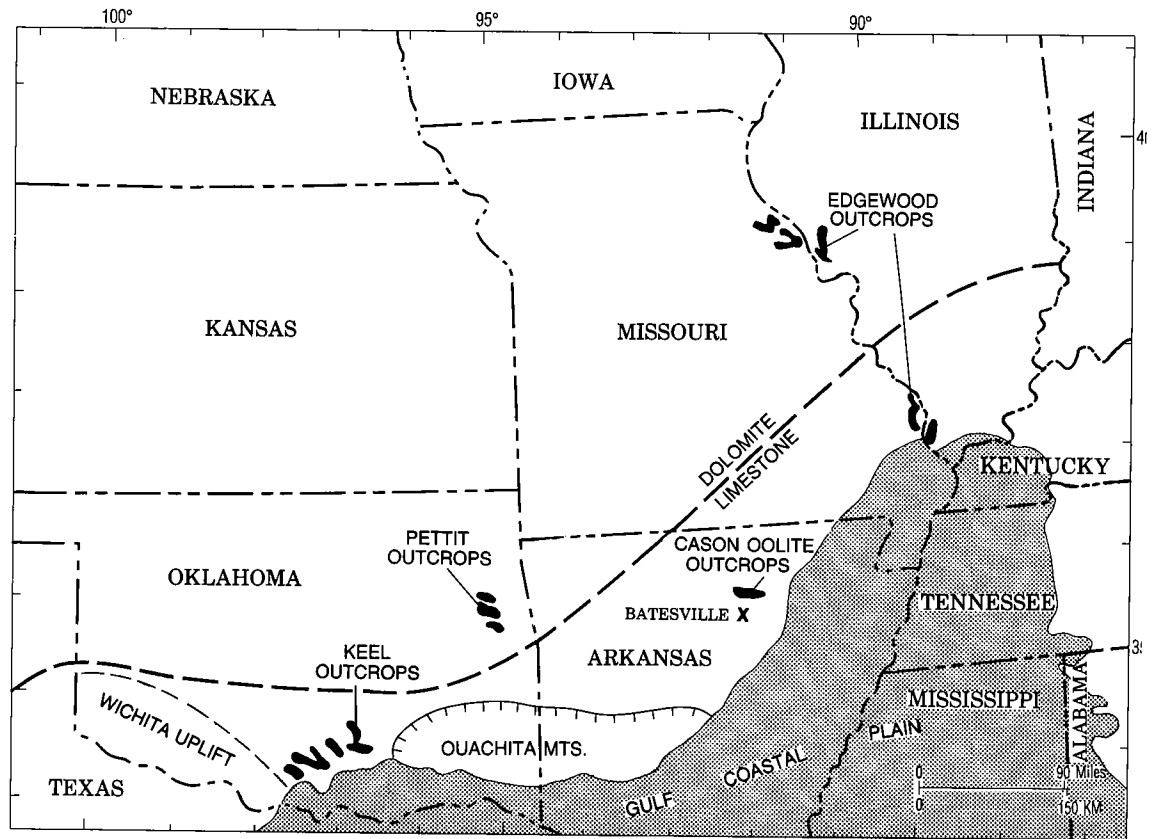
Text-figure 2. Map showing location of Keel–Pettit–Cason oolite–Edgewood outcrops in area of this report. (After Amsden, 1974, text-fig. 1.)

and silty limestones with widely scattered ooliths and thin, heavily silted beds of oolite.

A part of this region lies within the Late Ordovician–Silurian dolomite province that occupies much of the North American continental interior (text-fig. 2). I interpret this dolomitization as an early-stage replacement. Regardless of origin, dolomitization at places completely replaced the internal structure of the ooliths (pl. 2, fig. 2) and may have been sufficiently intense in some beds to have obscured completely the primary textures and the stratigraphic relationships.

The origin of ooids is a complex problem that has attracted the attention of numerous investigators for more than 100 years (Simone, 1981, in a recent review of ooids, listed four pages of references). Keel–Edgewood ooids show a considerable range of structures some of which may be of algal origin (Amsden, 1960, p. 31, pl. 20, figs. 1–3). In the present study no attempt is made to determine the precise modes of origin of the ooids except to note that all are believed to have formed in warm, shallow water of moderate to strong energy level (see section on Paleoenvironment).

Neda Hematitic Oolite

This stratigraphic unit is not a part of the present study but is discussed because of its geographic and stratigraphic proximity to the Keel–Edgewood oolite province. In its type area, in Wisconsin, the Neda overlies the Maquoketa Shale and underlies the Mayville Dolomite. Previous investigators generally agreed that the Neda is unconformably overlain by the Mayville Dolomite, but its relationship with the underlying Maquoketa Shale is less apparent. Savage and Ross (1916, p. 190) reported an unconformity involving truncation between the Neda and the Maquoketa, whereas Mikulic and Kluessendorf (1983, p. 2) showed it as a surface of at least apparent conformity. Savage and Ross (1916, p. 189) reported the brachiopods *Herbertella occidentalis*, *Platystrophia acutilirata*, and *Rhynchotrema capax* from Maquoketa strata immediately beneath the Neda at Neda. These authors also reported a fauna of nine species, including the brachiopods *Strophomena wisconsinensis* and *Dalmanella tersa*, from the Neda iron-ore bed at Cascade Falls;
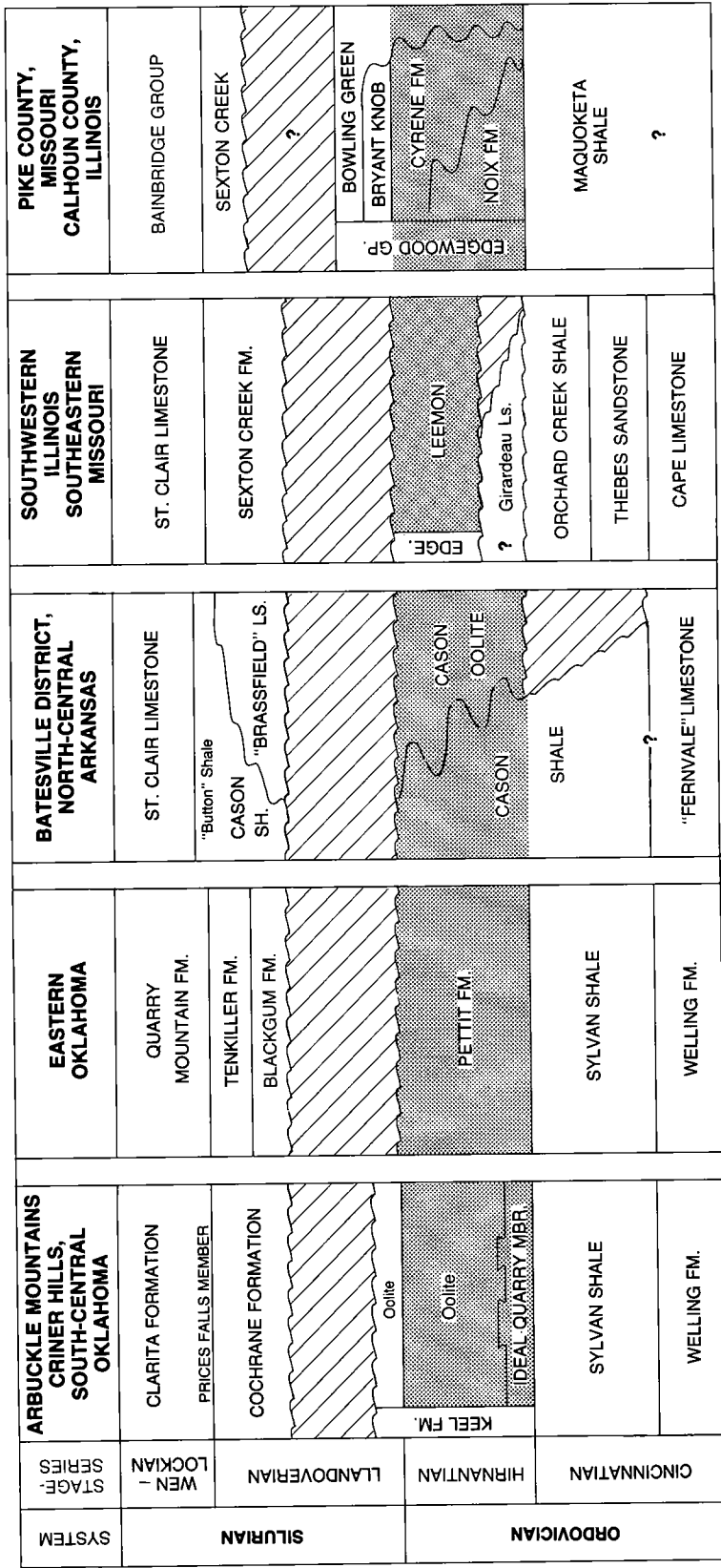
Text-figure 3. Stratigraphic chart showing inferred correlation and age of Late Ordovician–Early Silurian strata. Not to scale in terms of thickness or of time.

they interpreted this as an *in-situ* fauna of Ma-
quoketa age. Mikulic and Kluessendorf noted that
Maquoketa fossils in the Neda could have been
reworked, although they did find some evidence
for interbedding of Maquoketa-like sediments
with the Neda. The age of the Neda cannot be
resolved until more definitive faunal data are
available, but I regard the Keel–Edgewood
brachiopod fauna as taxonomically distinct from,
and phylogenetically younger than, the Maquoke-
ta brachiopod fauna as reported by Savage and
Ross (1916), Wang (1949), and others.

Previous Investigations

   The stratigraphy of Edgewood strata in the Mis-
sissippi Valley was recently described by Thomp-
son and Satterfield (1975) and Amsden (1974);
both publications include an extensive review of
earlier studies. The Keel Formation in Oklahoma
and the Texas Panhandle was described by
Amsden (1960, 1967, 1974, 1975, 1980), and the
Arkansas strata were described by Craig (1969),
Lemastus (1979), and Amsden (1980). The Keel–
Edgewood strata contain a diverse benthic mega-
fauna, but the only groups to have received mod-
ern taxonomic treatment are the corals (Elias,
1982) and the brachiopods (Amsden, 1974). A con-
odont fauna in the Edgewood was described by
Thompson and Satterfield (1975) and McCracken
and Barnes (1982). Craig (1969) discussed the con-
odont faunas from Batesville, Arkansas. Con-
odonts from the Keel Formation and Cason oolite
are described in Part II of the present report.

Acknowledgments

KEEL AND PETTIT FORMATIONS IN OKLAHOMA AND THE TEXAS PANHANDLE

Stratigraphic Relationships

   The Keel and Pettit Formations crop out in the
Arbuckle Mountains–Criner Hills of south-
central Oklahoma and in eastern Oklahoma. They
are widely distributed in the subsurface of Okla-
homa, extending into the Texas Panhandle (text-
fig. 4). The type section for the Keel Formation
and its basal Ideal Quarry Member is at the Law-
rence Quarry (text-figs. 5, 6) near the north end of
the Arbuckle Mountains (Amsden, 1960, p. 34–
44). The type section for the Pettit Formation is
near the town of Pettit in eastern Oklahoma
(Amsden and Rowland, 1965, p. 22–27). No di-
agnostic fossils have been obtained from the
Pettit; however, it occupies the same stratigraphic
position as the Keel, and the two formations are
believed to be essentially contemporaneous.
   These oolitic strata rest directly on the Sylvan
Shale throughout Oklahoma and the Texas Pan-
handle. There is no evidence of pre-Keel trunca-
tion at this boundary, and deposition may have
been continuous, at least in areas where the Keel
is preserved. Locally, uppermost Keel strata carry
Silurian conodonts (Part II) whose precise position
in the Llandoverian Series is unknown. Through-
out the outcrop area of the Arbuckle Mountains–
Criner Hills, the Keel Formation is unconform-
ably overlain by the Cochrane (text-figs. 5, 6). On
the basis of the brachiopod *Triplesia alata* Cooper,
I assign a late Llandoverian (C_{1-2}) age to the
Cochrane age (Amsden, 1971, p. 145; see discus-
sion below). Barrick and Klapper (1976, p. 66)
reported the conodont *Pterospathodus celloni* from
a bed at the top of the Cochrane Formation and
assigned this a late Llandoverian (C_5) age (see
Part II). There is physical evidence for pre-
Cochrane induration and truncation (Amsden,
1963, p. 631–635; *T. alata* is assigned a late Llan-
doverian age (C) on the basis of its association
with *Stricklandia protriplesiana*, plus its close
stratigraphic proximity to *P. celloni*; however, the
possibility that *T. alata* ranges into younger or
older strata cannot be eliminated on the basis of
present evidence).
   In eastern Oklahoma the Pettit Formation rests
on the Sylvan Shale and is unconformably over-
lain by the Blackgum Formation (Amsden and
Rowland, 1965, p. 23). Based on the brachiopods
Triplesia alata and *Stricklandia protriplesiana*,
the Blackgum Formation is assigned a late Llan-
doverian (C_2) age and is correlated with the
Cochrane Formation of the Arbuckle Mountain
region (Amsden, 1966, p. 1012–1015; 1971, p. 145–
146).
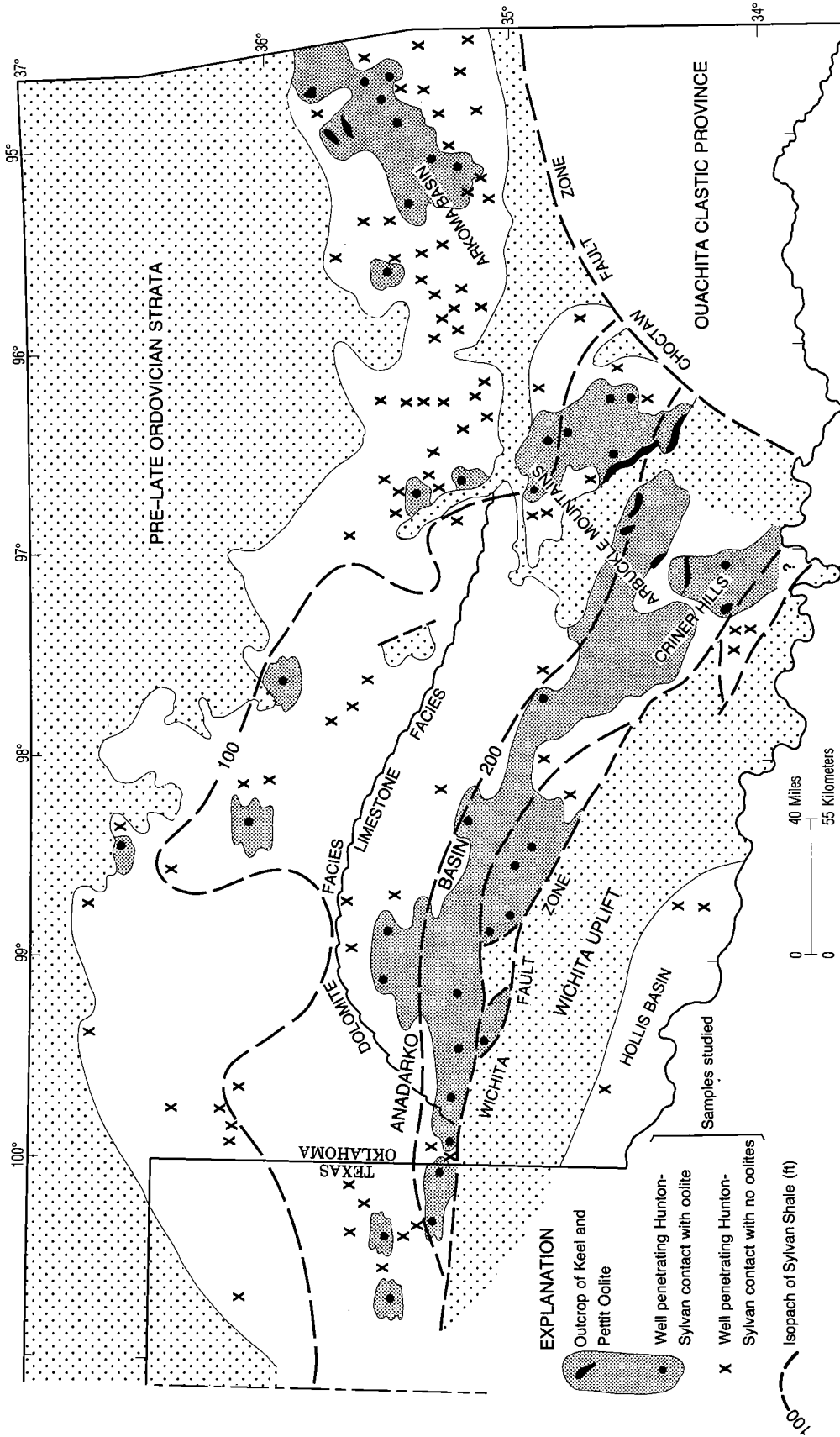
Text-figure 4. Map showing distribution of Keel and Pettit oolites in Oklahoma and in Texas Panhandle. (These oolites constitute the basal unit in the Hunton Group.) Interpretation based on surface and subsurface data, the latter obtained from a study of cores and samples including thin sections; all control points shown.

Text-figure 5. Photograph of Sylvan Shale, Keel Formation, and Cochrane Formation at east rim of Lawrence Quarry, sec. 36, T3N, R6E, Pontotoc County, Oklahoma. Arrows point to Keel–Cochrane contact. See also text-figure 6.

Text-figure 6. Photograph of Sylvan Shale, Keel Formation, and Cochrane Formation at east rim of Lawrence Quarry, sec. 36, T3N, R6E, Pontotoc County, Oklahoma. Hammer head rests on Keel–Cochrane contact. See also text-figure 5.

Distribution and Thickness

The Keel–Pettit oolite is irregularly distributed in a broad belt extending from the eastern Texas Panhandle across Oklahoma (text-fig. 4). Within this region are two major belts of reasonably continuous oolitic strata. One belt extends from the eastern outcrop area southeastward into the Arkoma Basin, and the other extends from the Arbuckle Mountains–Criner Hills westward along the structurally deep part of the Anadarko Basin. The latter area is the depocenter for early and middle Paleozoic strata in the Anadarko Basin and is undoubtedly related to basin subsidence. This is another example of a shallow-water stratigraphic unit extending from the eastern "shelf" area into the deep Anadarko Basin with little or no change in facies (Amsden, 1983b).

The irregular distribution of the Keel oolite may be accounted for by several hypotheses or a combination of hypotheses:

1. Nondeposition: The Keel–Pettit Formations are essentially intrabasinal in origin, being composed almost entirely of oolites, matrix, and skeletal material, all derived directly from the sea water. To eliminate deposition of this lithobiofacies, it would be necessary either to elevate the depositional interface above sea level (see 2 below) or to change the environment to eliminate completely carbonate sedimentation and the accompanying benthic faunas (deep water, cold water, etc.).

2. Removal of the Keel–Pettit strata by pre-Cochrane erosion: Evidence in both the Arbuckle Mountains and the eastern outcrop areas indicates local erosional truncation of the oolite (Amsden, 1960, p. 43; 1963, p. 631–636; Amsden and Rowland, 1965, p. 23).

3. The oolite is lost by lateral gradation into shale resembling the underlying strata: Evidence for this relationship exists in northwestern Oklahoma (Amsden, 1980, p. 33–41) and in Arkansas (see discussions of the Keel oolite in Arkansas).

In most places in the Arbuckle Mountains–Criner Hills outcrop area the Keel is less than 10 feet (3 m) thick, although along the eastern margin it is as thick as 15 feet (4.5 m) (Amsden, 1960, p. 34). It is difficult to determine the maximum thickness in the subsurface, but core and sample studies suggest that the Keel probably does not exceed 20 feet (7 m). In the eastern Oklahoma outcrop area the Pettit has a maximum thickness of about 3 feet (1 m).

Lithology

Typically the Keel is composed of medium- to pale-gray oolite. The ooliths make up from 30 to almost 60 percent of the total rock volume, averaging about 50 percent. Most individual ooliths are less than 2 mm in diameter, but some attain a diameter of almost 5 mm. In some strata, bedding is defined by differences in oolith size, and some shows a subdued type of crossbedding (pl. 6, figs. 1, 3). Most ooliths are symmetrical, well-rounded spheres with sharply defined radial and concentric structures (pl. 3, fig. 3). In thin section many ooliths show a core, commonly a pelmatozoan plate, and probably most have such a center. Most of the skeletal material has at least some coating of calcium carbonate, and all gradations can be observed from organic fragments with only a thin veneer to fully formed oolites with radial and concentric ornamentation (Amsden, 1960, pls. 10, 11). On some ooliths the outer rim is crinkled or fluted; these may be of algal origin (Amsden, 1960, p. 31, pl. 10, figs. 1–3). The most common matrix is spar; point counting shows a range from 12 to 32 per-

cent, averaging about 28 percent (text-fig. 7). At some places the spar and micrite are interbedded (pl. 3, fig. 3), and at other places the spar grades laterally into micrite. Irregular pellets of structureless micrite are common, which typically merge imperceptibly into solid micrite cement (Amsden, 1960, pl. 11, figs. 4, 5). Some of these pellets also may be of algal origin.

At most places the basal foot or so of the Keel Formation is rich in skeletal material and grades into oolitic skeletal limestone. This is the Ideal Quarry Member (Amsden, 1960, p. 30–35), which is discussed in the next section (Lithofacies–Biofacies).

It is not uncommon for broken ooliths and rip-up clasts to be mixed with well-formed, whole ooliths, suggesting lithification of ooliths, breakage, and redeposition of newly formed ooliths (pl. 1, figs. 1, 2). This does not imply any significant interruption of sedimentation, as induration probably took place soon after formation. The fossil material tends to be well preserved and without excessive breakage; however, the brachiopod shells are largely disarticulated, which indicates a moderately high energy level (pl. 1, fig. 6; pl. 3, figs. 1–3). None of the fossils appears to be in growth position, and at places light brachiopod shells such as *Brevilamnulella thebesensis* were concentrated into shell banks by wave or current action (see Brenchley and Cocks, 1982, p. 803; also the major section on Hirnantian Stage, this report). No reefs or boundstone were observed, and evidence for bioturbation is minimal.

Distorted, split ooliths, many with curved apophyses connecting neighboring ooliths, are present in the Keel Formation (pl. 1, figs. 3, 5, 6). These are similar to those described and illustrated by Carozzi (1961, p. 263–273, figs. 5, 6, 8, 9), who interpreted these structures as resulting from deformation that took place before cementation and while the ooliths, in various stages of induration, were being moved about on the sea floor by waves or currents (pl. 1, fig. 5). This explanation agrees with other evidence for predepositional movement, such as disarticulation of brachiopod shells and organisms not in growth position. The clearly broken fragments can be interpreted as fully indurated ooliths that impacted against one another or against the skeletal material that is present to some degree in all the oolites.

The Keel Formation includes very little extrabasinal, terrigenous detritus. Excluding the Ideal Quarry Member, which commonly incorporates considerable silicification, the Keel oolite is low in HCl-insoluble residue (text-fig. 8). Thin sections commonly show at least traces of silicification but very little detritus.

The Keel outcrop area lies south of the dolomite front (text-fig. 2), and most beds are high-calcium limestones (text-figs. 9, 10). Most beds contain less than 1 percent $MgCO_3$, although locally, as at

stratigraphic section J4 (Amsden, 1960, p. 218), the formation is heavily dolomitized (36 percent $MgCO_3$). However, this dolomitization is almost certainly related to local Keel mineralization (see later section on Fe–Mn Mineralization).

Lithofacies–Biofacies

The most persistent and widespread facies in the Keel Formation is an oolite with a shelly fauna dominated by disparate pelmatozoan plates. The skeletal material ranges from 3 to 39 percent of the total rock volume, averaging about 18 percent (text-fig. 7). This includes a moderately diverse benthic fauna, although most species are sparsely represented. Excluding the iron–manganese-rich strata discussed below, two well-marked facies variants can be distinguished in the Keel oolite in the Arbuckle Mountains–Criner Hills outcrop area: (1) oolitic skeletal limestones and (2) laminated limestones, as follows:

1. The volume of skeletal material varies considerably in the Keel oolite. Locally, this organic material increases sharply, and the typical oolite grades into a skeletal limestone with scattered ooliths. These variations are well displayed in the east rim of the Lawrence Quarry (sec. 36, T3N, R5E, Pontotoc County, Oklahoma), where the Sylvan–Keel–Cochrane sequence is completely exposed for about 100 yards (91 m) (text-fig. 11; see also text-fig. 6). The basal 2 feet (60 cm), which represents the Ideal Quarry Member, is a skeletal-rich oolitic limestone dominated by pelmatozoans; it also includes a number of brachiopods, mostly *Brevilamnulella thebesensis* (Savage) (Amsden, 1974, p. 64–65, p. 1, figs. 1–5, pl. 2, figs. 1, 2), a species that is also common in the Noix and Leemon Formations of eastern Missouri and western Illinois. A second oolitic skeletal limestone zone is well developed in the upper oolite beds, slightly more than 3 feet (1 m) above the Sylvan Shale. This is mainly a brachiopod–coral–pelmatozoan oolitic limestone, locally with a moderate concentration of gastropods and pelecypods. The dominant brachiopod is *B. thebesensis*, which at places is abundant enough to make a coquinoid limestone. Favositid and halysitid corals are present, as well as specimens of a solitary tetracoral that Dr. Robert Elias (personal communication) identifies as *Streptelasma* with affinities to *S. subregulare* (Savage), a species that is present in the Leemon Formation, Cape Girardeau County, Missouri; the Cyrene Formation (Noix Formation) of Pike County, Missouri; and the Wilhelmi Formation, Will County, Illinois (Elias, 1982, p. 57–58, pl. 4, figs. 7–22). In the oolitic skeletal facies the organic material ranges from about 45 to 53 percent of the total rock volume, and the ooliths from about 5 to 19 percent (text-fig. 12). Little, if any, of the skeletal material in the Keel Formation
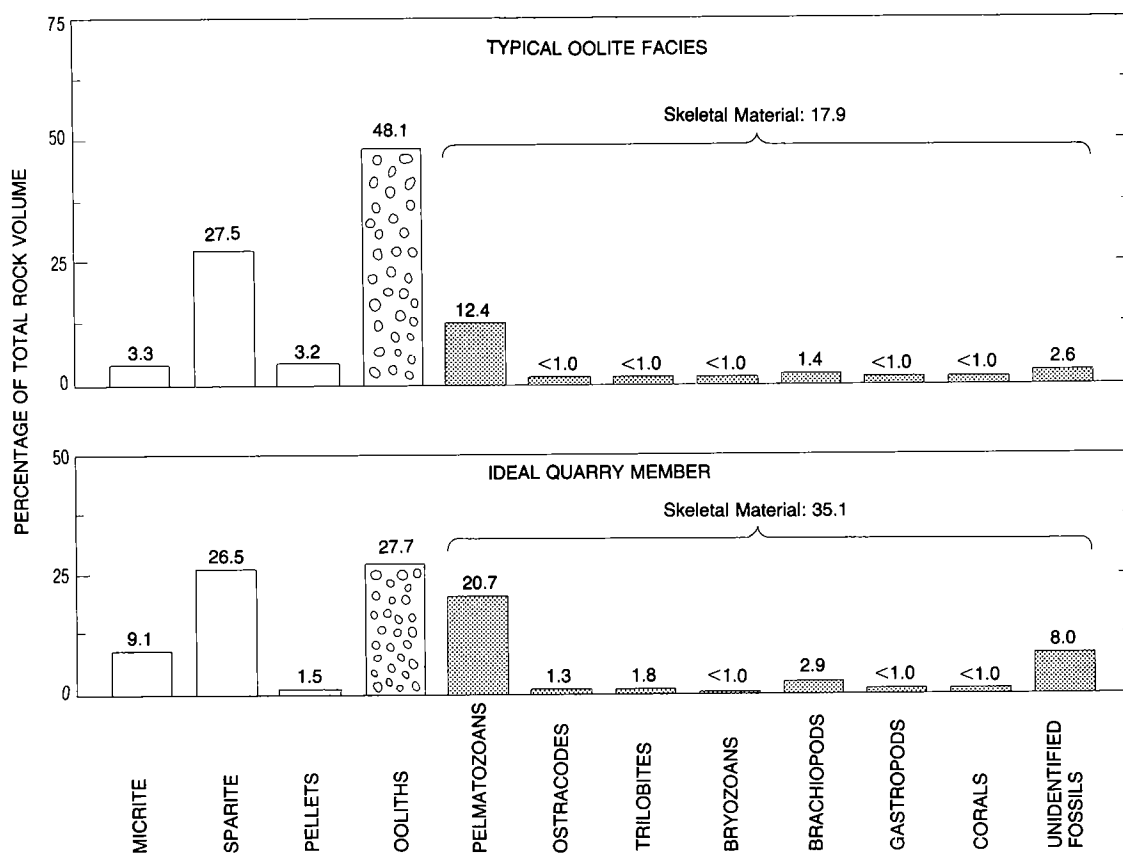
Text-figure 7. Graph comparing matrix and skeletal components in typical Keel oolite with those in Ideal Quarry Member (skeletal–oolite facies). These are averages derived from point counts of 12 thin sections prepared from Keel strata collected in various parts of Arbuckle Mountains.

appears to be in growth position, although its preservation and distribution suggest that it has not moved far.

The oolitic skeletal limestone facies is well developed in Pike County, Missouri, where it is represented by the Cyrene Formation; the Noix Formation represents the typical oolite facies (see section on Edgewood Group in the Mississippi Valley).

2. The laminated limestone facies, which has a restricted development in the eastern part of the Arbuckle Mountains, is known from two exposures in southeastern Pontotoc County (stratigraphic sections P9, P10, Amsden, 1960, p. 279–283) and from one exposure in northeastern Johnston County (stratigraphic section J1, Amsden, 1960, p. 215). This stratigraphic unit consists of 6 to 7 feet (2 m) of thinly laminated limestone overlying a lower oolite and overlain by a thin oolite bed at least a part of which is of Early Silurian age (text-fig. 13). This unit is micritic limestone, perhaps in part of algal origin, with

moderately but distinctly higher HCl-insoluble residues than those of the underlying or overlying oolites (text-fig. 13). Ten analyses of samples from the laminated beds at the three localities have HCl insolubles ranging from 1.0 to 7.8 percent, averaging 3.8 percent; most Keel oolite beds have less than 1.5 percent (text-fig. 8). These insolubles appear to be mostly fine silt- to clay-sized extrabasinal detritus. Weathered beds are tan to yellowish-brown and commonly show a fine lamination of 1 to 3 mm (Amsden, 1960, pl. 4, fig. 1).

Most laminated beds are micrites with a sparse megafauna consisting of scattered small pelmatozoan plates, brachiopods, and thin-shelled ostracodes making up less than 10 percent of the total rock volume. However, within this unit are beds with numerous specimens of streptelasmid coral, proetid trilobites, and the brachiopod *Stegerhynchus*? sp. The latter is conspecific with shells from the Cason oolite at St. Clair Springs, Independence County, Arkansas, and congeneric with
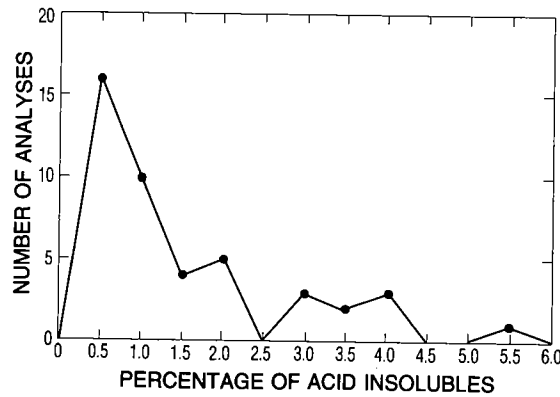
Text-figure 8. Frequency diagram showing distribution of HCl-insoluble residues in Keel Formation exclusive of Ideal Quarry Member. Based on analyses of 44 rock samples from Arbuckle Mountains–Criner Hills area. (Prepared in analytical-chemistry laboratory of Oklahoma Geological Survey.)
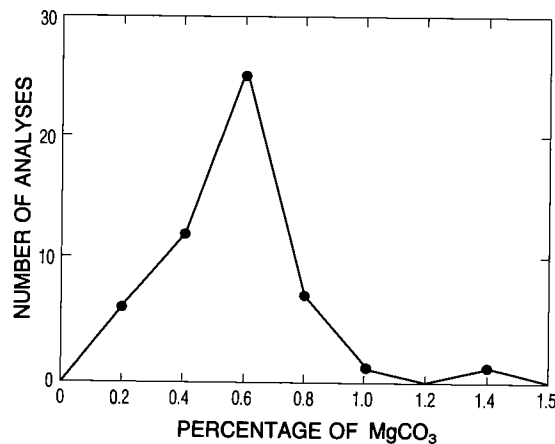
Text-figure 9. Frequency diagram showing distribution of $MgCO_3$ in Keel Formation exclusive of Ideal Quarry Member. Based on analyses of 52 rock samples from Arbuckle Mountains–Criner Hills outcrop area. (Prepared in analytical-chemistry laboratory of Oklahoma Geological Survey.)
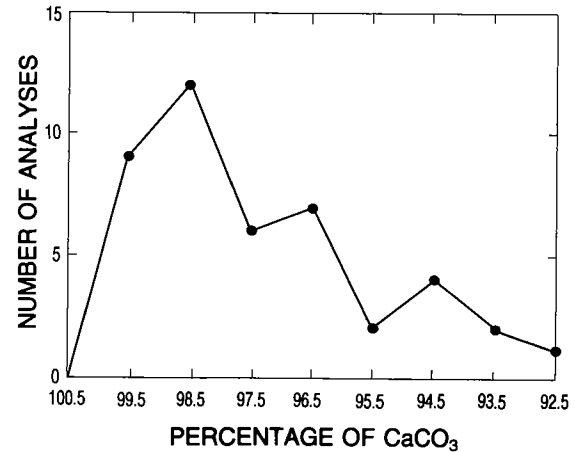
Text-figure 10. Frequency diagram showing distribution of $CaCO_3$ in Keel Formation exclusive of Ideal Quarry Member. Based on 43 rock analyses of samples from Arbuckle Mountains–Criner Hills outcrop area. (Prepared in analytical-chemistry laboratory of Oklahoma Geological Survey.)

specimens from the Cyrene Formation, Pike County, Arkansas. (I am proposing a new genus for these brachiopods in a forthcoming publication). The corals from this unit are being studied by Dr. Robert Elias, University of Manitoba, and the trilobites by Dr. Rolf Ludvigsen, University of Toronto. Closely associated with these brachiopod and coral beds are thin stringers of brachiopod-rich sparites with a skeletal volume making up almost 50 percent of the total rock volume (based on point counts). None of the organic material appears to be in growth position. However, the corals are not strongly fragmented, and a number

of the brachiopod shells are articulated, suggesting that this fauna is a life assemblage.

A similar stratigraphic sequence is exposed at stratigraphic section J1 near Wapanucka (text-fig. 14). Both sections P9 and J1 yield conodonts, indicating that the upper oolite bed is Silurian in age; the conodonts are discussed in Part II.

The laminated beds represent a restricted facies developed in the eastern Arbuckle region, marked by thinly laminated bedding, reduction in ooliths, and articulated brachiopod shells. At the Coal Creek exposures (text-fig. 13) the lower oolite bed grades into the laminated strata, and the up-
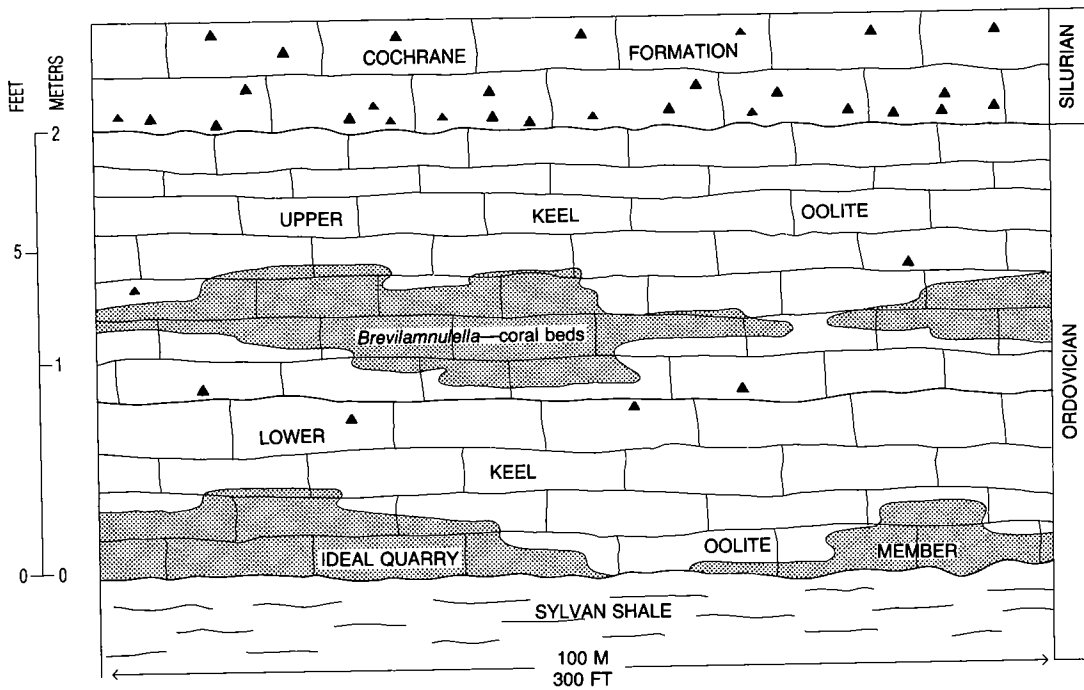
Text-figure 11. Stratigraphic section showing Keel Formation, east rim of Lawrence Quarry, NW¼SE¼NE¼ sec. 36. T3N, R6E., Pontotoc County, Oklahoma. Nonstippled areas are typical oolite; stippled areas are oolitic skeletal limestones (*Brevilamnulella*–coral beds above, Ideal Quarry Member below). See text-figure 12.

permost laminated beds also contain ooliths. Furthermore, at section J1 (text-fig. 14), oolite bands are scattered throughout the laminated unit. Many of these ooliths are broken; however, this is common in the Keel oolitic strata, as discussed elsewhere. These laminated beds appear to represent a local environment marked by a moderate reduction in energy, as evidenced by the articulated brachiopod shells and thin, evenly laminated bedding.

Dolomitization

Keel (and Edgewood) strata are involved in the regional dolomitization that affects Late Ordovician, Silurian, and Early Devonian strata in the central part of North America (Amsden, 1974, p. 43–56; 1980, p. 51–56; this report, text-fig. 2). North of the dolomite front, Keel oolites have been subjected to varying degrees of dolomitization, including complete replacement of the ooliths by crystalline dolomite (pl. 2, fig. 2). All of the Keel outcrops in the Arbuckle Mountains region lie south of this front, and the few, small localized areas of Keel dolomitization are believed to be related to the Fe–Mn mineralization discussed below.

