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SEQUENCE STRATIGRAPHY OF THE LANE-ISLAND CREEK SHALES AND THE FARLEY LIMESTONE IN NORTHEASTERN KANSAS AND GEOLOGIC FACTORS AFFECTING THE QUALITY OF LIMESTONE AGGREGATES

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16 Abstract

Procedures should be implemented for rapidly evaluating durability of limestone aggregate to prevent use of substandard material in highway construction and to assure availability of highly durable aggregate. The objective of this study is to evaluate lithologic (rock type) variables that control durability of limestone aggregate. The Farley Limestone (Pennsylvanian, Missourian) is one of many limestone units quarried in Kansas for production of highly durable, Class 1 aggregate. By understanding the lithologic factors that control durability of aggregate from the Farley, an analog for other limestone units can be developed. The Farley Limestone was described from 17 localities to define associations of rock types (lithofacies) and to establish correlations to aggregate durability. Data on lithofacies characteristics, spar (coarse calcite or dolomite) percentage, spar size, and insoluble residue percentage exhibit no correlations to durability factor or expansion percentage. Data on total percentage of clay-rich rock, clay distribution, and mineralogy of insoluble residues are correlated to durability and expansion percentage. Limestones containing low percentages of diffuse or disseminated clay are more likely to produce aggregates of high durability. Aggregates containing multiple clay minerals exhibit reduced durability. Smectite, even in small quantities, negatively impacts durability, whereas illite apparently has little impact on durability. If changes in clay content deleterious to aggregate quality can be identified during lateral production of a ledge, then quarrying can be halted or can proceed in another direction while physical tests are run. Such a procedure could prevent use of substandard concrete in highway construction projects. Aggregate-producing phylloid-algal limestones of the lower Farley Limestone thicken into the local depositional lows. However, fine quartz-, feldspar-, and clay-rich sediments (siliciclastics) also seem to be deposited preferentially in paleotopographic lows. Thus, local paleotopographic low areas most distal from sources of siliciclastics can be predicted as the prime areas for location of durable aggregate.

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Sequence Stratigraphy of the Lane-Island Creek Shales and the Farley Limestone in Northeastern Kansas and Geologic Factors Affecting the Quality of Limestone Aggregates

By

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PREFACE

This research project was funded by the Kansas Department of Transportation K-TRAN research program. The Kansas Transportation Research and New-Developments (K-TRAN) Research Program is an ongoing, cooperative and comprehensive research program addressing transportation needs of the State of Kansas utilizing academic and research resources from the Kansas Department of Transportation, Kansas State University and the University of Kansas. The projects included in the research program are jointly developed by transportation professionals in KDOT and the universities.

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ABSTRACT

Procedures should be implemented for rapidly evaluating durability of limestone aggregate to prevent use of substandard material in highway construction and to assure availability of highly durable aggregate. The objective of this study is to evaluate lithologic (rock type) variables that control durability of limestone aggregate. The Farley Limestone (Pennsylvanian, Missourian) is one of many limestone units quarried in Kansas for production of highly durable, Class 1 aggregate. By understanding the lithologic factors that control durability of aggregate from the Farley, an analog for other limestone units can be developed. The Farley Limestone was described from 17 localities to define associations of rock types (lithofacies) and to establish correlations to aggregate durability. Data on lithofacies characteristics, spar (coarse calcite or dolomite) percentage, spar size, and insoluble residue percentage exhibit no correlations to durability factor or expansion percentage. Data on total percentage of clay-rich rock, clay distribution, and mineralogy of insoluble residues are correlated to durability and expansion percentage. Limestones containing low percentages of diffuse or disseminated clay are more likely to produce aggregates of high durability. Aggregates containing multiple clay minerals exhibit reduced durability. Smectite, even in small quantities, negatively impacts durability, whereas illite apparently has little impact on durability. If changes in clay content deleterious to aggregate quality can be identified during lateral production of a ledge, then quarrying can be halted, or can proceed in another direction while physical tests are run. Such a procedure could prevent use of substandard concrete in highway construction projects. Aggregate-producing phylloid-algal limestones of the lower Farley Limestone thicken into the local depositional lows. However, fine quartz-, feldspar-, and clay-rich sediments (siliciclastics) also seem to be deposited preferentially in paleotopographic lows. Thus, local paleotopographic low areas most distal from sources of siliciclastics can be predicted as the prime areas for location of durable aggregate.

ACKNOWLEDGMENTS

We are indebted to a number of people for their assistance and contacts. Our thanks to Robert Henthorne of the Kansas Department of Transportation for his help in setting up quarry access, providing needed KDOT materials and for lending us the services of James Burns and Dave Ely who patiently drilled eight invaluable cores for us. Our appreciation also goes to Frank Rockers of Shawnee Rock Company for his useful knowledge of the Class 1 aggregate testing process and for his patience and assistance in all the quarries he knows so well.

Thank you to the Kansas Department of Transportation for providing funding for this project and to Barbara Smith for serving as official contact with KDOT. The University of Kansas Department of Geology provided additional funds so that this report could be completed.

EXECUTIVE SUMMARY

Identifying lithologies that produce highly durable (class 1) construction aggregates is of utmost importance to both aggregate producers and consumers. The high demand for class 1 aggregate by state, county and private agencies has increased the need for its efficient recognition. This study provides a geologic understanding of the controls on the distribution of highly durable aggregates and should be useful in locating and maintaining them as a resource. The major objective of this study is to reveal the possible sequence-stratigraphic controls on variability of aggregate quality and to evaluate lithologic variables that can be used to identify rock that is or is not suitable for use as class 1 aggregate.

The Farley Limestone (Pennsylvanian, Missourian) is one of many limestone units quarried in northeastern Kansas for production of class 1 aggregate and it is used as the test case for the study. By understanding how the lithologic factors interact to produce highly durable rock in the Farley, an analog for other similar limestone units in different locations can be developed. By monitoring lithologies and other geologic factors as quarrying progresses laterally, changes in quality may be detected and the aggregate reexamined, preventing the unintentional use of lower-quality aggregate.

