ALLOSTRATIGRAPHIC CONTROL OF THE
OCCURRENCE OF CHERT:
LOWER DEVONIAN, PENNSYLVANIA

A Thesis Submitted

to the

Temple University Graduate Board

in Partial Fulfillment

of the Requirements for the Degree

Master of Arts

Tarja M. Wolf-Eskel

January, 1997

Peter W. Goodwin

Dr. Peter W. Goodwin, Advisor

7/29/96

Date

David E. Grandstaff

Dr. David E. Grandstaff, Committee Member

July 29, 1996

Date

George H Myer

Dr. George H. Myer, Committee Member

7/29/96

Date

ABSTRACT

ALLOSTRATIGRAPHIC CONTROL OF THE OCCURRENCE OF CHERT: LOWER DEVONIAN, PENNSYLVANIA

by

Tarja M. Wolf-Eskel

Master Of Arts

Temple University, January 1997

Major advisor: Dr. Peter W. Goodwin

Chertification in the 4^{th}-order (400 ky) sequence of the Lower Devonian New Creek and Corriganville Formations is primarily controlled by high-frequency sea-level fluctuations. The New Creek Formation (one or two 5^{th}-order sequences) is divisible into six small-scale allocycles, in which chert occurs at cycle boundaries. The Corriganville Formation (two 5^{th}-order sequences) is composed of nine laterally correlative small-scale cycles, in which chert occurs at cycle boundaries as well as at sea-level-fall surfaces and in high-stand portions of the cycles. The position of chert in the allocyclic framework is primarily controlled by stratigraphic processes, while inhomogeneities in sediments and supply of diagenetic ingredients are secondary controls. For example, chert morphology,

which varies from bedded to nodular, seems to be controlled by inhomogeneities in the sediments. Stratigraphic processes act through control of sedimentation rates; in these shallow, below-wave-base environments, sedimentation of carbonate and terrigeneous matter ceased at cycle boundaries in the New Creek and Corriganville Formations and at sea-level-fall surfaces in the Corriganville Formation, and was intermittent during the high-stand portions of cycles in the Corriganville Formation. Silica accumulated undiluted during cycle boundary times; the silica from these primary locations of accumulation migrated later to a nearby host. In addition to controlling concentrated accumulation of siliceous sediments, stratigraphic processes enhanced chert formation by promoting diagenetic reactions in the sulphate reduction zone. In this manner the occurrence of chert in the New Creek and Corriganville Formations corresponds to the allostratigraphic framework and was controlled by stratigraphic processes.

ACKNOWLEDGMENTS

I would like to acknowledge and thank my thesis advisor and committee members. In the beginning of the thesis, Dr. Goodwin, Pete, endured long, lengthy discussions on hypotheses and their implementations, which eventually became woven into this thesis. He also allowed me to strive to achieve the best. Drs. Myer and Grandstaff have proved invaluable in both their specialties, crystallography and geochemical/diagenetic reactions, and their never failing encouragement throughout the thesis. Roger Cutitta has been ever helpful in his technical know-how and his patience in teaching AutoCAD.

I thank John Brauer of Lycoming Sand for access to the quarries of Limestoneville, Muncy and Grovania. Spectra Inc. cut and polished some of thin-sections used in this thesis. Doug Johnson, Princeton University, and Lapidabrade, Havertown, provided information on how to cut the very tough chert samples.

Very valuable field assistance was provided by fellow students William Chadwick, Andrew Clark and music student and my friend Cathy Mayer. I also thank the rest of the faculty and the supportive staff at Temple, especially Sheila Burgess.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

The purpose of this study is two-fold: first, to document the occurrence of chert within a small-scale allostratigaphic framework; second, to postulate a model to explain the genetic relationship of chert within that cyclic framework. Previous work (Orzechowski, 1995) suggested a coincidence of chert and 6^{th}-order cycle boundaries in the New Creek and Corriganville Formations of the Helderberg Group of Pennsylvania. Within that stratigraphic interval this study will record in detail all occurrences of chert beds and nodules in a hierarchic framework of correlative cycles, compare these patterns with Milankovitch predictions and present a model linking high-frequency sea-level fluctuations with the process of chertification.