Fe–Mn Mineralization

Keel and Cochrane strata exposed in the east rim of the Lawrence Quarry, Ideal Cement Co. (sec. 36, T3N, R5E, Pontotoc County, Oklahoma), locally grade into a pale-reddish-brown to dark-reddish-brown, earthy carbonate. Both chemical analyses and thin sections show that most of this alteration is produced by the replacement of the primary rock fabric with euhedral crystals of an Fe–Mn carbonate, provisionally identified as siderite (table 1, text-fig. 15; pl. 2, figs. 3–5). Within the mineralized facies are all gradations from beds with only scattered crystals of siderite to those in which the primary rock fabric has been largely replaced by crystalline siderite. The mineralized strata extend for about 200 feet (60 m) along strike, and the mineralization affects all the Keel and the lower meter or so of the Cochrane limestone. The mineralization is not clearly reflected in chemical analyses of the Sylvan Shale; however, the clay minerals in the shale could mask any subsequent mineralization. The upper few feet of the Sylvan is locally discolored, which could be related to the mineralizing solutions. The Lawrence Quarry exposure is especially useful, as it shows the stratigraphic and geographic dis-

OOLITIC-SKELETAL LIMESTONE FACIES
Brevilamnulella beds
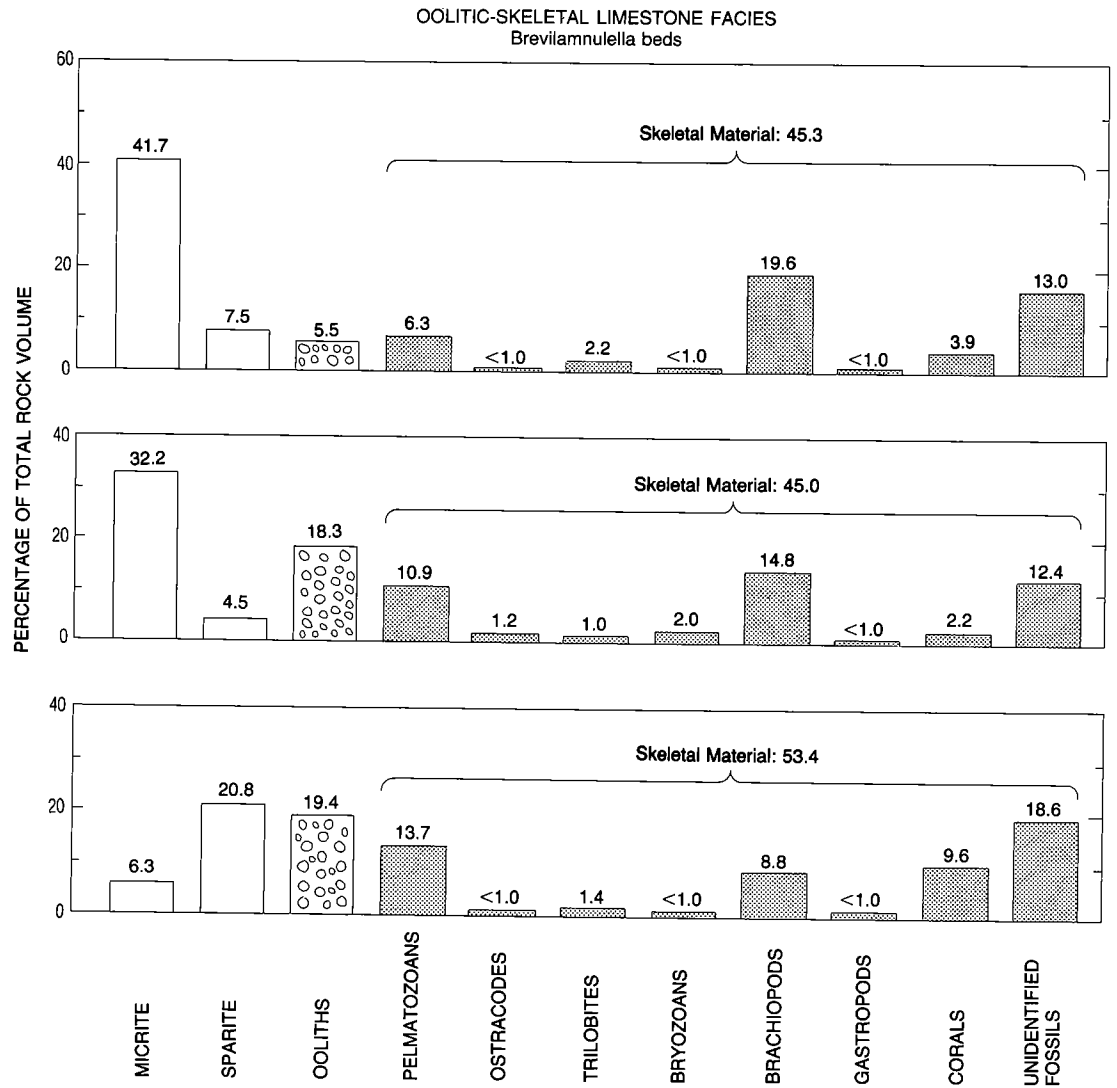
Text-figure 12. Graph showing variations in matrix and skeletal components in oolitic skeletal limestone facies of Keel Formation. Based on point counts of three thin sections from *Brevilamnulella* beds in Keel Formation, Lawrence Quarry, Pontotoc County, Oklahoma (see text-fig. 11).

tribution of mineralization in the Keel and lower Cochrane strata.

Although less intense, the mineralization affecting Keel–Cochrane strata in the Lawrence Quarry appears to be related to the manganese mineralization of the same strata near Bromide in the southeastern Arbuckle Mountains. These deposits have been known for many years, and some manganese ore was actually shipped in 1891, 1917–18, and 1942. Ham and Oakes (1944), in a well-researched study, presented an excellent discussion on the geologic occurrence, mineralogy, and origin of these deposits. The deposits are con-

centrated in two areas, one in Coal County, 1 to 4 miles (1.5 to 6.5 km) north of Bromide, and the other in Johnston County, about 3 miles (5 km) southwest of Bromide (Ham and Oakes, 1944, figs. 2, 3). According to Ham's geologic maps, the mineralization is concentrated in the Keel and Cochrane Formations (= oolitic and glauconitic limestone members of the Chimneyhill Formation) and to a lesser extent in the Clarita Formation (= pink crinoidal member, Chimneyhill Formation). The mineral suite is complex, but it is primarily represented by Mn–Fe–Mg carbonates similar to those in the Batesville, Arkansas, man-
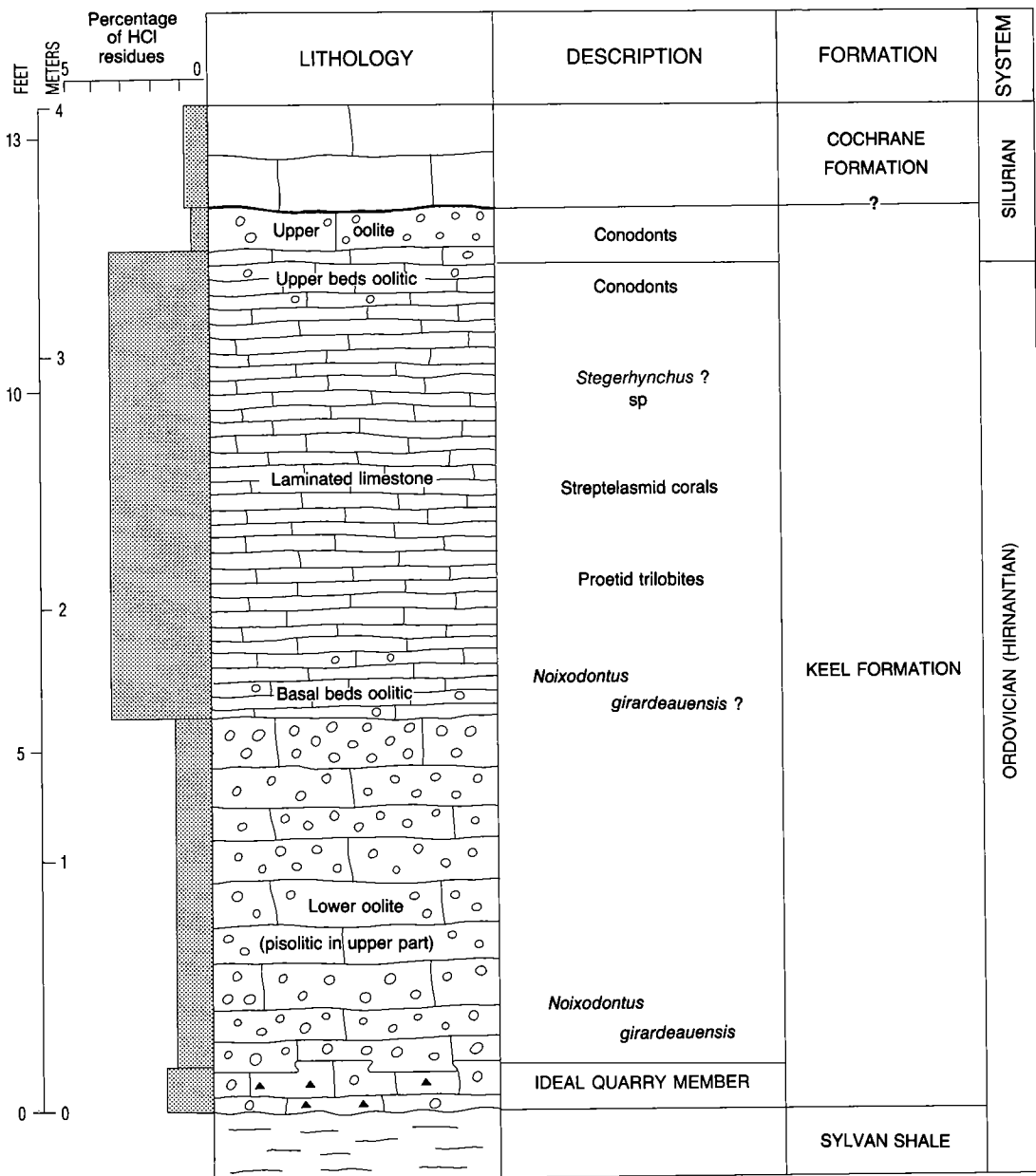
Text-figure 13. Stratigraphic diagram of Keel Formation, stratigraphic section P9, Coal Creek, NW¼NW¼ sec. 22, T1N, R1E, Pontotoc County, Oklahoma (Amsden, 1960, p. 282). Ordovician–Silurian boundary based on conodonts; conodonts are described in Part II. (HCl-insoluble residues prepared in analytical-chemistry laboratory, Oklahoma Geological Survey.)

ganese district in strata of the same age (Miser, 1922; this report, Batesville District, Mineralization). Ham and Oakes' explanation of the origin of this mineralization is similar to that Miser noted for the Batesville district. They postulated introduction of the Mn–Fe–Mg, probably as carbonates, into Upper Ordovician–Lower Silurian strata at the time of deposition, followed by a later period or periods of dissolution by warm, meteoric waters that redistributed these elements to their present position. Ham and Oakes believed that localization of the mineralization was controlled mainly by premineral faults.

The widespread distribution of similar mineralization in strata of the same age in Oklahoma and Arkansas points to a common origin.
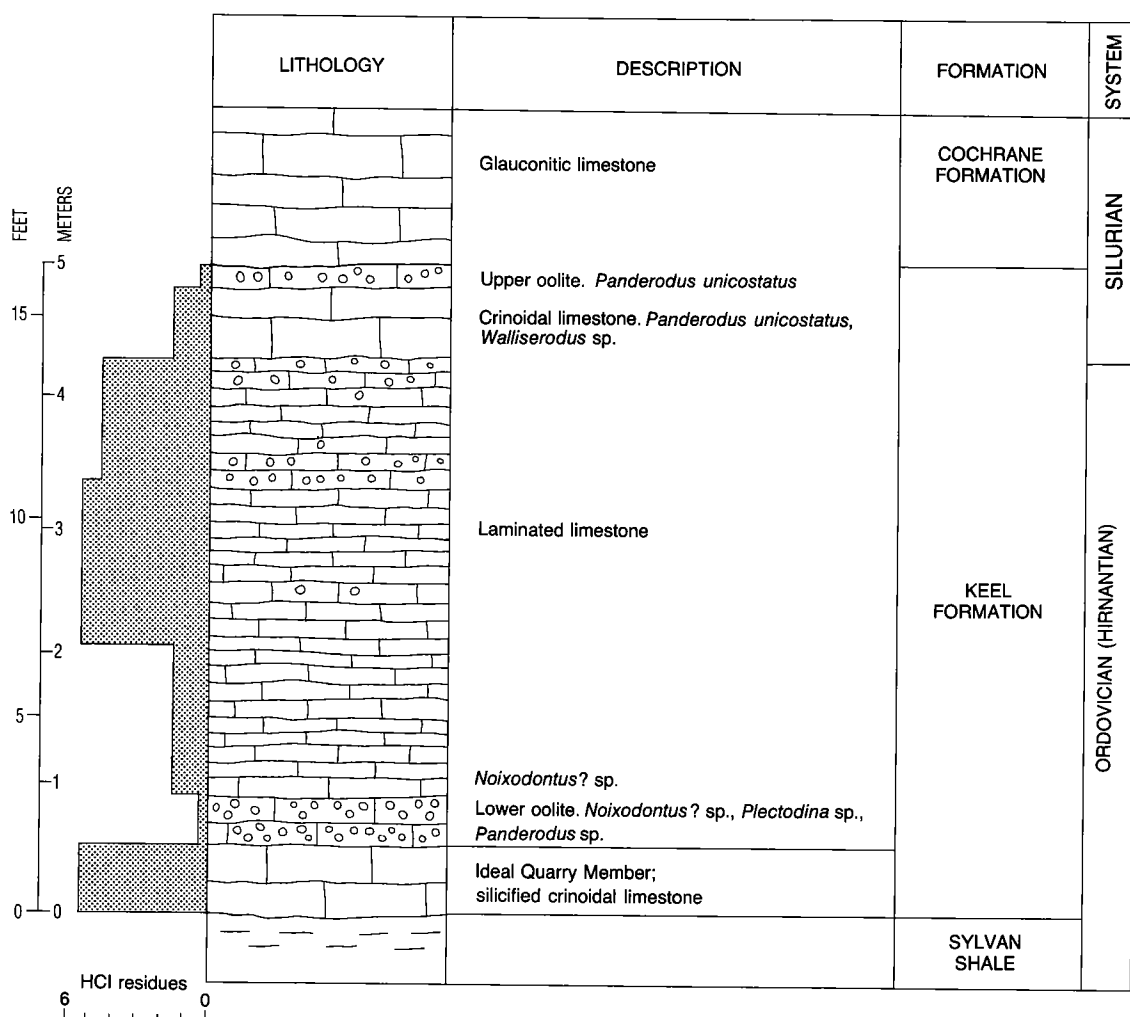
Text-figure 14. Stratigraphic diagram of Keel Formation, stratigraphic section J1, southwest of Wapanucka, NE¼SE¼ sec. 27, T2S, R8E, Johnston County, Oklahoma (Amsden, 1960, p. 215). Ordovician–Silurian boundary based on conodonts (see Part II). (HCl-insoluble residues prepared in analytical-chemistry laboratory, Oklahoma Geological Survey.)

The present stratigraphic distribution is best explained by postulating concentration of the iron and related elements at the time of Keel deposition, possibly as an Fe–Mn-rich carbonate. Subsequent movement (post-Clarita Formation, Wenlockian) of meteoric waters through the strata dissolved these minerals and redeposited them in their present position. Viewed in a regional context, these mineral deposits do not appear to be related to faulting, and I believe the present locus was controlled by the original distribution of the minerals.

The stratigraphic position and geographic distribution of the iron-rich Neda deposits (text-fig. 1) suggest that they are genetically related to the Batesville–Arbuckle Mountains mineralization. The entire mineralized belt is probably related to

the Late Ordovician regressive sedimentary cycle that affected such a large part of North America and Europe. This postulated relationship cannot be effectively appraised until the biostratigraphy of the hematitic-oolite province is more precisely defined.

Brachiopod Biostratigraphy of the Keel Formation

The Keel Formation crops out in the Arbuckle Mountains–Criner Hills, where it rests on the Sylvan Shale. Decker (1935, p. 702), on the basis of *Dicellograptus complanatus*, assigned a Richmondian age to the Sylvan Shale (Ross and others,

1982). Jenkins (1970) described a chitinozoan fauna from the Sylvan, assigned it a late Ashgillian age, and noted the presence of reworked specimens in the upper part of the Sylvan. At most localities in the Arbuckle Mountains–Criner Hills the Keel is overlain by the Cochrane Formation, although locally it is directly overlain by the Prices Falls Member of the Clarita Formation (Amsden, 1963, p. 634). Barrick and Klapper (1976, p. 63) described *Pterospathodus amorphognathoides* from this member and assigned it a late Llandoverian–early Wenlockian age. The Cochrane contains numerous specimens of *Triplesia alata*, which I assign a late Llandoverian age (Amsden, 1971, p. 145); the uppermost strata of this formation yield the conodont *Pterospathodus celloni* of late Llandoverian age (Barrick and Klapper, 1976, p. 66). No middle or early Llandoverian fossils have been reported from the Cochrane, and there is physical evidence for an unconformity between this formation and the Keel. The base of the Cochrane is probably diachronous.

In eastern Oklahoma the Pettit Formation is underlain by the Sylvan Shale, from which Decker and Huffman (1953, p. 451) reported *Dicellograptus complanatus*. The Pettit is overlain by the Blackgum Formation, from which I de-

scribed the late Llandoverian (C1–2) brachiopods *Stricklandia protriplesiana* (Amsden, 1966, p. 1010) and *Triplesia alata* Ulrich and Cooper (Amsden, 1971, p. 144). No fossils have been recovered from the Pettit, and its correlation with the Keel is based on lithologic similarity, stratigraphic position, and geographic distribution (text-fig. 3).

Reeds (1911, p. 259) reported *Favosites niagarensis* and a new species of *Clorinda* (= *Brevilamnulella thebesensis*) from the oolitic limestone (= Keel Formation) and assigned these strata to the Early Silurian Clinton Stage of the Alexandrian Series. Maxwell (1936, p. 49, 54) reported the following species from the Hawkins Limestone (= Ideal Quarry Member) and the Keel Formation:

Hawkins Limestone

Halysites catenularia
Lyella thebesensis
Zaphrentis subregularis
Cyphotrypa expanda
Hindella cf. *H. congregata*
Mytilarca cf. *M. foerstei*
M. cf. *M. daytonensis*
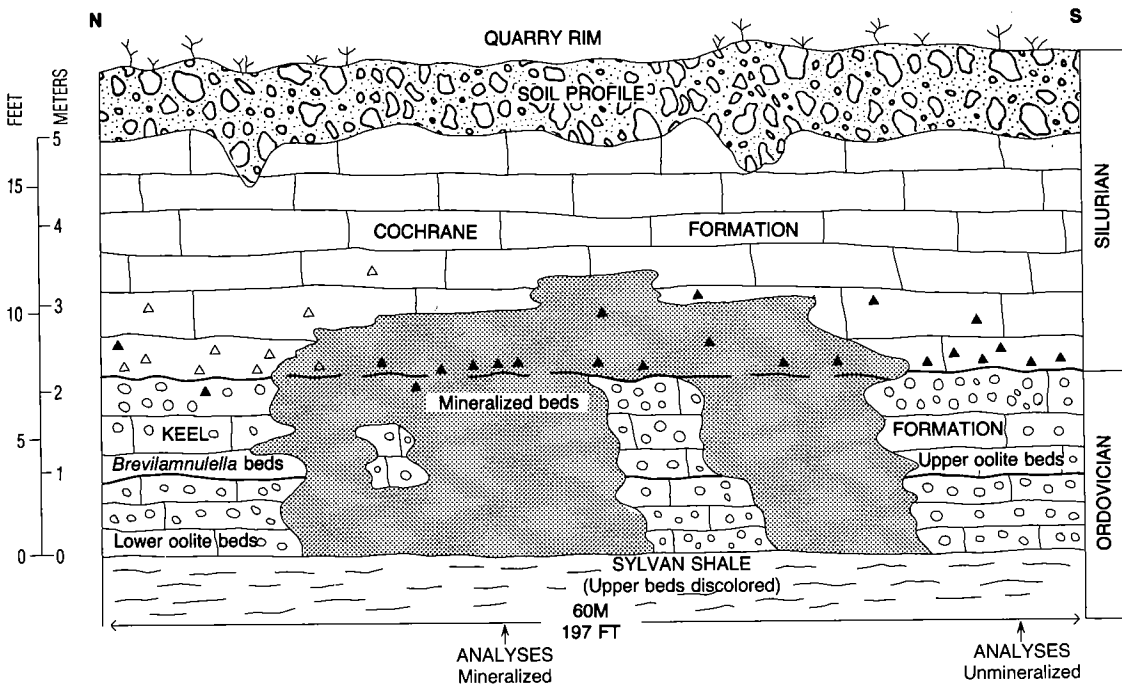
Text-figure 15. Stratigraphic section showing distribution of Fe–Mn mineralized beds in Cochrane, Keel, and Sylvan formations, east rim of Lawrence Quarry Ideal Cement Co., NW¼SE¼NE¼ sec. 36, T3N, R5E, Pontotoc County, Oklahoma (just south of section in text-fig. 11). Chemical analyses of mineralized samples 180, 80, and 20, and unmineralized samples A and B (A is about 70 m south of B) given in table 1. See also text-figures 11, 12.

Keel Formation

Favosites favosus
Favosites sp.
Halysites catenularia
Lyella thebesensis
Streptelasma sp.
Dalmanella sp.
Hindella cf. *H. congregata*
Liospira cf.
Pleurotomaria cf. *P. filtexta*

Maxwell also assigned these strata to the Early Silurian Clinton Stage, Alexandrian Series.

In 1974 I described and illustrated the following 10 species of articulate brachiopods from the Keel Formation:

Orthostrophella sp., *Dolerorthis savagei, Dalmanella edgewoodensis, Leptoskelidion septulosum, Cliftonia tubulistriata, Leptaena* sp., *Brevilamnulella thebesensis, Stegerhynchus concinna, ?Cryptothyrella ovoides,* and *Dictyonella* sp.

All these species are present in the Noix and Cyrene Formations, Pike County, Missouri, and six are present in the Leemon Formation, Cape Girardeau County, Missouri, and Alexander County, Illinois (Amsden, 1974, p. 26). Based on these brachiopods, the Keel, Noix, Cyrene, and Leemon Formations are considered correlative and are assigned to the Hirnantian Stage of the Late Ordovician.

Recently I collected a number of specimens of a small oligorhynchiid brachiopod (n.g. and n. sp.) from the laminated beds of the Keel Formation at stratigraphic section P9 on Coal Creek (text-fig. 13). This is conspecific with specimens from the basal Cason oolite at St. Clair Springs, Arkansas, and is closely related to specimens from the Cyrene Formation in Pike County, Missouri, which I identified as *Stegerhynchus?* sp. (Amsden, 1974, p. 68, pl. 16, figs. 1a–1j).

Conodonts are present in the Keel, and these are described in Part II of the present report.

CASON SHALE IN NORTH-CENTRAL ARKANSAS

Stratigraphic Relationships

The Late Ordovician to Silurian stratigraphic sequence in north-central Arkansas is as follows (in ascending order): "Fernvale" Limestone (= Welling Formation of Oklahoma; Amsden, *in* Amsden and Sweet, 1983, p. 40, text-fig. 23), Cason Shale, and St. Clair Limestone (text-fig. 3). The Ordovician–Silurian boundary falls within the Cason Shale, and at places the upper part of the Cason grades into the "Brassfield" Limestone

of Early Silurian age (= Cochrane and Blackgum Formations of Oklahoma; *Triplesia alata* beds of Amsden, 1971, p. 145); at places the lower part of the Cason Shale grades into an oolite, here informally called the Cason oolite and correlated with the Keel–Pettit–Leemon–Noix Formations (Amsden, 1980, p. 34–41). "Fernvale–Cason–St. Clair strata are exposed in an east-trending belt extending across Independence, Izard, Stone, Searcy, and Newton Counties of north-central Arkansas (text-fig. 16). The Cason oolite facies, however, is developed only in the eastern areas, in parts of Independence and Izard Counties (Lemastus, 1979, p. 3, 60–90; this report, text-fig. 16). In the Batesville district the Cason Shale, lower St. Clair Limestone, and upper "Fernvale" Limestone have been altered to varying degrees by manganese mineralization (see section on Batesville District, Mineralization).

Batesville District, Independence and Izard Counties

Previous Investigations

The manganese deposits of the Batesville district were described by Miser (1922) in a report that included much stratigraphic information, especially for the heavily mineralized "Fernvale," Cason, and St. Clair Formations. Miser (p. 27) noted that the "occurrence of fossils of the Brassfield limestone in residual clays above the altered Cason Shale at the Montgomery mine shows that the Brassfield once overlay the Cason shale at that locality." No oolites were reported from within the Cason Shale, but Miser (p. 23) did report that "the upper surface of the Fernvale is irregular, containing channels and fissures, some as much as 2 feet deep, that are filled with materials of the succeeding deposit, which is usually conglomeratic or earthy, but at a few places the fissures contain gray oolitic limestone." In 1968 (Amsden, 1968, p. 6; 1971, p. 144) I described a limestone lens within the Cason Shale at the Love Hollow Quarry (SW ¼ sec. 4, T14N, R8W, Izard County, Arkansas) which consists of a lower oolite and an upper skeletal limestone bearing the brachiopod *Triplesia alata,* and later (Amsden, 1980, p. 34–41) I discussed the regional implications of this relationship. Craig (1969, p. 1622–1627; 1975, p. 73–77) described a similar limestone sequence within the Cason Shale. He noted Early Silurian *Pterospathodus celloni* and upper Bereich 1 conodont faunas in the upper pelmatozoan limestones (= at least in part the *T. alata* beds of Amsden), and an Upper Ordovician–lower Bereich 1 conodont fauna in the oolite bed. Lemastus (1979) traced the Cason Shale across its outcrop belt and gave a detailed description of its stratigraphic distribution and lithostratigraphy.

TABLE 1.—CHEMICAL ANALYSES OF MINERALIZED AND UNMINERALIZED BEDS OF SYLVAN, KEEL, AND COCHRANE FORMATIONS IN EAST RIM OF LAWRENCE QUARRY, 1982, 1983

(Geographic and stratigraphic location of sampled intervals shown in text-figure 15.)

Note: the original is a very wide, densely printed analytical table. It is reproduced below in transposed form (each analyzed sample as a row). The 12 major-component columns and 3 trace columns are not individually labeled in the source image; values are given as read. Uncertain minor cells are left blank.

Facies	Formation	Unit	Sample	Field no.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	Total						
Mineralized	Sylvan Shale	Upper 2 ft	14269[a]	180-2[b]	22.9	1.32	33.1	.72	5.50	10.9	.09	2.67	3.66	1.36	20.74	13.18[b]	98.6	<.20	16.4	48.59	38	2100	<30
Mineralized	Sylvan Shale	10 ft below top	14270[a]	180-3[b]	7.95	5.82	45.1	1.38	5.65	14.5	.13	3.66	1.49[e]		20.74	13.18[e]	97.5	.24	20.2	67.37[e]	85	1100	40
Mineralized	Keel Fm.	Lower oolite	14250[a]	20-2[b]	50.0	.24	1.05		8.16[e]	.05	<.01	.13	.01	.24	39.06		98.5	<.20	8.21	.3	15	7400[c]	40
Mineralized	Keel Fm.	Lower oolite	14254[a]	180-2[b]	50.5	.17	1.17		6.44[e]	.13	<.01	.01	.02	.08	40.80		99.5	<.20	6.57	1.7	27	2200[c]	<30
Mineralized	Keel Fm.	Average lower oolite			50.2	.20	1.05		7.30	.09	<.01	.01	.01	.16	39.93		99.0	<.20	7.39	1.0	22	4800	40-<30
Mineralized	Keel Fm.	Upper oolite (*Brevilamnulella* beds)	14251[a]	180-3[b]	48.9	.19	1.02		8.38[e]	.08	<.01	.27	.01	.11	42.57[e]		98.8	<.20	8.46	.7	11	5400[c]	40
Mineralized	Keel Fm.	Upper oolite (*Brevilamnulella* beds)	14255[a]	180-3[b]	53.7	.20	1.33	1.21[c]	7.68[e]	.17	<.01	.04	.11	.06[e]	40.44		99.3	<.20	7.70	.2	88	930[c]	<30
Mineralized	Keel Fm.	Upper oolite (*Brevilamnulella* beds)	14258[a]	80-1B[b]	50.6	.19	1.02		5.76	.09	<.01	.02	.11	.15	40.44		99.6	<.20	5.85	.9	28	6300	<30
Mineralized	Keel Fm.	Average upper oolite			51.1	.19	1.02		5.76	.09	<.01	.02	.15	.15	40.93		99.2	<.20	6.62	.9	42	4210	<33
Mineralized	Keel Fm.	Average Keel Formation			50.6	.19	1.03		6.53	.09	<.01	.02	.15	.15	40.43		99.1	<.20	6.62	.9	32	4505	<33
Mineralized	Cochrane Fm.	Lower 2 ft	14252[a]	20-4[b]	52.8	.18	1.50	1.41[c]	5.06[e]	.10	<.01	.03	.10	.20	41.02		100.9	<.20	5.16	1.5	25	3000[c]	50
Mineralized	Cochrane Fm.	Lower 2 ft	14256[a]	180-4[b]	54.7	.18	1.50	1.41[c]	5.06[e]	.13	<.01	.01	.03	.10	42.06		101.0	<.20	1.54	2.6	71	1100[c]	<30
Mineralized	Cochrane Fm.	Average Cochrane Formation			53.7	.18	1.93	3.23	3.23	.11	<.01	.02	.15	.15	41.54		100.9	<.20	3.35	2.1	48	2050	
Unmineralized	Sylvan Shale	Upper 1 ft	14267[a]	BO 1[b]	30.5	.99	24.8	6.81	7.50	.10	2.99	1.61	1.14		26.25		99.6	<.20	14.31	33.96	32	3600	30
Unmineralized	Sylvan Shale	4 ft below top	14268[a]	BO 2[b]	20.5	1.61	36.7	6.81	11.6	.10	2.99	1.36	1.36		18.72		98.4	<.20	16.4	52.89	47	2400	30
Unmineralized	Keel Fm.	Lower oolite	14217[a]	B1[b]	53.0	.11	.79	.58	.09	<.01	.03	.01			42.35		97.0	<.20	.67	1.3	85	380	<30
Unmineralized	Keel Fm.	Lower oolite	1428[a]	B2[b]	55.5	.18	.45	.12	.09	<.01	.01	.02			42.94		98.9	<.20	.14	.2	77	490	<30
Unmineralized	Keel Fm.	Average lower oolite			54.2	.14	.45	.35	.09	<.01	.02	.01			42.64		97.9	<.20	.40	.75	81	435	<30
Unmineralized	Keel Fm.	Upper oolite (*Brevilamnulella* beds)	14219[a]	B3[b]	55.2	.21	.30	.19	.14	<.01	.01	.06			43.26		99.2		.16	.4	76	440	<30
Unmineralized	Keel Fm.	Upper oolite (*Brevilamnulella* beds)	14220[a]	B4[b]	54.2	.19	.80	.69	.04	<.01	.01	.04			43.01		99.5		.23	.8	76	420	<30
Unmineralized	Keel Fm.	Upper oolite (*Brevilamnulella* beds)	14221[a]	B5[b]	52.2	.27	3.14	1.44	.50	<.01	.09	.09			41.14		99.5		2.13	4.0	71	460	<30
Unmineralized	Keel Fm.	Upper oolite (*Brevilamnulella* beds)	14222[a]	B6[b]	53.70	.22	2.93	.12	.40	<.01	.02	.03			41.94		99.2		.34	3.3	85	435	<30
Unmineralized	Keel Fm.	Average upper oolite			53.8	.22	1.79	.31	.12	<.01	.03	.17			42.34		99.1		.71	2.12	308	435	<30
Unmineralized	Keel Fm.	Average Keel Formation			54.0	.18	1.12	.33	.22	<.01	.03	.09			43.17		98.5	<.20	.55	1.43	83	435	<30
Unmineralized	Cochrane Fm. lower 1 ft		14266[a]	BC 1[b]	54.7	.27	1.08	.39	.12	<.01	.04	.16			42.76		99.8	<.20	.40	1.03	87	530	<30
Average Keel Formation	Mineralized facies				50.6	.20	1.03		6.53	.09	<.01	.02	.15	.15	40.43		99.1	<.20	6.62	.9	32	4505	<33
Average Keel Formation	Unmineralized facies				54.6	.20	.86	.25	.14	.01	.02	.05			42.76		98.9	<.20	.39	1.06	89	446	<30

TABLE 1.—CHEMICAL ANALYSES OF MINERALIZED AND UNMINERALIZED BEDS OF SYLVAN, KEEL, AND COCHRANE FORMATIONS IN EAST RIM OF LAWRENCE QUARRY, 1982, 1983

(Geographic and stratigraphic location of sampled intervals shown in text-figure 15.)

Column groupings:
- **Mineralized facies** — *Sylvan Shale:* Upper 2 ft (14269a), 10 ft below top (14270a); *Keel Formation — Lower oolite:* 14250a, 14254a, Average lower oolite; *Upper oolite, Brevilamnulella beds:* 14251a, 14255a, 14258a, Average upper oolite, Average Keel Formation; *Cochrane Formation — Lower 2 ft:* 14252a, 14256a, Average Cochrane Formation.
- **Unmineralized** — *Sylvan Shale:* Upper 1 ft (14267b), 4 ft below top (14268a); *Keel Formation — Lower oolite:* 14217a, 14228b, Average lower oolite (14219a), 14220a; *Brevilamnulella beds:* (column at right edge cut off).

Constituent	14269a 180-2b	14270a 180-3b	14250a 20-2b	14254a 180-2b	Avg lower oolite	14251a 20-3b	14255a 180-3b	14258a 80-1Bb	Avg upper oolite	Avg Keel Fm	14252a 20-4b	14256a 180-4b	Avg Cochrane Fm	14267b BO 1b	14268a BO 2b	14217a B1b	14228b B2b	14219a B3b (avg)	14220a B4b
Ca as CaO, %	22.9	7.95	50.0	50.5	50.2	48.9	53.7	50.6	51.1	50.6	52.8	54.7	53.7	30.5	20.5	53.0	55.5	54.2	55.2
Mg as MgO, %	1.32	5.82	.24	.17	.20	.19	.20	.19	.19	.18	.18	.18	.18	.99	1.61	.18	.14	.21	.14
Si as SiO$_2$, %	33.1	45.1	.72	1.38	1.05	1.17	1.33	1.02	1.02	1.05	1.50	2.37	1.93	24.8	36.7	.79	.12	.45	.30
Fe as Fe$_2$O$_3$, %	5.50	5.65	8.16c	6.44c	7.30	8.38c	1.21c	7.68c	5.76	6.53	5.06c	1.41c	3.23	6.81	4.80	.58	.12	.35	.30
Al as Al$_2$O$_3$, %	10.9	14.5	.05	.13	.09	.08	.17	.09	.09	.09	.10	.13	.11	7.50	11.6	.12	.02	.05	.14
Na as Na$_2$O, %	.09	.13	<.01	.01	.01	<.01	.01	<.01	<.01	<.01	.01	.01	.01	.09	.12	.02	<.01	<.01	.02
K as K$_2$O, %	2.67	3.66	.01	.02	.01	<.01	.04	<.01	<.01	<.01	.01	.01	.01	2.99	2.99	<.01	.01	.01	.01
Loss at 110°C[d], %	1.36	1.49e	.24	.08	.16	.27	.06e	.11	.15	.15	.20	.10	.15	1.61	1.36	.03	.02	.02	.01
LOI at 1000°C[d], %	20.74	13.18e	39.06	40.80	39.93	39.79	42.57e	40.44	40.93	40.43	41.02	42.06	41.54	26.25	18.72	42.35	42.94	42.64	43.26
Total, %	98.6	97.5	98.5	99.5	99.0	98.8	99.3	99.6	99.2	99.1	100.9	101.0	100.9	99.6	98.4	97.0	98.9	99.2	99.5
P as P$_2$O$_5$, %	<.20	.24	<.20	<.20	<.20	<.20	<.20	<.20	<.20	<.20	<.20	<.20	<.20	<.20	<.20	<.20	<.20	<.20	<.20
R$_2$O$_3$, %	16.4	20.2	8.21	6.57	7.39	8.46	1.38	7.70	5.85	6.62	5.16	1.54	3.35	14.31	16.4	.67	.14	.40	.44
HCl insolubles[d], %	48.59	67.37e	.3	1.7	1.0	.7	1.8e	.2	.9	.9	1.5	2.6	2.1	33.96	52.89	1.3	.2	.75	.8
Ca as CaCO$_3$, %	40.8	14.2	89.2	90.1	89.6	87.4	95.8	90.4	91.2	90.3	94.3	97.6	95.9	54.4	36.5	94.6	99.1	96.8	98.6
Mg as MgCO$_3$, %	2.76	12.2	.50	.36	.43	.40	.42	.39	.41	.41	.38	.40	.39	2.06	3.37	.24	.38	.31	.31
Fe as FeCO$_3$, %	7.98	8.20	11.8c	9.34c	10.57	12.2c	1.76c	11.1c	8.35	9.46	7.34c	2.04c	4.69	9.88	6.96	.84	.17	.50	.44
Mn as MnCO$_3$, %	.37	.19	1.5c	.46c	.28	1.1c	.19c	1.3c	.86	.92	.63c	.23c	.43	.62	.41	.08	.10	.09	.08
Sr, µg/g	38	85	15	27	22	88	88	28	42	32	25	71	48	32	47	85	77	81	76
Mn, µg/g	2100	1100	7400c	2200c	4800	5400c	930c	6300c	4210	4505	3000c	1100c	2050	3600	2400	380	490	435	440
Cu, µg/g	<30	40	40	40–<30	<30	40	<30	<30	<33	<33	50	<30	<30	30	30	<30	<30	<30	<30

(A further column at the far right — Brevilamnulella beds, lab no. 14220a / field B4b — is cut off at the page edge.)
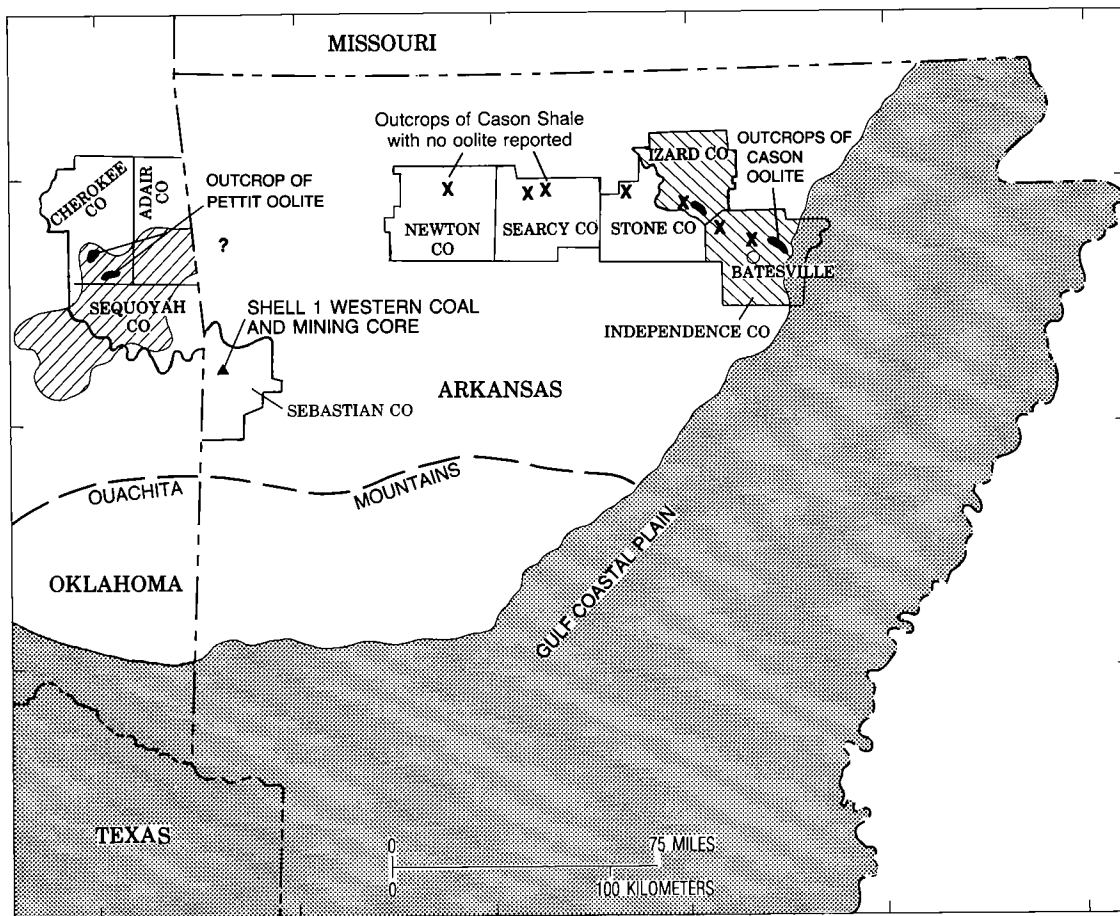
a Laboratory no.
b Field no.
c From HCl-insolubles filtrate.
d From reports dated 11/17/82, 11/18/82.
e Average of 2 determinations.

Determinations by J. Lea, R. Powell, S. Weber.
Note: Elements determined by lithium metaborate fusion and ICP spectrometry. Some elements checked by ICP on HCl-insolubles filtrate. Phosphorus determined by ICP on HCl-insolubles filtrate.

Text-figure 16. Map showing location of Pettit oolite outcrops examined for this report and inferred subsurface distribution (ruled areas) in eastern Oklahoma, and Cason Shale and Cason oolite outcrops in north-central Arkansas (after Amsden and Rowland, 1965; Amsden, 1974, 1980; Lemastus, 1979; this report, text-fig. 4). The Shell 1 Western Coal and Mining Co. well cored the Hunton–Sylvan contact; Hunton strata are heavily dolomitized skeletal carbonates, and upper Sylvan is greenish-gray argillaceous dolomite; no oolitic strata were observed in this core (Amsden, 1980, p. 33–34, 103–104).