This report is divided into two major papers in addition to an introductory section, conclusions and appendices. The first major paper, Chapter 2, discusses possible controls on the stratigraphy and sedimentation of the Farley Limestone in the study area as a way of developing a geologic understanding of its lithologic variation. The Farley Limestone was described from 17 core and outcrop localities to define lithofacies and to establish correlations. The observations indicate deposition during two cycles of relative sea-level fluctuation. Low relative sea-level was dominated by deposition of siliciclastics, whereas marine carbonate deposition dominated periods of high relative sea level. Detailed cross-sections and isopach maps show that local paleotopography controlled the distribution of many lithofacies, with deltaic siliciclastics and phylloid-algal limestones of the lower Farley preferentially deposited in depositional low areas. Likewise, in the middle Farley, lithofacies distribution appears to have been controlled by paleotopography. Laterally continuous distributions of lithofacies in the upper Farley indicate that the eventual filling of depositional low areas created subdued paleotopography. Paleotopography on the top of the Farley was caused by erosion that predated deposition of the Bonner Springs Shale.

The second major paper, Chapter 3, deals with the main factors thought to have a significant effect on quality of aggregate. Geologic parameters hypothesized to have had an impact on the durability of limestone construction aggregates include: (1) lithofacies characteristics, (2) bulk spar percentage, (3) average spar crystal size, (4) total percentage of clay-rich strata, (5) distribution of clays within the rock, (6) bulk percentage of insoluble residue and (7) mineralogy of insoluble residue. These parameters were measured in the Farley Limestone and compared to results of those physical tests used by the Kansas Department of Transportation to determine aggregate durability. Data on lithofacies characteristics, bulk spar percentage, average spar crystal size, and bulk insoluble residue percentage exhibit no convincing correlations. Data on total percentage of clay-rich strata, clay distribution, and mineralogy of insoluble residues produce useful correlations. Limestones containing low percentages of diffuse or disseminated clay are more likely to produce aggregates of high

durability. Aggregates containing multiple clay minerals exhibit reduced durability. Smectite, even in small quantities, negatively impacts durability, whereas illite apparently has little or no impact on durability.

The final section, Chapter 4, summarizes the conclusions of the previous chapters and integrates the two by presenting a prediction of the spatial distribution of aggregate quality in the Farley. This model can be used for more effective placement of quarries in the Farley limestone. The correlation between aggregate quality and clays in limestone aggregates can be used to monitor aggregate quality during the quarrying operation, useful as a rapid and inexpensive "first-cut" indication of a degradation in aggregate quality.

Implementation

The location and maintenance of sources of Class 1 aggregate is an important problem to address. The use of the best, most durable aggregate in both state and local projects is economically important. This study represents one step in producing a set of geologic criteria that can be used to identify limestones that are likely to produce class 1 aggregates. Furthermore, this study has shown that by understanding the regional and local controls on the distribution of carbonate lithofacies, the chances of locating and maintaining sources of Class 1 aggregates are greatly enhanced. Future study will be needed not only in continuing to test these conclusions, but also in evaluating the application of the concepts developed to other similar limestone units from which Class 1 aggregates are produced.

Site Selection of Quarries in the Farley

As development continues in the Kansas City area, it is essential that any new quarrying operations be located at sites most likely to produce a reliable source of Class 1 aggregate. Opening quarries in areas of poor sources of aggregate disrupts communities needlessly and does not assure Kansas Department of Transportation (KDOT) with a reliable source of Class 1 aggregate. To prevent needless disruption to communities and to assure a reliable source of Class 1 aggregate for KDOT, we have developed a geologic model whereby sources of Class 1 aggregate can be pre-sited, in the Farley Limestone of NE Kansas, before quarrying operations have begun.

As facies change laterally and vertically so do the geologic properties that have an impact on quality of aggregate. The property that seems to have the greatest impact on the lateral variability of carbonate facies is depositional topography. This topography, the relative sea-level history, and the location of the source area of the siliciclastics are the most important factors in controlling the distribution of fine siliciclastics within the Farley Limestone. Because the distribution of fine siliciclastic sediment has the most negative impact on aggregate quality, understanding the controls of fine-siliciclastic distribution results in the understanding of the distribution of durable aggregates.

To show the distribution of Class 1 aggregate and non-Class 1 aggregate in the Farley, the results of KDOT physical tests and known distribution of clay-rich limestone can be integrated with the stratigraphic cross-sections presented in Figures 2.30 to 2.34. The integrated cross-sections are presented in Figures 4.1 to 4.5. These cross-sections can be used as predictions of the distribution of Class 1 aggregate in the Farley, suitable for use in site selection for new quarries.

Site Selection for Quarries in Other Units

As new construction projects begin in various areas of Kansas, it is essential that KDOT be assured a reliable source of Class 1 aggregate in each area. Without such sources, costs of projects may be increased, delays in construction may be experienced, and inadvertent production of substandard aggregate and concrete is more likely. To assure KDOT with reliable sources of Class 1 aggregate for these new projects, we recommend application of geologic models, which will allow location of the best new resources of Class 1 aggregate in each area.

Geologic reasons explain the distribution of Class 1 and non-Class 1 aggregate. We showed that the phylloid-algal limestones of the lower Farley Limestone thicken into the local depositional lows such as those found at localities SRBS, FRQ, WR, and C6 (Figures 4.1-4.5). We also concluded that phylloid-algal limestones commonly produce durable aggregates. However, siliciclastics also seem to be deposited preferentially in paleotopographic lows. Thus, local paleotopographic low areas most distal from sources of siliciclastics are the prime areas for location of Class 1 aggregate.

Therefore, locating high-quality aggregate requires more than simply locating thick successions of phylloid-algal limestone. Having an understanding of the conditions under which the rocks were originally deposited should aid in the location and maintenance of Class 1 aggregate resources. The most important conditions to understand seem to be paleotopography and source direction and distribution of siliciclastics. It seems likely that the implementation of these ideas to other limestone units of similar origin, such as the Argentine Limestone, the Spring Hill Limestone and other units of the Pennsylvanian of Kansas will assist in locating high-quality limestone construction aggregates.