To date there has not been a study relating chert to a small-scale cyclic framework; hence this study adds a new aspect to the understanding of chert formation. Traditionally the chert problem has entailed questions of silica source, timing of silicification and host rock association of the authigenic silica (*e.g.* Hesse, 1989). The focus of chert research has been, on one hand, the analysis and description of chert fabric in thin-sections, and on the other, the timing of silicification and the postulation of geochemical conditions based on field relations (Hesse, 1988). The question of adequate silica source for chertification was and still is problematic; the source may be either biogenic (*e.g.* Meyers, 1977; Matheney and Knauth, 1993; Lawrence, 1994) or abiogenic (*e.g.* Noble and Stempvoort, 1989). The source of silica may be related to genesis of chert (abiogenic vs. biogenic, intraformational vs. interformational) and hence connected to processes involved in the formation of chert.

Recent chert studies significant to this thesis have included stratigraphic, geochemical and sedimentological studies. Each has contributed to the understanding of chert in general, and has relevance to the occurrence of chert in the study interval. For example, Maliva and Siever (1988) suggested that chert is confined to particular stratigraphic units which represent below-wave-base environments. Lawrence (1994) divided chert-bearing limestone sequences into sub-formation scale units, which were based on visual estimation on the proportions of chert and dolomite in limestone. Chert distribution was correlative with deeper environment at the stratigraphic base of the study section (vertical distribution) and in the basin center (lateral distribution). Further, chert-bearing intervals or some particularly distinct chert beds were correlated for distances of miles to hundreds of miles (km to hundreds of km) (Mortimore and Wood, 1986; Noble and Stempvoort, 1989), suggesting allostratigraphic control of chert-rich facies. At one locality chert was observed to be related to exposure at a large-scale unconformity (Namy, 1974), but the predictability of this claim was disputed by others (Meyers, 1977).

Chert formation, as precipitation of an authigenic mineral, may be analogous to the formation of other authigenic minerals, which tend to form in particular and clearly defined, geochemically active zones (*e.g.* chert description in association with phosphate and barite, Graber and Chafetz, 1990). For example, the combination of pyrite, organic matter and carbonate rhombs embedded in chert indicates the association of chert formation within the sulphate reduction zone (Geeslin and Chafetz, 1982; Noble and

Stempvoort, 1989; Misik, 1993; Lawrence, 1994). Facies association is related through correlation with porosity and permeability (*e.g.* Meyers, 1977; Baltuck, 1986; Gao and Land, 1991), and organic matter content in selected facies (*e.g.* Noble and Stempvoort, 1989; Lawrence, 1994). Thus facies, with its associated lithological parameters, may control the exact chert location by allowing certain authigenic mineral precipitation. These studies provide a feasible foundation for the hypothesis that the strictly defined geochemical conditions for the formation of chert horizons are controlled primarily by the stratigraphic process of high-frequency sea-level changes.

The uniqueness of this study lies in the correlation of chert occurrences with small-scale cyclicity. Thus, before focusing on a particular diagenetic or facies-related feature of chert, this study attempts to relate chert bands and nodules to a cyclic framework laterally and vertically. Correlation of small-scale cycles reveals whether or not chert nodules and beds occur in clearly identifiable and hence predictable horizons in this cyclic framework, and if so, whether the horizons are located within a particular section of the cycle. This type of analysis will determine if these chert layers are time-stratigraphic, thereby providing more understanding of the relationship of chert to high-frequency sea-level changes.

Objectives

In order to describe and explain the relationship between chert and a cyclic framework the following objectives must be met. First, small-scale cycles that constitute the cyclic framework have to be determined by documenting repetitive shallowing-upward facies patterns bounded by sharp surfaces of discontinuity. The Milankovitch-driven framework of Orzechowski (1995) was a starting point; preliminary work (Eskel and Goodwin, 1994) suggested some modification of Orzekowski's findings will be necessary. The next task is to correlate the cycles by matching the degrees of facies changes across the study area. Within these correlative cycles the location of chert will be shown, with attention to sedimentological detail. Finally the chert-bearing cyclic framework will be compared to the hierarchic patterns predicted by Milankovitch orbital forcing theory for the purpose of developing a stratigraphic model to explain the occurrence of chert.