Cason Shale

The Cason Shale is predominantly a clastic rock overlain by the St. Clair Limestone and underlain by the "Fernvale" Limestone. It is everywhere thin and probably does not exceed 20 feet (6 m) in the Batesville district (Miser, 1922, p. 24). According to Miser (p. 23–28), it is predominantly shale mixed with sandstone and phosphate rock, although the proportions of these rock types are widely variable. This author stated that the Cason Shale is separated from the St. Clair by an unconformity; however, it should be kept in mind that Miser believed that the Cason was overlain locally by the "Brassfield" Limestone of Early Silurian age, whereas more recent studies show that this limestone (= *Triplesia alata* beds) is a local facies of the upper Cason Shale. Miser postu-

lated an unconformity between the Cason Shale and the underlying "Fernvale" Limestone, and his observation that the upper surface of this limestone has channels filled with oolites would seem to be reasonably convincing evidence (Miser, 1922, p. 23). Lemastus (1979) characterized the clastic facies of the Cason Shale as predominantly phosphatic rock composed of shales and quartz sandstones, with marine skeletal material consisting of pelmatozoans, trilobites, bryozoans, and others heavily invaded by phosphatic mineralization. He noted the presence of well-formed ooliths in the phosphatic beds at the Love Hollow Quarry (p. 27). The phosphatic mineralization was interpreted as an *in situ* replacement of indigenous fossils (Lemastus, p. 23). The phosphatic beds are overlain by the dolomitic, sandy "button" shale (Lemastus, p. 73).

Love Hollow Quarry—This quarry in the south-eastern part of Izard County (SW ¼ sec. 4, T14N, R8W) provides an excellent exposure of the upper "Fernvale" Limestone (= Welling), Cason Shale, and lower St. Clair Limestone. In October 1982 I revisited this quarry with Mr. Orville Wise of the Arkansas Geological Commission and collected samples from the upper "Fernvale," Cason Shale, and lower St. Clair for chemical analysis and thin sections (text-fig. 17; table 2). The basal Cason strata are represented by a thin sequence of maroon and green shale overlain by a dark, reddish-brown calcareous siltstone. This latter unit contains abundant fossil fragments, most of which appear to have been extensively invaded by phosphatic and glauconitic mineralization (table 2). The skeletal material, which is extensively fragmented and to some degree abraded, includes pelmatozoans, trilobites, brachiopods, and other marine shelly fossils. Overlying this unit is a brown shelly carbonate with considerable sub-angular silt and some rock fragments; it also includes abundant shelly fragments, some abraded, which represent marine pelmatozoans, trilobites, etc. These fragments also have been mineralized by phosphatic solutions (table 2). The uppermost Cason strata are reddish-brown clays with small manganiferous nodules as much as 25 mm or so in diameter ("button" shale). This unit is low in phosphorus (table 2). No identifiable fossils were recognized in this interval. The primary rock textures of the Cason Shale, the lower St. Clair, and the upper Fernvale are to some extent obscured by Fe–Mn mineralization (see later section on Mineralization).

When I first visited the Love Hollow Quarry in 1966 with Dr. Tom L. Rowland, independent geologist, and Mr. Orville Wise, Arkansas Geological Commission, the Cason Shale included the elongate limestone lens shown on plate 5. When I reexamined this quarry in 1967, quarrying operations had extended the face back to a part of the Cason Shale where the lens was not present; this lens also was not present when I visited the quarry in 1982 (text-fig. 16). I have discussed this unit in earlier publications, and therefore only a summary is presented here (Amsden, 1968, p. 6–7; 1971, p. 143–146; 1980, p. 36–38, pls. 4–6). These limestones formed a thinly lenticular, elongate body having a maximum thickness of 2 to 3 feet (80 to 100 cm). It was clearly interbedded with the Cason Shale and showed no evidence of stratigraphic discordance with the enclosing sediments (Amsden, 1968, text-fig. 5; 1980, pl. 4; this report, pl. 5, fig. 2). The lens consisted of two distinct layers: a lower oolite overlain by, and sharply marked off from, an upper skeletal limestone (Amsden, 1980, pls. 5, 6; this report, pl. 5, fig. 1). The skeletal limestone contains a benthic fauna dominated by pelmatozoan plates with numerous trilobites and brachiopods, the latter including

well-preserved specimens of *Triplesia alata*. On the basis of the brachiopod I correlated the upper limestone with the Blackgum and Cochrane Formations of Oklahoma and assigned it a late Llandoverian (C) age. The *T. alata* beds include some subangular quartz silt and glauconite and minor evidence of mineralization, but the gradation of this unit and the underlying unit into the Cason oolite facies is relatively abrupt (Amsden, 1980, pl. 4). The underlying bed is a typical oolite similar in all respects to the Keel and the Noix. The ooliths exhibit excellent radial and concentric structure, and the fauna is sparse and dominated by pelmatozoan plates (text-fig. 18). Terrigenous detritus is minimal in the oolitic lens, but some ooliths are present in the clastic Cason Shale. Some quartz silt and mica are reported from the oolites at St. Clair Springs by Lemastus (1979, p. 63); however, the thin sections I examined from the Cason oolite at this locality show minimal quartz detritus.

St. Clair Springs—The Ordovician–Silurian boundary section near St. Clair Springs is of special interest, because it is the only exposure I know where the sequence between the "Fernvale" and the St. Clair Limestone is represented entirely by carbonate strata (text-fig. 19). These strata were first discussed by Craig (1969, p. 1623–1624, fig. 1), and later Lemastus (1979, p. 61–64) provided a detailed description of the Cason interval at this locality. In September 1983 I measured this section, took samples for thin sections and conodonts (Part II), and collected a moderate brachiopod fauna from the lower 3 feet of the Cason oolite. The "Fernvale" here is overlain directly by 8 feet of Cason oolite, which is in turn overlain by about 9 feet of Cason "Brassfield"-type pink crinoidal limestone. The latter is directly overlain by light-gray skeletal limestones with the algal(?) "button" bed at its base, here provisionally assigned to the St. Clair Limestone. The beds are somewhat slumped, but the exposures are adequate to show clearly that no shale is present. The position of the Ordovician–Silurian boundary shown in text-figure 19 is based on biostratigraphic information supplied by the conodonts (Part II).

The lower 3 to 4 feet of the Cason oolite is an oolitic skeletal limestone with a diverse benthic megafauna containing numerous brachiopods (many articulated), crinoids, bryozoans, trilobites, snails, and others. It is difficult to collect shells because the rock is well cemented and tends to break through rather than around the specimens, but with perseverance it was possible to assemble enough material to demonstrate a Keel–Edgewood assemblage. The dominant species is *Cliftonia tubulistriata* (Savage) (Amsden, 1974, p. 48–50, pl. 20). About 60 specimens were collected, most of which are typical representatives of this species. The collection does, however, include two larger, more transverse specimens which resem-
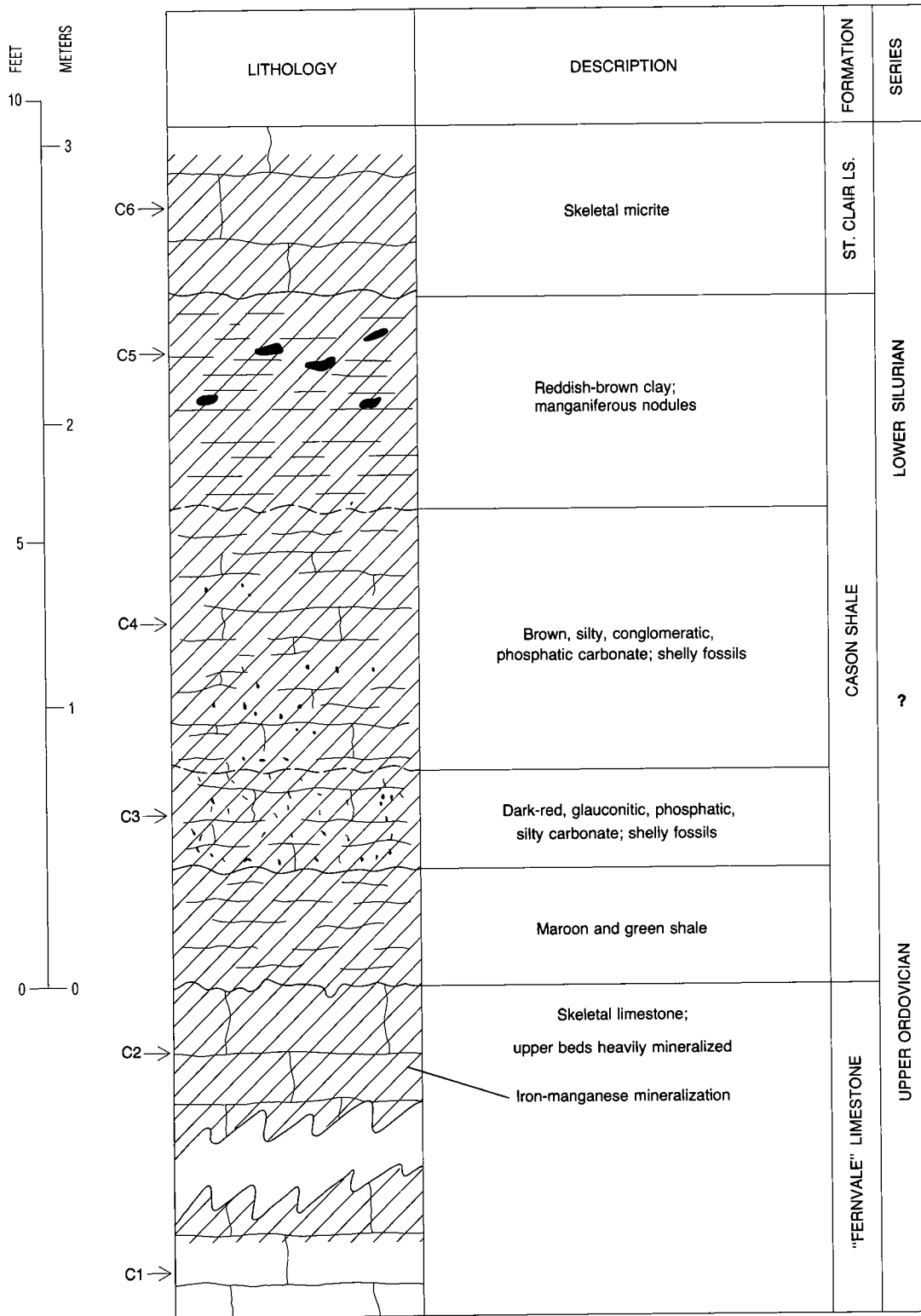
Text-figure 17. Stratigraphic section of upper "Fernvale" Limestone, Cason Shale, and lower St. Clair Limestone at Love Hollow Quarry; SW¼ sec. 4, T14N, R8W, Izard County, Arkansas. Chemical analyses of spot samples (C1, C2, etc.) given in table 2; see also plate 5, figure 2. Section measured and sampled in October 1982.

TABLE 2.—ANALYSES OF SPOT SAMPLES COLLECTED IN OCTOBER 1982
FROM UPPER "FERNVALE" LIMESTONE, CASON SHALE,
AND LOWER ST. CLAIR LIMESTONE AT LOVE HOLLOW QUARRY,
SW¼ SEC. 4, T14N, R8W, IZARD CO., ARKANSAS

(Stratigraphic position of samples given in text-fig. 17. Compare to table 1.)

Constituent	"Fernvale"		Cason			St. Clair
	14260[a] C1[b] About 15 ft below Cason	14261[a] C2[b] Upper 1 ft	14262[a] C3[b] 2 ft above base	14263[a] C4[b] 4 ft above base	14265[a] C5[b] Upper 2 ft	14264[a] C6[b] Basal 1 ft
Ca as CaO, %	54.4	53.4	21.4	44.3	1.10	54.7
Mg as MgO, %	.19	.28	1.96	.68	1.25	.32
Si as SiO$_2$, %	.71	1.54	31.2	8.17	53.0	1.20
Fe as Fe$_2$O$_3$, %	.27[c]	.73[c]	17.3	4.76	10.4	.15[c]
Al as Al$_2$O$_3$, %	.12	.69	6.42	2.57	19.4	.40
Na as Na$_2$O, %	.01	.02	.11	.08	<.01	.01
K as K$_2$O, %	.06	.24	1.58	.27	1.73	.16
Loss at 110°C[d], %	.08	.10	.86[e]	1.20	4.32[e]	.07
LOI at 1000°C[d], %	43.00	41.27	3.53[e]	3.11	7.56[e]	42.74
Total, %	98.8	98.3	84.4	65.1	98.8	99.8
P as P$_2$O$_5$, %	<.20	<.20	14.5[e]	31.1	<.20	<.20
R$_2$O$_3$, % (Fe$_2$O$_3$+Al$_2$O$_3$)	.39	1.42	23.7	7.33	29.8	.55
HCl insolubles[d], %	.9	2.6	35.0[e]	7.8	71.2[e]	1.6
Ca as CaCO$_3$, %	97.1	95.3	38.2	79.0	1.96	97.6
Mg as MgCO$_3$, %	.40	.59	4.10	1.42	2.61	.68
Fe as FeCO$_3$, %	.39[c]	1.06[c]	25.0	6.91	15.04	.20[c]
Mn as MnCO$_3$, %	.35[c]	.67[c]	.19	1.91	1.93	.25[c]
Sr, μg/g	100	110	540	630	55	170
Mn, μg/g	1700[c]	3200[c]	920	9100	9200	1300[c]
Cu, μg/g	50	<30	70	50	90	60

[a]Lab no.
[b]Field no.
[c]From HCl-insolubles filtrate.
[d]From reports dated 11/17/82, 11/18/82.
[e]Average of 2 determinations.
Determinations by J. Lea, R. Powell, S. Weber.
Note: Elements determined by lithium metaborate fusion
and ICP spectrometry. Some elements checked by ICP on
HCl-insolubles filtrate. Phosphorus determined by ICP
on HCl-insolubles filtrate.

ble *Cliftonia oxoplecioides* Wright (1963, p. 761–763, pl. 109, figs. 3, 4, 6–8, 10, 11) from the Hirnantian Chair of Kildare Limestone, Ireland. Other brachiopods include *Dalmanella edgewoodensis* Savage (Amsden, 1974, p. 35–38, pls. 6, 7, 8), *Stegerhynchus concinna* (Savage) (Amsden, 1974, p. 66–68, pls. 14, 15), *Cryptothyrella ovoides*? (Savage) (Amsden, 1974, p. 70–72, pls. 16, 17), *Leptaena aequalis*? Amsden (1974, p. 56–57, pls. 22, 23), and a new genus and species of oligorhynchid brachiopod which is conspecific with specimens from the laminated limestone, Keel Formation,

stratigraphic section P9 (text-fig. 13); it is congeneric with *Stegerhynchus*? sp. from the Cyrene Formation, Pike County, Missouri (Amsden, 1974, p. 56–57, pl. 16, figs. 1a–1j).

Relationship of Oolitic and Triplesia alata Beds to Cason Shale

In 1969 Craig (p. 1623) noted the stratigraphic conformity between the oolitic beds and the

enclosing Cason strata at the Love Hollow Quar- ry. Later, Craig (1975, p. 77) questioned this con- formable relationship because of the sharply de- fined boundary between the Cason phosphatic beds and the oolite, which combined with the ex- treme purity of the oolite, seemed to preclude any lateral gradation between the two. Lemastus (1979, p. 28–29) also noted that the oolites in- cluded almost no phosphatic material but pointed out the presence of well-formed phosphatic oolites in the Cason phosphatic beds. He believed that this, plus Craig's indication that the Cason phosphatic beds are essentially the same age as the oolites, suggested that the oolites formed in meandering channels in the Cason tidal flat. I concur with Lemastus that the oolites were depos- ited at the same time as, and in close proximity to, the phosphatic silts and muds of the Cason. It is true that most of the oolites studied for this report are high-calcium deposits, and the oolitic lens at the Love Hollow Quarry is no exception. However, the presence of ooliths in the phosphatic siltstones at the Love Hollow Quarry, combined with their known development in the Sylvan Shale (Amsden, 1980, pl. 7), Maquoketa Shale (pl. 4, fig. 3), and calcareous shales at Thebes, Alexander County, Illinois, demonstrates that ooliths can develop locally in an environment dominated by ter- rigenous sedimentation. Finally, regional stratigraphic and biostratigraphic relationships

(text-fig. 20) argue strongly for interpreting the oolites and *Triplesia alata* skeletal limestones ("Brassfield" Limestone) as contemporaneous lateral facies of the Cason phosphatic siltstones (see later section on Paleoenvironment).

This interpretation, however, introduces some complications, because here and elsewhere the biostratigraphic relationship between the *T. alata* beds and the underlying oolites indicates a chronostratigraphic gap spanning a considerable part of early and middle Llandoverian time. Such an interpretation almost mandates an interrup- tion of all Cason sedimentation during a part of Llandoverian time, with the return of Cason ter- rigenous sedimentation in the later Llandoverian again accompanied by, and closely associated with, carbonate sedimentation. Although this complicates the depositional history, it is not an implausible explanation and would appear to be the most reasonable interpretation of the stratigraphy in the Batesville district. Deposition of the "Brassfield" limestones and shales was fol- lowed by deposition of the "button" shale (*Pteros- pathodus amorphognathoides* zone; Craig, 1969, p. 1622; = Prices Fall Member of Oklahoma; text-fig. 3) and then the St. Clair Limestone (Wenlockian) (see later section on Paleoenvironment). Deposi- tion of these units is assumed to have been es- sentially continuous, although the stratigraphic and biostratigraphic evidence is certainly in-
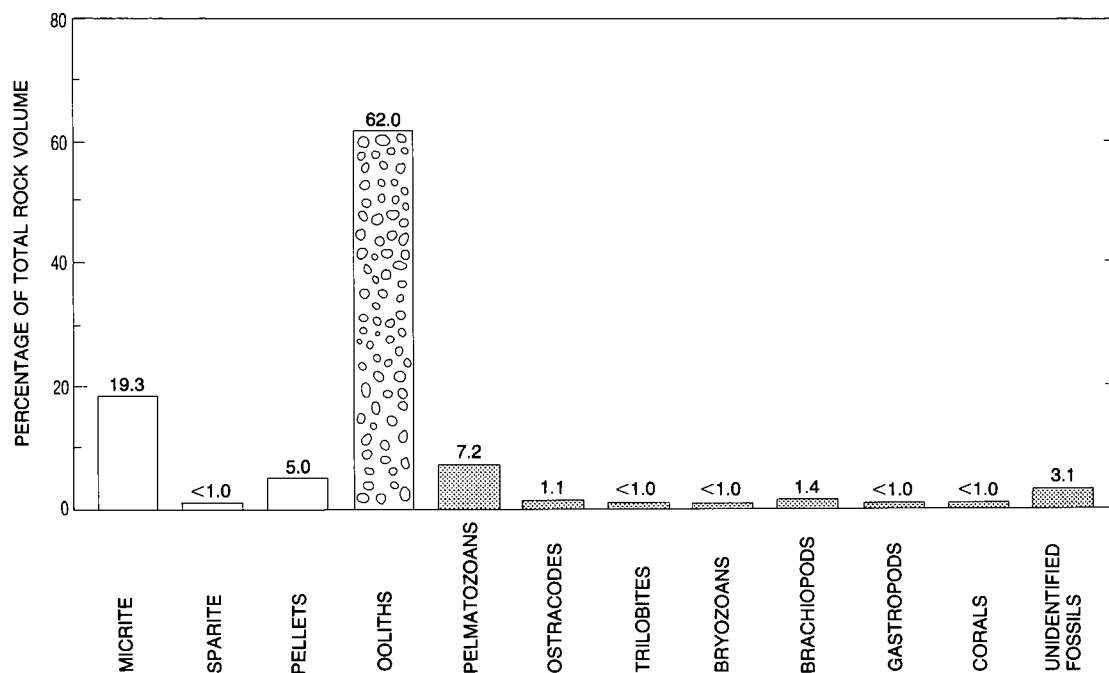

Text-figure 18. Graph showing composition of Cason oolite lens at Love Hollow Quarry, SW¼ sec. 4, T14N, R8W, Izard County, Arkansas. Based on point counts of two thin sections. (See pl. 5, fig. 4.)
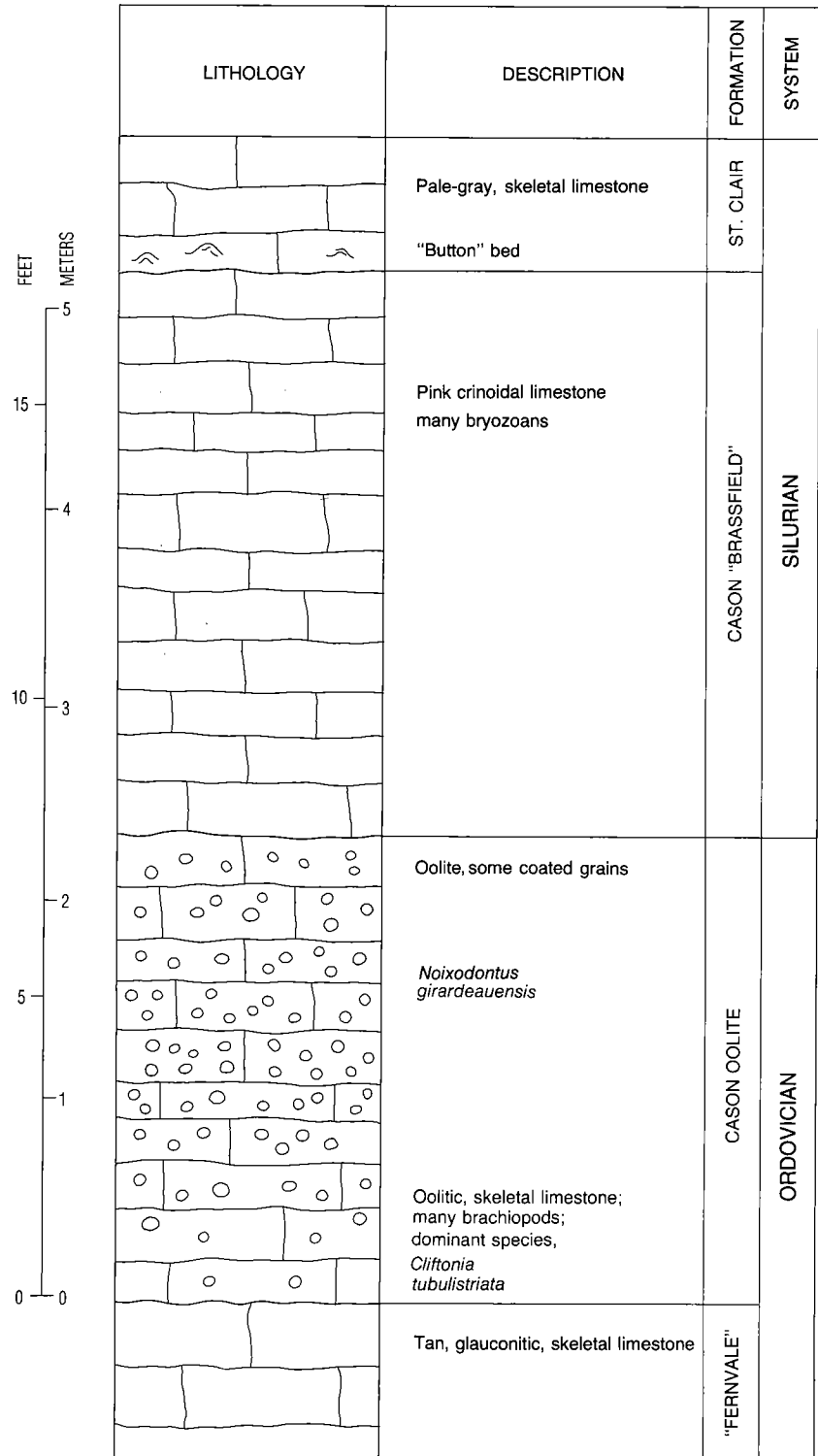
Text-figure 19. Stratigraphic diagram of Cason oolite and Cason "Brassfield" strata near St. Clair Springs. Conodonts from this section discussed in Part II (0.3 mile northeast of St. Clair Springs; SE½SW½ sec. 18, T14N, R5W, Independence County, Arkansas (measured and sampled by Amsden, September 1983).
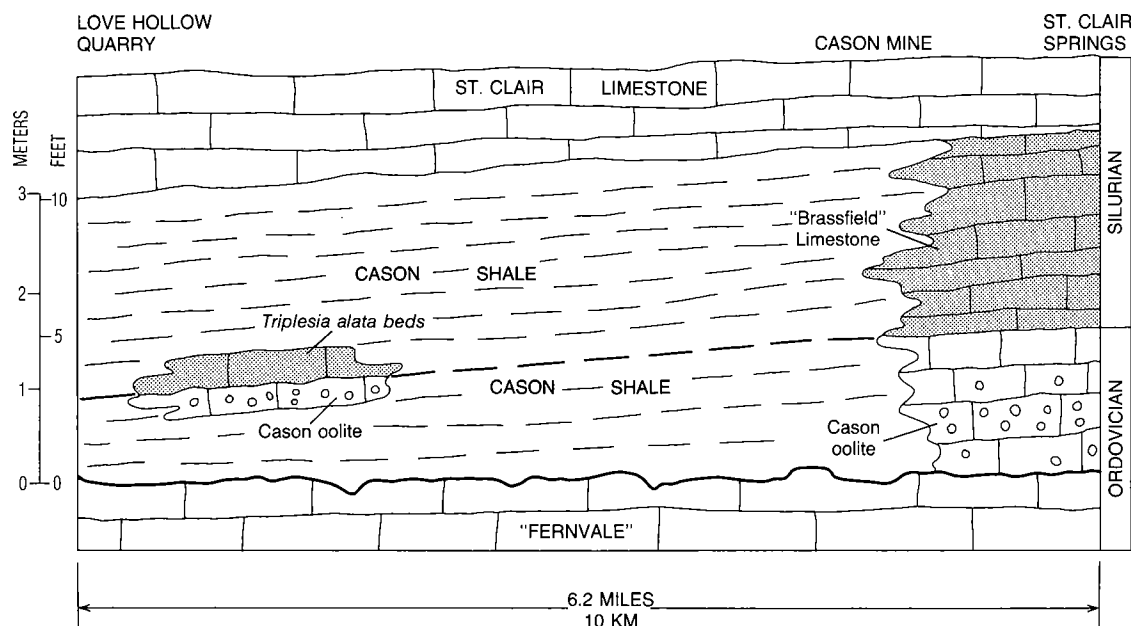
Text-figure 20. Stratigraphic section showing Cason Shale and its inferred relationship to Late Ordovician Cason oolite and Early Silurian "Brassfield" Limestone (*Triplesia alata* beds) in Batesville district, north-central Arkansas. See text-figures 18 and 19 and plate 5, figure 2. (After Craig, 1969, p. 1622; Lemastus, 1979, p. 62, 63; Amsden, 1980, p. 37.)

complete. It should be emphasized that any understanding of Late Ordovician–Early Silurian history is handicapped by the meager Cason exposures and the moderate to intense Fe–Mn mineralization of these strata.

Mineralization

Miser (1922) gave a lucid description and discussion of the geology, mineralogy, and chemical composition of the manganese deposits in the Batesville district. The distribution of the mineralization is stratigraphically controlled, being confined to the Cason Shale, lower St. Clair Limestone, and upper "Fernvale" Limestone. Although more intense, the Batesville Fe–Mn mineralization is similar in mineral composition and stratigraphic position to that in the Keel–Cochrane–Clarita of the Arbuckle Mountain region, and the two are believed to be genetically related (Ham and Oakes, 1944; this report). My primary interest in these deposits is related to their concentration in strata centering around the Late Ordovician–Early Silurian strata and the probability that these elements were introduced at the time of deposition.

According to Miser (1922, p. 77–81), the manganese was deposited as a carbonate at the same time the other Cason sediments were laid down. (Miser regarded the "Brassfield" Limestone as younger than, and stratigraphically distinct from,

the Cason Shale; in the present report the "Brassfield" or *Triplesia alata* beds are treated as a facies of the upper Cason; text-figs. 3, 20). During one of the periods of erosion following deposition of the Cason Shale, "much of the manganese was transferred from the Cason shale to the upper part of the Fernvale limestone where it was apparently deposited as a carbonate replacing the limestone" (Miser, 1922, p. 79). Additional concentration and alteration took place during later periods of uplift and erosion. This explanation is in reasonable accord with the distribution of mineralization in the Love Hollow Quarry (text-fig. 17). Here, mineralization affects all of the Cason Shale (including the upper, Early Silurian portion) and extends up into the basal 2 to 3 feet (1 m) of the St. Clair Limestone and down into the "Fernvale" Limestone for some 12 to 15 feet (6–7 m). The focal point of manganese mineralization in the Lawrence Quarry, Arbuckle Mountains, also appears to have been in the Late Ordovician–Early Silurian strata, suggesting some primary source of manganese at this time, with local concentration controlled by poorly understood depositional factors. A later period or periods of dissolution and redistribution of these elements took place here as in the Arkansas region. As noted previously, the stratigraphic position and geographic distribution of the iron-rich Neda oolite suggests that it is genetically related to the Oklahoma–Arkansas mineralization, and that the original source of these elements throughout this large area was

ultimately related to a Late Ordovician–Early Silurian regressive sedimentary cycle. However, this interpretation cannot be appraised effectively until the lithostratigraphy and biostratigraphy of the northern hematitic-oolite province is better defined.

Biostratigraphy of the Cason Stratigraphic Interval

In 1968 I described and illustrated 45 species of articulate brachiopods from the St. Clair Limestone and assigned this fauna a Wenlockian age (Amsden, 1968). In 1980 and 1981, Holloway described the trilobites from this formation and also assigned them to the Wenlockian Series. In 1971 I described and illustrated the brachiopod *Triplesia alata* from the upper part of a limestone lens in the Cason Shale at the Love Hollow Quarry and assigned to these strata a late Llandoverian (C) age. Craig (1969) reported a *Pterospathodus amorphognathoides* conodont fauna from the "button" shale at the top of the Cason Shale and lower St. Clair Limestone, and a *Pterospathodus celloni* conodont fauna from the pelmatozoan limestone in the Cason Shale (at least in part = "Brassfield" Limestone of Miser and *Triplesia alata* beds of Amsden). In this same paper Craig reported a lower Bereich 1 conodont fauna (Late Ordovician) from the oolitic beds in the Cason Shale. Keel–Edgewood brachiopods are present in the Cason oolite at St. Clair Springs, and conodonts from the Cason oolite and the Cason "Brassfield" are described in Part II of the present report. In 1983 I (Amsden, *in* Amsden and Sweet, 1983, p. 40) described and illustrated specimens of the brachiopod *Lepidocyclus cooperi* from the upper 10 feet of the "Fernvale" Limestone at West Lafferty Creek (NW ¼ sec. 10, T14N, R8W) near the Love Hollow Quarry. On the basis of this brachiopod I correlated the upper beds of the "Fernvale" with the upper beds of the Welling Formation of Oklahoma, assigning to them a Maysvillian age (Amsden and Sweet, 1983, p. 3). Thus, present biostratigraphic data would correlate the St. Clair of Arkansas with the Fitzhugh Member of the Clarita Formation, Arbuckle Mountains, Oklahoma; the "button" shale with the Prices Fall Member, Clarita Formation; the *T. alata–P. celloni* skeletal limestones with the Cochrane Formation; the Cason oolite with the Keel Formation; and the upper "Fernvale" with the upper Welling Formation. According to this biostratigraphic model, the Sylvan Shale (including the *Dicellograptus complanatus* graptolite zone), which is assigned to the Richmondian Stage (Ross and others, 1982), would appear to be locally absent in the Batesville district. This interval of time is represented by a chronostratigraphic gap between the "Fernvale" and the Cason oolite (text-fig. 3).

EDGEWOOD GROUP IN THE MISSISSIPPI VALLEY

Stratigraphic Relationships

Distribution of Major Edgewood Facies

Edgewood strata are exposed in two areas along the Mississippi Valley, one in southwestern Illinois–southeastern Missouri, and the other in west-central Illinois and northeastern Missouri (text-fig. 2). Oolitic strata are present in both outcrop areas. However, Edgewood strata are represented by two distinctly different facies: (1) a southern facies cropping out in Cape Girardeau County, Missouri, and Alexander County, Illinois, characterized by much silt- and clay-sized detritus (text-fig. 21); and (2) a northern facies marked by a generally low detrital content and varying degrees of dolomitization (Bowling Green Dolomite). The latter is a part of the Late Ordovician–Silurian dolomite province which occupies much of the North American continental interior. Also note that the Edgewood Group in the southern area consists only of Ordovician (Hirnantian) strata, whereas in the northern region it includes Early Silurian strata.
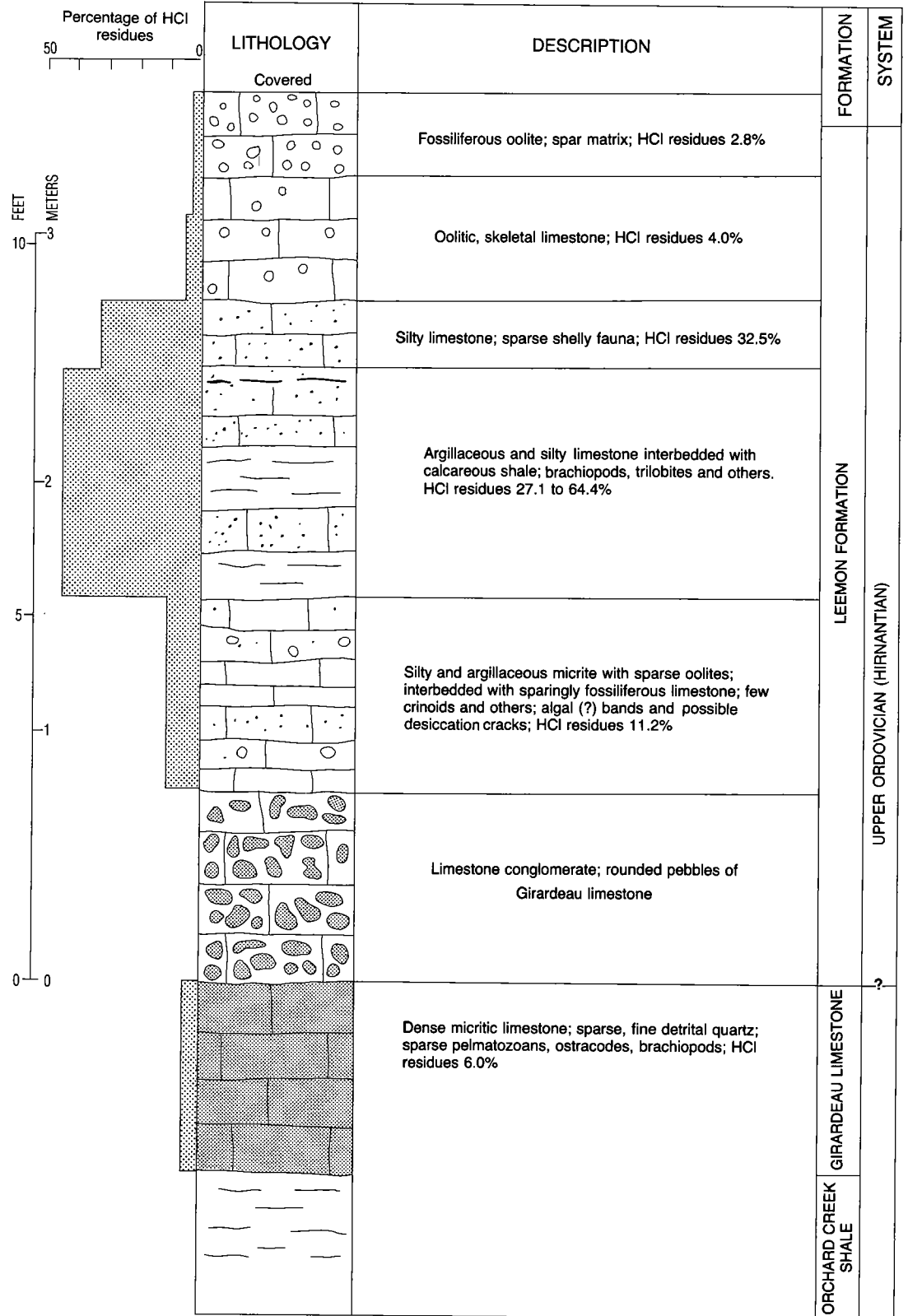
Pre-Edgewood Formations

In the southern outcrop area the Edgewood rests on the Girardeau Limestone or the Orchard Creek Shale, and in the northern outcrop area it rests on the Maquoketa Shale. These pre-Edgewood formations are Late Ordovician; however, their precise age is uncertain. The Edgewood in the southern area is separated from the underlying strata by an unconformity, and at the Thebes section (text-fig. 22) well-rounded pebbles of Girardeau Limestone are incorporated into the basal beds; near the Short farm the Girardeau was entirely removed, allowing the Edgewood to be deposited directly on the Orchard Creek Shale. In the northern outcrop area the Edgewood rests with apparent conformity on the Maquoketa Shale, the upper part of which locally includes ooliths (pl. 4, fig. 3).

Ordovician–Silurian Boundary

Throughout the Mississippi Valley sequence, as discussed in this report, the Edgewood Group commonly is overlain by the Sexton Creek Limestone. Outcrops of Sexton Creek near Thebes yield specimens of the brachiopod *Stricklandia protriplesiana*, indicating a late Llandoverian (C_{1-2}) age. In Calhoun County, Illinois, the Sexton Creek furnishes specimens of *S. triplesiana* with an interior similar to *S. lens ultima* Williams, indicating a late Llandoverian (C_{4-5}) age (Amsden,
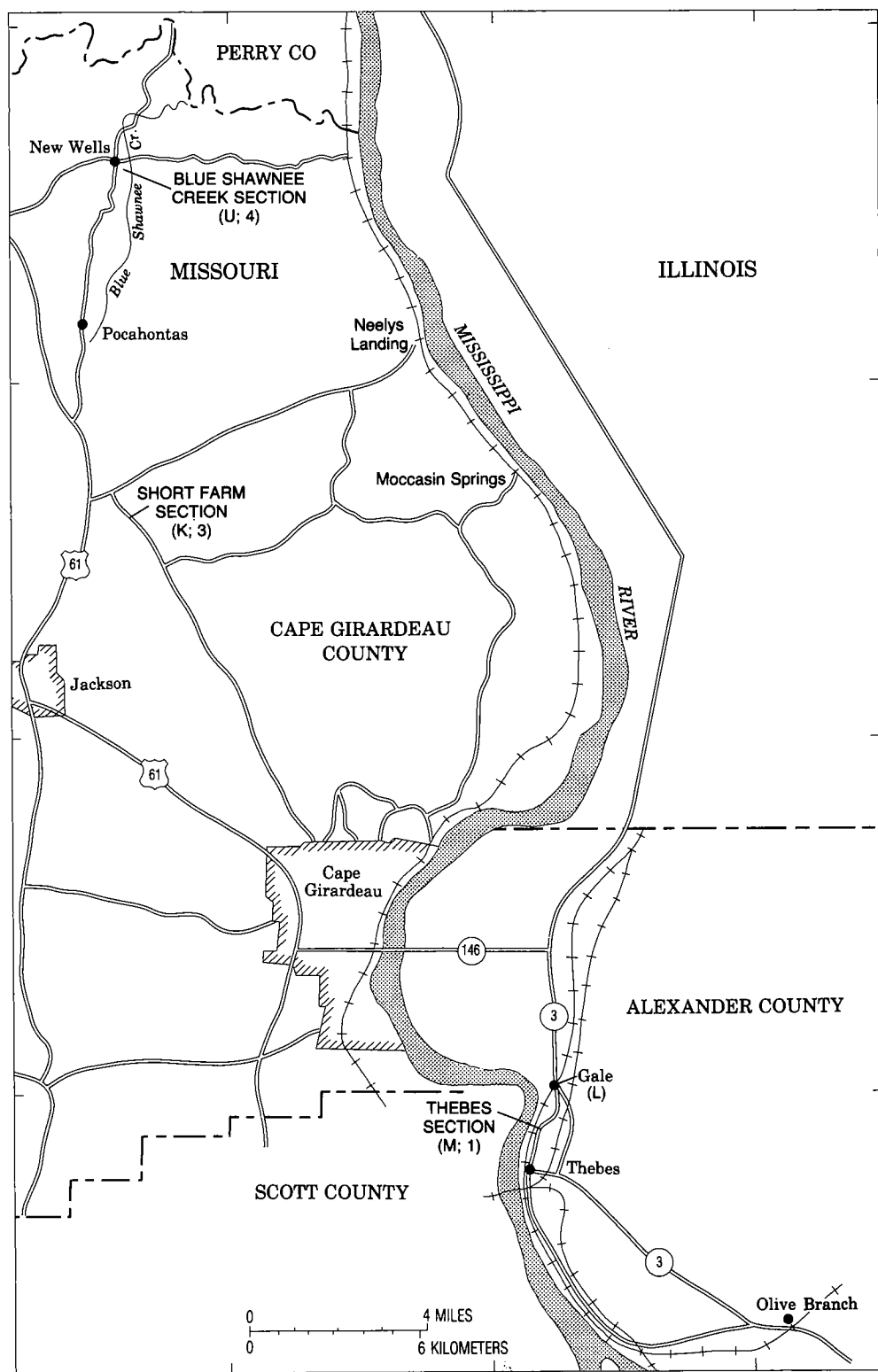
Text-figure 21. Map showing location of Thebes, Gale, Short farm, and Blue Shawnee Creek stratigraphic sections in Alexander County, Illinois, and Cape Girardeau County, Missouri. Letters are stratigraphic-section designations given by Amsden (1974, p. 83–87), and numbers are designations given by Thompson and Satterfield (1975, p. 75–92). (After Amsden, 1974, text-fig. 15.)