In addition to phylloid-algal limestone, many facies deposited in higher energy depositional environments, such as oolite and peloidal, skeletal packstone, produce Class 1 aggregate. This is likely related to the relatively low clay content in these high-energy facies. Some of these high-energy facies in the Farley Limestone are located on or immediately adjacent to paleo-highs, whereas others are located in subtle paleo-lows in the lower Farley. Clearly, more work remains to be done on the location and durability of high-energy facies in other units before any geologic concepts are implemented for development of this resource.

We propose that effective exploration for Class 1 aggregate should be enhanced by understanding the regional context and rock properties of each rock unit. Before new areas of quarry development are opened, KDOT geologists, geology students, consultants, or quarry personnel should conduct regional studies of the geologic environment into which the units were deposited. These studies should emphasize the geologic factors, learned from the Farley study, that are important in location of Class 1 aggregate. Lithofacies, abundance of clay-rich zones, spar content, percent insoluble residue, and mineralogy of the insoluble residues would be incorporated to develop a predictive 3-dimensional model of the likely distribution of class-1 aggregate for the new area. Although not foolproof, these models would provide a tool in making decisions regarding future quarry production and locations of new quarries.

Monitoring Rock Properties During Quarrying

Once production of Class 1 aggregate has begun, it is essential that aggregate quality remains Class 1 as limestone is quarried laterally. It is now well known, however, that aggregate quality can change laterally and that substandard aggregate can inadvertently be used in highway construction projects. Currently, there is no way to assure aggregate quality without a time-consuming testing procedure that normally can take about six months. During this testing period, substandard aggregate can be produced, yielding highways susceptible to d-cracking. To avoid production of non-Class 1 aggregate, we propose that a "first cut" analysis be applied as ledges are quarried laterally. The analysis should be inexpensive, rapid, and simple to complete, and could be used as an indication of a negative change in aggregate quality that should precipitate further testing and a cessation of production in the location until KDOT physical tests can be run.

The data from our study indicate that the higher the total percentage of clay-rich strata present in the rocks, the lower the durability factor and the higher the expansion percentage. Furthermore, if three different clay minerals are present in the insoluble residues, durability is likely to decline. Smectite seems to have the most significant impact, which is likely due to its expansion properties upon absorption of water. Thus, even small amounts of smectite are likely to have a negative impact on aggregate durability. The critical threshold of smectite content is unknown at this time. Once quarrying has begun, it is important to maintain production of Class 1 aggregate and avoid use of substandard material. If changes in clay content can be identified during lateral production of a stratigraphic unit, then quarrying can be halted or can proceed in another direction while KDOT physical tests are run. We propose that methods be developed for identification of such changes using inexpensive and rapid techniques. Once these methods have been developed, we propose training of KDOT and quarry personnel to identify such lithologic changes.

One applicable technique that could be applied for monitoring is the measurement of the total thickness of diffuse stylocumulate and clay-rich limestone. If this measurement increases laterally, then there is reason to recommend testing of aggregates, while quarrying is either halted or continued elsewhere. Initial testing would be accomplished rapidly, identifying the presence or absence of clays such as smectites in the samples. If such clays were identified, then KDOT physical tests should be run. Through short courses, KDOT and quarry personnel could be trained to recognize such changes. However, quality control with this approach may be difficult, as it relies on visual recognition of features in the field under variable environmental conditions.

Geophysical tools should prove to be more useful. One such tool is the gamma-ray log, which measures the natural gamma radiation of the rocks and can be used to discriminate between clay-rich limestones and clean limestones. Higher levels of natural radiation in clay-rich rocks are caused by the adsorption of thorium by clay minerals, the potassium content of clay minerals, and uranium fixed by associated organic material (Doveton, 1994). This is useful in the location of durable aggregates because gamma-ray logs give an indication of the amount of clay contained within a limestone unit. Furthermore, the measurement is relatively simple to obtain using either a hand-held scintilometer at the outcrop, or a gamma-ray logging tool in a borehole. However, the standard gamma-ray tool provides little mineralogical information and may yield false positives for clay.

A more useful tool is spectral gamma-ray logging. This tool allows estimations of the separate contributions of the individual elements, which can then be used to estimate clay mineral volumes and types, and can eliminate false positives for clays (Doveton, 1994). If the spectral gamma ray indications of clay content increase laterally during aggregate production, then there is reason to recommend testing while quarrying is either halted or continued elsewhere. Initial testing would be accomplished rapidly, identifying the presence or absence of clays such as smectites in the samples using X-ray diffraction. If such clays were identified, then KDOT physical tests should be run. Through short courses, KDOT and quarry personnel could be trained to use the relatively inexpensive spectral gamma ray tool for evaluating lithologic variation that could indicate a decrease in aggregate durability.

Chapter 1: Introduction

Purpose

Identifying lithologies that produce highly durable (class 1) construction aggregates is of utmost importance to both aggregate producers and consumers. As defined in Kansas, class 1 aggregate is construction-grade material that results from the processing of quarried rock that meets a minimum set of requirements concerning durability, freeze-thaw properties, and expansion percentages.

The Farley Limestone (Pennsylvanian, Missourian) is one of many units quarried in northeastern Kansas for production of class 1 aggregate. Many of the major, active quarries in the Kansas City area of northeastern Kansas currently are producing aggregate from the Farley Limestone. The high demand for class 1 aggregate by state, county and private agencies has increased the need for the efficient recognition of class 1 aggregate.

At present, the Kansas Department of Transportation (KDOT) uses a costly, six-month testing process to determine quality of aggregate. The major objective of this study is to reveal the possible sequence-stratigraphic controls on variability of aggregate quality and to evaluate lithologic variables that can be used to efficiently identify rock suitable for use as class 1 aggregate.

During the preliminary stages of the project we visited several quarries currently producing class 1 aggregate out of a variety of local limestone units. The units examined included the Tarkio Limestone, the Argentine Limestone, the Merriam and Spring Hill Limestones and the Farley Limestone. Based on preliminary observations, we found that some lithologic variables seemed to have an effect on whether a unit passes or fails class 1 aggregate testing. These lithologic variables allowed the development of several working hypotheses.

(1) Micrite-rich, phylloid-algal lithologies consistently produce durable aggregates.

(2) Distinct, sharp stylocumulates have little to no impact on durability, whereas diffuse stylocumulates have a negative impact.

(3) Argillaceous limestone tends to fail testing; therefore the presence of clays in the insoluble residues has a negative impact.

(4) Abundant, coarse, sparry calcite in the rock has a negative impact.

(5) High microporosity (measured as absorption) does not have a negative impact.

(6) Fine-grained, matrix-rich limestones tend to pass physical testing, whereas coarser carbonate grainstones with coarse cements tend not to pass.

The Farley Limestone is used as the test case for the study because it exhibits significant lateral and vertical variation in quality of aggregate and allows initial examination of all of the above listed hypotheses. By understanding how the lithologic factors interact to produce highly durable rock in the Farley, an analog for other similar limestone units in different locations can be developed. Furthermore, better quality control can be established by realizing that stratigraphic units vary laterally in both geometry and lithology (Figure 1.1). By monitoring lithologies and other geologic factors as quarrying progresses laterally, changes in quality may be detected and the aggregate reexamined, preventing the unintentional use of lower-quality aggregate.

Organization

This report is divided into two separate but related, stand-alone papers. The first paper, Chapter 2, discusses possible controls on the stratigraphy and sedimentation of the Farley Limestone in the study area as a way of developing a geologic understanding of the lithologic variation. Topics include a stratigraphic outline of the deposits of the Farley

Limestone and surrounding units, description and environmental interpretation of the major lithofacies, and a discussion of stratigraphic correlations and factors responsible for the vertical and lateral distribution of lithofacies. These factors include relative sea level, paleotopography and source and distribution of siliciclastics.

The second paper, Chapter 3, deals with the main factors thought to have a significant effect on quality of aggregate. These factors include observations made on two levels. First, lithologies and the amounts of visible, coarse-calcite spar and diffuse or concentrated clay and stylocumulates were examined on outcrop and in hand sample. Second, the percentage and composition of the insoluble residues and the type, average crystal size and amount of calcite spar found in the crushed aggregates were examined petrographically and using x-ray diffraction. Correlations between these factors and KDOT physical tests are made in an attempt to simplify the identification of lithologies suitable or not suitable as class 1 aggregate.

The final section, Chapter 4, summarizes the conclusions of the previous chapters and integrates the two. The potential of using the Farley as a predictive model for aggregate distribution is discussed as are topics for future study concerning both the Farley Limestone and research on class 1 aggregate.

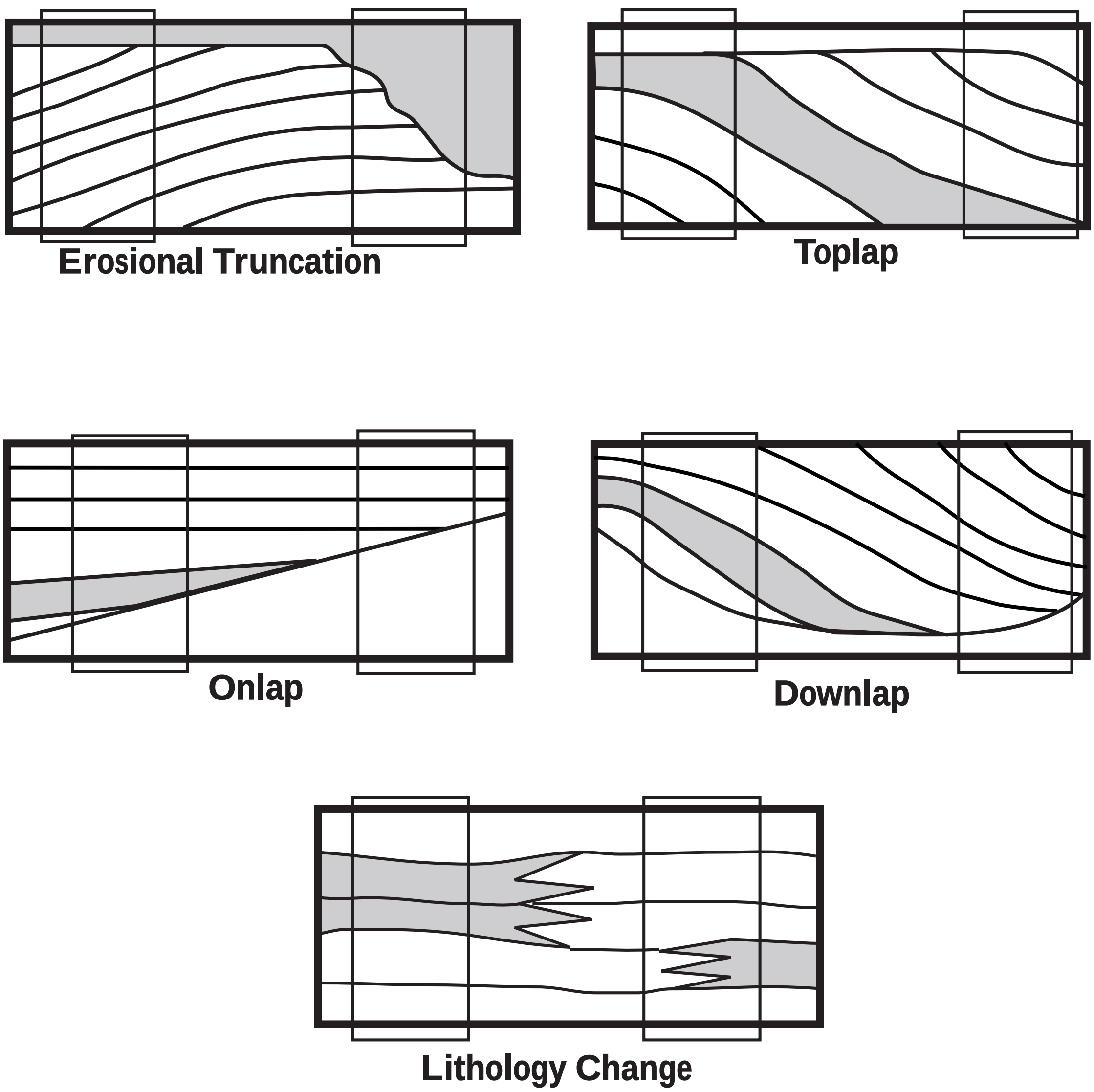

Figure 1.1. Illustration of four common internal geometries and an example of lithology change in cross-section. For each, hypothetical units of class 1 aggregate are shaded gray. Two boxes within each diagram represent quarry locations. Note how adjacent quarries may have differing stratigraphic successions and how geometric relationships and lithology changes can cause significant variation in the distribution of class 1 aggregates from one quarry to the next. The diagram illustrates the importance of understanding the lateral and vertical variability of stratigraphic units in relation to location and production of class 1 aggregates. Understanding the changes will allow aggregate producers to better maintain sources of class 1 aggregate.