Percentage of HCl residues

LITHOLOGY

Covered

DESCRIPTION

FORMATION

SYSTEM

Fossiliferous oolite; spar matrix; HCl residues 2.8%

Oolitic, skeletal limestone; HCl residues 4.0%

Silty limestone; sparse shelly fauna; HCl residues 32.5%

Argillaceous and silty limestone interbedded with calcareous shale; brachiopods, trilobites and others. HCl residues 27.1 to 64.4%

Silty and argillaceous micrite with sparse oolites; interbedded with sparingly fossiliferous limestone; few crinoids and others; algal (?) bands and possible desiccation cracks; HCl residues 11.2%

Limestone conglomerate; rounded pebbles of Girardeau limestone

Dense micritic limestone; sparse, fine detrital quartz; sparse pelmatozoans, ostracodes, brachiopods; HCl residues 6.0%

LEEMON FORMATION

UPPER ORDOVICIAN (HIRNANTIAN)

GIRARDEAU LIMESTONE

ORCHARD CREEK SHALE

FEET   METERS

Text-figure 22. Stratigraphic diagram of Leemon Formation, east bank of Mississippi River about 1 ½ miles (2 ½ km) north of Thebes, Alexander County, Illinois, SE¼ sec. 5, T15S, R3W. This is the section described by previous workers (Savage, 1913; 1917, p. 78; Amsden, 1974, locality M, p. 86; Satterfield, 1971, text-fig. 4; Thompson and Satterfield, 1975, section 1, p. 78). (See discussion in text under Girardeau Limestone.)

1974, p. 24). Throughout this area there is physical evidence for a pre-Sexton Creek unconformity. In the southern area, near Thebes, the Sexton Creek rests on the Edgewood, whereas across the Mississippi River at the city of Cape Girardeau this formation rests directly on the Girardeau Limestone. In the northern outcrop belt, in Calhoun County, Illinois, the upper Edgewood Group (Bowling Green Dolomite) was deeply channeled before deposition of the Sexton Creek (Amsden, 1974, p. 18).

The Ordovician–Silurian boundary in the southern area is drawn at the unconformable contact of the Sexton Creek with the Edgewood Group. This brings the Late Ordovician (Hirnantian) Leemon Formation of the Edgewood Group into direct contact with the overlying Sexton Creek Formation of late Llandoverian age. However, in the northern outcrop area (text-fig. 3) the upper part of the Edgewood Group (Bryant Knob Formation and the upper part of the Bowling Green Dolomite) is assigned an Early Silurian age (stage unspecified). It should be noted that the evidence for this Early Silurian age assignment is based almost entirely on conodont biostratigraphy.

In 1974 (p. 14–15) I pointed out that the brachiopod evidence bearing on this Silurian age assignment was at a rather low taxonomic level. Collections made in 1982 further reduced this distinction by demonstrating that some of the brachiopod species that in 1974 appeared to be confined to the Bryant Knob Formation are also present in the underlying Noix–Cyrene strata. The somewhat sporadic geographic and stratigraphic distribution of brachiopods in the Edgewood Group of the Mississippi Valley (Amsden, 1974, p. 8) makes it difficult to obtain a completely unified picture of the brachiopod biostratigraphy. It is therefore possible that a better defined brachiopod phylogeny is represented in the Edgewood sequence than can be demonstrated at this time. Present evidence would, however, seem adequate to show that the brachiopod faunas do not clearly duplicate the well-defined and regionally identified faunal break of the conodonts (Part II).

Girardeau Limestone

The Girardeau is a dense, micritic limestone that is unconformably overlain by the Leemon Formation (text-figs. 22, 25; Satterfield, 1971, p. 267) and, according to Satterfield (1971, p. 267), conformably underlain by the Orchard Creek Shale. Savage (1913, p. 95–112, pls. 3, 4) described and illustrated 28 species of crinoids, bryozoans, brachiopods, mollusks, and trilobites. The brachiopods comprise 10 species, of which two, *Rafinesquina mesicosta* (Shumard) (Amsden, 1974, pl. 13, figs. 3a, 3b) and *Schuchertella missouriensis* (= *Coolinia? missouriensis* [Shumard];

(Amsden, 1974, pl. 4, figs. 4a–d), also were reported from the overlying Edgewood (Leemon Formation). Savage's diagnoses are inadequate by modern standards, making comparison of his fauna with the Edgewood brachiopod fauna difficult.

Thompson and Satterfield (1975, p. 74–75, 78) reported the conodonts *Prioniodus ferrarius, Prioniodus giradeauensis,* and *Trichonodella asymmetrica,* suggesting that the Girardeau Limestone should be included in the Hirnantian Stage (see Part II). A biostratigraphic restudy of post Cape–pre-Leemon faunas would be most useful in resolving the faunal relationships in this critical interval.

Leemon Formation, Southwestern Illinois and Southeastern Missouri

Edgewood strata are sparingly exposed in Alexander County, Illinois, and across the Mississippi River in Cape Girardeau County, Missouri (text-fig. 21). Pre-Sexton Creek erosion is probably a major factor affecting their distribution in this area. These are low-magnesium strata, which include a substantial amount of clay- and silt-sized detritus. In fact, the Edgewood beds exposed near Thebes contain the most terrigenous detritus of any strata examined in the Mississippi Valley area. No pre–Sexton Creek Silurian rocks have been identified in the Edgewood of this area, and all strata are referred to the Leemon Formation (text-fig. 3).

Thebes and Gale Areas, Alexander County, Illinois

The Leemon Formation crops out on the east bank of the Mississippi River about 1 ½ miles (2 ½ km) north of Thebes (SE ¼ sec. 5, T15S, R3W; loc. M, Amsden, 1974, p. 86; sec. 1, Thompson and Satterfield, 1975, p. 78). This exposes the Orchard Creek Shale, the Girardeau Limestone, and about 12 feet (3 ½ m) of the Leemon Formation, with the top covered (text-fig. 22). The basal bed of the Leemon is a conglomerate composed of well-rounded pebbles derived from the underlying Girardeau Limestone (see previous section, Girardeau Limestone). Overlying this conglomerate is about 6 feet (2 m) of argillaceous and silty limestones, grading into calcareous shales, with as much as 64 percent HCl-insoluble residues. This interval includes some structures that may represent algal mats, and some of the calcareous shales have sparse ooliths with well-developed radial and concentric structure (pl. 4, fig. 4). This exposure is of special interest because it shows the formation of typical ooliths either directly within, or in very close proximity to, an environment re-

ceiving a substantial influx of terrigenous de-
tritus. This relationship is not unique, although
the overwhelming majority of oolites and oolitic
skeletal limestones studied for this report are
characterized by a very low volume of ex-
trabasinal terrigenous detritus. The uppermost
exposed bed is an oolitic skeletal limestone with
sparse, subrounded detrital quartz as much as 0.2
mm in diameter, grading upward into typical
oolite with almost no extrabasinal detritus (text-
fig. 23). This uppermost oolite includes many bro-
ken ooliths and intraformational rip-up clasts.

The Leemon Formation is also exposed near
Gale, a short distance north of Thebes (text-fig.
21). In 1974 I described this outcrop, which con-
sists of about 2 feet (60 cm) of oolite (Amsden,
1974, p. 86); the overlying and underlying strata
are covered. This is near the quarry section de-
scribed by Savage (1913; 1917, p. 79). It consists,
in ascending order, of the Thebes Sandstone,
Orchard Creek Shale, Edgewood oolite (Leemon),
and Sexton Creek Limestone. The exposed
Leemon is entirely oolite, and the ooliths have
well-defined radial and concentric structure. Most

of the ooliths are complete, but some broken and
abraded fragments were seen. There are also a
number of limestone fragments, some of which
appear to be rip-up clasts of oolite, whereas others
appear to be eroded fragments of Girardeau Lime-
stone (pl. 4, figs. 5, 6). Of particular interest is the
substantial quantity of subangular detrital
quartz, which constitutes 12.4 percent of the total
rock volume (text-fig. 24). A minor quantity of this
may have been derived from the underlying
strata, but most grains appear too coarse to have
been eroded from the Orchard Creek Shale and
probably represent silt derived from an external
source. The Leemon oolite at Gale is similar to the
oolite at the Short farm, although the latter has
much less detrital quartz.

Savage (1913; 1917, p. 78) recorded the follow-
ing fauna from Edgewood (Leemon) strata near
Thebes: 1 stromatoporoid, 2 corals, 8 brachiopods,
1 snail, and 1 trilobite from the upper oolite; and 4
brachiopods, 1 snail, and 1 trilobite from the un-
derlying argillaceous beds; he assigned this fauna
to his Early Silurian Alexandrian Series. In 1974 I
described nine articulate brachiopods from the up-
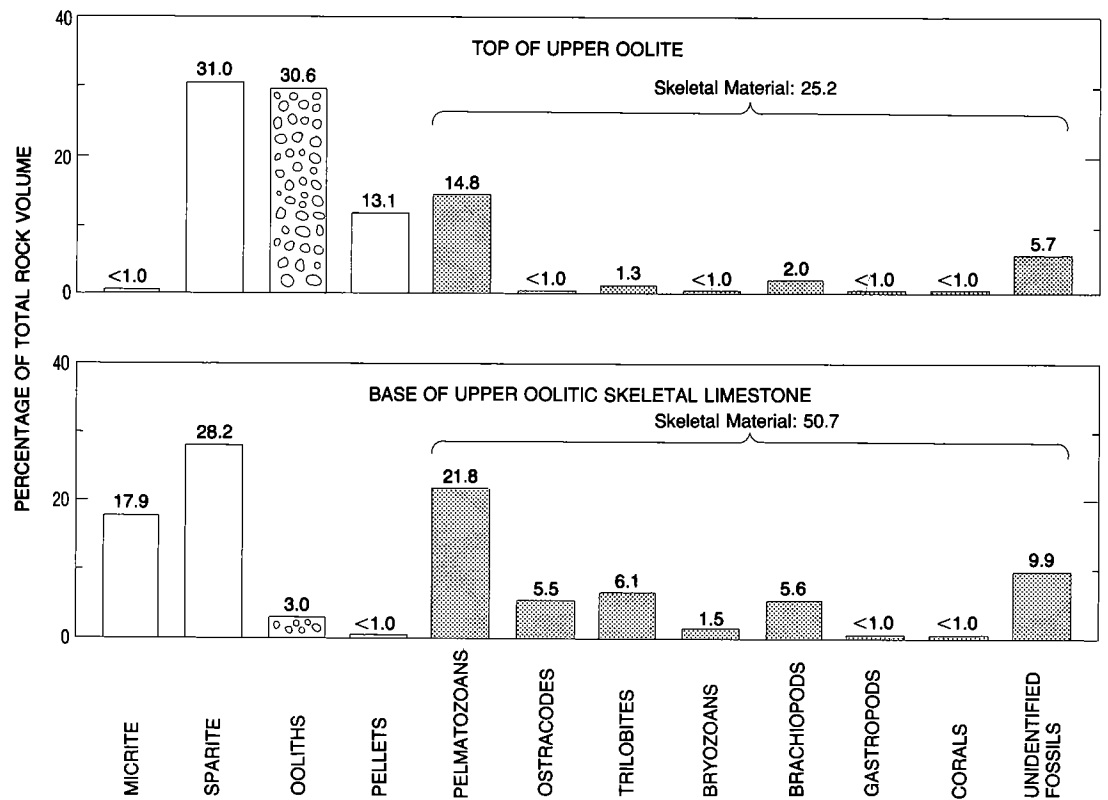
Text-figure 23. Graph showing matrix and skeletal components from upper oolite bed, Leemon Formation, east bank of
Mississippi River north of Thebes, SE¼ sec. 5, T15N, R3W, Alexander County, Illinois (text-fig. 22). Lower graph
shows texture of oolitic skeletal limestone 3 feet below top; upper graph is from uppermost exposed oolite with a fairly
typical oolitic texture. Each graph based on point count of a single thin section.
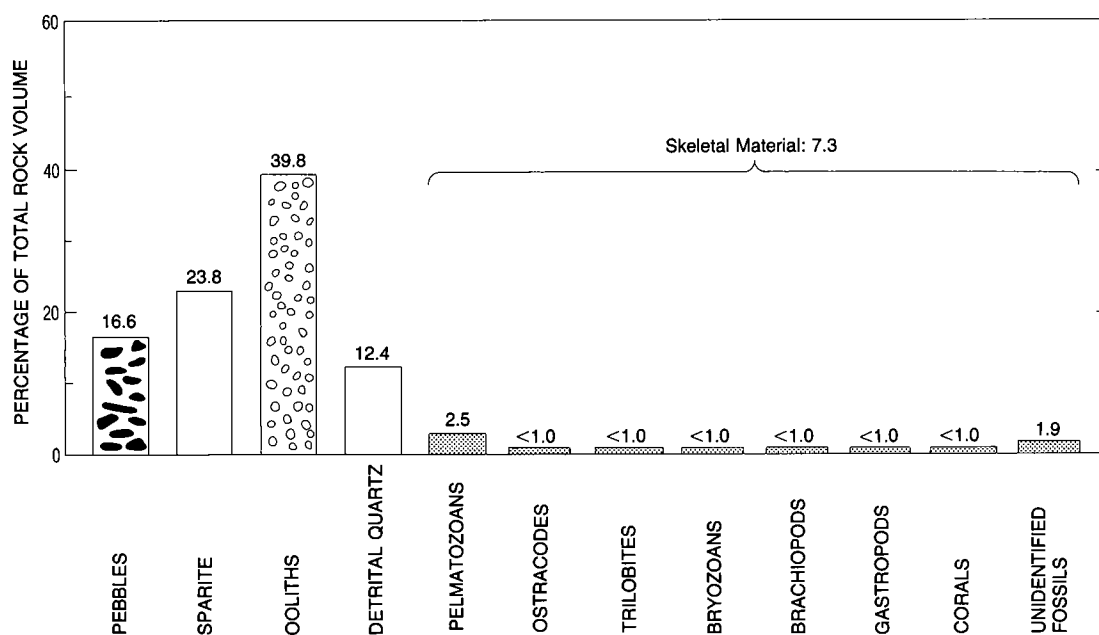
Text-figure 24. Graph showing matrix and skeletal components in Leemon Formation near Gale, NE¼ sec. 4, T14S, R3W, Alexander County, Illinois. Based on point counts of a single thin section. Compare to Leemon Formation at Short farm, text-figure 26.

per oolite, assigning this fauna to the Late Ordovician Hirnantian Stage (Amsden, 1974, p. 24, 86). Thompson and Satterfield (1975, p. 78) listed the conodonts from the Leemon Formation at this locality and assigned all the exposed beds to the Late Ordovician (Part II).

I did not recover any fossils from the Gale exposure, but Savage reported an Edgewood (Leemon) fauna consisting of 2 snails, 3 corals, and 8 brachiopods.

The Gale and Thebes exposures represent the most southeasterly extension of the oolite province known to me. The Edgewood strata include a substantial amount of argillaceous and silty detritus, some of which was probably derived from erosion of the underlying strata. However, the quantity and grain size would suggest that most of this came from some external source (see section on Paleoenvironment).

Short Farm, Cape Girardeau County, Missouri

This is Thompson and Satterfield's (1975, p. 74–77) section 3 and was designated the type locality for the Leemon Formation (locality K, Amsden, 1974, p. 19–21, 85). The Formation is about 15 feet (4.5 m) thick and is underlain by the Orchard Creek Shale and overlain by the Sexton Creek Formation (text-fig. 25). The lower 6 feet (2 m) is an oolite with well-rounded ooliths having ex-

cellent radial and concentric structure. Broken ooliths are also common in this part of the Leemon as well as numerous rounded pebbles and cobbles of micritic limestone ranging up to 8 inches (20 cm) in length. Lithologically, these limestone pebbles have a striking resemblance to the Girardeau Limestone, but the Girardeau is not present here and the Leemon rests directly on the Orchard Creek Shale. However, similar pebbles are present at the base of the Leemon Formation near Thebes (text-fig. 22) where this formation does rest on the Girardeau. In all probability the pebbles at the Short Farm locality were derived from the Girardeau, with all *in situ* traces of this formation stripped away by pre-Leemon erosion (see Girardeau Limestone). These relationships indicate a pre-Leemon unconformity, although its duration is not ascertainable from present biostratigraphic information. Some of the pebbles are fine siltstone, possibly eroded from the Orchard Creek Shale; a few are oolitic and micritic and probably represent rip-up clasts. The basal part of the Leemon also includes some quartz detritus, much of which is angular to subangular silt-sized material but including some well-rounded quartz grains up to 0.6 mm in diameter (pl. 1, fig. 4). In size and shape these resemble quartz grains common in the lower part of the Welling Formation (Amsden, 1980, pl. 11, fig. 7) and older Ordovician formations. Their source is uncertain, but presumably they represent a
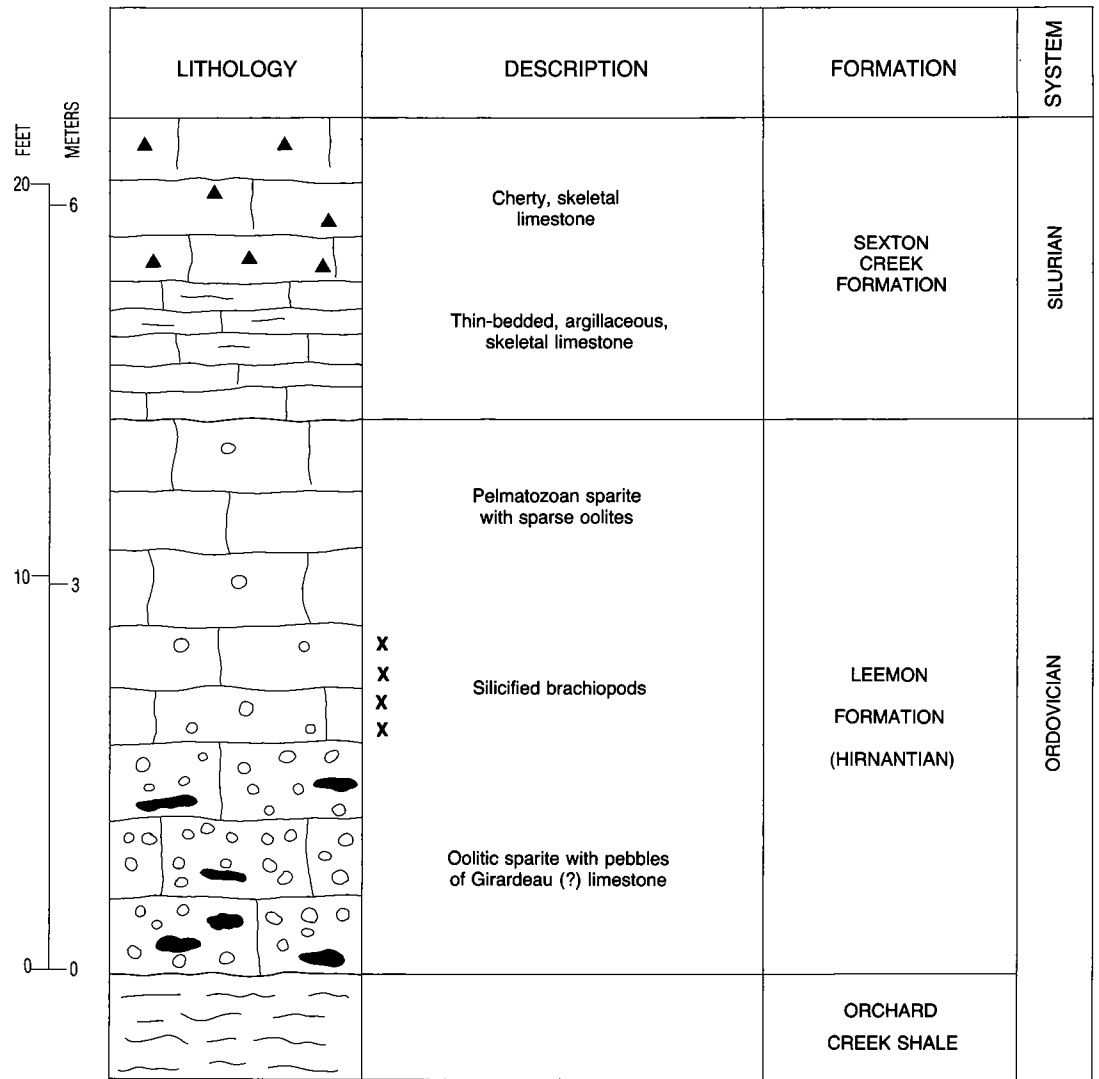
Text-figure 25. Stratigraphic diagram showing Orchard Creek, Leemon, and Sexton Creek Formations at Short farm, sec. 21, T32N, R13E, Cape Girardeau County, Missouri. After Amsden, 1974, text-figure 16. Silicified brachiopods (xxx) described in Amsden (1974). Ordovician–Silurian boundary based on conodont biostratigraphy (Thompson and Satterfield, 1975, p. 77).

second-generation sand. Progressing upward in the formation, the pebbles and quartz detritus decrease in abundance, and at 2 m above the Orchard Creek the pebbles have disappeared and the quartz is very sparse. Accompanying these changes is a sharp decrease in ooliths, and the upper Leemon is a skeletal sparite with only widely scattered ooliths (text-fig. 26). Disparate pelmatozoan plates dominate the oolitic and non-oolitic facies, and bryozoans are abundant in the skeletal limestones. In 1974 I described nine species of brachiopods from the Leemon strata. On the basis of this fauna I correlated these beds with the Leemon Formation at Thebes and Blue Shawnee

Creek; the Noix Formation of Pike County, Missouri, and Calhoun County, Illinois; and the Keel Formation of Oklahoma. Thompson and Satterfield (1975, p. 76) reported Ordovician conodonts from the Leemon Formation and Early Silurian conodonts from the overlying thin-bedded limestones, which they refer to the Sexton Creek (Part II, this report).

Blue Shawnee Creek, Cape Girardeau County, Missouri

The Edgewood Group is represented by a distinctive and unusual facies at an outcrop on Blue
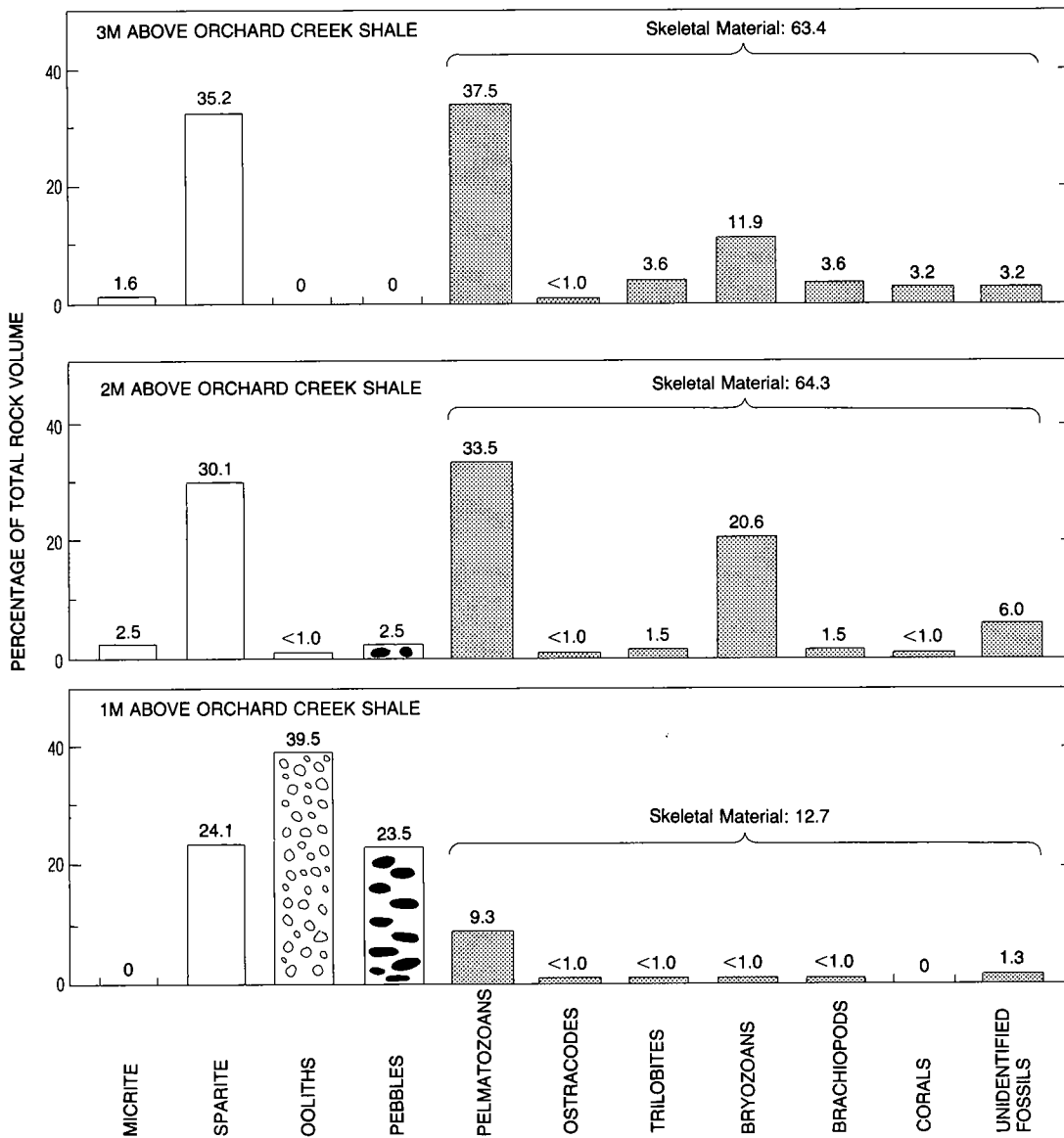
Text-figure 26. Graphs showing variations in matrix and skeletal components in Leemon Formation at type locality, Short farm, sec. 21, T32N, R13E, Cape Girardeau County, Missouri. Based on point counts of three thin sections prepared from samples collected 1 m, 2 m, and 3 m above Orchard Creek–Leemon contact (locality K, Amsden, 1974, p. 85).

Shawnee Creek near New Wells in northern Cape Girardeau County, Missouri (stratigraphic section U, NW¼SE¼SE¼ sec. 9, T33N, R13E; Amsden, 1974, p. 21–22, 87). Here, the basal 2 or 3 feet (1 m) of the Leemon Formation comprises a biohermal limestone resting on the Orchard Creek Shale. A partially etched block about 1 foot (30 cm) in diameter is composed of ramose bryozoans knitted together to make a frame; attached to this frame are numerous brachiopods, many of which are articulated. This block and other asso-

ciated limestones also include small, solitary tetracorals, trilobites, pelmatozoan plates, a few ostracodes, and massive bryozoans. The matrix is mainly lime mud with a substantial volume of clay- and silt-sized angular to subangular detritus ranging up to 0.2 mm in diameter. Much of the Leemon is nonoolitic, but some beds of oolite are present. A thin section prepared from one of these oolites shows well-rounded ooliths with radial and concentric structure (pl. 4, fig. 1). Mixed in with the unbroken, well-rounded ooliths are numerous
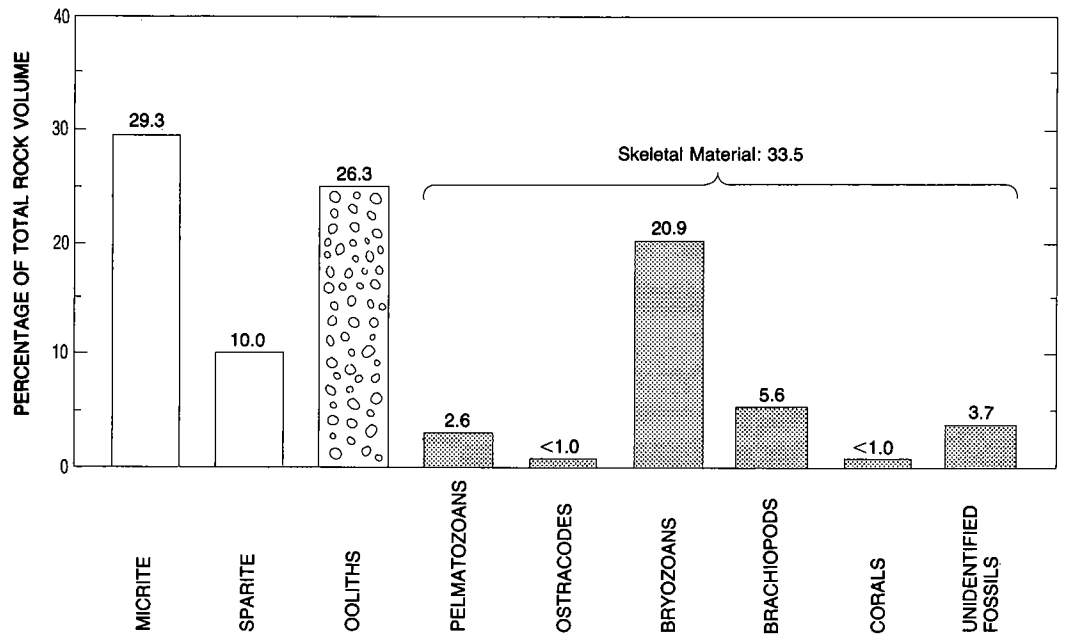
Text-figure 27. Graph showing composition of Leemon oolitic bed at Blue Shawnee Creek, northern Cape Girardeau County, Missouri (locality U, Amsden, 1974, p. 87). Based on point counting of one thin section from bed in lower 3 feet of formation.

broken ooliths. Point counting shows almost 34 percent skeletal material, 20 percent of which is bryozoan skeletons (text-fig. 27). The high volume of skeletal material dominated by bryozoans is an unusual composition for an oolite (compare text-figs. 7, 12, 18, 23, 24, 26, 27).

The skeletal and biohermal beds of the Leemon Formation are about 6 feet (2 m) thick at the Blue Shawnee Creek locality. These beds are overlain by 8 feet (1.5 m) of thin-bedded, micritic limestone, followed by cherty Sexton Creek Limestone. In 1974 I described 10 species of articulate brachiopods from the basal 2 feet (60 cm) of the Leemon Formation, assigning this fauna a Late Ordovician (Hirnantian) age. Thompson and Satterfield (1975, p. 80) reported Ordovician conodonts from the Leemon Formation and Silurian conodonts from the overlying thin-bedded limestone (Part II).

The Leemon brachiopod fauna at Blue Shawnee Creek includes the following brachiopods: *Strophomena satterfieldi, Thaerodonta johnsonella, Leptaena aequalis, Biparetis paucirugosus, Dolerorthis savagei, Dalmanella testudinaria, Cliftonia tubulistriata, Leptoskelidion septulosum, Stegerhynchus concinna, Thebesia thebesensis,* and *Whitfieldella billingsana.* This interesting assemblage comprises fairly typical pre-Hirnantian genera, Hirnantian genera, and post-Hirnantian Silurian genera. *Strophomena* and *Thaerodonta* are typical pre-Hirnantian

genera, which, to my knowledge, have not heretofore been recognized in either Hirnantian or post-Hirnantian faunas. *Dalmanella* and *Cliftonia* are common and widespread in Hirnantian-age strata. *Stegerhynchus* and *Dolerorthis* are widely distributed in the Keel–Edgewood strata but are certainly not common in Hirnantian strata elsewhere, but they have been found in the Oslo–Asker area (Cocks, 1982) and in northeastern USSR (Koren' and others, 1983). *Stegerhynchus* is present in the Hirnantian beds of China (Rong and Xu, 1983) and in northeastern USSR. *Thebesia,* which is an uncommon species in the Edgewood, is also present in northeastern USSR and in the Oslo–Asker area. *Whitfieldella* is a typical Silurian genus, with the Edgewood occurrence being the oldest record known to me.

Noix–Cyrene, Bryant Knob, Bowling Green Formations, Northeastern Missouri and Western Illinois

Introduction

The Edgewood Group is well exposed in Pike County, Missouri, and across the Mississippi River in Calhoun County, Illinois (text-fig. 28). In this area it consists of the Noix, Cyrene, Bryant Knob, and Bowling Green Formations (Amsden, 1974, p. 8–10; Thompson and Satterfield, 1975, p. 81–100;
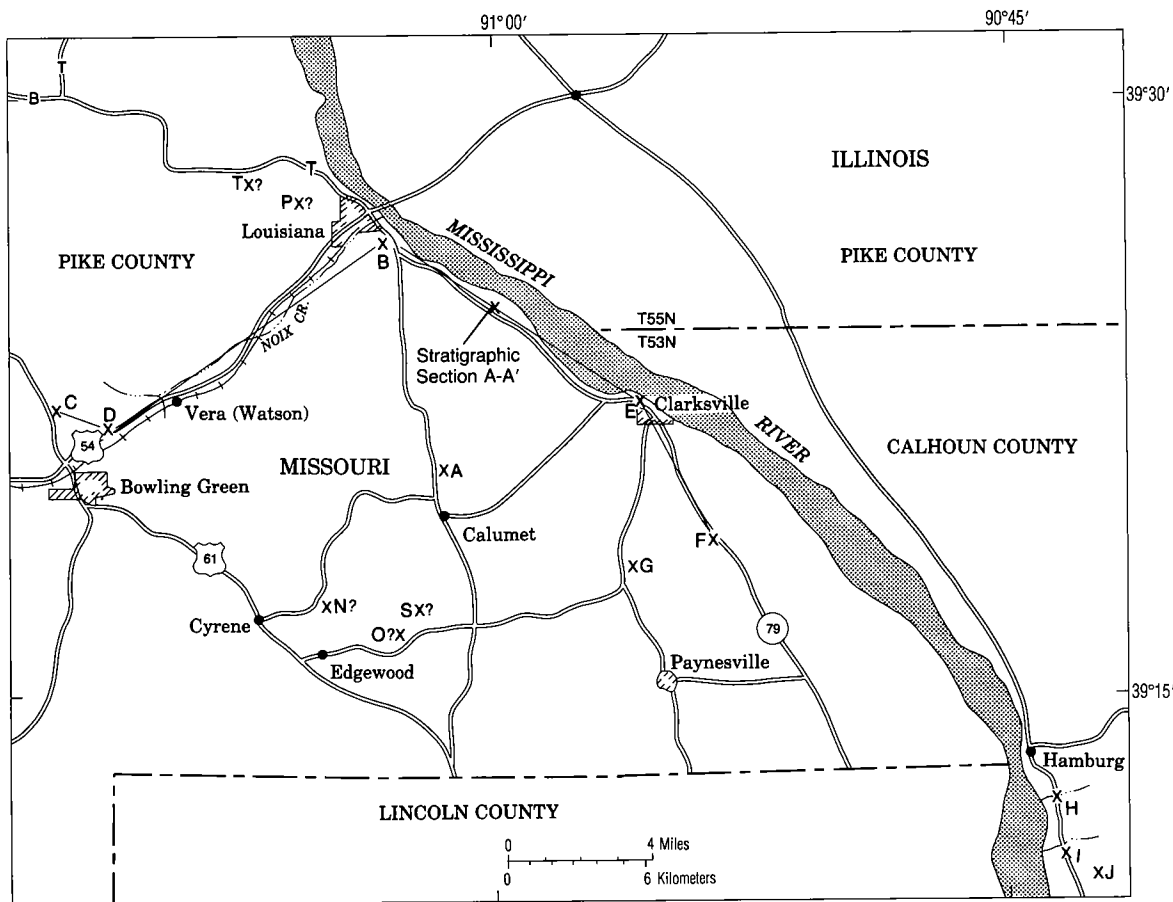
Text-figure 28. Map showing locations of stratigraphic sections in Pike County, Missouri, and Calhoun County, Illinois. After Amsden (1974, text-fig. 3; sections described in Amsden, 1974, Appendix). Cross section *C–F* shown in text-figure 34.

this report, text-figs. 2, 3). These strata include more extrabasinal terrigenous detritus than is present in the Keel Formation of Oklahoma, although not as much as in the Thebes section, Alexander County, Illinois. This area lies north of the dolomite front (text-fig. 2), and Edgewood strata have been exposed to various degrees of dolomitization. In general, dolomitization increases to the west, and in western Pike County the Edgewood is represented entirely by crystalline dolomite. Edgewood conodonts have been studied by Thompson and Satterfield (1975) and by McCracken and Barnes (1982) and Barrick (Part II, this report). The Ordovician–Silurian boundary cited in the present report is based mainly on conodont biostratigraphy (see Part II).

In Pike County, Missouri, the Edgewood is underlain by the Maquoketa Shale and unconformably overlain by Late Devonian–Mississippian strata. This erosional unconformity controls the distribution of Edgewood in Pike County. In Calhoun County, Illinois, Edgewood strata are un-

derlain by the Maquoketa Shale and unconformably overlain by the Sexton Creek Limestone of Early Silurian age (Amsden, 1974, p. 18). It should be noted that physical evidence and brachiopod biostratigraphic evidence indicate that both these unconformities are post-Edgewood (i.e., post-Bryant Knob–Bowling Green) in age.

Pike County, Missouri

The Noix Formation is well exposed in the eastern part of Pike County, where it composes the basal unit of the Edgewood Group (Amsden, 1974, p. 9). It is an oolite with well-rounded ooliths having sharply defined radial and concentric structure. The matrix is predominantly spar, although some micrite is present in most beds. The volume of skeletal material is low, averaging about 20 percent, and the fauna is dominated by pelmatozoans (text-fig. 29). The Noix is probably not more than 6 feet (2 m) thick in Pike County, and its
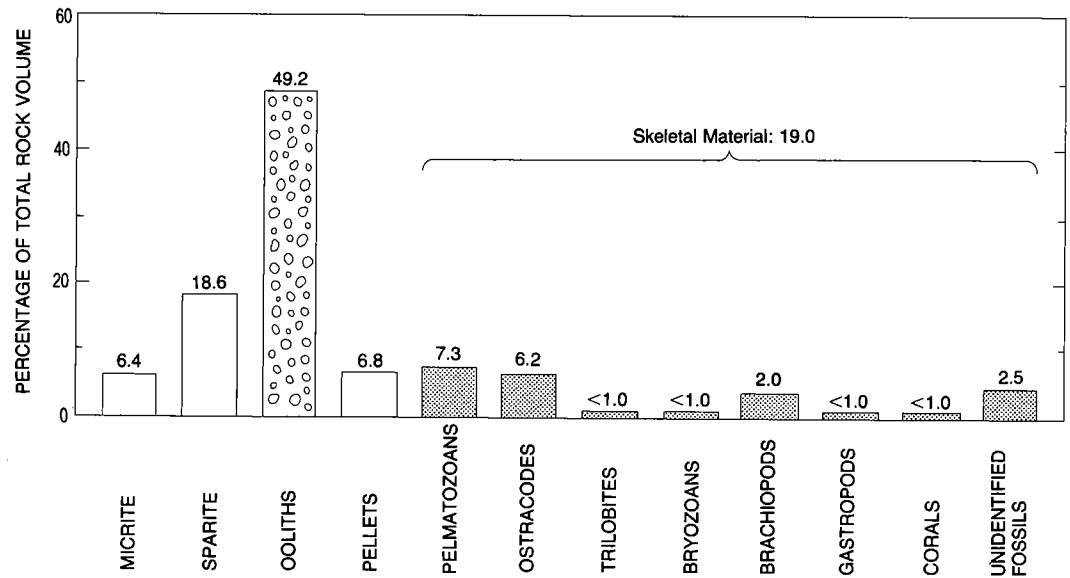
Text-figure 29. Graph showing composition of Noix oolite, Pike County, Missouri, and Calhoun County, Illinois. Based on point counts of five thin sections.

general characteristics are similar to the Keel Formation of Oklahoma. The Noix oolite grades laterally into oolitic skeletal limestones and pellet limestones with increased skeletal volume, and these strata are referred to the Cyrene Formation (text-fig. 30). Both the Noix and Cyrene facies are low in HCl-insoluble detritus, commonly less than 2 percent, and their general lithologic and faunal composition is remarkably like that of the Keel Formation in Oklahoma (compare text-figs. 7, 12, with text-figs. 29, 30). In Pike County the Noix or Cyrene is overlain by skeletal limestones bearing Silurian conodonts (Thompson and Satterfield, 1975), and these strata are referred to the Bryant Knob Formation. Ooliths are present although not common in these strata, and the skeletal material is generally enclosed in micrite envelopes. These strata have a close lithologic similarity to the Cyrene Formation, and the lithostratigraphic separation of these units is based on stratigraphic position and conodont biostratigraphy.