Chapter 2: Sequence Stratigraphy of the Lane-Island Creek Shales and the Farley Limestone

Introduction

Historically, Pennsylvanian carbonate units of Kansas such as the Farley Limestone generally have been thought of as continuous layers. Upon close inspection, however, they reveal significant lateral and vertical variability of facies and geometry. The objective of this paper is to describe the stratigraphy and sedimentology of the Farley Limestone in northeastern Kansas with emphasis on evaluating the controls of the lateral and vertical distribution of both facies and stratal geometries. We hypothesize that the Farley was affected by depositional topography, source and distribution of siliciclastics, and changes in relative sea level. The development of a high-resolution sequence-stratigraphic framework for the Farley Limestone allows better understanding of how these factors controlled heterogeneity of facies.

A firm understanding of the sequence-stratigraphic framework of a unit such as the Farley Limestone provides a better understanding of the interaction of factors that control lithologic heterogeneity and provides predictive capabilities that are applicable to other Pennsylvanian limestone units similar to the Farley. Because many Pennsylvanian carbonate units similar to the Farley are petroleum reservoirs, these predictive capabilities are potentially useful for locating potential petroleum reservoirs in addition to identification of high-quality limestone aggregate resources.

Area of Study

The field area in this study includes a combination of 18 quarry exposures, roadcuts, and drill cores in Johnson, Wyandotte, and Leavenworth counties in the Kansas City area of northeastern Kansas (Figure 2.1). Appendix 1 is a list of legal descriptions of all field localities and contains locality maps, photographs, and

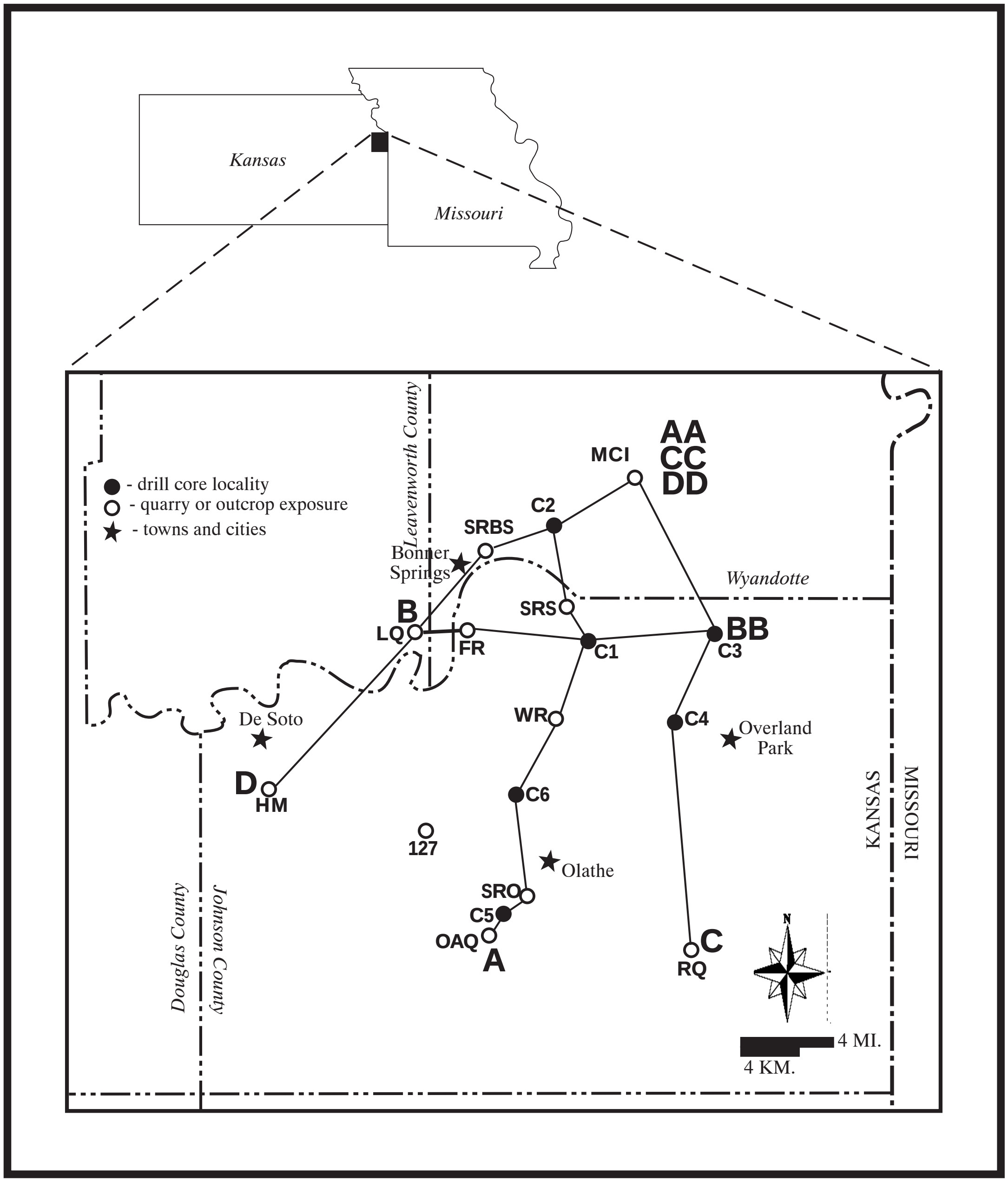

Figure 2.1: Index map showing location and type of field localaties and major towns for reference. Reconstructed cross-sections along lines A-AA, B-BB, C-CC, and D-DD are illustrated in Figures 2.30, 2.31, 2.32, and 2.33.

measured stratigraphic sections of each. Access to quarries was arranged through the quarry operator, and cores were drilled by the Kansas Department of Transportation and are reposited at the Kansas Geological Survey, Lawrence, Kansas.

Stratigraphy

Described first in Missouri by Hinds and Green (1915), the Farley Limestone was defined as a thin limestone lying between the Argentine and Plattsburg Limestones and was placed as the middle member of the Lane Shale (Watney and Heckel, 1994). Moore (1932) and Newell (1935) later identified the Farley in northeastern Kansas (Johnson County) as two lithologically similar limestones separated by a shale unit and placed it as the upper member of the Wyandotte Limestone. Still later, Moore (1949) showed that in Kansas, north of Miami County, the Farley occurs as an extremely variable assemblage of limestone and shale beds above the more laterally persistent Argentine Limestone.

The stratigraphic nomenclature presented in this paper (Fig. 2.2A) reflects recent changes made by Arvidson (1990) and Watney and Heckel (1994), to the traditional stratigraphic classification (Figure 2.2B). The new stratigraphic nomenclature corrects a miscorrelation made by Moore (1936) who placed the Lane Shale below the Argentine Limestone rather than above it. The Farley is located above one of three different units depending on location within the field area. In the north and northeast the Farley is located immediately above the Island Creek Shale. In the southwest it overlies the Lane Shale and in the areas where these shale units are absent the Farley is found directly overlying the Argentine Limestone. The unit located directly over the Farley Limestone in all localities is the Bonner Springs Shale. A brief introduction to each of these units is presented below.

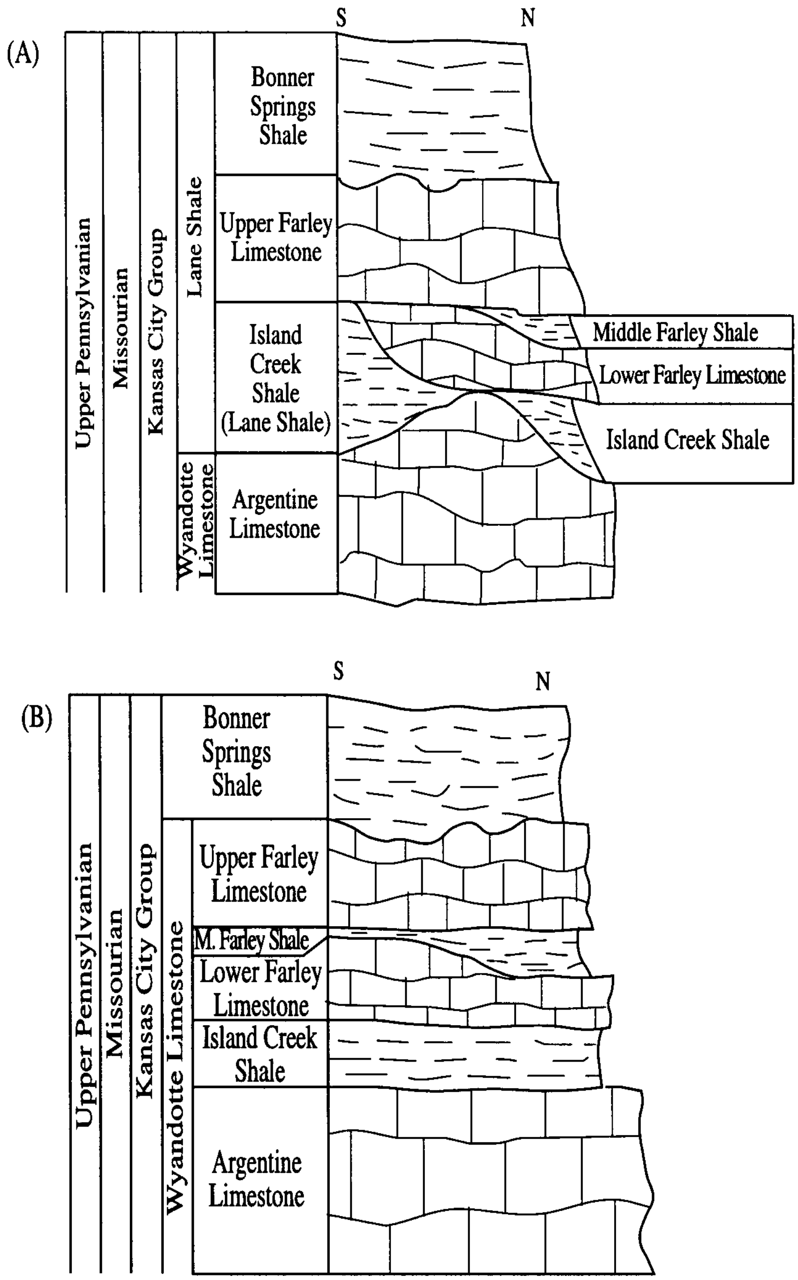

Figure 2.2. Generalized stratigraphic sections showing general relationships and lithologies of the units examined for this study. (A) Section showing revised stratigraphic nomenclature based on the work of Arvidson (1990) and Watney & Heckel, (1994). Major revisions include splitting the Farley Limestone and the Bonner Springs Shale out of the Wyandotte Limestone and regrouping them as part of the Lane Shale. This reflects the correlation of type Lane Shale to lie between Argentine and Farley Limestones in southeastern Kansas (southwest Johnson County, Miami and Anderson counties). See the text for further discussion of revisions. (B) Generalized stratigraphic section showing the traditional stratigraphic classification into which the Farley Limestone fits (after Arvidson, 1990).