The Noix oolite has a moderately high-diversity benthic fauna in spite of its low volume of skeletal material. Savage (1913; 1917, p. 82–83) listed 46 species from the Noix oolite near Louisiana, Missouri, including corals (both tabulates and tetracorals), brachiopods, trilobites, gastropods, and cephalopods. (Although reported from the Noix, this list probably includes specimens from the Bryant Knob Formation, which overlies the Noix in this area; Amsden, 1974, p. 83). In 1974 I described 17 species of brachiopods from the Noix,

and most of these also occur in the Cyrene and Bryant Knob Formations (conodonts are also present; McCracken and Barnes, 1982, Part II, this report).

Dolomitization—Throughout Pike County the Noix oolite and the Cyrene and Bryant Knob skeletal limestones are overlain by the Bowling Green Dolomite, which has been defined as the uppermost stratigraphic unit in the Edgewood Group (Thompson and Satterfield, 1975, p. 68). The Bryant Knob is a tan-weathering, fine- to medium-crystalline dolomite (crystals mostly less than 0.10 mm in diameter). Some silt- and clay-sized detritus is present. Spot samples analyzed range up to 35 percent $MgCO_3$ and 10 percent HCl. Some of the dolomites are fossiliferous; however, in the more intensely dolomitized beds, fossils are sparse and where present are preserved as molds or as spar replacement. In 1974 I described five species of articulate brachipods from the lower 9 feet (3 m) of the Bowling Green Dolomite at the Magnesium Mining Co. quarry (Amsden, 1974, p. 83–84; see also in this report, Biostratigraphy of the Edgewood Group).

There is a question concerning the relationship of the Bowling Green Dolomite to the underlying Edgewood strata. Throughout Pike County the Bowling Green is the uppermost unit in the Edgewood Group; however, at several places dolomite beds are interbedded with the Cyrene and Bryant Knob limestones (localities D, F, text-figs. 31, 32), and at the Magnesium Mining Co. quarry (locality
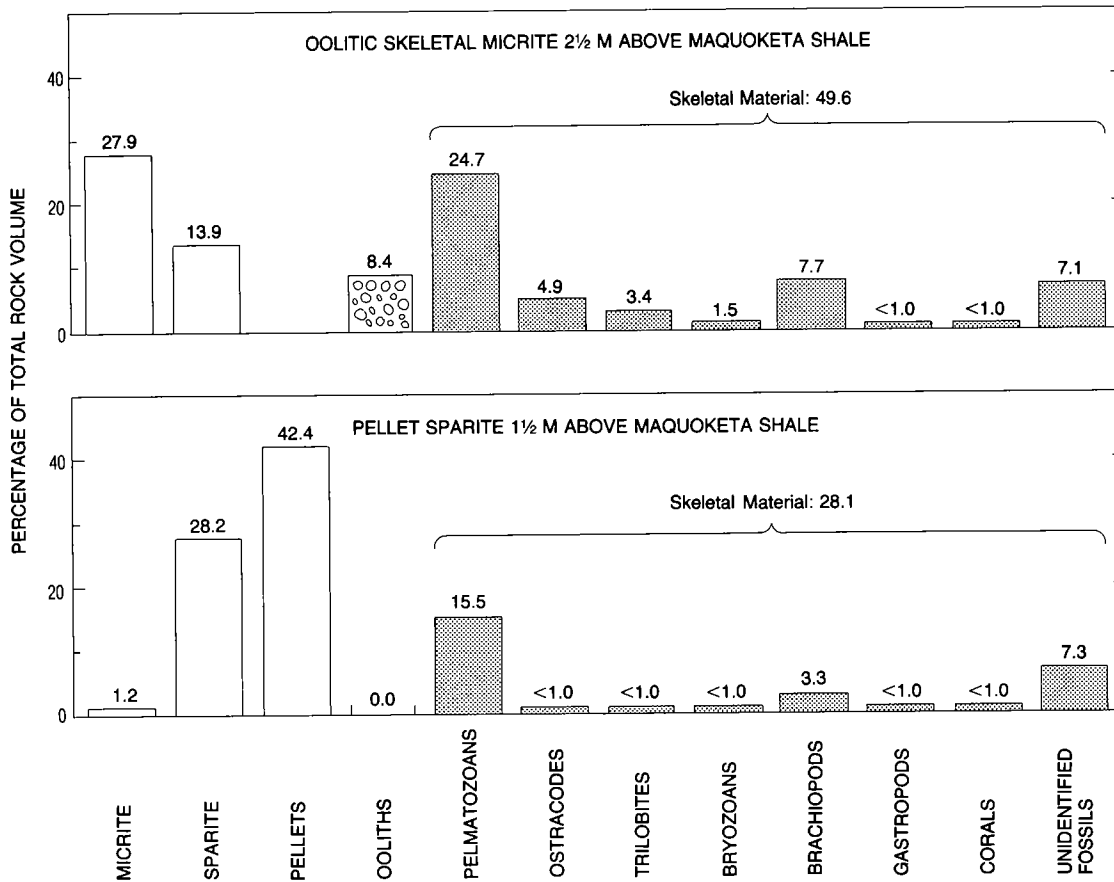
Text-figure 30. Graphs showing matrix and skeletal components of oolitic skeletal micrite and pellet sparite in Cyrene Formation, locality D (text-fig. 31), U.S. Highway 54 near Bowling Green (SE¼SW¼ sec. 13, T53N, R3W), Pike County, Missouri (Amsden, 1974, p. 84). Based on point counts of thin sections; see text-figure 29.

C, Amsden, 1974, p. 83–84, text-fig. 11) the entire Edgewood down to the Maquoketa Shale is dolomite. Thompson and Satterfield (1974, p. 68, 96, 99–100) regarded the Bowling Green Dolomite as a discrete lithostratigraphic unit that was younger than the underlying Edgewood formations. In 1974 I suggested as an alternative explanation that the Bowling Green Dolomite represented dolomitized Edgewood, best developed in the younger strata but locally extending down to include the Noix (Amsden, 1974, p. 17). In October 1982 I reexamined Edgewood strata in Pike County, especially the limestone–dolomite relationships. Of particular interest are the excellent Pinnacle Cliff exposures on the west side of Highway 79 at the north edge of Clarksville (loc. E, text-fig. 33). The Maquoketa–Noix–Bowling Green is completely exposed for several hundred feet, and the Noix–Bowling Green contact appears to be a sharp lithologic boundary (Amsden, 1974, text-figs. 5, 6). Thompson and Satterfield (1975, p. 90) interpreted this as an unconformity, and

McCracken and Barnes (1982, p. 1474) stated that both lithologic and paleontologic data suggested a post-Richmondian hiatus (see section on Biostratigraphy of the Edgewood Group). However, a close inspection of this contact shows that it is not a sharp lithologic break (hard ground surface) but a gradational limestone-dolomite boundary as shown in text-figure 33. This certainly does not preclude the presence of an unconformity within the Edgewood sequence, but I believe the lithostratigraphic-biostratigraphic evidence shows that dolomitization (i.e., the Bowling Green dolomite facies) extends down into Hirnantian-age strata as shown in text-figure 34.

Calhoun County, Illinois

The Edgewood Group in Calhoun County is represented by the Noix Formation and the Bowling Green Dolomite, underlain by the Maquoketa Shale and unconformably overlain by the Sexton
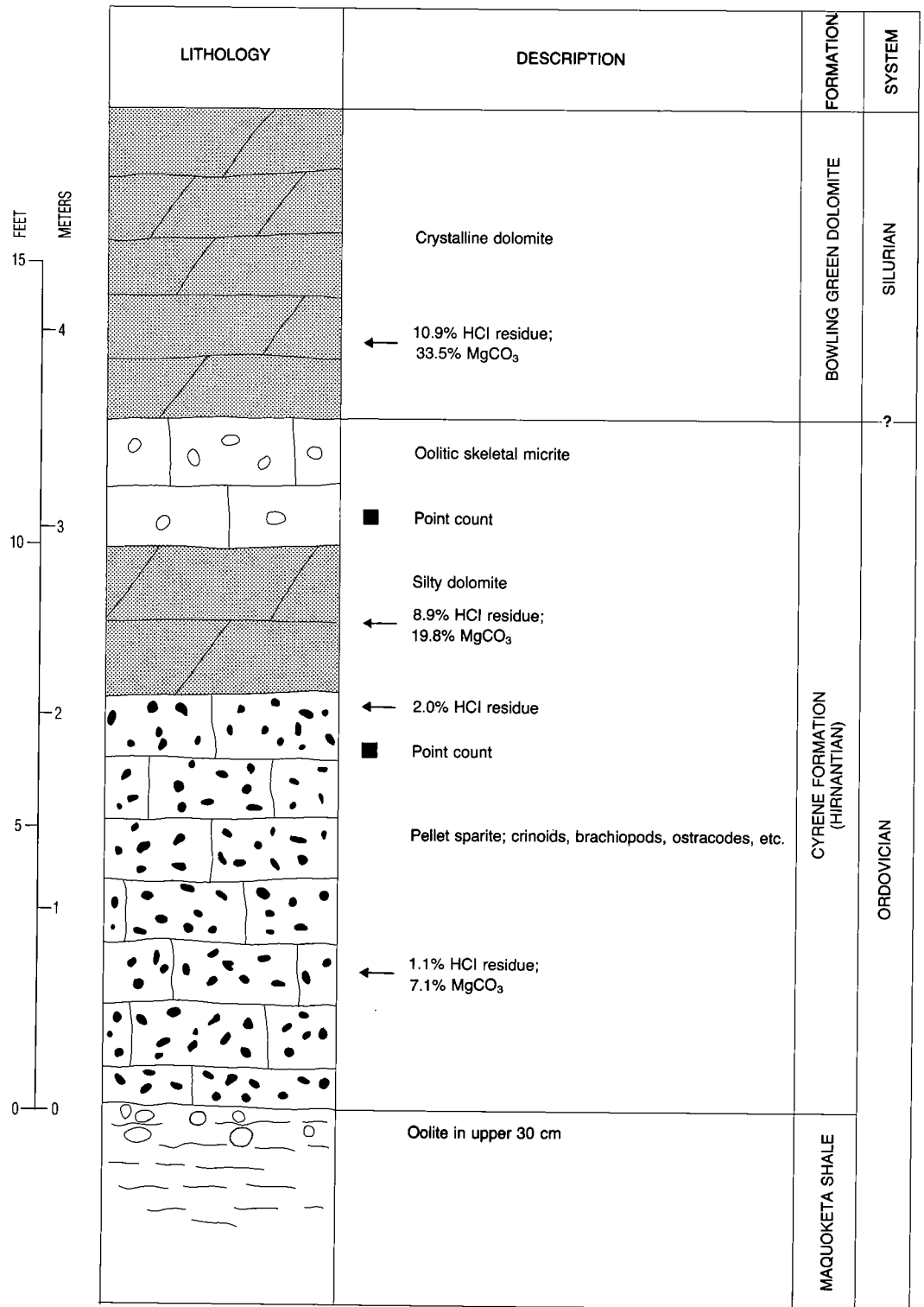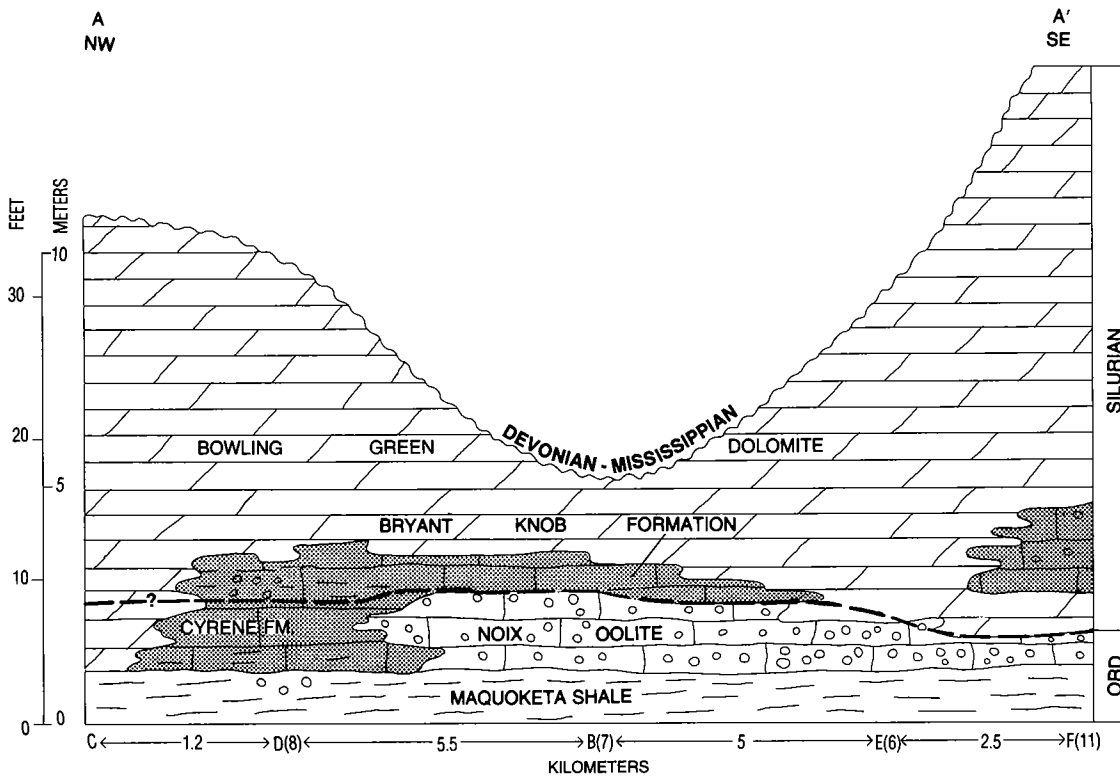
Text-figure 31. Stratigraphic diagram of Edgewood Group at locality D, U.S. Highway 54 near Bowling Green, Pike County, Missouri (Amsden, 1974, p. 84; Thompson and Satterfield, 1975, p. 88). Fossil and rock components of pellet sparite and oolitic skeletal limestone (solid squares) are shown in text-figure 30. Amsden (1974) described and illustrated 10 species of articulate brachiopods from the Cyrene Formation. Ordovician–Silurian boundary based on conodont biostratigraphy of Thompson and Satterfield (1975); see Part II. (Chemical analysis by analytical-chemistry laboratory, Oklahoma Geological Survey.)
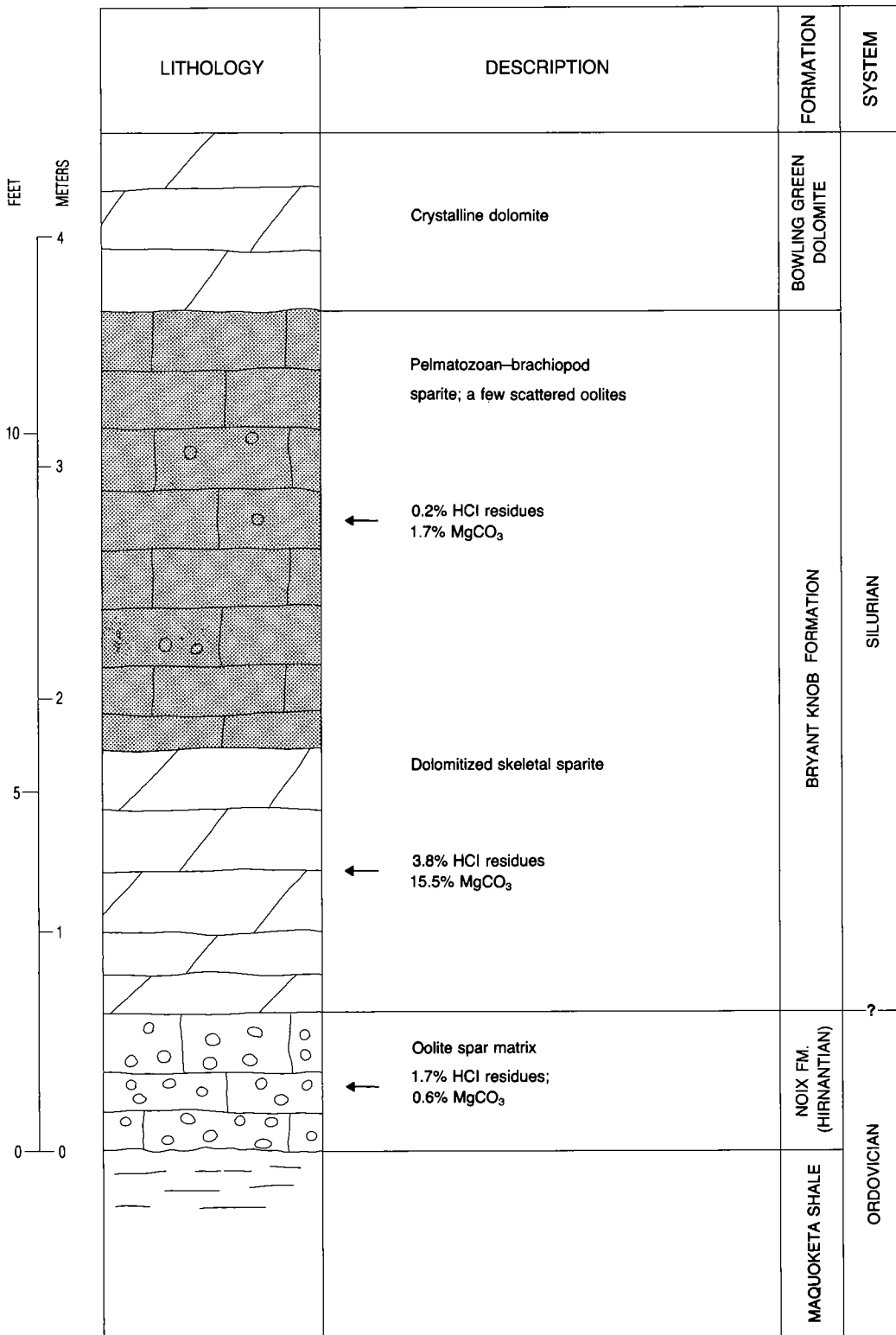
Text-figure 32. Stratigraphic diagram of Edgewood Group at locality F, U.S. Highway 79 about 4 miles south of Clarksville, Pike County, Missouri (Amsden, 1974, p. 84; Thompson and Satterfield, 1975, p. 92). Amsden described and illustrated five species of articulate brachiopods from the Byrant Knob Formation. Ordovician–Silurian boundary based on conodont biostratigraphy of Thompson and Satterfield. (See Part II of this report.)
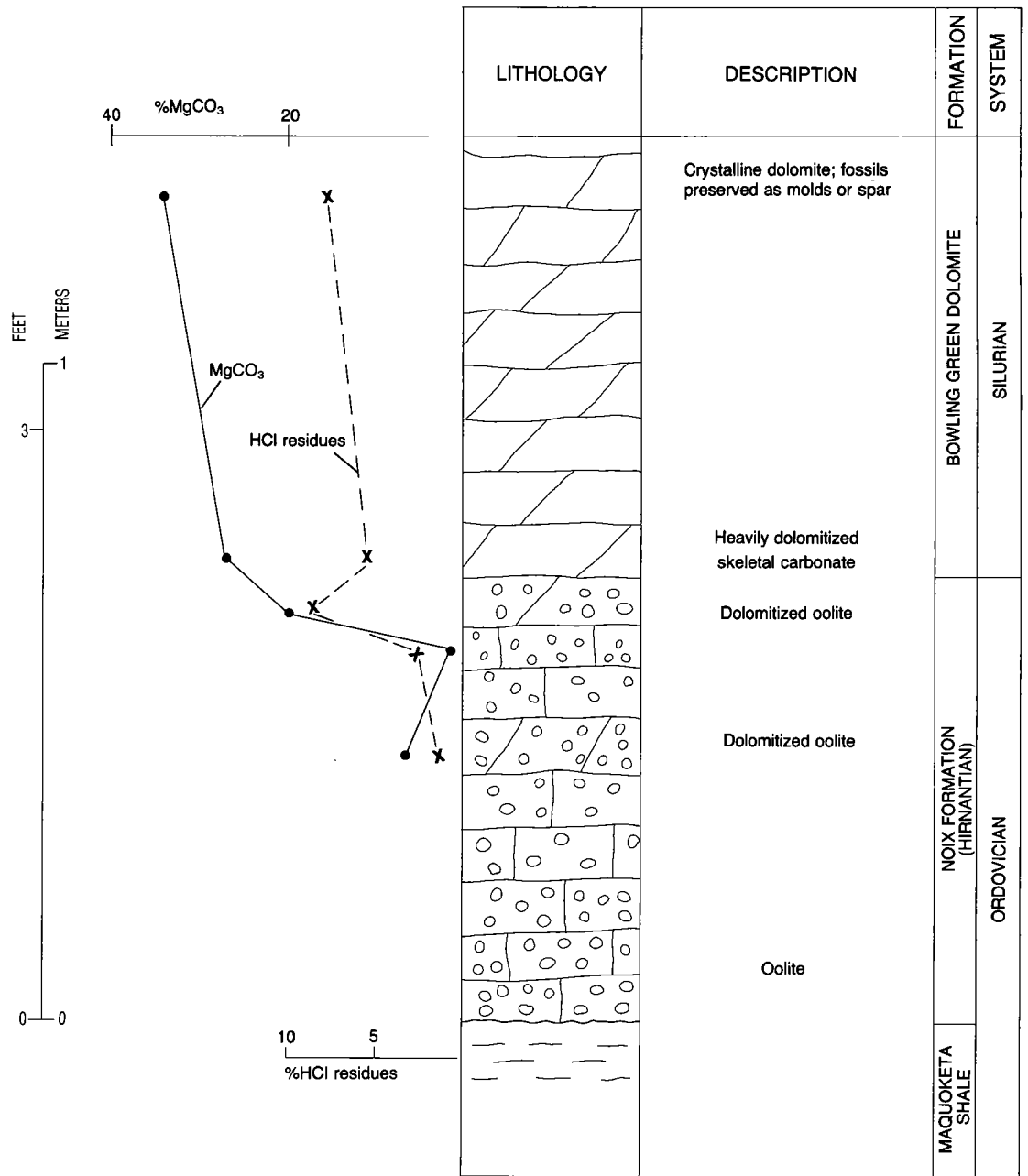
Text-figure 33. Stratigraphic diagram of Edgewood Group at Pinnacle Cliff exposure, west side of State Highway 79, north edge of Clarksville, Pike County, Missouri (Amsden, 1974, p. 10, 84; Thompson and Satterfield, 1975, p. 91). $MgCO_3$ and HCl-insoluble-residue data based on chemical analyses of spot samples by analytical-chemistry laboratory, Oklahoma Geological Survey. Ordovician–Silurian boundary based on conodont biostratigraphy of Thompson and Satterfield (1975; McCracken and Barnes, 1982; see Part II, this report).

Text-figure 34. Cross section showing inferred relationships of Edgewood strata in Pike County, Missouri. Locations of stratigraphic sections C, D, B, E, and F shown in text-figure 28. Descriptions are given in Amsden (1974, p. 83–87); numbers in parentheses refer to stratigraphic-section designations of Thompson and Satterfield (1975). Ordovician–Silurian boundary based on conodont biostratigraphy of Thompson and Satterfield (1975) and the brachiopod biostratigraphy of Amsden (1974, p. 83–84). See Figure 28 for locations.

Creek Limestone. The Noix is an oolite that is similar in all respects to the Noix in Pike County. Seven brachiopods were described from the Noix (Amsden, 1974, p. 19), all but one of which are represented in the Noix of Pike County, Missouri. The Edgewood is separated from the overlying Sexton Creek by an unconformity marked by deep channels cut in the Bowling Green and filled with Sexton Creek (Amsden, 1974, p. 19, 35). The Sexton Creek Limestone furnishes specimens of *Stricklandia triplesiana* (Foerste) with an internal structure similar to that of *S. lens ultima* Williams, indicating a late Llandoverian (C_{4-5}) age.

Biostratigraphy of the Edgewood Group

Savage (1909, p. 516) referred the Edgewood strata exposed along both sides of the Mississippi River to the Alexandrian Series, which he regarded as the earliest series in the Silurian System. This age assignment was accepted by most North American stratigraphers and biostratigraphers (see Amsden, 1974, p. 4–6, for a discussion of early investigations). In 1974 I described and illustrated the articulate brachiopods from the Keel–Leemon–Noix–Cyrene formations and assigned them to the Late Ordovician (see earlier section on Brachiopod Biostratigraphy of the Keel Formation). This age assignment was based in part on an analysis of the general phylogenetic stage attained by the various taxonomic elements and in part of a direct comparison with the Hirnantian brachiopod fauna of Europe (Amsden, 1974, p. 26–29). The generic suite of the Hirnantian fauna is similar to the North American fauna, although there are a number of taxonomic differences that I attributed to the very different ecological niches occupied by these assemblages. The Bryant Knob and upper Bowling Green Formations were assigned to the Early Silurian, although the taxonomic distinction between the brachiopods from these formations and the underlying Noix–Cyrene was admittedly at a low

taxonomic level (Amsden, 1974, p. 11). A recent reexamination of the brachiopod faunas, including new collections made in 1982, further moderates this distinction, and the brachiopod biostratigraphy requires no significant interruption in the Noix–Bryant Knob sequence. My Ordovician age assignment was questioned by Lespérance (1974, p. 22) and Lespérance and Sheehan (1976, p. 720), who believe that the Keel–Leemon–Noix–Cyrene brachiopods represent a Silurian fauna with a few Ordovician holdovers (Amsden, 1974, p. 30).

Thompson and Satterfield (1975, p. 69–73, 100–103) referred the Leemon, Noix, and Cyrene conodont faunas to the Late Ordovician, and the Bryant Knob and Bowling Green to the Early Silurian; however, they did not provide any more exact positioning of these faunas with respect to regional or worldwide conodont zonation (see Part II). According to these authors, deposition of the Noix was terminated, at least locally, by a period of erosion, and a second period of erosion separated Bryant Knob deposition from Bowling Green deposition.

Elias (1982, p. 36–39), in a study of the solitary rugose corals, assigned the Keel, Leemon, and Edgewood (Cyrene, Noix) to the Late Ordovician (post-Richmondian; ?Gamachian).

McCracken and Barnes (1982) studied conodonts from the Noix and Bowling Green strata collected from the Pinnacle Cliff exposures at the north edge of Clarksville (Amsden, 1974, location E; Thompson and Satterfield, 1975, section 6; this report, text-fig. 33 and Part II). According to them, the dominant conodont in the Noix is *Noixodontus girardeauensis* (Satterfield), a species that does not occur with *Gamachignathus* in Fauna 13 on Anticosti Island (Gamachian Stage, Hirnantian Stage) but that does occur with *Gamachignathus* in the Yukon Territory (McCracken and Barnes, 1982, p. 1477; this report, Part II). McCracken and Barnes stated that "the Noix Limestone fauna has the characteristics of a slightly modified late Richmondian Fauna 12 (Sweet and others, 1971) rather than the younger Gamachian Fauna 13," and concluded that "both lithological and paleontological data suggest a post-Richmondian hiatus" (see discussion of conodont faunas in Part II).

The Edgewood brachiopod faunas are at variance with the conodont data cited above. These brachiopod faunas are taxonomically distinct from, and phylogenetically younger than, the Richmondian–Maysvillian brachiopod faunas. The Keel–Edgewood brachiopods are taxonomically much more closely allied to Hirnantian faunas from the calcareous facies of Europe and USSR than they are to the brachiopod faunas from the Richmondian–Maysvillian of the Cincinnati region, the Maquoketa Formation of Iowa (Wang, 1949), or the Welling Formation of Oklahoma (Alberstadt, 1973).

Finally, it should be stressed that both the physical stratigraphy and the brachiopod biostratigraphy indicate that the significant erosional and phylogenetic break occurs at the top of the Keel–Edgewood sequence—i.e., between the Keel and the Cochrane, the Pettit and the Blackgum, the Cason oolite and the *Triplesia alata* beds, and the Edgewood and the Sexton Creek.

PALEOENVIRONMENT

General Considerations

The study of past environments is a complex problem that can and does produce widely differing interpretations, intensified in part by material differences of opinion on the basic data to be used in support of the postulated model. I believe that the basic requirement for any paleoenvironmental study is a *biostratigraphic* analysis to establish a basic time frame for the strata studied. The biostratigraphy of these Late Ordovician–Early Silurian strata is discussed elsewhere and will not be reviewed here other than to note that the Keel–Cason oolite–Leemon–Noix–Cyrene and lower Bowling Green formations (text-fig. 3) are believed to be essentially contemporaneous deposits of Late Ordovician (Hirnantian) age. Other factors of importance include (1) *distribution and lithostratigraphy*—defined to include not only the stratigraphic and geographic distribution of the entire facies, but also the distribution and ultimate source of the extrabasinal detrital portion of the facies; (2) *textures*—matrix-cement versus clasts; bedding characteristics; oolith structure, including deformation and replacement; fossil preservation, breakage, and articulation versus disarticulation; bioturbation; (3) *extrabasinal terrigenous detritus*—size, shape, and composition; (4) *fauna*—detailed studies of major groups to determine taxonomic composition; quantitative data on the major faunal elements. The following discussion summarizes elements that I believe provide major clues to the regional paleoenvironmental pattern of these Late Ordovician–Early Silurian strata.

Oklahoma and the Texas Panhandle

The Keel Formation is a reasonably well-defined lithostratigraphic unit, which can be traced throughout Oklahoma and into the Texas Panhandle (text-fig. 4). The more important elements bearing on its depositional environment are discussed below:

1. The typical Keel oolite has well-rounded ooliths with radial and concentric structure; many show a core, commonly a small pelmatozoan plate. Most ooliths are less than 2 mm in diameter, and the bedding is commonly defined by oolith size differences. Sparite is the dominant matrix; however, micrites are present, and some bedding

is marked by alternate layers of micrite and spar-
ite. Minor irregularities in bedding are common,
and some include a subdued type of crossbedding.
Some micrites are pelletiferous, and in some
strata the pellets merge imperceptibly into the
micrite. These relationships point to deposition in
a shallow-marine environment of moderate to
strong energy level.

2. Throughout this area, terrigenous detritus in
the Keel is low. Thin sections show very little
visible detritus, and chemical analyses show a
high-calcium stone averaging less than 1 percent
HCl insolubles (text-figs. 8, 9, 10). This points to
clear water and a substrate of calcareous sand,
mainly oolites and shelly debris. Locally, thin-
bedded limestones with only sparse ooliths are
interbedded with the typical oolites, and these
beds contain as much as 4 percent fine silt and clay
detritus (text-fig. 13, 14). These strata, which are
known from only a small area, have a low-
diversity fauna and appear to represent a slightly
more turbid, reduced energy environment than
that of the oolite.

3. Broken ooliths are fairly common and may be
associated with rip-up clasts, all pointing to
breaking of indurated parts of the sediments by
wave action. The fact that these are widely distrib-
uted geographically and stratigraphically sug-
gests that induration took place shortly after dep-
osition, with both free and cemented ooliths more
or less continuously disrupted, probably by storm-
induced waves. Ooliths with apophyses, and
ooliths with sides flattened against adjacent
ooliths, indicate soft-sediment deformation. Not
uncommonly these are associated with fractured
ooliths, showing that soft-sediment deformation
and indurated deformation occurred simul-
taneously. This offers additional support for the
concept of early induration.

4. Dolomitization and mineralization. North of
the dolomite front (text-fig. 2), Keel strata have
been altered by dolomitization, which in its most
extreme form completely replaces the original tex-
tures by crystalline dolomite (pl. 2, fig. 2). This
dolomitization is a part of the widespread Late
Ordovician, Silurian, and Early Devonian (Hel-
derbergian) dolomitization that is present over
much of the continental interior of North America
(Amsden, 1980, p. 52–56). I interpret this as an
early placement; however, the paleoenvironmen-
tal and paleoecological conditions associated with
this process are poorly understood. The Fe–Mn
mineralization that occurs locally in the Arbuckle
Mountains region also is interpreted as having
originated in the Late Ordovician, later modified
by solution and redeposition. These deposits may
be genetically related to the hematitic oolites to
the north (text-fig. 1).

5. The typical Keel oolite has a variable volume
of skeletal material, averaging about 18 percent

and ranging to almost 54 percent of the total rock
volume in the oolitic skeletal limestones (text-
figs. 7, 12). The fauna in the strongly oolitic beds is
dominated by pelmatozoan plates, but all facies
have a moderately diverse, exclusively marine,
mostly benthic fauna including brachiopods, cor-
als, trilobites, ostracodes, bryozoans, and mol-
lusks. (A conodont fauna is also present; see Part
II.) Locally, brachiopods and corals form a dis-
tinctive assemblage (Brevilamnulella beds), but
there is no evidence of any reef development. Evi-
dence for bioturbation is minimal, and few, if any,
of the fossils appear to be in growth position. Dis-
articulation of the brachiopods is extensive;
however, for the most part breakage of the shelly
material is moderate, and many well-preserved
whole shells, including articulated specimens, can
be collected (Amsden, 1974, pls. 1–26). It seems
evident that the shelly material was shifted about
on the sea floor by waves and (or) currents; howev-
er, the preservation indicates that this material
was not moved far and that the present fossil
assemblages are essentially life assemblages of
organisms living together in an oolite-forming
environment.

6. Keel oolitic strata are widely distributed in a
broad band extending across the Arkoma Basin of
eastern Oklahoma, the Arbuckle Mountains–
Criner Hills, and the Anadarko Basin of western
Oklahoma and the Texas Panhandle (text-fig. 4).
These strata do not form a continuous sheet across
this region but are known to occupy some very
broad, continuous areas. Moreover, at least some
of the discontinuity in the present Keel
distribution is almost certainly the result of
pre-Cochrane, pre-Blackgum (pre-late Llan-
doverian) erosion, and the original deposits
probably covered a considerably larger area. The
present distribution shows that the Keel
depositional basin occupied a large area, extend-
ing at least 300 miles (480 km) east–west and
some 150 miles (240 km) north–south, possibly as
a series of large, interconnected, shallow-water,
tropical to subtropical seaways. In some areas the
oolitic basins were associated with basins receiv-
ing fine terrigenous detritus. All of this basin
appears to be shallow water with a fairly high
energy level. However, the absence of intertidal
(birdseye) sediments would seem to rule out the
presence of much intertidal facies, and the broad
geographic distribution would seem to preclude an
offshore oolitic bar.

Arkansas and the Mississippi Valley

The distribution of oolites in the subsurface of
western Arkansas is presently unknown; howev-
er, as noted above, Late Ordovician (Hirnantian)
oolites are developed locally in north-central
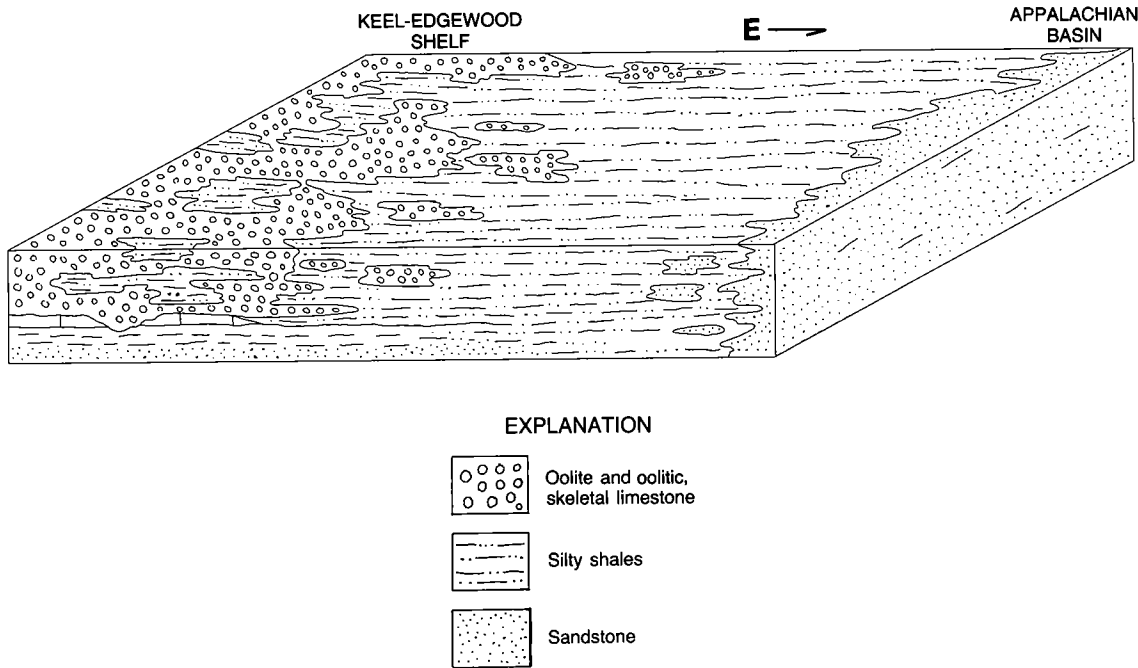Arkansas (text-figs. 2, 16). These oolites are sim-

ilar in all respects to the Keel oolites, and it seems reasonable to interpret them as developing in a similar marine environment. The Arkansas oolites are, however, closely associated with, and almost certainly a facies of, marine, phosphatic, fossiliferous siltstones and silty carbonates of the Cason Shale (text-fig. 20). Lemastus (1979, p. 28) suggested that the oolite lenses were built up in a meandering tidal channel of a large tidal flat. The fact that all of these sediments contain marine fossils would place them in a subtidal environment, but the concept of channels in a silt-sedimentation environment seems reasonable. Fe–Mn mineralization similar to that developed in the Keel Formation is widespread in the Batesville district. I believe these elements were originally introduced into the sediments at the time of deposition; however, the effect of this, if any, on the environment is unknown. The origin of this mineralization may well be similar to that which produced the hematitic Neda oolites north of the calcareous-oolite province (text-fig. 35; Mikulic, 1980, p. 253–254).

Generally similar stratigraphic relationships are present near Thebes in southwestern Illinois (text-fig. 22), where Late Ordovician strata are represented mainly by silty and argillaceous limestones with scattered ooliths and thin beds of oolite. This suggests that the region extending from north-central Arkansas eastward to southwestern Illinois lies near the southern and eastern margin of oolitic deposition, in the area where the oolitic province is grading into a siltstone–shale facies (text-figs. 35, 36). In the Cape Girardeau area of southeastern Missouri the oolites are not associated with calcareous siltstones and shales but do include considerable detrital quartz. This marly–silty environment does not appear to have had any significant effect on the shelly biofacies, and there is no clear evidence of the typical Hirnantian mudstone fauna in this area (see Hirnantian Stage).

Late Ordovician strata of Gamachian age have not been identified in the region between Illinois and the Appalachian Basin (text-fig. 35), and this part of the sequence is commonly represented by a
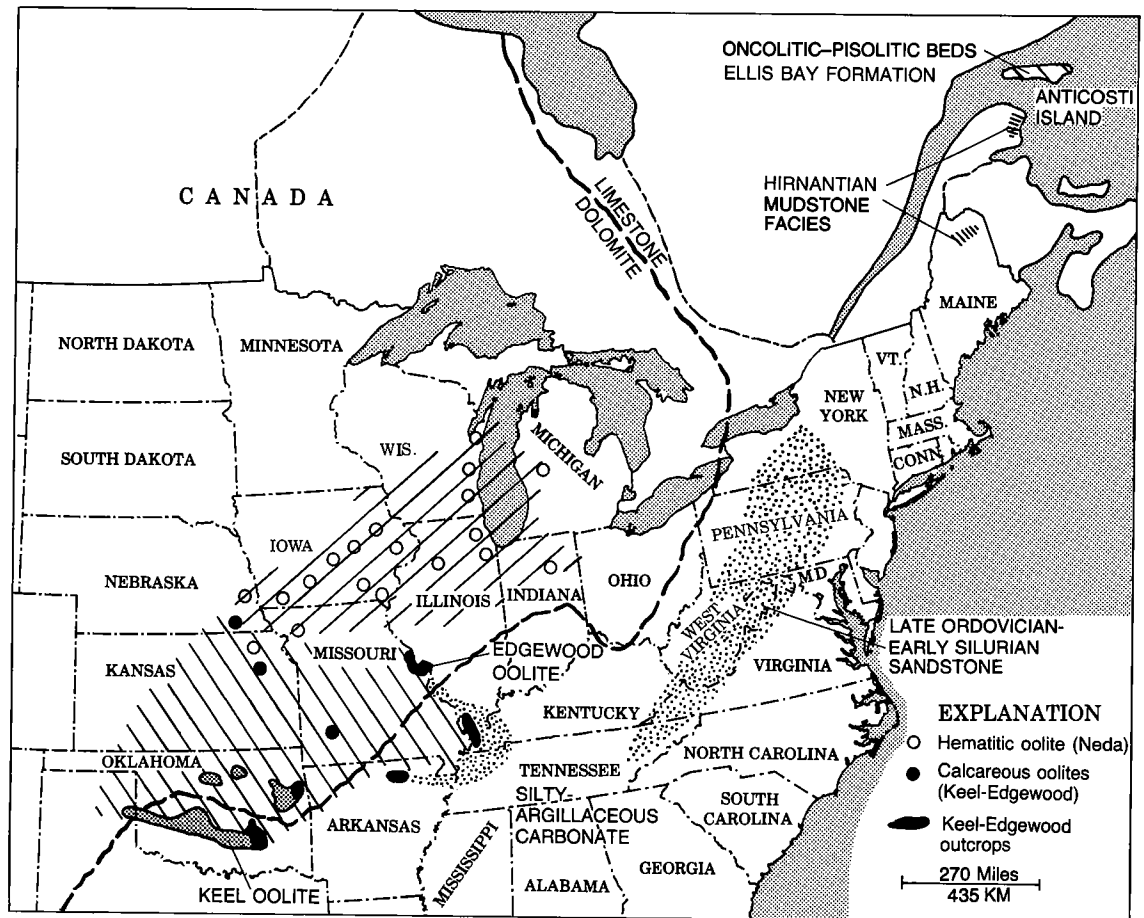
Text-figure 35. Map showing distribution of major Late Ordovician–Early Silurian facies in eastern United States and Canada: Neda hematitic oolite (diagonal lines in northern Midcontinent region) and Keel–Edgewood calcareous oolite (diagonal lines in southern Midcontinent region); information from Amsden (1974), Mikulic and Kluesendorf (1983), and Carlson (1983).

KEEL-EDGEWOOD
SHELF

E →

APPALACHIAN
BASIN

EXPLANATION

| Oolite and oolitic, skeletal limestone |
| Silty shales |
| Sandstone |

Text-figure 36. Interpretive block diagram showing inferred stratigraphic relationships extending from eastern margins of oolite province into Appalachian Basin.

chronostratigraphic gap (Ross and others, 1982, chart 3). Gamachian-age strata are probably represented in the Juniata–Tuscarora clastic sequence of the Appalachian Basin, with an east–west depositional relationship as shown in text-figure 36.

Edgewood strata do not crop out in the area between Cape Girardeau County, Missouri, and Pike County, Missouri (text-fig. 2). Edgewood strata in Pike County, Missouri, and Calhoun County, Illinois, lie north of the dolomite front and are weakly to heavily dolomitized. The Noix, Cyrene, and Bryant Knob strata appear to represent a shallow-water-marine facies similar to that of the Keel. The Bowling Green Dolomite, which I believe to be a facies of the Bryant Knob, Cyrene, and Noix, does include a moderate amount of terrigenous detritus probably derived from an eastern source.

The distribution of Hirnantian-age oolitic strata across Missouri and into eastern Kansas and Nebraska is not well understood; however, data from Mikulic (1980, fig. 24) and Carlson (1983) show the presence of oolites in this region, suggesting an original distribution similar to that in Oklahoma and the Texas Panhandle.

Warm-Water Deposition

Extensive carbonate buildups are confined to low latitudes in modern seas, and the Keel–

Edgewood oolites and skeletal limestones must certainly represent deposition in tropical to subtropical seas. Similar temperature conditions are believed to have existed over a considerable part of the world in Late Ordovician time (see Hirnantian Stage).

Regressive Sedimentary Cycle

Keel–Edgewood strata represent an exclusively marine, shallow-water oolite province occupying a large area in the central United States (text-fig. 35). Toward the east the oolites become silty, ultimately merging into the sandstones of the Appalachian Basin, as suggested in text-figures 35, 36. To the north the Neda hematitic-oolite province of similar or perhaps slightly older age is interpreted as being of subtidal to supratidal origin. Over much of this region the oolite province was succeeded by an Early Silurian period of emergence, thus representing a regressive sedimentary cycle of impressive dimensions. A regressive cycle of this scale can be related to a eustatic lowering of sea level produced by the continental-scale glaciation that affected North Africa during Late Ordovician–Early Silurian time. This is discussed in the following section on Late Ordovician–Early Silurian glaciation.

LATE ORDOVICIAN–EARLY SILURIAN GLACIATION

Continental glaciation affected a large area in North Africa in the middle Paleozoic. Dating of the glacial duration is not precise, but apparently it spanned a considerable time interval in the Late Ordovician–Early Silurian (Fairbridge, 1969; Beuf and others, 1971; Legrand, 1974, 1981). A number of sedimentary and faunal changes have been ascribed to the effects of inferred eustatic changes in sea level associated with this glaciation (Berry and Boucot, 1973; Sheehan, 1973, 1975; Dr. Phillipe Legrand, personal communication, 1983, stated that the chronology of North African glaciation is compatible with a eustatic change in sea level at this time, although he does not necessarily endorse such an interpretation). Petryk (1981, p. 81–85) attributed a transgressive–regressive sedimentary cycle in the upper Vauréal–Ellis Bay–Becscie sequence on Anticosti Island (text-fig. 37) to the effects of North African glaciation. Petryk did not recognize an emergent phase, nor to my knowledge has anyone else recognized a clearly supratidal facies or any chronostratigraphic break, and the island is generally considered to have a complete or nearly complete sequence of Late Ordovician–Early Silurian carbonate strata. However, an oncolitic–

oolitic zone at or near the top of the Ordovician (Hirnantian) indicates shallow water during this time.

Johnson and others (1981) proposed a water-depth profile for Late Ordovician–Early Silurian strata on Anticosti Island linked to the effects of North African glaciation. This zonation was based on brachiopods, with the shallowest depth attained being marked by the oncolite–pisolite bed at the top of the Ellis Bay Formation (text-fig. 35). These authors proposed a correlation between the Anticosti Island profile and water-depth profiles in Iowa, Michigan, and New York; however, only the New York section was extended back to the Ordovician. Aside from noting that no intertidal-supratidal sediments were observed on Anticosti Island, these authors provided very little lithostratigraphic or lithofacies data, their depth analysis having been based almost exclusively on brachiopod faunas. As noted in earlier publications (Amsden, 1978, p. 9–19; 1981, p. 154), I do not believe that depth analyses based on brachiopods to the virtual exclusion of any lithofacies or other megafaunal data provide a reliable indicator of the environment of deposition. However, I do believe that the oncolitic-oolitic zone at the top of the Ordovician on Anticosti Island indicates shoal water.

Brenchley and Cocks (1982) gave an excellent description and analysis of the lithofacies–

SYSTEM	SERIES	STAGE	SOUTHERN OKLAHOMA	EASTERN MISSOURI	ANTICOSTI ISLAND	OSLO FIORD
					?	
SILURIAN	LLANDOVERIAN	C	PRICES FALLS MEMBER	SEXTON CREEK FORMATION	CHICOTTE FORMATION	SOLVIK FORMATION
			COCHRANE FORMATION	?	JUPITER FORMATION	
		B	?		GUN RIVER FORMATION	
		A		? BRYANT KNOB	BECSCIE FORMATION	
ORDOVICIAN	CINCINNATIAN	RICHMONDIAN / HIRNANTIAN	KEEL FORMATION	NOIX–CYRENE FORMATION / BOWLING GREEN DOLOMITE	GAMACHIAN HIRNANTIAN BRACHIOPODS ELLIS BAY FORMATION ?	LANGØYENE FORMATION ?
			SYLVAN SHALE	MAQUOKETA SHALE		HUSBERGØYA FORMATION
					? VAUREAL FORMATION	

Text-figure 37. Stratigraphic chart showing inferred correlation of Late Ordovician–Early Silurian strata in central United States (Arbuckle Mountains–Criner Hills, south-central Oklahoma; Pike County, eastern Missouri), eastern Canada (Anticosti Island), and Norway (Oslo Fjord). Based on conodont studies of Thompson and Satterfield (1975), McCracken and Barnes (1981a, 1981b, 1982), Nowlan (1982), Barrick and Klapper (1976), Barrick (Part II, this report); brachiopod studies of Amsden (1966, 1971, 1974), Cocks and Copper (1981), Cocks (1982). Not to scale in terms of stratigraphic thickness or of time.

biofacies of Late Ordovician shallow-water strata in the Oslo–Asker district of Norway (text-fig. 37), which they ascribed to the shoaling of water associated with North African glaciation. As discussed in the section on the Hirnantian Stage, this sequence is similar in many respects to the Keel–Edgewood.

One of the best known Early Silurian sections is in the Llandovery area of Wales, where the sequence is represented by a mudstone–siltstone facies. This is the type Llandoverian Series and provides the large brachiopod fauna described by Williams in 1951. Of particular interest is the recent finding of the Hirnantian brachiopod fauna in the Scrach Formation, which consists of a sequence of shales and sandstones immediately underlying the Llandoverian strata (Cocks and others, 1983). These authors reported no chronostratigraphic break in the late Ashgillian–Hirnantian–early Llandoverian sequence, but they believed that the Scrach Formation represents a shallow-water, possibly intertidal, environment. They related it to the postulated lowering of sea level during North African glaciation.

The widespread distribution of a shallow-water, regressive depositional sequence in latest Ordovician strata of North America and Europe points to some intercontinental event such as the eustatic lowering of sea level produced by continental glaciation. There are, however, two factors which I think should be kept in mind. First, the widespread distribution of Hirnantian-age carbonate strata in many parts of the world indicates deposition in subtropical to tropical waters. This does not rule out a glacially induced lowering of sea level, although I think it should be incorporated into any paleoenvironmental analysis of Late Ordovician–Early Silurian time. Second, this explanation presumes the presence of a regressive facies in all regions where the Hirnantian–Silurian boundary is represented by a shallow-water facies; this requires further study and definition.

Berry and Boucot (1973) and Sheehan (1973, 1975, 1982) stated that Late Ordovician North American seas were populated with an endemic, provincial brachiopod fauna having little in common with its European counterpart. However, as noted in the section on Hirnantian Stage, I believe there was open access between the North American and European seas during Late Ordovician–Early Silurian time, and that where similar environments were present there was a reasonably free interchange of benthic organisms. These authors also identified a major phylogenetic break between the Late Ordovician and Early Silurian brachiopod faunas. I see no compelling evidence in the recent biostratrigraphic studies of Cocks (1982), Cocks and others (1983), and Baarli and Johnson (1982) to support a major faunal break between the Hirnantian and Early Silurian brachiopods. However, discussion of this question

is best deferred until a detailed taxonomic-biostratigraphic study of the rich Anticosti Island shelly faunas has been completed.

HIRNANTIAN STAGE

In 1974 I described the Keel–Edgewood brachiopod fauna, assigned it to the Late Ordovician, and compared it with the Hirnantian brachiopod fauna of Europe. This study identified a number of genera common to United States and European brachiopod faunas (no common species were identified). There were, however, a number of Hirnantian genera that were not known to be present in the Keel–Edgewood, and a number of Keel–Edgewood genera, including new genera proposed in 1974, that were not known to be present in the Hirnantian fauna. Thus the Keel–Edgewood brachiopods were not considered to be a typical Hirnantian mudstone assemblage, although the fauna was assigned to the Hirnantian Stage. These faunal differences were ascribed primarily to ecological factors rather than to paleogeographic or phylogenetic factors. Since publication of this bulletin, much new information has become available on the distribution of the Hirnantian fauna, especially for the more calcareous facies.

Dobb's Linn in southern Scotland was recently proposed as the stratotype section for the Ordovician–Silurian boundary, with *Parakidograptus acuminatus* marking the base of the Silurian (Williams, 1983, p. 605–611; Holland and others, 1984, p. 184; Ross and others, 1982, sheet 1), and this definition is followed in the present report. Graptolites are sparse in the Keel–Edgewood outcrop area and contribute little to the biostratigraphy of these strata. In Oklahoma, *Dicellograptus complanatus* is the youngest graptolite zone (Sylvan Shale) underlying the Keel Formation, and the oldest graptolites overlying this formation (Henryhouse Formation) are of probable latest Ludlovian age (H. Jaegar, written communication, Jan. 19, 1982). The Hirnantian brachiopod–trilobite fauna is widely distributed in Europe and was assigned to the Hirnantian Stage by Ingham and Wright (1970, p. 238–240), who regarded it as the youngest stage in the Ashgillian Series. The Hirnantian brachiopod fauna is associated with graptolites at a number of places in Europe, USSR, and China. Rong Jia-yu (1982, 1984) has shown that in China the Hirnantian fauna ranges from the *typicus* Zone to the *bohemicus* Zone, and at Kazakhstan (Apollonov and others, 1980) it is present in the *persculptus* Zone; in northeastern USSR, it is present in the *persculptus* and *extraordinarius* Zones (Koren' and others, 1983) (see below, *China, USSR*). The Hirnantian fauna is thus diachronous, ranging from the *typicus* to the *persculptus* Zones, but has not to my knowledge been reported from the *acuminatus* Zone. These

and other areas where Hirnantian faunas are closely associated with a graptolite biofacies are important because they permit reasonably precise positioning of this widespread fauna with respect to the Ordovician–Silurian boundary as determined at Dobb's Linn and elsewhere.

The following discussion is concerned largely with the Hirnantian brachiopod faunas. It is not intended as a complete register of all known Hirnantian localities but is concerned primarily with those areas in Great Britain, Europe, North Africa, USSR, and China for which reasonably detailed biostratigraphic and taxonomic data are available.

Europe

The Hirnantian brachiopod fauna is widely distributed across Europe. The fauna from Poland was described by Temple (1965), from Czechoslovakia by Marek and Havlíček (1967), from Sweden by Bergström (1968), from Ireland by Wright (1968), and from the Oslo–Asker area of Norway by Cocks (1982). This fauna occurs in strata ranging from low-calcium siltstone–mudstone to calcareous mudstones, silty limestones, limestones, and oolitic limestones. Many of these strata are at least to some degree decalcified. The megafauna also shows substantial variation, from a low-diversity brachiopod assemblage with sparse associated shelly benthic fauna to a moderately high-diversity brachiopod and high total benthic assemblage. Temple provided quantitative information on brachiopod diversity for Hirnantian strata in Poland, Aber Hirnant, and Westmorland, and Cocks and Price (1975) provide some data for the South Wales–Västergötland faunas. However, there are almost no quantitative data available for the brachiopods in the other sections, and even fewer for the total benthic assemblage. Information on the lithofacies is also sparse except for the Oslo–Asker area, where Brenchley and Cocks (1982) provided substantial lithofacies–biofacies information on Hirnantian strata. The following observations, which are based largely on published records plus information derived from my own collections, admittedly have an inadequate data base. Nevertheless, there would seem to be sufficient information on Hirnantian faunas in Europe, China, USSR, and eastern North America to support the general conclusion that the benthic faunas increase in skeletal volume (expressed as a percentage of the total rock volume) and megafaunal diversity as the strata grade from silty mudstones to impure limestones to limestones with relatively little terrigenous detritus. It should be emphasized that in categorizing faunal diversity a clear distinction is made in this report between *brachiopod diversity* and *total benthic diversity* (i.e., brachiopods, trilobites, pelmatozoans, corals, bryozoans, etc.).

The generic chart shown in text-figure 38 was compiled from the published sources cited in the explanation. It will be noted that the various Hirnantian localities in Europe show considerable variation in diversity of the brachiopod faunas, with the biofacies in Czechoslovakia (15 species), central Sweden (16 species), and Oslo–Asker (24 species) showing the greatest diversity. The brachiopod diversity of the Swedish Hirnantian strata (16) stands in sharp contrast to the low-diversity fauna from Poland (7); having collected from both areas, I can provide additional lithofacies–biofacies information to that given by Bergström (1968) and Temple (1965). The Polish strata I observed are all low-calcium, micaceous, silty mudstones. Two thin sections show this to be a silty, micaceous, weakly glauconitic mudstone ranging to an argillaceous siltstone. The silt is mostly angular to subrounded quartz detritus, generally less than 0.05 mm in diameter, with a few grains ranging up to 0.2 mm. The fauna is very largely brachiopods, which in some beds are associated with various concentrations of trilobites (Kielan, 1959). Disarticulation of the brachiopods is extensive, but breakage of the valves is minimal, indicating a moderate to strong energy regime. As noted by Temple (1965, p. 416), the dominant species is the small *Kinella kielanae*, which commonly occurs as isolated valves scattered through the matrix. I have observed very few other benthic fossils, and the Polish Hirnantian fauna can be characterized as a low-diversity brachiopod, and low-diversity total benthic, fauna.

According to Bergström (1968, p. 3), the Hirnantian strata of central Sweden consist of interbedded shales and limestones. All the material in my collections from this area consists of heavily decalcified silty mudstones and argillaceous siltstones. Three thin sections show a weakly micaceous, silty mudstone with a high concentration of shelly material, ranging to an argillaceous siltstone. The silt is mostly angular to subrounded quartz detritus, generally less than 0.05 mm in diameter but with a few grains ranging up to 0.1 mm or slightly larger. The concentration of shelly material has increased sharply over the Polish strata, with parts approaching a grain-supported texture, and I suspect that prior to decalcification many of the beds approached a fossiliferous, calcareous marlstone. Accompanying the brachiopods and trilobites are numerous crinoid plates and abundant ramose and stick bryozoans. On the whole, the biofacies of the Swedish Hirnantian is characterized by a moderately diverse brachiopod fauna and a moderately diverse total benthic fauna.

Of particular interest are the excellent recent studies by Cocks (1982) and Brenchley and Cocks (1982) of the Hirnantian beds in the Oslo–Asker area. This sequence, which attains a maximum

	EUROPE								NORTH AMERICA	
	Aber Hirnant, Wales; Temple (1965)	Hol Beck, Westmorland: Temple (1965)	Llandovery, Wales: Cocks and others (1983)	Ireland: Wright (1968)	Oslo-Asker, Norway; Cocks (1982)	Västergötland, Sweden; Bergström (1968)	Cnechoslovakia; Marek and Havlíček (1967)	Poland, Holy Cross Mountains; Temple (1965)	Anticosti Island, Canada; Cocks and Copper (1981)	Midcontinent, U.S.A.; Amsden (1974)
Giraldibella						X	X			
Dolerorthis					X					X
Platystrophia					X					X
Hesperorthis					X					
Bancroftina								X		
Dalmanella	X	X	X	X	X	X	X	X	X	X
Hirnantia	X	X	X	X	X	X	X	X	X	X
Kinnella	X	X				X		X		
Drabovia					X	X	X			
Draborthis						X	X			
Horderleyella						X				
Comatopoma							X			
Onniella					X		X			
Paucicrura					X					
Dicoelosia-Epitomyonia					X					X
Cliftonia										X
Leangella						X				
Aphanomena						X				
Leptaena					X	X	X			X
Biparetis										X
Leptaenopoma				X		X	X			
Titanomena						X				
Rafinesquina (Eostropheodonta)	X	X		X	X	X	X	X	X	X
Strophomena					X					
Platymena?									X	
Kjerulfina					X					
Christiania					X					
Eoplectodonta					X					
Aegiromena							X			
Coolinia					X	X			X	X
Fardenia							X			
Brevilamnulella					X					X
Holorhynchus					X					
Plectothyrella	X	X	X	X	X	X	X	X		
Thebesia					X					X
Stegerhynchus					X					X
Leptoskelidion					X					X
Laticrura					X					
Cryptothyrella				X		X	X			X
Eospirigerina					X					X
Zygospira?							X			
Hindella?					X				X	

Text-figure 38. Chart showing distribution of Hirnantian articulate-brachiopod genera in Europe, Anticosti Island, Québec, and Keel-Edgewood strata in the Midcontinent of the United States. (Note that only those Keel-Edgewood genera are recorded that also occur in Europe.)

thickness of about 60 m (Brenchley and Cocks, 1982, text-fig. 3), consists of an intergrading sequence of calcareous mudstones, impure limestones, limestones, oolitic limestones, and sandstones. In these studies the authors recognize 10 faunal associations for which they provide a coordinated analysis of the biofacies and lithofacies. The *Hirnantia* Association (Brenchley and Cocks, 1982, p. 795–798) is at the base of the sequence and includes such typical Hirnantian species as *Hirnantia sagittifera, Dalmanella testudinaria,* and *Eostropheodonta hirnantensis.* The total fauna recorded has eight articulate brachiopod genera and four trilobite genera, along with gastropods, thin stick bryozoans, and halysitid corals. Occurring in the same zone is the *Hindella–Cliftonia* Association (Brenchley and Cocks, 1982, p. 798–799), which includes about 20 articulate brachiopod genera including Keel–Edgewood genera such as *Cliftonia, Dalmanella, Coolinia, Dolerorthis, Eospirigerina, Epitomyonia (Dicoelosia?),* and *Platystrophia.* The enclosing lithofacies is more calcareous than that of the *Hirnantia* Association and includes a limestone bed as much as 1 m thick. A series of other faunal associations is present in the overlying sandstones and shales (Brenchley and Cocks, 1982, text-fig. 7). At the top of the Hirnantian sequence is the *Thebesia* Association (Brenchley and Cocks, 1982, p. 802–803), which includes *Thebesia, Leptoskelidion, Hindella(?), Comotopoma, Dalmanella, Dolerorthis, Eostropheodonta, Kjaerina?, Hesperorthis, Onniella,* and *Stegerhynchus?,* along with trilobites, streptelasmatid corals, bryozoans, and mollusks. (*Thebesia* and *Leptoskelidion* are based on Keel–Edgewood species.) These are described as tidal-channel-fill deposits composed of a variety of sediments, some representing a fairly high energy level.

The *Brevilamnulella* Association also occurs near the top of the Ordovician. This is generally a low-diversity fauna composed mainly of *B. kjerulfi;* however, locally it is associated with *Rostricellula?, Eoplectodonta, Eospirigerina, Hesperorthis?, Hindella(?), Leptaena, Onniella,* bryozoans, and streptelasmatid corals. Brenchley and Cocks (1982, p. 803–804) characterized this as a coquina fauna and expressed uncertainty about its relationship to the underlying strata. They reported it from two localities, the first being a "development of up to 9 m of bioclastic limestone containing some ooids, which might either be a local facies variant of the ooidal shoals, or alternately might lie within a channel cut into the oolite." The second occurrence of the *Brevilamnulella* fauna is at the northern margin of the study area at two places near Sem Vatern (Grid Refs. NM 799364, NM 800364), where it is abundant in several beds in calcareous siltstones near the top of the Ordovician sequence at each locality. *Brevilamnulella thebesensis* is widely distributed

in the Keel and Edgewood strata, and locally it is concentrated into a low-diversity conquina similar to that found in the Oslo–Asker area; however, *B. thebesensis* also is associated with most of the other Keel–Edgewood brachiopods.

Dr. Nils Spjeldnaes, University of Aarhus, Denmark (personal communication, October 1983) does not agree with Brenchley and Cocks that these represent channel deposits. He believes they are separated from the underlying beds by a regional unconformity. These points of view are perhaps not as divergent as they might appear, because all three agree that the strata in question are of Late Ordovician age (Hirnantian) and are overlain by the Early Silurian dark shales (*acuminatus* Zone). According to present information, the Hirnantian fauna ranges through three graptolite zones, and the possibility of some detectable phylogenetic changes in the brachiopod faunas should not be ignored. Thus the *Brevilamnulella–Thebesia* Association may be the result of faunal changes occurring at the unconformity reported by Dr. Spjeldnaes. There is, however, nothing in the reported associated faunas that would support such an explanation. I think the explanation by Brenchley and Cocks, that these represented specialized faunas that colonized carbonate shoals, is a more reasonable explanation, especially as they were well adapted to such an environment in the Keel–Edgewood seas. Moreover, in the North America Hirnantian faunas, *Brevilamnulella* and *Thebesia* are associated with a varied benthic fauna, including many of the genera present in the lower beds of the Oslo–Asker area (text-fig. 38). (*Leptoskelidion* is an uncommon brachiopod in the Keel–Edgewood strata.)

The Oslo–Asker Hirnantian strata have the most diverse brachiopod fauna (text-fig. 38) of any of the described European faunas, and also the most diverse total benthic fauna. I believe this can be correlated with lithofacies changes reflecting distinct changes in the paleoenvironment. The paleoenvironment of the typical Hirnantian silty mudstone must have been a soft mud substrate with much turbidity and fine siltation, whereas the more calcareous facies of the Oslo–Asker area points to a firmer substrate with sharply reduced terrigenous sedimentation. The Oslo–Asker Hirnantian fauna also has the closest resemblance to the Keel–Edgewood fauna (a total of 26 articulate brachiopod genera) of any of the European localities, with 14 of the Norwegian genera present in the Keel–Edgewood (text-fig. 38; if the three genera from the channel deposits discussed above are eliminated, there are 11 genera). Halysitid and streptelasmatid corals are also a common element in both faunas. Finally, it should be noted that the phylogenetic stage of development of the articulate brachiopods is similar in both areas, as shown in such groups as the dicoelosiids, rafinesquinids, leptaenids, pentamerids, and meekellids.

According to Brenchley and Cocks (1982, p. 783, 790–792), the Hirnantian strata of the Oslo–Asker area were deposited in subtropical latitudes and the regression at the close of the Ordovician was caused by eustatic changes in sea level associated with Late Ordovician–Early Silurian glaciation.

Maine

Neuman (1968, p. 44) reported a small fauna of shelly fossils from a thin bed of gray, pebbly mudstone at Ashland, Aroostook County, Maine. The brachiopods reported were *Skenidioides* sp., ?*Horderleyella* sp., *Hirnantia* sp., an undetermined enteletacean, *Leptaena* sp., *Cryptothyrella* sp., and *Plectothyrella* sp. He reported a second fauna northeast of Ashland from a gray, conglomeratic siltstone with volcanic pebbles which included *Hirnantia* sp., *Triplecia*, *Oxoplecia* sp., *Cryptothyrella* sp., and *Plectothyrella* sp. Most of these are typical Hirnantian genera, indicating a correlation with the Whitehead (unit 5) fauna from Gaspé, Quebec, and the Hirnantian mudstone fauna from Europe and elsewhere. Elias (1982, p. 41, text-fig. 22, p. 73) reports the coral *Grewingkia pulchella* (Billings) from a collection made by Neuman 9 km east of Ashland, Maine; it is not clear, however, whether the Hirnantian brachiopods and this coral came from the same locality and bed.

Canada

Recently, Cocks and Copper (1981) reported a Hirnantian brachiopod fauna from the upper part of the Ellis Bay Formation at the eastern end of Anticosti Island. (These strata comprise the upper part of the Gamachian stage of Twenhofel, 1928, p. 15.) This fauna came from a crossbedded, arenaceous limestone about 4 ½ m below the Ordovician–Silurian boundary (Ellis Bay–Becscie contact), the topmost bed of the Ordovician being a pisolitic algal limestone (Cocks and Copper, 1981, fig. 2). Based on conodonts collected from this same section, Nowlan (1982, p. 1332–1335) placed the Ordovician–Silurian boundary at the same stratigraphic position (see Part II). This fauna consisted of the following articulate brachiopod species: *Dalmanella testudinaria, Fardenia* aff. *F. dalmani* (*Coolinia dalmani*), *Eostropheodonta* cf. *E. latisculptilis* [*Rafinesquina?*], *Hirnantia* sp., and *Hindella?* sp. These authors correlated this fauna with the Hirnantian fauna of Europe and suggested that the pisolite at the top of the Ordovician represents shallow water caused by the eustatic lowering of sea level during Late Ordovician–Early Silurian glaciation. All of these genera, with the possible exception of *Hindella?* and one of the species (*R.? latisculptilis*), are

present in the Keel–Edgewood (text-fig. 38), and I believe that the upper part of the Ellis Bay and the Keel–Edgewood strata are essentially contemporaneous.

Lespérance and Sheehan (1976, 1981) described Hirnantian brachiopods from unit 5 of the Whitehead Formation at two localities on Gaspé, one at Cape Blanc and the other along the Flynn road about a mile inland from the cape (text-fig. 35). These fossils were collected from red mudstones and calcareous sandstones and include the following brachiopods: *Dalmanella testudinaria, Hirnantia sagittifera, Plectothyrella* n. sp., *Eostropheodonta siluriana*, and *Hindella?* sp. Associated with the brachiopods were representatives of the trilobites *Mucronaspis* and *Brongniartella*, a calcareous sponge, and the graptolite *Climacograptus venustus venustus*. (Williams, 1983, p. 609, discussed this graptolite occurrence.) A number of solitary and colonial corals have been reported from unit 4 of the Whitehead Formation (Elias, 1982, p. 41–43).

In 1981 I made a small collection from the Hirnantian beds at the Flynn road exposure, which consisted largely of brachiopods along with a few trilobite fragments and rare specimens of a small bryozoan. Lespérance and Sheehan characterized this as a typical Hirnantian fauna, and it certainly has a low-diversity brachiopod fauna and a low-diversity total benthic fauna similar to that from the Hirnantian silty mudstones of Eurpoe and China. Four thin sections show a sandstone composed largely of angular to subrounded quartz grains, most of which are less than 0.15 mm in diameter. There is a substantial volume of shelly material, predominantly brachiopod shells along with some bryozoans (stick or dendroid forms), a few pelmatozoan plates, and trilobites. Most of the brachiopods are strophomenids, presumably *Eostropheodonta siluriana* (Lespérance and Sheehan, 1981, p. 232). The brachiopod shells are largely disarticulated and most of the shelly material shows some breakage, suggesting a fairly high-energy depositional environment for these particular beds. Lithologically, this rock differs from the typical Hirnantian mudstones of Europe in having a much higher volume of quartz detritus, much of which is fine-sand size (it is not decalcified). This rock also has a relatively high concentration of shelly debris, and some beds may approach a grain (shell)-supported texture. Most of the brachiopods are disarticulated, but the individual valves are not heavily fragmented. Thus the unit appears to represent a relatively shallow-water deposit exposed to considerable wave and (or) current action, although not of the intensity found in beach or near-beach environments. The Whitehead Hirnantian exposures are about 150 km southwest of the Anticosti Island Hirnantian beds (text-fig. 35).

North Africa

Havlíček (1971) described and illustrated a small fauna from the Grès du deuxième Bani in the Anti–Atlas Mountains of southwestern Morocco. Specifically identified specimens include the following: *Horderleyella* cf. *H. bouceki*, *Arenorthis arenaria*, *Destombesium ellipsoides*, *D. zagoraensis*, *Hirnantia sagittifera*, *Dalejina nascens*, *Eostropheodonta squamosa*, *E. jebiletensis*, *Plectothyrella chauveli*, and *Undithyrella undosa*. Havlíček (1971, p. 13) compares the stratigraphic position of these strata to that of the Kosov Formation of Czechoslovakia, and the composition of the brachiopod fauna certainly indicates Hirnantian affinities. Havlíček also notes that J. Destombes considers the Grès du deuxième Bani to be of glacial origin.

Havlíček and Massa (1973) described and illustrated specimens of *Hirnantia* aff. *H. sagittifera*, and *Plectothyrella libyca* from the Memouniat Formation of western Libya. This formation was assigned a probable late Ashgillian age and is considered to be a cold-water deposit of subglacial or periglacial origin.

Massa, Havlíček, and Bonnefous (1977, p. 3–9) provide a short but informative discussion on the distribution of glacial strata in Libya and Tunisia. Of particular interest are their comments on the Memouniat Formation which they believe "coincides with the second and ultimate, cycle of glaciation resting with an erosional unconformity (discordance de raviement) on the earlier formations of Ordovician or even Cambrian age. . . . Its sediments, mostly sandy, are affected by glaciation as shown by the common occurrence of striae." To my knowledge, only the two articulate brachiopods cited above have been described from this formation. Although these certainly suggest a correlation with the Hirnantian fauna of Europe, a larger, more definitive fauna would be helpful.

China

The Hirnantian fauna is widely distributed in central and eastern China (Hubei, Anhui, Zhejiang, Jiangxi, Sichuan Provinces), southwestern China (Hunan and Guizhou Provinces), and Tibet (Xizang Province). Rong (1979) stated that this fauna is known from about 90 localities. In most areas it is interbedded with graptolites representing the standard European zones and thus can be correlated with Hirnantian strata in many parts of Europe. In east-central China, Hirnantian beds are silty mudstones with a brachiopod–trilobite assemblage of low total benthic diversity. However, at the section near Beijong in Anhui Province, the Hirnantian fauna occurs in a mudstone with *Diplograptus bohemicus* and an assortment of benthic forms including brachiopods, trilobites, cephalopods, bivalves, ostracodes, and gastropods

(Li Ji-jin and others, 1983, p. 123–129). In Tibet the Hirnantian fauna occurs in a silty dolomite and dolomitic siltstone and includes the following species: *Hirnantia sagittifera*, *Dalmanella testudinaria*, *Kinnella kielanae*, "*Horderleyella*" *xainzaeusis*, *Cliftonia* cf. *C psittacina*, *Aegiromena ultima*, *Aphanomena ultrix*, *Paromalomena polonica*, *Plectothyrella uniplicata*, and *Eospirigerina* sp. (Rong Jia-yu and Xu Han-kui, 1983, p. 139–140). (*Eospirigerina* is present in the Oslo–Asker area, where it is found with the *Hindella–Cliftonia* Association. It is also abundant in the Edgewood strata of the Mississippi River sections).

Hirnantian beds are exposed at several places in the Yangtze Gorges area (Hubei Province) of central China (Mu En-zhi and others, 1983, p. 94–106; Rong Jia-yu, 1983, p. 110–112). In 1983 I examined and collected from four sections in this area: Wangjiawan, trench 502 near Huanghuachang, Baoshan, and Fenxiang. The Hirnantian beds consist of some 10 to 50 cm of blocky, silty mudstones interbedded with graptolitic shales. Seven thin sections from the four outcrops show a fairly consistent lithology of burrowed, micaceous, silty mudstone. The silt is sparingly dispersed and consists of fine (less than 0.05 mm), angular to subangular quartz detritus. Some beds are extensively burrowed, and these burrows are commonly filled with concentrations of quartz detritus whose individual grains are consistently coarser (up to 0.5 mm) and better rounded than most of the grains randomly dispersed through the mudstones. Also, one lens 10 mm thick was observed with a concentration of rounded quartz grains as large as 1 mm in diameter. With the exception of these highly localized concentrations of quartz grains, Hirnantian beds I observed in the Hubei Province differ from the Polish and Västergötland strata in having a distinctly reduced volume of quartz detritus, which is for the most part composed of finer and more angular quartz grains.

According to Rong (1983, p. 110), this is a fairly high-diversity brachiopod fauna with a total (all localities in western Hubei Province) of more than 20 genera, and with each of the separate localities yielding from 15 to 19 genera. Common genera reported by Rong are *Hirnantia*, *Aphanomena*, *Kinnella*, *Cliftonia*, and *Paromalomena*, and less common are *Toxorthis*, *Dalmanella*, "*Horderleyella*," *Onniella*, "*Bancroftina*," "*Sphenotreta*," *Plectothyrella*, and *Hindella*(?). Trilobites are also present and Zhu Zhao-ling and Wu Hong-ji (1983, p. 112–113) reported *Dalmanitina*, *Platycoryphe*, and *Leonaspis*. The collections I made from these four sections have many brachiopods, some trilobites, and a few small, isolated crinoid plates. The brachiopods are largely disarticulated, but the preservation of the isolated valves is excellent. This appears to be the typical brachiopod–trilobite

low total-benthic-diversity Hirnantian silty-mudstone fauna representing a depositional environment with a moderate energy level and a continuous supply of clay and silt-sized terrigenous detritus.

The Hirnantian beds appear to have a greater concentration of quartz detritus than the overlying and underlying graptolitic beds. This lithologic distinction is, however, not clearly marked, and at some localities the Hirnantian brachiopod fauna is associated with graptolites (Li and others, 1983).

Chen (1984), in a recent paper, discussed the influence of Late Ordovician–Early Silurian glaciation on the Yangtze Platform. He believes the maximum regression associated with this glaciation occurred in Hirnantian time and that it was followed by a relatively rapid transgression in early Llandoverian time. Chen provided three paleogeographic maps showing the inferred distribution of land and sea during the early Wufengian (early Ashgillian), late Wufengian (late Ashgillian), and Early Silurian. The precise distribution of the Hirnantian sea(s) across Europe, USSR, and China is beyond the scope of this report. However, as noted below, I do believe there was a reasonably free interchange of benthic faunas in the region extending from eastern North America across Europe into eastern USSR and China (see the later section on Paleoenvironment). Chen (1984, p. 57), following the interpretation of Rong (1979), stated: "The occurrence of the *Hirnantia* fauna in the Yangtze basin is closely related to lithology, it is present mainly in marls and mudstones, rarely in argillaceous siltstones, and is entirely absent in dolomites, pure limestones and reefal limestones (Rong, 1979). It appears that the *Hirnantia* fauna is mainly a shallow, cool-water fauna, although at the 1982 Oslo symposium Rong reported that the *Hirnantia* fauna possibly also existed in warm waters."

USSR

A substantial Hirnantian brachiopod fauna has been described from southeastern Kazakhstan (Apollonov and others, 1980, p. 35–74, 214, fig. 7). According to these authors:

In the continuous succession in Kazakhstan the following stratigraphic units are distinguished:

1) the Chokpar horizon containing graptolites of the *supernus* zone, brachiopods and corals, characteristic of the *Holorhynchus giganteus* beds and another diverse shelly fauna;

2) the Durben horizon with *persculptus* zone s.l. graptolites, the *Dalmanitina mucronata* trilobite assemblage and the typical Hirnantian brachiopod assemblage in its upper part; (Mu En-zhi and Rong Jia-yu, 1983, p. 15, state that the *persculptus* Zone of the Kazakhstan sections should be considered

equivalent to either the *D. bohemicus* (W6) Zone or the *C. extraordinarius* Zone);

3) the Alpeis horizon with graptolites of the *acuminatus, vesiculosus, cyphus,* and probably *gregarius* zone.

The Chokpar and Durben zones (pre-*acuminatus* beds) comprise a sequence of interbedded limestones and silty shales (Apollonov and others, 1980, fig. 1). This report describes a large benthic fauna of corals, brachiopods, trilobites, and mollusks, presumably all coming from these two stratigraphic units. Thirty-one species of brachiopods are described, representing the following articulate genera: *Dalmanella, Hirnantia, Triplesia, Cliftonia, Streptis, Sowerbyella, Anisopleurella, Eoplectodonta, Aegiromena, Kassinella, Rafinesquina(?), Leptaena, Leptaenopoma, Bracteoleptaena, Eostropheodonta, Coolinia, Holorhynchus, Proconchidium, Tcherskidium?, Prostricklandia, Rhynchotrema, Zygospiraella, Spirigerina, Eospirigerina, Iliella,* and *Cryptothyrella?.* This is a high-diversity brachiopod and high-diversity total benthic fauna. The brachiopod fauna is similar to that of the Hirnantian beds in the Oslo–Asker area, with the following eight genera in common: *Dalmanella, Hirnantia, Eoplectodonta, Rafinesquina (Eostropheodonta), Leptaena, Coolinia, Holorhynchus,* and *Eospirigerina.* It is also similar to that from the Keel–Edgewood, with the following eight genera in common: *Dalmanella, Hirnantia, Cliftonia, Leptaena, Rafinesquina (Eostropheodonta), Coolinia, Eospirigerina,* and *Cryptothyrella.*

A large Hirnantian fauna was reported by Oradovskaya (1977, p. 954–956) in the Omulensk Mountains of the Kolyma River basin (Mirny Creek section) of northeastern USSR. This fauna ranges through about 70 m of marls, calcareous marls, and thin limestones in the upper part of the Q Member. Oradovskaya listed the following brachiopods from calcareous lenses: *Hesperorthis* sp., *Giraldiella* sp., *Drabovia agnata* Marek and Havlíček, *Hirnantia* cf. *H. sagittifera, Dalmanella* cf. *D. testudinaria* Dalman, *Sowerbyella* sp. indet., *Rafinesquina (Playfairia)* sp., *Leptaena,* cf. *L. aequalis* Amsden, *Bekkeromena(?)* sp., *Eostropheodonta* cf. *E. hirnantensis lucavica* Oradovskaya *Brevilamnulella thebesensis* (Savage), *Thebesia admiranda* (Oradovskaya), *Stegerhynchus concinna* (Savage), and *Eospirigerina putilla prisca* (Oradovskaya). The yellow marls underlying these limestones contain fragments of *Eostropheodonta* cf. *E. hirnantensis lucavica* Oradovskaya and *Eospirigerina putilla prisca* (Oradovskaya). Strata that overlie the brachiopod beds contain *Dalmantina* cf. *D. olini* Temple and *Leptaena* cf. *L. aequalis* Amsden. Above the trilobite beds are black, silty-calcareous shales with *Akidograptus(?) acuminatus* (Williams, 1983, p. 609, questions this generic assignment).