Argentine Limestone Member

The Argentine Limestone is the uppermost member of the Wyandotte Limestone (Fig. 2.2A) and shows great variation in thickness throughout the area (Crowley, 1969; Arvidson, 1990; this study). Crowley (1969) attributed these thickness variations to the presence of a series of phylloid algal banks that attained thicknesses as great as 50 feet (Figure 2.3). In developing the sequence-stratigraphic framework of the Farley Limestone in this study, the paleotopography on the top of the Argentine Limestone is important because it could have influenced deposition of the Lane-Island Creek shales and Farley Limestone. Arvidson (1990) demonstrated the topographic influence of the Argentine and stated that the Lane Shale is confined to areas where the underlying Argentine Limestone member is thin. Crowley (1969) also demonstrated this topographic influence and stated that the Island Creek Shale extends southward from northern Wyandotte County between areas of thickened Argentine. For these reasons, the top of the Argentine Limestone is included in the correlations and cross-sections developed for this study discussed later.

Lane-Island Creek Shales

Work by Arvidson (1990) indicated that the shales located below the Farley Limestone represent two distinct units and source directions. The isopach maps of Crowley (1969) and this study show that the Island Creek Shale had a northern source and extended southward in a thickened lobe into Johnson County (Fig. 2.4). Arvidson (1990) confirmed this source direction but showed that Crowley misscorrelated the Lane Shale, placing it below the Argentine instead of above. The new correlations of Arvidson (1990), however, also showed that the stratigraphic position of the type Lane Shale between Argentine and Farley Limestones demonstrates its equivalency with the

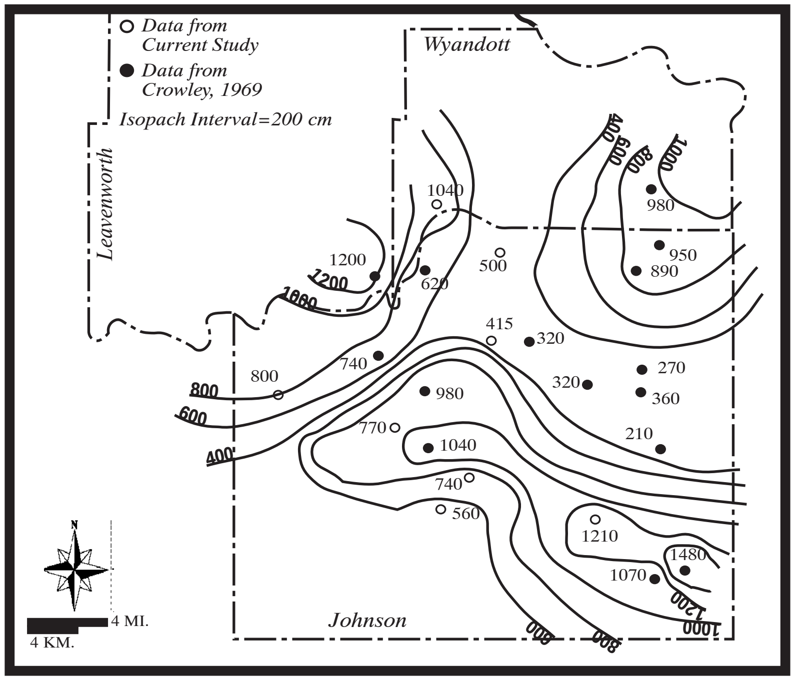

Figure 2.3. Isopach map showing thickness of the Argentine Limestone within the field area. Data taken from current study and from Crowley, 1969.

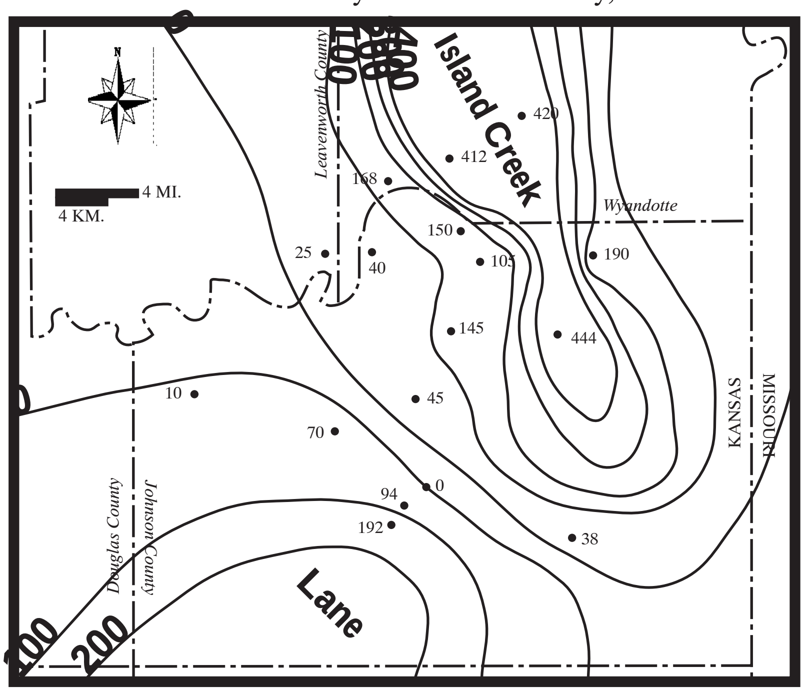

Figure 2.4. Isopach map showing the thickness of the Lane-Island Creek Shale. Note how thickness of these shale compliments thickness of Argentine Limestone illustrated above. Where the Lane-Island Creek shales are thin the Argentine is thick, and where the Lane-Island Creek is thick the Argentine is thin. Data taken from current study and Crowley, 1969. Isopach interval=100 cm.

Island Creek Shale. Furthermore, Arvidson (1990) argued that the siliciclastic interval separating the Argentine from the Farley in southern Johnson County represents material supplied primarily from southern sources, whereas siliciclastics with a northern source were not deposited here. The work done in the current study confirms that the Island Creek Shale member of the Lane Shale (Fig. 2.2A) does in fact represent two distinct shale units with little to no shale in the areas between them. This distinction of time-equivalent siliciclastics with different source directions is important to make. These siliciclastics are therefore referred to as Lane-Island Creek shales in order to establish that they are time-equivalent but in fact need to be thought of as separate units within the sequence-stratigraphic framework; this distinction is not made in the stratigraphic nomenclature presented in Figure 2.2A.