Additional information on the Mirny Creek section was presented by Oradovskaya and Sobolevskaya (1979, p. 74–76, charts figs. 4, 5) in a guidebook providing details on the lithostratigraphy and faunas, including illustrations of a number of brachiopods. Unit 70, which falls within the *Glyptograptus persculptus* Zone of the Q Member, comprises a sequence of calcareous siltstones with interbeds of organogenetic limestones. (Mu Eh-zhi and Rong Jia-yu, 1983, p. 16, state that the *G. persculptus* forma B Zone in the Mirny Creek section is actually equivalent to the *C. extraordinarius* Zone.) This interval includes a 1.1-m-thick bed of gray detrital limestone with abundant brachiopods, trilobites, corals, bryozoans, and gastropods. The following brachiopod species were reported: *Hesperorthis* cf. *H. davidsoni* Verneuil, *Giraldibella* ex gr. *subsilurica* (Marek and Havlíček), *Drabovia* ex gr. *asperula* (Barrande), *Dalmanella* cf. *D. testudinaria* (Dalman), *Hirnantia* aff. *H. sagittifera* (M'Coy), *Kinella* ex gr. *kielanae* (Temple), *Isorthis* sp., *Enteletacea, Dicoelosia*? sp., *Cliftonia* sp. indet., *Eoplectodonta* sp. indet., *Biparetis paucirugosus* Amsden, *Leptaena aequalis* Amsden, *Eostropheodonta hirnantensis lucavica* Oradovskaya, *Parastrophinella* sp., Virgianidae, *Brevilamnulella thebesensis* (Savage), *B.* sp., *Plectothyrella* sp., oligorhynchiidae, *Rhynchotrema* sp., *Stegerhynchus concinna* Amsden, *Thebesia admiranda* (Oradovskaya), *Eospirigerina putilla prisca* (Oradovskaya), *E.* aff. *E. sublevis* (Rozm.), *E.* sp., *Plectatrypa* sp., *Cryptothyrella terebratulina* (Wahlenberg), and *Hyattidina* sp. *Holorhynchus* cf. *H. giganteus* Kiaer is present in the underlying unit. Member Q is overlain by Member R, with *Akidograptus*(?) *acuminatus praecedens* reported from the lower part and *A.*(?) *acuminatus* from the upper part, and underlain by *Paraorthograptus pacificus* (Oradovskaya and Sobolevskaya, 1979, p. 76–77, fig. 5).

The Hirnantian fauna from this region (unit Q, *extraordinarius–perscuptus* zones) was described and illustrated in a recent monograph by Koren' and others (1983). These authors included several species in addition to those cited above, including *Dolerorthis* aff. *intermedius* Nikiforova, *D.*? *savagei* Amsden, *Giraldibella* aff. *bella* (Bergström), *Rafinesquina* aff. *latisculptilis* (Savage), *Biparetis paucirugosus* Amsden, *Coolinia* sp., and *Eospirigerina gaspeensis* (Cooper).

The Mirny Creek Hirnantian beds consist of limestones and calcareous marlstones interbedded with some graptolitic shales. The preservation of the illustrated brachiopods (Koren' and others, 1983, pls. 1–18) is good, including a number of articulated shells, which suggests that this is essentially an *in situ* assemblage. The limestones contain a high-diversity brachiopod fauna and a high-diversity total benthic fauna consisting of abundant brachiopods associated with trilobites, corals, bryozoans, and gastropods

(Oradovskaya and Sobolevskaya, 1979, p. 53). In its faunal diversity the Mirny Creek resembles the Oslo–Asker and Keel–Edgewood biofacies, and the brachiopods from these three regions also have marked taxonomic affinities. The following Keel–Edgewood genera and species are reported from the Mirny Creek strata: *Dalmanella, Dolerorthis, Hirnantia, Dicoelosia*?, *Cliftonia, Coolinia, Biparetis, Leptaena, Rafinesquina* (*Eostropheodonta*), *Brevilamnulella, Stegerhynchus, Thebesia, Eospirigerina, Dolerorthis savagei, Biparetis paucirugosus, Rafinesquina* aff. *latisculptilis, Leptaena aequalis, Brevilamnulella thebesia, Stegerhynchus concinna, Eospirigerina putilla prisca*. The quality of plate reproduction in these publications makes it difficult to verify all species identifications: however, the taxonomic similarity between the Mirny Creek and the Keel–Edgewood brachiopods is readily apparent. Ten of the reported Mirny Creek genera are also present in the Oslo–Asker area.

Hirnantian strata from Kazakhstan and the Mirny Creek area provide additional evidence that environment played a major role in controlling the distribution of the benthic faunas. The clear carbonate seas supported a much higher diversity assemblage than did those areas receiving a heavy influx of fine silt and clay detritus. Moreover, the carbonate buildup in the Mirny Creek Hirnantian strata appears to represent deposition in a subtropical to tropical environment. This is in accord with the interpretation expressed elsewhere in this report, that Hirnantian seas in many areas were warm.

Paleoenvironment

Late Ordovician seas commonly have been interpreted as characterized by relatively cold water (Berry and Boucot, 1973; Sheehan, 1973; Sheehan and Lespérance, 1981, p. 247). This interpretation appears to be based partly on a world-wide extension of the effects of Late Ordovician glaciation and partly on inferences drawn from the widespread Hirnantian mudstones with their restricted benthic faunas. For some time it has been known that the Hirnantian silty mudstones are locally interbedded with skeletal limestones, as at Västergötland and Ireland. The recent study by Brenchley and Cocks (1982) shows an even stronger development of the carbonate facies in the Oslo area, which these authors interpret as representing a subtropical marine environment. When the carbonate facies now known to be present in the USSR, the U.S. Midcontinent area, and Anticosti Island are included, it becomes apparent that during latest Ordovician time large areas must have been occupied by warm-water seas. Moreover, the close association of silty mudstones and carbonate strata in these and other Hirnantian localities places a severe strain on the cold-water hypothe-

sis, and I believe that the Hirnantian silty mudstones which were not in close proximity to the center of North African glaciation were also deposited in warm, relatively shallow water (Rong, 1984, p. 108–109). According to this explanation, the major factors controlling the distribution of the restricted Hirnantian mudstone faunas were a soft substrate and a continuous influx of clay- and silt-sized terrigenous detritus. In areas where the flood of clay- and silt-sized terrigenous detritus was reduced or eliminated, the seas cleared, the substrate firmed, and a more diverse benthic fauna was established. This is not to exclude all phylogenetic and (or) paleogeographic influence on the Hirnantian benthic faunas, but the lithofacies–biofacies relationship suggests that these paleoenvironmental shifts were the major factors during the relatively short period of Hirnantian time.

The Hirnantian brachiopod–trilobite lithofacies–biofacies is presently known to be distributed across a broad belt extending from eastern North America (Midcontinent U.S.A., Anticosti Island, Gaspé), North Africa, Europe (Ireland, Wales, England, Scandinavia, Czechoslovakia, Poland), USSR (Kazakhstan, northeastern USSR), and China (central and eastern regions and Tibet). All of these localities are in the northern hemisphere. If North America is placed in proximity to Europe, as it most probably was in Late Ordovician time, the localities appear to represent a belt of shallow-marine sediments deposited in a widespread cratonic basin or series of interconnected basins with a free interchange of benthic organisms where compatible environments were present. Substantial quantities of fine terrigenous detritus were being supplied to this basin. The most likely source of this detritus would seem to be in the region to the south, centering around the North African glaciation (Havlíček, 1976, p. 350). From time to time this influx of detritus was locally reduced, the seas cleared, and a varied benthic fauna was established.

Phylogeny of Late Ordovician–Early Silurian Shelly Faunas

In recent years there has been much discussion on the phylogeny of Late Ordovician–Early Silurian shelly faunas. Sheehan (1973, 1975), Berry and Boucot (1973), and others expressed a belief that large-scale extinctions took place at this time, extinctions generally postulated to be related to environmental changes associated with late Ordovician–Early Silurian North African glaciation. Faunal evidence to support these conclusions has been sketchy, partly because Late Ordovician–Early Silurian time in many parts of the world is represented by either a chronostratigraphic gap or by sparingly fossiliferous mudstones. Until recently, information on the shelly faunas came largely from the restricted Hirnantian mudstones and Williams' 1951 study of Llandoverian strata. Recent studies on the calcareous facies of the Hirnantian Stage (Amsden, 1974; Cocks and Copper, 1981; Cocks, 1982; Elias, 1982) and of the Llandoverian strata (Cocks and others, 1983; Baarli and Johnson, 1982) provide substantial new information on key faunas, which strongly suggests that the faunal changes at this time were gradational rather than catastrophic. Undoubtedly, the best potential source of information on the phylogeny of shelly faunas is the richly fossiliferous carbonate sequence on Anticosti Island, which probably represents an essentially uninterrupted sequence of Late Ordovician–Early Silurian strata (Twenhofel, 1928; Lespérance, 1981). Since Twenhofel's 1928 monographic study, only restricted faunal studies covering small stratigraphic intervals have been published; however, the pressing need is for comprehensive biostratigraphic–taxonomic studies of selected groups (brachiopods, trilobites, etc.) covering the complete stratigraphic interval exposed on the island. This should go far toward resolving the questions concerning evidence used to support the postulated major extinctions.

Diachronism

The Hirnantian fauna is known to range from the *Diplograptus bohemicus* Zone into the *Glyptograptus persculptus* Zone (Rong and Xu, 1983, p. 139). In a recent paper, Sundberg and Miller (1982, fig. 2) indicated that the Hirnantian Stage transects the late Ashgillian and early and middle Llandoverian up to the base of the *P. celloni* Zone of the late Llandoverian; however, I am not aware that faunas of this age have ever been found associated with, or in strata younger than, the *Parakidograptus acuminatus* Zone of the basal Llandoverian Series.

PART II—CONODONT FAUNAS
OF THE KEEL AND CASON FORMATIONS

JAMES E. BARRICK

Abstract—Two conodont faunas of different ages were recovered from the Keel Formation of southern Oklahoma and the Cason Formation of northern Arkansas. A sparse fauna characterized by *Noixodontus girardeauensis* (Satterfield) occurs in the lower oolitic-skeletal and laminated beds of the Keel and the Cason oolite. The association of *N. girardeauensis* with the Hirnantian shelly fauna in the central United States and its position in the graptolite sequence in northwestern Canada suggest that *N. girardeauensis* may be an indicator of the latest Ordovician, Hirnantian, age. The upper beds of the Keel at two sections, P9 and J1, and the Cason pelmatozoan limestone at St. Clair Springs, yielded the relatively nondiagnostic Early Silurian conodonts *Walliserodus curvatus* (Branson and Branson) and *Distomodus* sp. indet.

INTRODUCTION

The Keel Formation of the Arbuckle Mountain region of southern Oklahoma constitutes the most westerly and southerly part of the Late Ordovician (Hirnantian)–Early Silurian outcrop area in the central United States. Although conodonts have been described from the Cason oolitic limestone in Arkansas (Craig, 1969, 1975) and the Noix Oolite in Missouri (McCracken and Barnes, 1982), their distribution in the Keel thus far has not been studied. Conodonts have been obtained from the Keel Formation at eight localities in southern Oklahoma (text-fig. 39, tables 3–7). Some sections were sampled by the author, but most conodont samples were collected by Thomas W. Amsden during his work on the lithofacies–biofacies and paleontology of the Keel. Amsden also provided samples from the Cason Formation at St. Clair Springs, Arkansas (Part I). The conodonts obtained from these samples constitute the basis for the following interpretation of the conodont biostratigraphy of Late Ordovician–Early Silurian strata in the southern Oklahoma and Arkansas area.

CONODONTS

Keel Formation, Oklahoma

Relatively few conodont elements were recovered from samples of the Keel Formation. Typically, fewer than 25 elements were recovered per kilogram of sample. Only two samples yielded more than 50 elements per kilogram; 16 of 43 samples were barren (tables 3–7). Despite the low abundance of elements, two distinct conodont associations are recognized in Keel strata.

The lower fauna, one that occurs in most samples of the Keel, is characterized by elements of *Noixodontus girardeauensis* (Satterfield), *Dapsilodus? mutatus* (Branson and Mehl), *Panderodus gracilis* (Branson and Mehl)?, and *Eocarniodus? sp.* (see Paleontology). Less common are elements of *Plectodina* species, *Decoriconus costulatus* (Rexroad), and *Pseudooneotodus beckmanni* (Bischoff and Sannemann). This *Noixodontus* fauna characterizes the oolitic-skeletal limestones of the Ideal Quarry Member, which lie at the base of the Keel Formation (text-fig. 39). The overlying oolitic limestone of the Keel was largely nonproductive of conodonts, but a few elements of *N. girardeauensis* and associated species were recovered. Conodonts are also rare in the laminated limestone unit that rests on oolitic strata at sections P9 and J1 (text-fig. 39). The fossiliferous laminated beds bearing numerous streptelasmid corals at section P9 yielded a moderate number of elements of species of the *Noixodontus* fauna (table 6, section P9, samples B2 and A7), but other samples produced only a few representatives of the fauna.

At sections P9 and J1 oolitic beds and skeletal limestones are present at the top of the Keel Formation (text-fig. 39). The sparse conodont fauna from these strata is dominated by elements of *Panderodus unicostatus* (Branson and Mehl) and *Walliserodus curvatus* (Branson and Branson). A few elements that belong to the apparatus of a *Distomodus* species are also present. This second fauna shares no species in common with the lower Keel conodont fauna but is almost identical with the conodont fauna of the overlying Cochrane Formation.

Cochrane Formation, Oklahoma

Samples from the basal part of the Cochrane Formation at the sections studied here are characterized by elements of *Panderodus unicostatus*, *Walliserodus curvatus*, and *Distomodus* ramiform
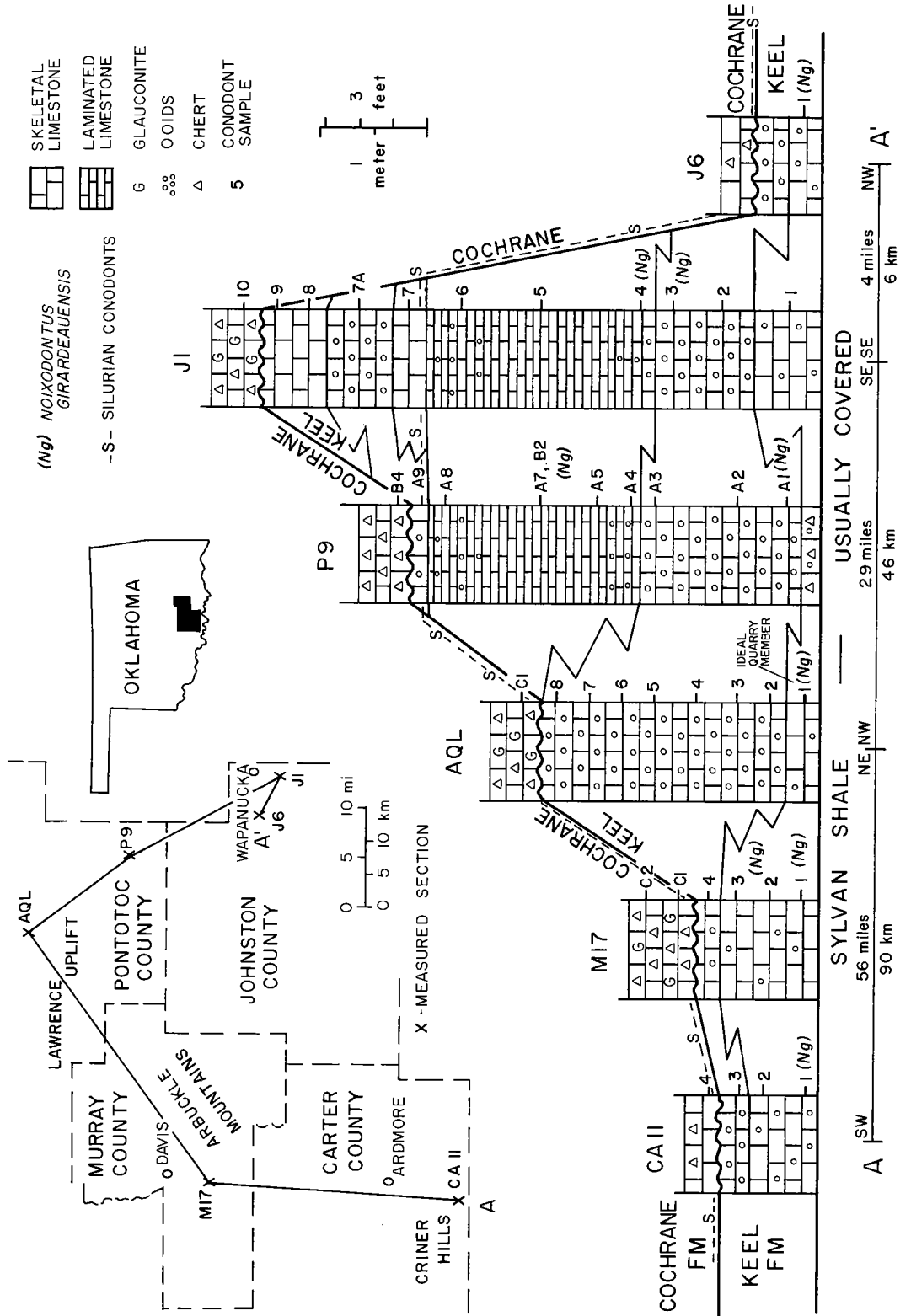
Text-figure 39. Stratigraphic cross section of Keel Formation showing distribution of conodont samples and facies relationships.

TABLE 3.—DISTRIBUTION AND FREQUENCY OF CONODONTS IN KEEL FORMATION AND LOWER COCHRANE FORMATION, SECTIONS M17 AND Ca11.

(Sample intervals measured from base of each formation: *C*, Cochrane samples; Keel samples comprise the remainder. Locations and descriptions of sections in Amsden (1967) and Amsden (Part I, this report).)

Section		M17						Call			
Sample		1	2	3	4	C1	C2	1	2	3	4
Sample interval (m) base		0.0	0.3	0.6	0.9	0.0C	0.3C	0.2	0.6	0.8	0.0C
top		0.3	0.6	0.9	1.1	0.3C	0.6C	0.3	0.7	0.9	0.2C
Sample weight (kg)		1.2	1.1	0.9	0.7	1.2	1.1	2.0	2.0	2.0	2.0
Noixodontus girardeauensis	Pa?	1	1					1		1?	
	Pb?		1					1			
	Sa	1?						1			
	Sb	1	1?	1				2			
	Sc·	1	1					1			
	Sd	1	1					2			
	A	13	8					1			
	B	4	4					1?			
Eocarniodus? sp.		11	8								
Dapsilodus? mutatus	oist.	12	2								
	M?	2	2								
	SbSc	10	4								
	Sa	3	1								
Panderodus gracilis?	M?	4	1								
	Sa	4	3					1			
	Sb	5	4								
Decoriconus costulatus	S	12	4								
Pseudooneotodus beckmanni		1									
Plectodina sp.	M	1	1?								
	Sb	1									
	Sc	3	2								
Panderodus sp.	Sb	1									
Walliserodus curvatus	M?										5
	Sa					1?	1?				2
	Sb						1				2
	Sc						1				1
	Sd						2				2
Panderodus unicostatus	M?						17				19
	Sa						14				17
	Sb					4	20				20
	Sc						4				2
P. recurvatus?	S						3				1
Distomodus sp.	M										1
	S										2
Indet. ramiform							2				
Indet. cone			1								
Total		92	50	1	0	5	65	9	0	1	74

TABLE 4.—DISTRIBUTION AND FREQUENCY OF CONODONTS IN KEEL FORMATION AND LOWER COCHRANE FORMATION, SECTION P9

(See caption to table 3 for further explanation.)

Section P9

Sample		A1	B1	A2	A3	A4	A6	A7	B2	A8	A9	B3	B4
Sample interval (m)	base	0.20	0.20	0.75	1.40	1.70	2.00	2.30	2.75	3.35	3.65	3.65	0.00C
	top	0.40	0.40	1.10	1.70	1.85	2.30	2.90	2.90	3.65	3.80	3.80	0.15C
Sample weight (kg)		1.9	2.0	3.0	2.0	2.7	3.8	3.3	2.0	2.0	2.0	2.0	2.0
Noixodontus	Pa?		5					1?	1				
girardeauensis	Pb?		2										
	Sa		2					1	1			1?	
	Sb		2										
	Sc		1					1?					
	indet.		2						3				
	A		1					2	3				
	B		2					3	5				
Eocarniodus? sp.				4	1	1			1				
Dapsilodus?	oist.			2		1		2	2				
mutatus	M?			1				7	5				
	SbSc			2				12	12				
	Sa							4					
Panderodus gracilis?	M?			1	1								
Decoriconus costulatus	S								4				
Plectodina	Pa								1				
tenuis?	Pb							2	3				
	M								2				
	Sa								1				
	Sb							1	1				
	Sc							1	2				
Walliserodus	M?										8?		5?
curvatus	Sa										3?		1?
	Sb										1?	1	1?
	Sc											1	
	Sd										2?		
Panderodus	M?										8	10	3
unicostatus	Sa										12	6	4
	Sb										6	10	11
	Sc										2	2	
Distomodus sp.	M											1	
	S										1		1
Indet. cones								2	7				
Total		0	17	10	2	2	0	39	54	0	43	32	26

TABLE 5.—DISTRIBUTION AND FREQUENCY OF CONODONTS IN KEEL FORMATION AND LOWER COCHRANE FORMATION, SECTION J1

(See caption to table 3 for further explanation.)

Section J1											
Sample		1	2	3	4	5	6	7	7A	9	10
Sample interval (m)	base	0.15	0.75	1.2	1.5	2.6	3.2	3.65	4.1	4.9	0.0C
	top	0.45	1.10	1.5	1.8	2.9	3.5	4.00	4.4	5.2	0.2C
Sample weight (kg)		1.7	1.7	1.3	1.8	1.7	1.5	1.4	1.7	1.9	1.4
Noixodontus	Pa?			1							
girardeauensis	Sc				1						
Eocarniodus? sp.			2								
Dapsilodus?	oist.		1	3							
mutatus	SbSc		1								
	Pa			1							
Plectodina	M			1							
tenuis?	Sa			1							
	Sc			1							
	M?							2?		9	8
Walliserodus	Sa							2?		5	1
curvatus	Sb							2?		9	5
	Sc									5	1
	Sd									6	1
	indet.										4
	M?							7		26	28
Panderodus	Sa							6		20	16
unicostatus	Sb							3		24	12
	Sc							1		5	4
	indet.							3			
Panderodus sp.	S									1	
Decoriconus costulatus	S										1
Indet. cone					1						
Total		0	4	8	2	0	0	26	0	110	81

TABLE 6.—DISTRIBUTION AND FREQUENCY OF CONODONTS IN KEEL FORMATION
AND LOWER COCHRANE FORMATION, SECTIONS A AND B, LAWRENCE QUARRY

(See caption to table 3 for further explanation.)

Sample	Section A									Section B						
	1	2	3	4	5	6	7	8	C1	1	2	3	4	5	6	C1
Sample interval (m) base	0.0	0.3	0.6	0.9	1.4	1.7	2.0	2.3	0.0C	0.0	0.30	0.75	1.05	1.4	1.7	0.0C
Sample interval (m) top	0.3	0.6	0.9	1.4	1.7	2.0	2.3	2.6	0.2C	0.3	0.75	1.05	1.40	1.7	2.0	0.2C
Sample weight (kg)	1.5	1.5	1.6	1.4	1.2	1.4	1.2	1.5	1.7	1.3	1.3	0.7	0.3	0.8	1.6	1.4
Noixodontus girardeauensis Pa?	2															
Pb?		1?														
Sb	1	1									1					
Sc		2														
B		1														
Eocarniodus? sp.	1	1														
Panderodus gracilis? M?										1						
Sb												1				
Walliserodus curvatus M?							1?		2?							1
Sa									2?							2
Sb									2?				1?			3
Sc																1
Panderodus unicostatus M?									8							5
Sa									8							5
Sb									12							
Sc									2							4
Panderodus sp. Sb									1		1					
Indet. cone																
Indet. ramiform										1						
Total	4	6	0	0	0	0	1	0	37	2	3	1	1	0	0	21

TABLE 7.—DISTRIBUTION AND FREQUENCY OF CONODONTS IN KEEL FORMATION AND LOWER COCHRANE FORMATION, SECTIONS J5 AND J6, AND IN CASON SHALE AT ST. CLAIR SPRINGS

(See table 3 for further explanation for sections J5 and J6. St. Clair Spring section: Sample interval measured from base of Cason Shale. *C* and *D*, Cason oolite; *E*, Cason biosparite. See Amsden (Part I, this report, text-fig. 19) for location and description of Cason section at St. Clair Springs.)

Section		J6		J5		St. Clair Springs		
Sample		1	2	101	102	C	D	E
Sample interval (m) base		0.20	0.0C	0.3	0.0C	1.1	1.7	2.7
top		0.50	0.2C	0.5	0.2C	1.3	1.9	3.0
Sample weight (kg)		2.0	2.0	1.2	2.0	1.6	1.5	1.4
Noixodontus girardeauensis	Pa?						1	
	Pb?					1		
	Sc	1		1				
Eocarniodus? sp.		3					2	
Dapsilodus? mutatus	oist.	3					8	
	M?	1						
	SbSc	1				1	5	
Panderodus gracilis?	M?					3		
	Sa					1	1	
	Sb					3	7	
Decoriconus costulatus	S					1	2	
Drepanoistodus suberectus						1	3	
Phragmodus undatus						1	1	
Plectodina sp.	Sa						2	
	Sb						3	
	Sc					1	1	
Belodella? sp.	S					3		
Panderodus unicostatus	M?		32		32			49
	Sa		31		9			54
	Sb		64		37			91
	Sc		2		1			16
Panderodus sp.	S				2			2
Walliserodus curvatus	M?		19		8			81
	Sa		6		8			61
	Sb		8		3			83
	Sc		1?		2			41
	Sd		3					23
Decoriconus fragilis?	SaSb							4
	Sc							7
Dapsilodus sp.	Sa							2
	SbSc							12
Panderodus recurvatus?	S		1		3			
Distomodus sp.	S		3		2			
	M				1			
Indet. ramiform	Sc							1
Indet. cones							3	
Total		9	170	1	108	16	39	527

elements and contain rare elements of *De-coriconus costulatus* and a species of *Panderodus* similar to *P. recurvatus* (Rhodes). At other sections, *Pterospathodus celloni* (Walliser) and *Distomodus staurognathoides* (Walliser) occur in the upper beds of the Cochrane (Barrick and Klapper, 1976, p. 66).

Cason Oolitic Limestone, Arkansas

A small conodont fauna was recovered from two samples of the Cason oolitic limestone at the St. Clair Springs section (text-fig. 19). Only two elements of *Noixodontus girardeauensis* were obtained, in addition to more common elements of *Dapsilodus*? *mutatus, Panderodus gracilis*? *Eocarniodus*? sp., *Decoriconus costulatus*, and a *Plectodina* species. Except for the presence of rare elements of *Phragmodus, Drepanoistodus suberectus* (Branson and Mehl), and denticulated *Belodella*-like elements, the Cason oolitic limestone fauna is like that of the lower Keel fauna.

Cason Pelmatozoan Limestone ("Brassfield"), Arkansas

Samples from the pelmatozoan limestone of the Cason Formation that overlies the Cason oolitic limestone at St. Clair Springs contain abundant simple cone elements. The fauna is dominated by elements of *Panderodus unicostatus* and *Walliserodus curvatus. Distomodus* ramiform elements, *Dapsilodus* elements, *Decoriconus fragilis* (Branson and Mehl)?, and less common simple cone elements that belong to other *Panderodus* species make up the remainder of the fauna. Elsewhere, at the Love Hollow Quarry, the lithologically similar *Triplesia alata* beds contain a diverse fauna that includes *Aulacognathus bullatus* (Nicoll and Rexroad) and *Distomodus staurognathoides*, in addition to the simple cone fauna found at St. Clair Springs.

CORRELATION

Noixodontus Conodont Fauna

Correlation of the *Noixodontus* fauna of the lower Keel Formation and the Cason oolite with other conodont faunas is difficult because of uncertainty about the age relationships of the characteristic species. *Noixodontus girardeauensis* is known from only three other areas (text-fig. 40).

The Girardeau Limestone of southeastern Missouri (Satterfield, 1971) contains *N. girardeauensis* as the only identifiable species. The Leemon Formation bears a more diverse fauna, including *Amorphognathus ordovicicus* (Branson and Mehl), *Phragmodus undatus* (Branson and Mehl), *Dapsilodus*? *mutatus*, and *Plectodina* species, in addition to *N. girardeauensis* (Thompson and Satterfield, 1975).

The Noix Limestone in eastern Missouri (McCracken and Barnes, 1982) contains an abundant and relatively diverse fauna dominated by elements of two species of *Plectodina, P. florida* (Sweet), and *P. tenuis* (Branson and Mehl), and *Aphelognathus grandis* (Branson, Mehl and Branson). Elements of *Noixodontus girardeauensis, Amorphognathus ordovicicus*, and simple cone species are relatively uncommon. McCracken and Barnes (1982, p. 1477) suggested that the Noix association has the characteristics of a slightly modified late Richmondian conodont Fauna 12, rather than the younger Gamachian Fauna 13, because of the absence of *Gamachignathus* and presence of *Plectodina*. A similar, but less abundant, fauna characterizes the Cyrene Formation (Thompson and Satterfield, 1975), which is interpreted to be a lateral facies of the Noix (Amsden, this report).

In the Yukon Territory, *Noixodontus girardeauensis* (*Prioniodus*? *girardeauensis*) occurs in one sample at the Blackstone River section (Lenz and McCracken, 1982, p. 1321). Besides *N. girardeauensis, Gamachignathus ensifer* (McCracken, Nowlan and Barnes) and *Plectodina tenuis* are present in addition to other Ordovician species. Because of the rarity of elements of *Gamachignathus* and the presence of *Plectodina* elements, this sample was considered to be a Fauna 12 association of Richmondian age.

In the lower Keel and Cason oolite conodont fauna, *Noixodontus girardeauensis* occurs with *Plectodina* elements, and *Gamachignathus* is absent. According to the arguments of the authors cited above, this association could be assigned to Fauna 12 (Richmondian). However, in the central United States, *N. girardeauensis* occurs only in strata bearing an Hirnantian-age shelly fauna (text-fig. 40; Amsden, 1974; this report). This conodont species does not occur in any unit with shelly fossils indicative of a Richmondian age assignment.

At the Blackstone River section in the Yukon (text-fig. 40; Lenz and McCracken, 1982) the sample with *Noixodontus girardeauensis* (50.3 m) occurs about 14 m above a graptolite fauna assigned to the *Pacificograptus pacificus* Zone (36.6 m). Williams (1983, text-fig. 2) indicates that this zone possibly extends from the upper part of the Rawtheyan into the Hirnantian Stage. The overlying Hirnantian *Climacograptus*? *extraordinarius* Zone has not been recognized at the Blackstone River section, nor elsewhere in the Yukon area (Lenz and McCracken, 1982, 1983). The succeeding upper Hirnantian *Glyptograptus persculptus* Zone was questionably identified at 53.3 m, 3 m above the level at which *N. girardeauensis* occurs. The lowermost Silurian *Parakidograptus acuminatus* Zone appears 5.5 m higher in the section (58.8 m). Although it is possible that the sample bearing *N. girardeauensis* could

REGION	LLANDOVERIAN (C)	LLANDOVERIAN (B)	LLANDOVERIAN (A)	ASHGILLIAN HIRNANTIAN	ASHGILLIAN RAWTHEYAN
YUKON BLACKSTONE RIVER	?		PARAKIDOGRAPTUS ACUMINATUS ZONE x 58.8 m	x 53.3 m GLYPTOGRAPTUS PERSCUPTUS ZONE ? (Ng,Ge) x 50.3 m — PACIFICOGRAPTUS PACIFICUS ZONE x 36.6 m x 33.5 m	?
ANTICOSTI ISLAND	CHICOTTE FORMATION	JUPITER FORMATION	GUN RIVER FORMATION / BECSCIE FORMATION	(H–upper part only) CONODONT FAUNA 13 (Ge) — ELLIS BAY FM. GAMACHIAN STAGE	(Ge) CONODONT FAUNA 12 / VAUREAL FM.
NORTHEASTERN MISSOURI	SEXTON CREEK FM.			BOWLING GREEN DOL. BRYANT KNOB NOIX–CYRENE FMS. (H,Ng)	MAQUOKETA SHALE ?
SOUTHEASTERN MISSOURI	BAINBRIDGE FM. (BASE)	SEXTON CREEK FORMATION		LEEMON FORMATION (H,Ng) / (Ng) GIRARDEAU LST.	ORCHARD CREEK SHALE ?
NORTHERN ARKANSAS	ST. CLAIR LST. (BASE) SHALE / PELMAT. LST.	CASON FORMATION		SHALE OOLITIC LST. (H,Ng)	
SOUTHERN OKLAHOMA	CLARITA FM. (BASE) COCHRANE FORMATION			KEEL FORMATION (H,Ng)	SYLVAN SHALE

STAGE	C	B	A	HIRNANTIAN	RICHMONDIAN
SERIES	LLANDOVERIAN			CINCINNATIAN	
SYSTEM	SILURIAN			ORDOVICIAN	

Text-figure 40. Stratigraphic chart showing inferred correlation of Upper Ordovician and Lower Silurian strata discussed in this report. Information is derived from a number of sources, but correlation is that of the author (see text). Sources of information: southern Oklahoma, Amsden (1960, 1974, Part I herein), Barrick and Klapper (1976); northern Arkansas, Amsden (1971), Craig (1969, 1975), Sgouras (1979); southeastern Missouri, Amsden (1974, Part I herein), Satterfield (1971), Thompson and Satterfield (1975); northeastern Missouri, Amsden (1974, Part I herein), McCracken and Barnes (1982), Thompson and Satterfield (1975); Anticosti Island, Québec, McCracken and Barnes (1981a, 1981b), Nowlan and Barnes (1981). Uyeno and Barnes (1983); Yukon, Lenz and McCracken (1982, 1983), Williams (1983). *Ge, Gamachignathus ensifer. H, Hirnantian brachiopods. Ng, Noixodontus girardeauensis.*

be Rawtheyan (Richmondian) in age, an alternative stratigraphic interpretation is that it is Hirnantian in age because of its position relative to the graptolite faunas.

The presence of elements of the simple cone species *Decoriconus costulatus* in three Keel samples (M17-1, 2; P9-B2; see tables 3 and 4) suggests a Gamachian to Llandoverian age for these samples. *Decoriconus costulatus* is typical of lower Llandoverian conodont faunas and ranges into the top of the Gamachian (Fauna 13) on Anticosti Island, Quebec (McCracken and Barnes, 1981b; *D. costulatus* occurs in two samples of Gamachian age in the Salmon River section: a single element in Member 4 of the Ellis Bay Formation, sample S19; one element in the topmost sample of the Gamachian, Member 6, S32; tables 5, 6). It is unlikely that the presence of elements of *D. costulatus* in the Keel and Cason oolite is a result of stratigraphic leak from the overlying Llandoverian formations. No other Silurian species are represented in these samples, and elements of *D. costulatus* are rare or absent in Cochrane samples.

The presence of elements of *Decoriconus costulatus* in the *Noixodontus* fauna of the lower Keel Formation and Cason oolite supports a Gamachian age assignment for these units. However, as noted above, *Noixodontus*-bearing conodont faunas have been previously assigned to Conodont Fauna 12 (Richmondian) rather than Conodont Fauna 13, which is thought to be indicative of the Gamachian (McCracken and Barnes, 1981b).

As Fauna 13 is presently defined it is difficult to recognize, and thus it is difficult to correlate strata to the Gamachian Stage using conodonts. The base of Fauna 13 is placed at the level where elements of *Gamachignathus* species become a dominant component of the conodont fauna (McCracken and Barnes, 1981b). On Anticosti Island this occurs at the base of the Ellis Bay Formation, but only at the type section of the Ellis Bay Formation. The base of the Gamachian Stage has also been placed at the base of the Ellis Bay Formation at its type section by McCracken and Barnes (1981b). At this section the rise to dominance of *Gamachignathus* elements (e.g., Fauna 13) corresponds to the base of the Gamachian.

Elements of *Gamachignathus* are not abundant at the base of the Ellis Bay Formation at the other Anticosti Island sections, Vauréal River and Salmon River, but begin to dominate some samples from strata placed with question in Member 2 and 3 (McCracken and Barnes, 1981b, fig. 13, tables 4–7). McCracken and Barnes (1981b, p. 69–71) indicated that the rise to dominance of elements of *Gamachignathus* at Vauréal River and Salmon River occurs later in time than at the Ellis Bay type section, owing to migration following the appearance of favorable ecologic conditions in the former areas. Fauna 13 thus appears to be an ecologic association of limited chronologic signifi-

cance even on Anticosti Island. Exclusion of samples from other areas that bear sparse representatives of *Gamachignathus* from the Gamachian (e.g., Lenz and McCracken, 1982) may not be appropriate, for, by the same reasoning, the lower part of the Ellis Bay Formation in eastern Anticosti Island could also be excluded as well. Similarly, the argument that *Gamachignathus* is significantly abundant (about 5 percent) in the Grog Brook Group to suggest equivalency with the Gamachian (Nowlan, 1983, p. 656) is open to question.

As the situation stands now, there is insufficient evidence to assign any conodont fauna outside of Anticosti Island to the Gamachian Stage. Only two species, *Staufferella inaligera* McCracken and Barnes and possibly *Gamachignathus hastatus* McCracken, Nowlan, and Barnes, have first occurrences above the base of the Gamachian at the Ellis Bay type section (although McCracken and Barnes and possibly *Gamachignathus hastatus* McCracken, Nowlan, and Barnes, have first occurrences above the base of the Gamachian at the Ellis Bay type section (although McCracken and others, 1980, and McCracken and Barnes, 1981, report that *G. hastatus* occurs in the underlying Vauréal Formation, Nowlan and Barnes, 1981, do not show this species as occurring in the Vauréal). These species have not been reported outside of Anticosti Island. found in the Vauréal Formation (Nowlan and Barnes, 1981), well below the base of the Gamachian. Because *G. ensifer* occurs in several Late Ordovician faunas, its first occurrence may be a reliable marker, but it would not entail a post-Richmondian age assignment.

The distribution of species of *Plectodina* in Upper Ordovician strata appears to be strongly controlled by local ecologic features. In addition, the representatives of the genus are restricted on the province level, as has been shown by Sweet and Bergström (1974) and discussed by other authors. Some species of *Plectodina* probably range through the Richmondian (Fauna 12), but on Anticosti Island ecological factors may have caused their disappearance before the end of Richmondian time.

The conodont faunas from Hirnantian strata in England (Orchard, 1980) are extremely sparse, including only a few species that range through the Ashgillian. Elements of *Noixodontus, Plectodina,* and *Gamachignathus* (? = *Birksfieldia* Orchard; see Nowlan, 1983, p. 655) are absent.

The *Noixodontus* fauna of the lower Keel Formation and Cason oolite cannot be assigned to, nor excluded from, the Hirnantian Stage on the basis of the ranges of the conodont species. However, the strong association of *N. girardeauensis* with the Hirnantian shelly fauna in the central United States and its position in the Yukon graptolite sequence suggest that this species may be restricted to the Hirnantian interval.

Upper Keel Formation

Walliserodus curvatus and *Distomodus* elements appear at the base of the Silurian on Anticosti Island (McCracken and Barnes, 1981b, fig. 12) and characterize many Llandoverian conodont faunas. These forms are not known to range into Ordovician strata. The association of *W. curvatus* and elements of an indeterminate species of *Distomodus* in the upper oolitic and skeletal carbonates of the Keel at sections P9 and J1 indicates a Llandoverian age for these beds. The position of these beds within the Llandoverian cannot be determined with certainty, for *W. curvatus* is known to range into Llandoverian C strata and *Distomodus* elements persist into the base of the Wenlockian (Aldridge, 1972). Only the somewhat more diagnostic fauna of the overlying Cochrane Formation places an upper limit on the age of the upper Keel fauna.

Cochrane Formation and Cason Pelmatozoan Limestone

The lower beds of the Cochrane Formation and the Cason pelmatozoan limestone at St. Clair Springs failed to yield conodonts diagnostic of any subdivision of the Llandovery. The uppermost beds of the Cochrane yield *Pterospathodus celloni*, indicative of the Llandoverian C_5 *celloni* Zone (Barrick and Klapper, 1976, p. 66). Sgouras (1979) reported *P. celloni* from the uppermost part of the Cason pelmatozoan limestone (= Brassfield) in the Gilbert area of Arkansas. The conodont fauna of the pelmatozoan limestone of the limestone lens in the Cason Shale at the Love Hollow Quarry (Amsden, this report) may also be assigned to the *celloni* Zone because of the presence of *Aulacognathus bullatus* (Nicoll and Rexroad) (Craig, 1969).

Because of the lack of diagnostic forms in the basal Silurian rocks in Oklahoma and Arkansas, it is not possible to date the oldest Silurian beds accurately using conodonts. Silurian deposition in both areas surely started by late Llandoverian (C_5) time, if not earlier (Amsden, this report).

PALEONTOLOGY

Most conodont species recovered from the Keel and Cochrane Formations and correlative strata in Arkansas have been adequately described and illustrated in the literature. Only the most significant forms have been illustrated on plate 7 and are discussed below.

There is some question as to the morphologic features, if any, that distinguish the Ordovician species *Panderodus gracilis* (Branson and Mehl) from the Silurian species *P. unicostatus* (Branson and Mehl). The Silurian panderodontan elements recovered here conform to descriptions of *P. unicostatus* from Llandoverian strata (e.g., Cooper, 1975) and are referred to this species. Too few panderodontan elements were recovered from Ordovician strata to make comparisons. These Ordovician elements have been assigned to *P. gracilis?*.

The correct generic assignment of the species referred to here as *Dapsilodus? mutatus* (Branson and Mehl) is uncertain. Sweet (Amsden and Sweet, 1983) places this species in the genus *Dapsilodus*; Nowlan and Barnes (1981) and McCracken and Barnes (1981) place it with question in *Paroistodus*. As Sweet (1979) has noted, the apparatus of *D.? mutatus* is unlike that of species typical of *Paroistodus*. Although most elements are similar to those of typical *Dapsilodus* species, the *D.? mutatus* apparatus may contain an oistodontiform element (*Oistodus venustus* Stauffer), an element absent in the *Dapsilodus* apparatus. For this reason this species cannot be assigned to *Dapsilodus* without considerable question.

Walliserodus curvatus (Branson and Branson) can be identified with certainty only if the diagnostic Sc element is present in the sample (Cooper, 1975). The presence of *W. curvatus* in samples lacking this element may be open to question.

Genus **Eocarniodus** Orchard, 1980

Eocarniodus gen. nov., Orchard, 1980, p. 20.

Type species.—Prioniodus gracilis Rhodes, 1955.

Remarks.—Orchard (1980) erected the genus *Eocarniodus* to comprise a group of minute elements that lack a pronounced symmetry transition series. Little is known about the composition of the apparatus.

Eocarniodus? sp.
Pl. 7, figs. 1–5

Remarks.—A number of small carminate elements of uncertain affinity occur in the Keel Formation and Cason oolitic limestone. These elements have a large, biconvex erect cusp, flanked on one or both sides by a few small, compressed denticles. The entire lower surface is excavated by the basal cavity, the width of which varies little along the length of the element. The tip of the basal cavity is a bluntly rounded protrusion that terminates at one-third of the height of the cusp.

More than one type of element appears to be present in the collections, but too few elements are present to distinguish clearly among them. One common form is uncurved and symmetrical; the cusp is flanked on each side by an equal number of erect denticles (pl. 7, figs. 1–3, 5). A second form is also uncurved, but the cusp lies on the posterior third. A thickened area may run below the den-

ticles (pl. 7, fig. 4). The third common form is curved; posterior of the cusp are few if any denticles. Other less common variations occur in the collections.

The specimens recovered from the Keel and Cason oolitic limestone resemble some elements illustrated by Orchard (1980, pl. 2, figs. 18, 19, 25, 30) as *Eocarniodus gracilis* (Rhodes). However, my collections do not contain the variety of forms that were illustrated and described by Orchard (1980).

Material.—Keel Formation, 33 elements; Cason oolitic limestone, 2 elements.

Genus **Noixodontus** McCracken and Barnes, 1982

Noixodontus n. gen., McCracken and Barnes, 1982, p. 1478–1480.

Type species.—Prioniodus girardeauensis Satterfield, 1971.

Remarks.—The genus is monotypic.

Noixodontus girardeauensis
(Satterfield, 1971)
Pl. 7, figs. 6–8, 11–16

Pa element.—Prioniodus girardeauensis Satterfield, 1971, p. 271, pl. 34, figs. 1, 6, 15, 18, 19.

Multielement.—Prioniodus? girardeauensis Satterfield; Lenz and McCracken, 1982, pl. 1, figs. 6–8 (Pa elements). *Noixodontus girardeauensis* (Satterfield, 1971); McCracken and Barnes, 1982, p. 1480–1481, pl. 2, figs. 5–12. (See for further synonymy.)

Remarks.—Elements of *Noixodontus girardeauensis* from the Keel Formation and Cason oolitic limestone conform in most respects to the descriptions and illustrations of McCracken and Barnes (1982). Larger specimens of the Sb and Sc elements (b and a elements of McCracken and Barnes) from the Keel may bear one denticle on the posterior process instead of being adenticulate, as described by McCracken and Barnes (1982).

McCracken and Barnes (1982) did not recover the M(e) element of *Noixodontus girardeauensis* from the Noix Limestone but suggested that the

elements illustrated by Thompson and Satterfield (1975, figs. 4H, I) may be the M(e) element. No elements of this type were found in Keel or Cason collections.

Two elements undescribed by McCracken and Barnes (1982) are invariably associated with typical elements of *Noixodontus girardeauensis* in Keel samples. The larger of these elements, referred to as Element A on tables 3–7 and plate 7, figs. 7, 8, 13, has a symmetrically biconvex cross section and a broad, erect cusp. The relatively large hyaline base is unequally expanded in the anteroposterior direction and tapers moderately to the base of the cusp. The cusp tapers gradually to the apex; the apical one-half is filled with white matter. A thin-walled base is completely excavated by a deep basal cavity. Margins of the base are commonly adenticulate but may bear one or two discrete denticles on a short posterior (?anterior) process. It is possible that Element A is the M(e) element of *N. girardeauensis*.

Many examples of Element A are only slightly smaller than the associated elements of *N. girardeauensis*, which they strongly resemble in white-matter distribution and other features. Element A also bears some similarity to the M(e) elements of *Gamachignathus* species, a group that shares some characters in common with *N. girardeauensis* (McCracken and Barnes, 1982, fig. 3). Small representatives referred here to Element A, however, may be only juvenile forms of S elements.

Element B is a small element with a short, flared base that generally has a strong anteroposterior elongation. The long, slender, biconvex cusp is strongly twisted to one side just above the base. The entire cusp is composed of white matter. A shallow basal cavity is present. Element B is always associated with elements of *Noixodontus girardeauensis*. Because it is always small relative to elements of *N. girardeauensis*, it is probably a juvenile form, perhaps of the Pa and the Pb elements.

Material.—Pa and Pb elements-17, Sa-6, Sb-8, Sc-7, Sd-3, Indet. S-12, Element A-34 (a number of small specimens are included here, some of which may be juvenile forms of S elements), Element B-14.

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PLATES

Plate 1

Keel and Leemon Formations
(Bar = 1 mm)

Fig. 1.—Thin section (oriented), showing broken oolites. Keel Formation 8 feet (2.4 m) above Sylvan–Keel contact, stratigraphic section J1 (Amsden, 1960, p. 215), 1 ½ miles southwest of Wapanucka, T2S, R8E, Johnston County, Oklahoma.

Fig. 2.—Thin section (oriented) of Leemon Formation, showing rip-up clasts. Upper oolite, 11.5 feet (3.5 m) above Leemon–Girardeau contact, east side of Mississippi River, about 1 ½ miles north of Thebes, SE¼ sec. 5, T2N, R3W, Alexander County, Illinois; locality M (Amsden, 1974, p. 86; this report, text-fig. 22).

Fig. 3.—Thin section, showing ooliths with apophyses. Keel Formation, lower oolite, 5 feet (1.5 m) above Keel–Sylvan contact; stratigraphic section P9 (Amsden, 1960, p. 279; this report, text-fig. 13), north side of Coal Creek, NW¼NW¼ sec. 22, T1N, R7E, Pontotoc County, Oklahoma.

Fig. 4.—Thin section, showing well-rounded detrital quartz grains. Leemon Formation, locality K (Amsden, 1974, p. 85; this report, text-fig. 25), lower 5 feet (1.5 m), Short farm, sec. 21, T32N, R13E, Cape Girardeau County, Missouri.

Fig. 5.—Thin section, showing ooliths deformed by contact with adjoining ooliths. Keel Formation, Arbuckle Mountain region, Oklahoma.

Fig. 6.—Thin section, showing deformed ooliths attached by apophyses; note articulated brachiopod shell in upper part. Keel Formation, upper oolite, 12 feet (3.6 m) above Keel–Sylvan contact, same location as figure 3; text-figure 13.

Plate 1   77
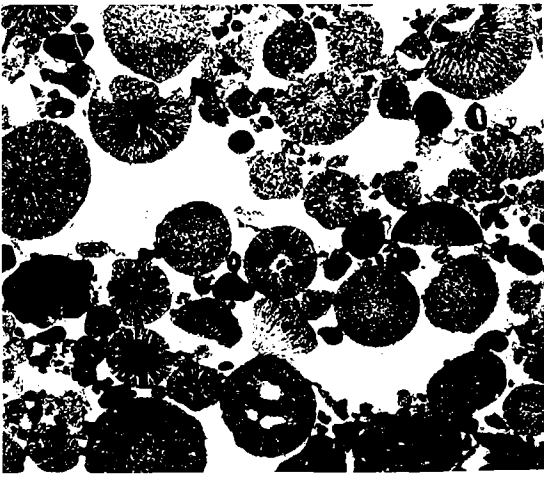
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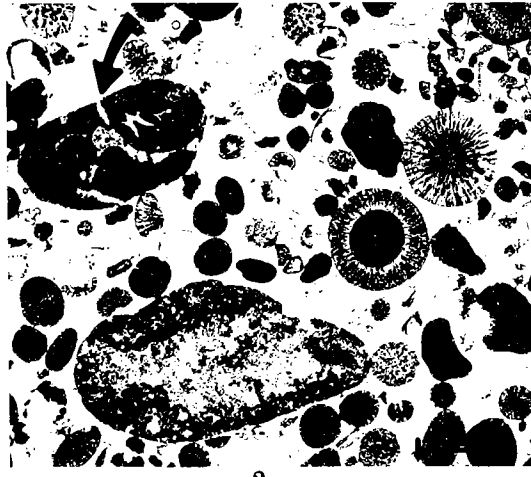
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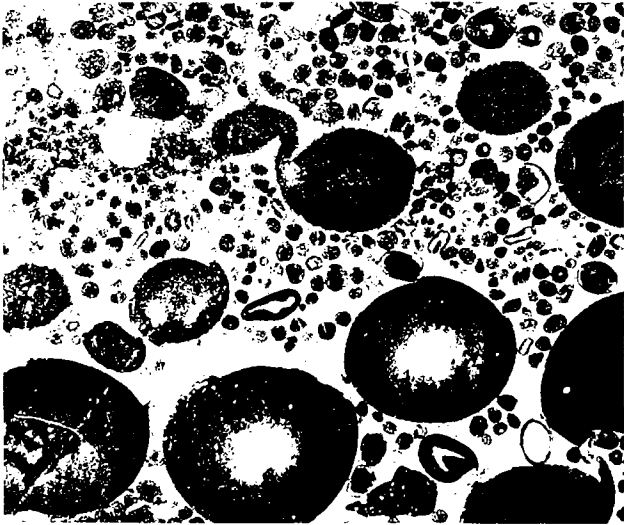
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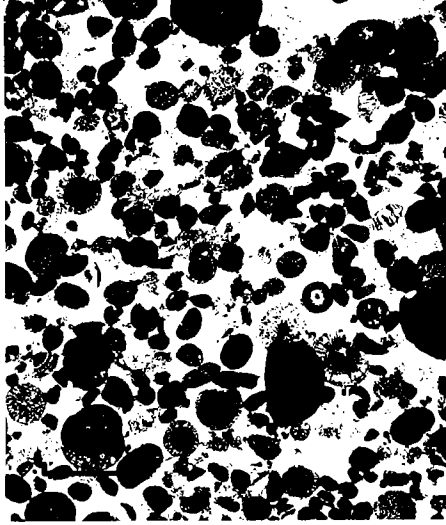
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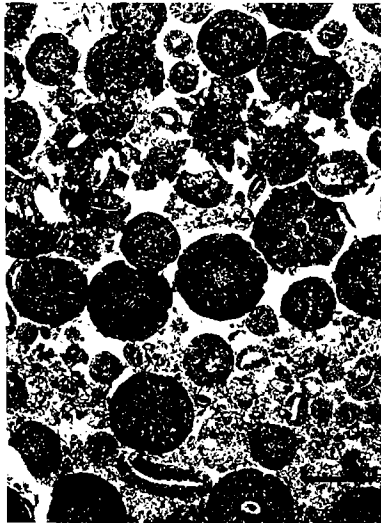
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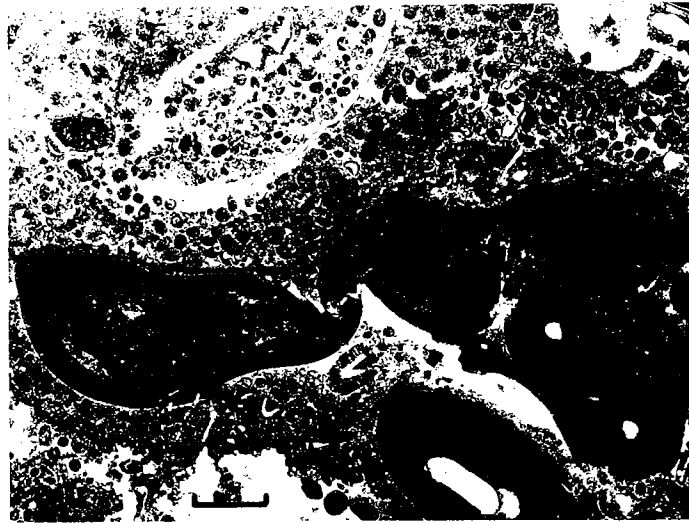
6

Plate 2

Keel Formation
(Bar = 1 mm)

Fig. 1.—Thin section of oolitic skeletal limestone facies of Keel Formation. These are the *Brevilamnulella* beds (text-figs. 11, 12), which, in addition to the specimens of *B. thebesensis* (arrow), trilobites, and snails shown in this thin section, also include both tetracorals and tabulate corals. Keel Formation, Lawrence Quarry, sec. 36, T3N, R6E, Pontotoc County, Oklahoma.

Fig. 2.—Thin section ($\times 20$) of Keel Formation, showing ooliths completely replaced with crystalline dolomite (from Amsden, 1971, pl. 12, fig. 6). Thin section prepared from a well sample, Phillips T. C. Lee, depth 15,320–15,330 feet.

Fig. 3–5.—Fe–Mn mineralized beds, Keel Formation, Lawrence Quarry; same location as figure 1, above. Figure 3 shows polished surface of a specimen (x2) grading from heavily mineralized (above) to weakly mineralized (below) oolite. Figure 4 is a photomicrograph of a thin section cut from the specimen illustrated on the left, showing ooliths largely replaced by siderite. Figure 5 also is a photomicrograph of a thin section cut from the specimen illustrated on the left, less heavily mineralized than figure 4 (arrow points to pelmatozoan plate). See text-figure 15 and table 1.

Plate 2

1
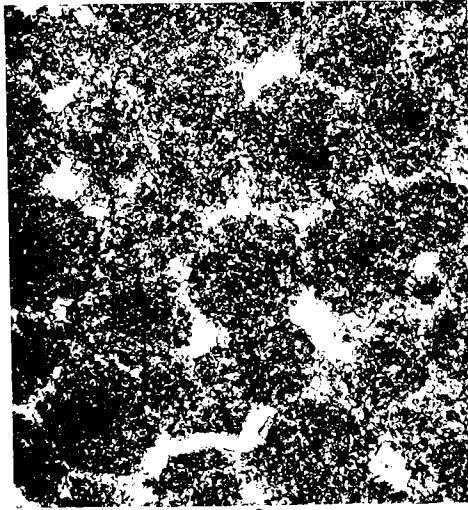
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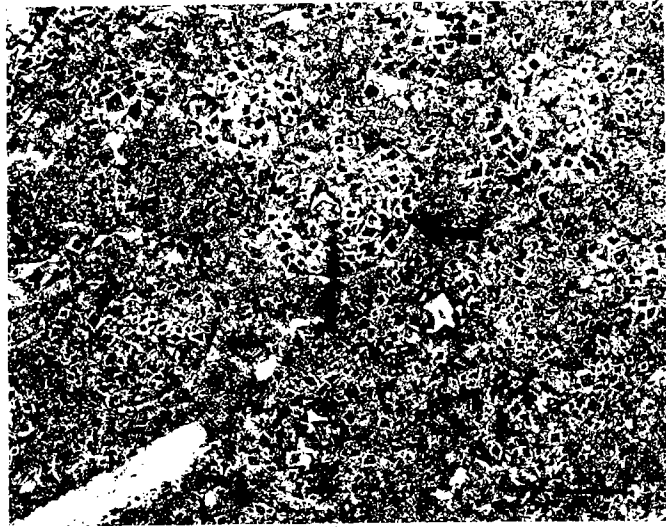
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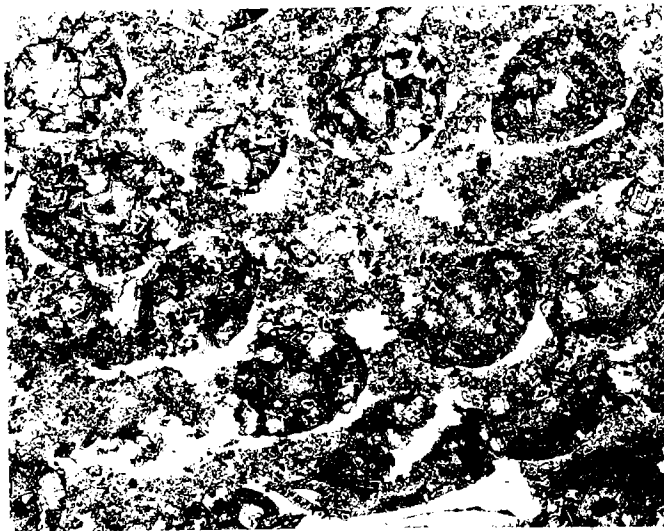
5

Plate 3

Keel Formation, Oolite Facies, and Oolitic Skeletal Facies
(Bar = 1 mm)

Fig. 1.—Thin section (oriented), showing oolitic skeletal limestone facies of Keel Formation. Two feet (60 cm) above Keel–Sylvan contact; stratigraphic section M17 (Amsden, 1960, p. 256), east side of I-35, Prices Falls interchange, NE¼NW¼ sec. 30, T12S, R2E, Murray County, Oklahoma.

Fig. 2.—Thin section, showing oolitic skeletal limestone facies. *Brevilamnulella* beds, 6 feet (1.8 m) above Keel–Sylvan contact (text-figs. 11, 12); sec. 36, T3N, R6E, Pontotoc County, Oklahoma.

Fig. 3.—Thin section (oriented), showing typical oolite facies of Keel Formation. Note bedding defined by large and small ooliths, and by micrite and spar. Veins cutting the Keel are post–middle Paleozoic fractures healed with calcite. Stratigraphic section M12A (Amsden, 1960, p. 251), 2 inches (5 cm) below Keel–Cochrane contact; east side of Falls Creek, Prices Falls, SW¼NW¼ sec. 33, T1S, R2E, Murray County, Oklahoma.

Plate 3   81

1

2
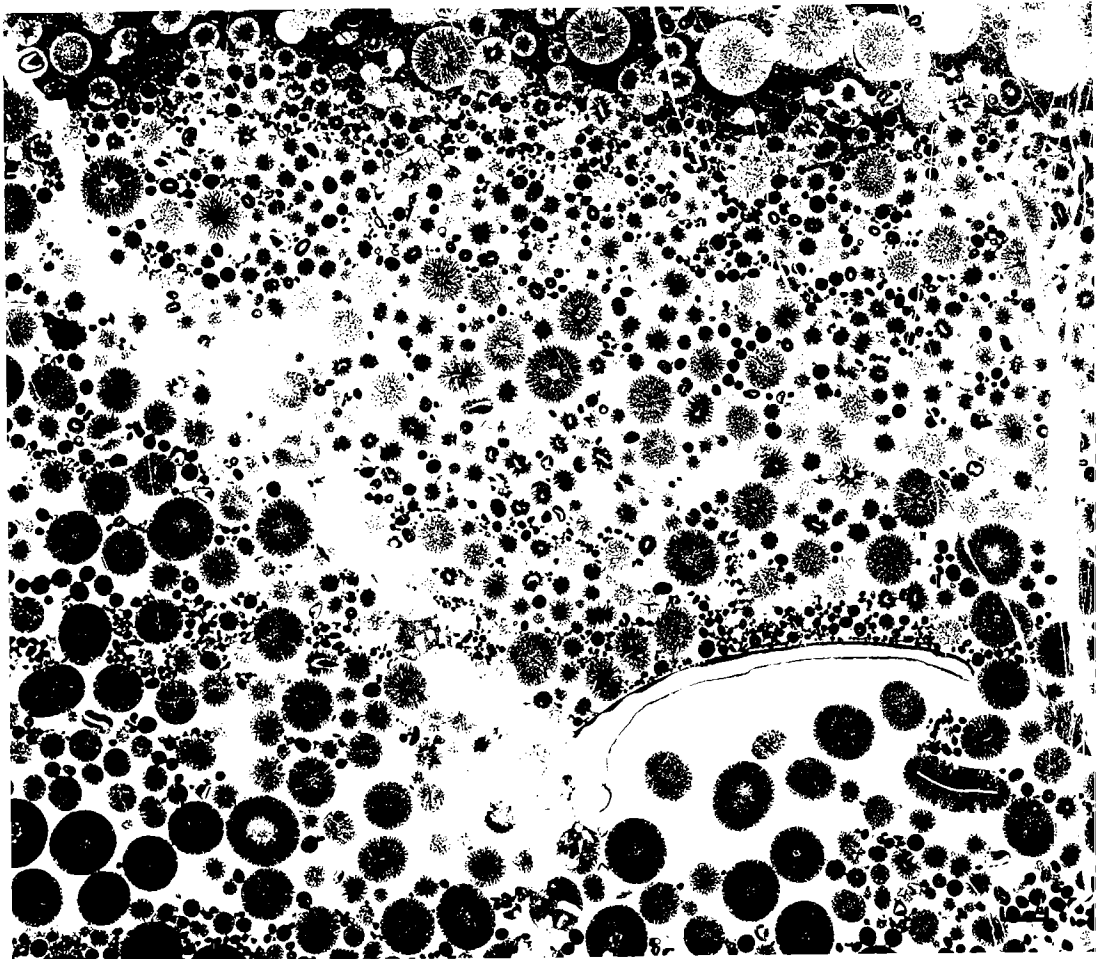
3

Plate 4

Leemon Formation and Langøyene Formation
(Bar = 1 mm)

Fig. 1.—Thin section, showing ooliths associated with bryozoan bioherm at Blue Shawnee Creek, Leemon Formation, south of New Wells, NW¼SE¼SE¼ sec. 9, T33N, R13E, Cape Girardeau County, Missouri (locality U, Amsden, 1974, p. 87).

Fig. 2.—Thin section, showing fine ooliths and well-rounded quartz grains (arrow) in top of Langøyene Formation, Asker district, Oslo Fjord.

Fig. 3.—Thin section, showing ooliths in upper 6 inches (15 cm) of Maquoketa Formation; road cut on U.S. Highway 54, 1 mile north of Bowling Green, SE¼SW¼ sec. 13, T53N, R3W, Pike County, Missouri (text-fig. 31).

Fig. 4.—Thin section (oriented), showing scattered ooliths in silty and argillaceous micrites of Leemon Formation; 4 feet (1.2 m) above Leemon–Girardeau contact, east bank of Mississippi River 1 ½ miles north of Thebes, SE¼ sec. 5, T15N, R3W, Alexander County, Illinois (text-fig. 22). (Cf. to Amsden, 1980, pl. 7, fig. 13.)

Figs. 5, 6.—Polished surface (× 1) and thin section of Leemon Formation near Gale, Illinois (text-fig. 24). Note substantial quantity of detrital quartz (arrow) interspersed with ooliths. Small outcrop on Illinois State Highway 3, about ¼ mile southeast of Gale, Alexander County, Illinois (locality L, Amsden, 1974, p. 86).

Plate 4 83
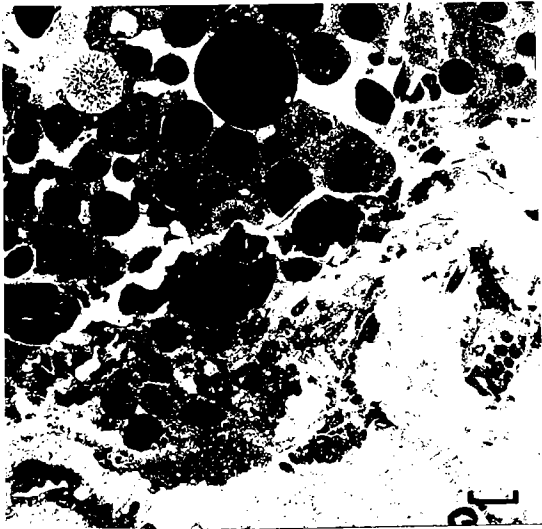
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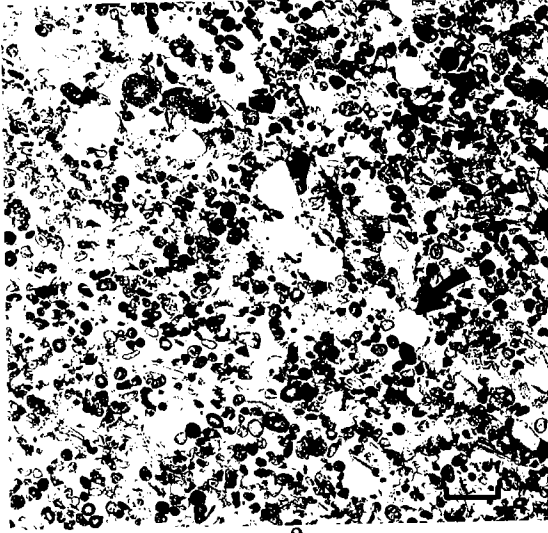
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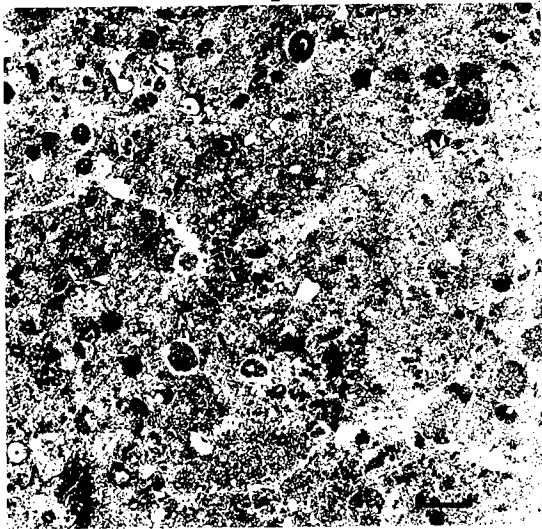
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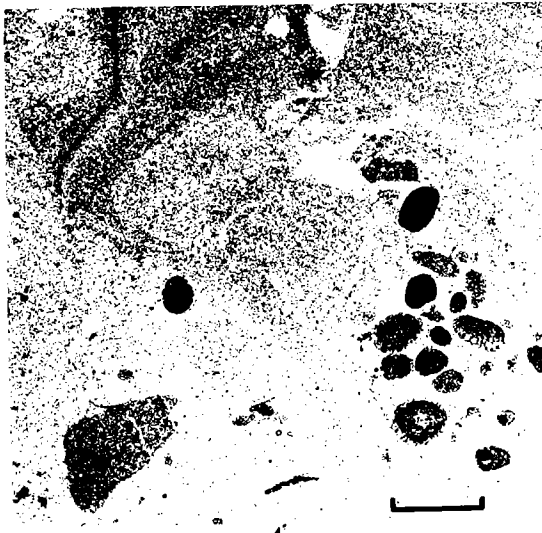
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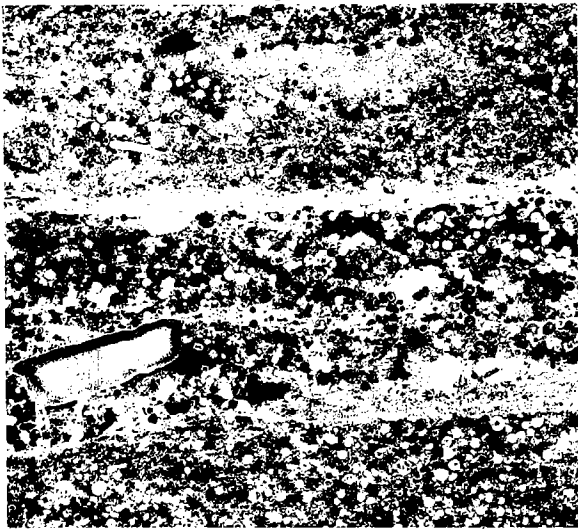
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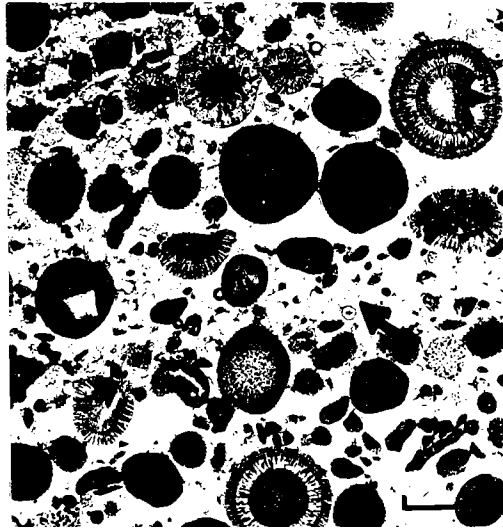
6

Plate 5

Limestone Lens, Cason Shale at Love Hollow Quarry

(Bar = 10 mm)

Fig. 1.—Polished slab, showing lower part of *Triplesia alata*–bearing skeletal limestones in contact with Cason oolite. Specimen collected from limestone lens shown in figure 2. Other views of this contact are illustrated in Amsden (1980, pl. 5, figs. 1–3, pl. 6, figs. 1, 2; see also this report, text-figs. 18–20).

Fig. 2.—View of Love Hollow Quarry taken in 1966; upper arrow points to Cason–St. Clair contact (above), and lower arrow points to limestone lens, part of which is illustrated in figure 1. Quarry is in SW¼ sec. 4, T14N, R8W, Izard County, Arkansas.

Plate 5   85
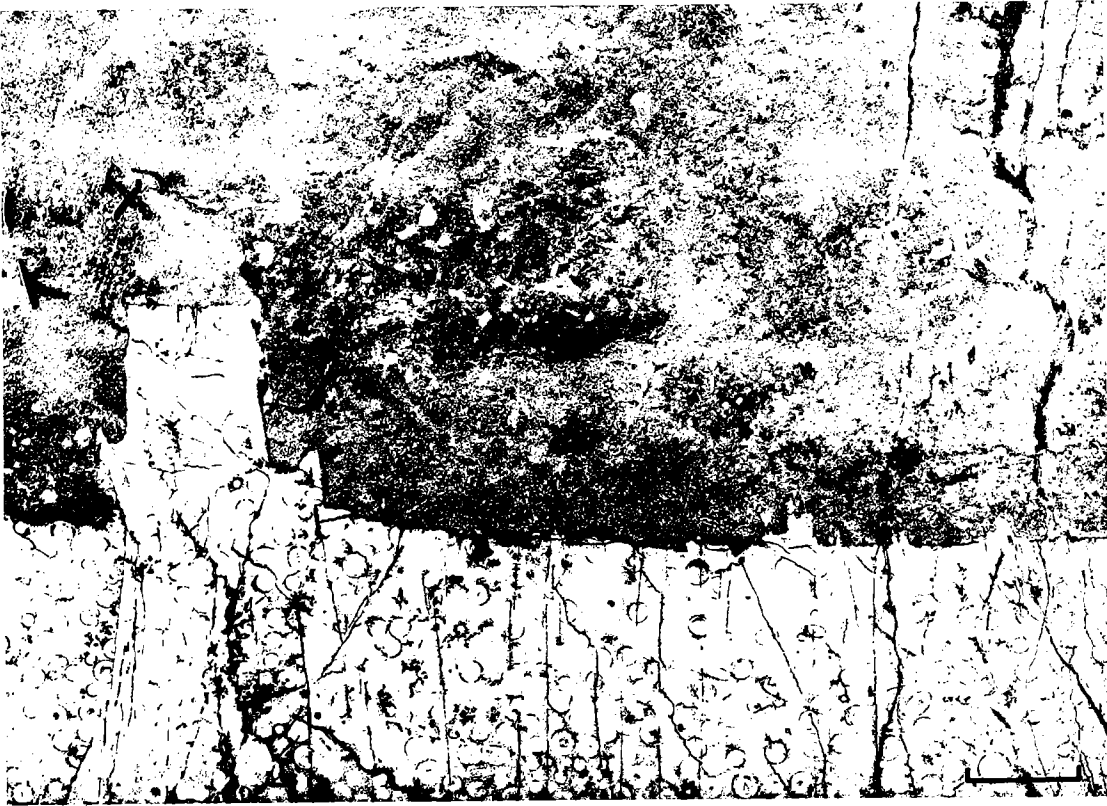
1

2

Plate 6

Keel and Cochrane Formations

(Bar = 10 mm)

Fig. 1.—Polished surface of Keel Formation, showing bedding defined by large and small ooliths and by alternating layer of oosparite and oomicrite. Lawrence Quarry, sec. 36, T3N, R6E, Pontotoc County, Oklahoma.

Fig. 2.—Oriented thin section, showing contact of Cochrane skeletal limestone (above) and Keel oolite (below). Vertical veins are post–middle Paleozoic fractures, healed with calcite. Stratigraphic section M12A (Amsden, 1960, p. 251), east side of Falls Creek, Prices Falls, SW¼NW¼ sec. 33, T1S, R2E, Murray County, Oklahoma (see also Amsden, 1962, fig. 5; 1980, pl. 6).

Fig. 3.—Oriented polished surface of Keel Formation, showing typical oolite facies above and oolitic skeletal limestone facies (Ideal Quarry Member) below; arrow points to contact, which is a stylolite. Note very fine ooliths and bedding defined mainly by oosparite and oomicrite. Lawrence Quarry; location from figure 1.

Plate 6   87
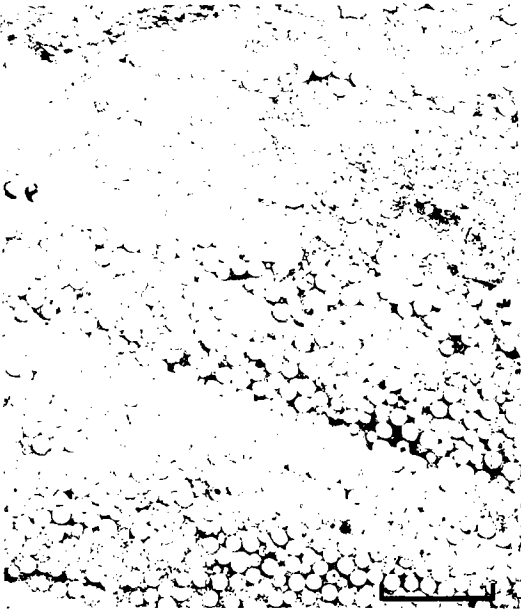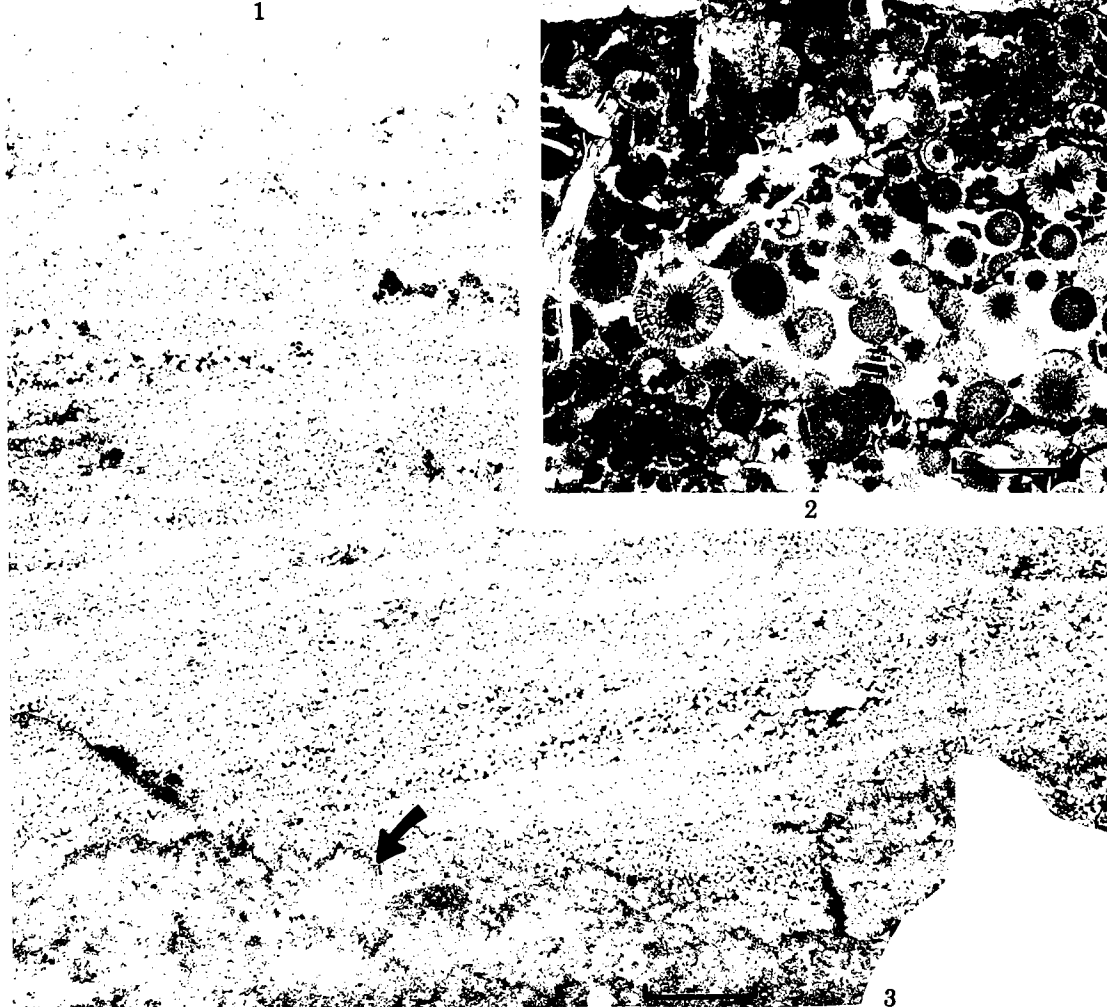
Plate 7

Keel and Cason Conodonts

Figures are SEM micrographs of specimens coated with gold. Numbers below prefixed with *SUI* refer to Paleontology Collections of the University of Iowa, Iowa City, where figured specimens are reposited. Figures 1–5, 7, 9–11 are approximately 150×; other figures are approximately 110×.

Figures 1–5.—*Eocarniodus?* sp. *1*, sample M17-1, SUI 51121. *2*, sample M17-1, SUI 51122. *3*, sample St. Clair Springs-D, SUI 51123. *4*, sample M17-1, SUI 51124. *5*, sample M17-1, SUI 51125.

Figs. 6–8, 11–16.—*Noixodontus girardeauensis* (Satterfield). *6*, Sb element, sample Call-1, SUI 51126. *7*, A element, sample M17-1, SUI 51127. *8*, A element, sample Call-1, SUI 51128. *11*, Sc element, sample J6-101, SUI 51129. *12*, Pb? element, sample M17-2, SUI 51130. *13*, A element, sample M17-1, SUI 51131. *14*, Pa? element, sample M17-1, SUI 51132. *15*, Pa? element, sample Call-1, SUI 51133. *16*, Pb? element, sample Call-1, SUI 51134.

Figs. 9, 10.—*Decoriconus costulatus* (Rexroad). *9*, Sc? element, sample M17-1, SUI 51135. *10*, Sb? element, sample M17-1, SUI 51136.

Plate 7   89