Farley Limestone Member

In the area of this study, the Farley Limestone is a mixed siliciclastic-carbonate unit typically composed of three individual submembers (Fig. 2.2A) of varying thickness and lithology; the lower, middle and upper Farley. The lower Farley is a carbonate unit and shows the greatest degree of lithologic and thickness variability. The middle Farley is dominantly siltstone but contains local accumulations of carbonate within it. In the southwest portion of the field area, the middle Farley is composed of a thick accumulation of skeletal carbonate with little to no shale. The upper Farley is exclusively carbonate and is the most lithologically consistent submember. Thickness variability in these units will be discussed in the later parts of this paper.

Bonner Springs Shale

The unit immediately overlying the Farley Limestone at all localities is the Bonner Springs Shale. The uppermost member of the Lane Shale, the Bonner Springs Shale, contains variable lithologies and thickness (90 cm to 9 m). Lithologies typically observed include mudstone, siltstone, and sandstone (Enos *et al.*, 1989; Crowley, 1969; Arvidson, 1990; this study). Erosional scouring and backfilling as well as the development of a paleosol in the upper few feet of the Bonner Springs Shale indicates widespread subaerial conditions near the end of Bonner Springs deposition (Enos *et al.*, 1989).

Lithofacies & Depositional Environments of the Farley Limestone

The Farley Limestone is divisible into ten distinct lithofacies. All facies were established based on details observed at outcrops, in cores, and in thin sections.

Phylloid Algal Facies

The most common facies in the Farley Limestone is the phylloid-algal facies (Fig. 2.5) that occurs as both boundstone and packstone. Present in all measured sections and cores, this facies is light to medium gray (N5-N7) on fresh exposures and weathered exposures are light brown to grayish-orange (5YR 5/6-10YR 7/4). Where the facies contains large percentages of disseminated argillaceous material (Fig. 2.5d) the rocks have a bluish hue (5B 7/1, 5B 5/1).

Bedding is thin to thick (25 to 100 cm) in scale and is accentuated by thin shale partings. These shale partings commonly contain abundant crinoidal and bryozoan material and are commonly diffused into overlying limestone beds and can account for as much as 30 percent of the rock mass. The main skeletal constituents are phylloid-algal blades, which account for more than 50 percent of the fossils and are present to the exclusion of other fossils in some areas. The phylloid algae have a variety of sizes but typically are wavy veinlets of calcite spar at least 3 cm in length and with lengths up to 12 cm.

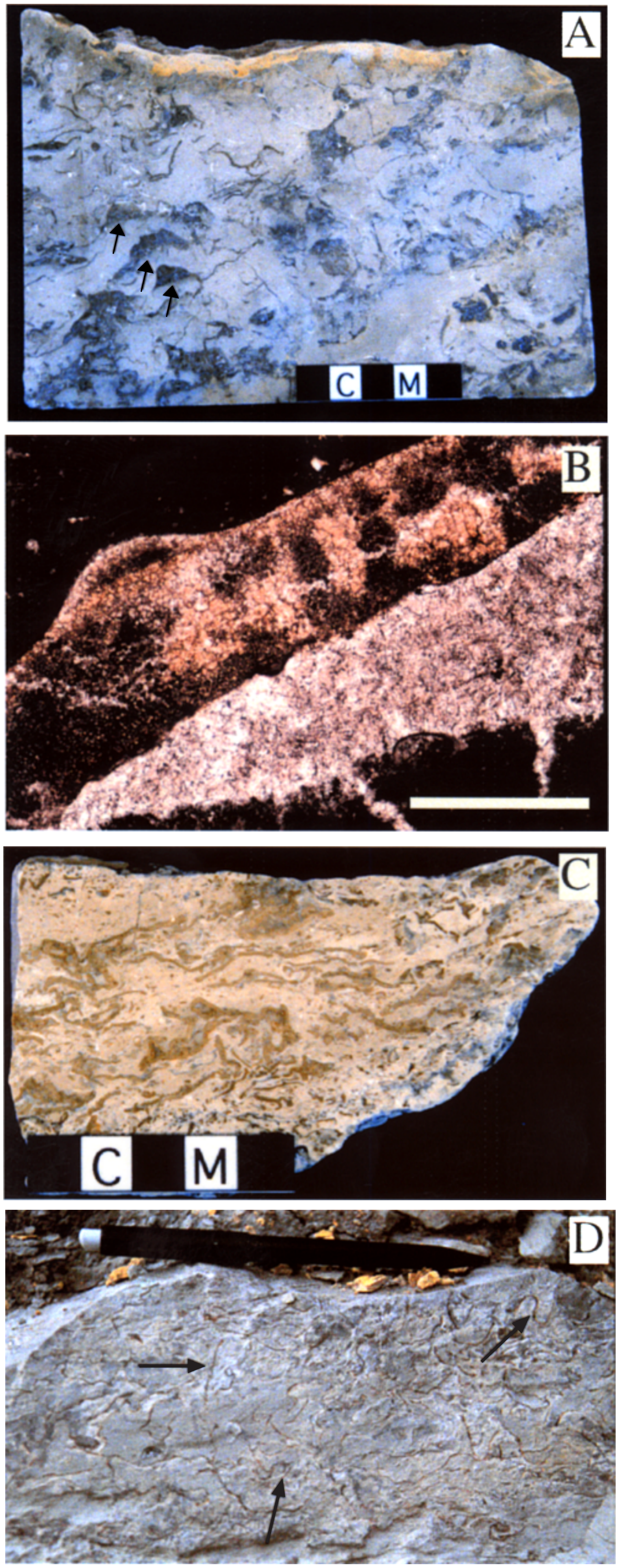

Figure 2.5 (A) Polished slab illustrating the appearance of the phylloid algal facies. Note the coarse calcite spar filling shelter pores beneath phylloid algal blades (arrows) (sample WR-1).
(B) Photomicrograph of phylloid algal blade with dense micrite above and spar filled shelter pore below (transmitted light; scale =1mm; sample S-7).
(C) Hand sample showing denser packing of lamelar phylloid algal blades (sample RQ-11).
(D) Nature of phylloid algal facies as seen on outcrop. Small wavy veins are phylloid algal blades. (arrows) Bluish color in this particular outcrop is the result of a high percentage of finely disseminated argillaceous material (locality LQ).