Methods

Although the New Creek-Corriganville interval has been described as a cyclic sequence, in this study the first issue was to find the smallest correlatable unit or cycle within cyclic framework. Columnar sections were drawn at a scale of one foot to 3/4" (0.31 m to 0.10 m), at which scale even small beds became significant. Hence the detailed drafting of the columns, in order to preserve detail of the identity of the cycles, became the most important part of the project. Seven localities near Altoona in Pennsylvania and one in east-central Pennsylvania provide the data for the study (Figures 1 and 2). These localities are, from the south: Cessna, St. Clairsville, Hollidaysburg, Altoona Bypass (Eldorado Quarry), Allegheny Furnace, Canoe Creek Quarry and Tyrone (Appendix 1). In the east the Lycoming Silica Sand quarry at Limestoneville was the primary section; supportive data were gathered at an actice quarry near Grovania. The columns were drafted by using the AutoCad drafting program.

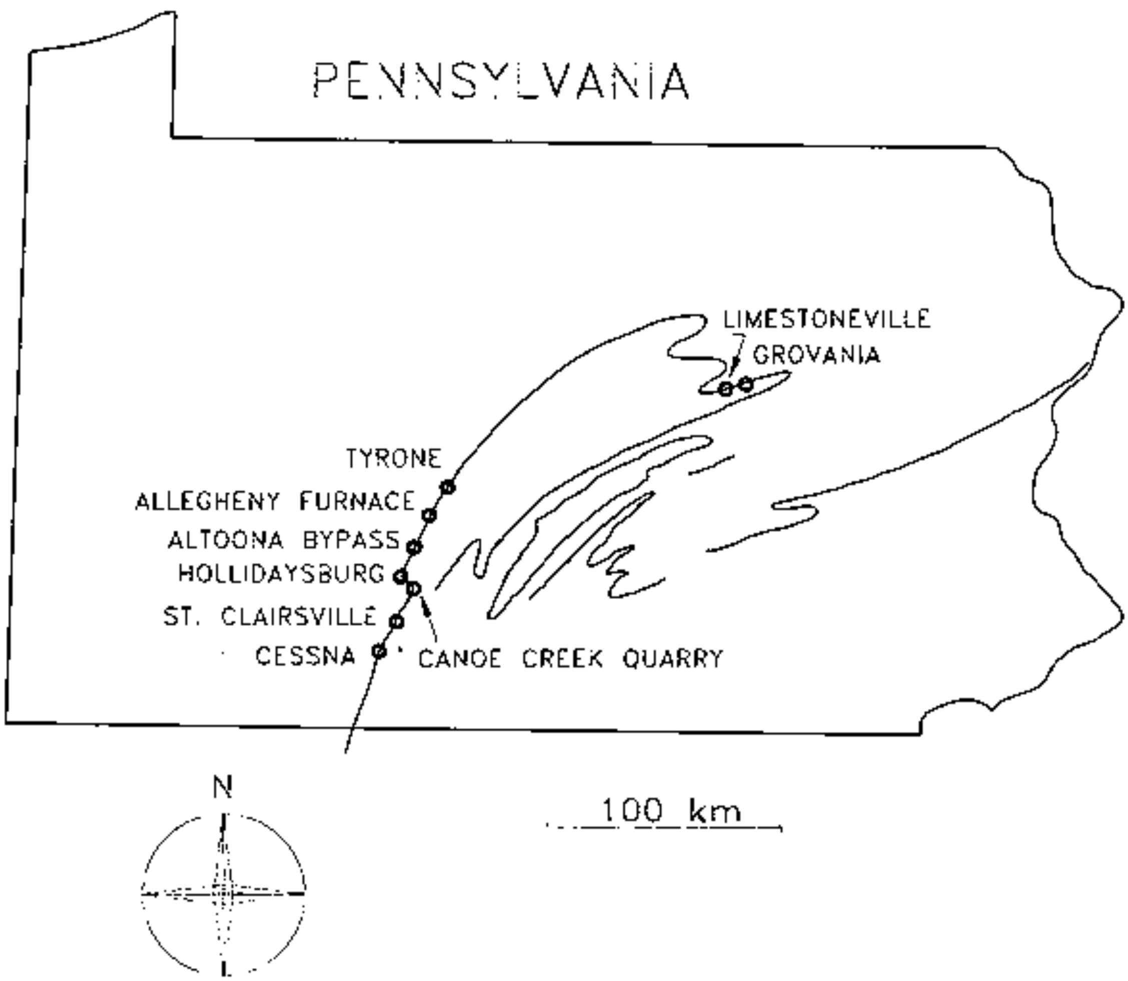


Figure 1. Outcrop localities.

The Helderberg Group outcrop belt of the study area extends from south-central Pennsylvania to central Pennsylvania. Detailed descriptions of outcrop localities are in Appendix 1.

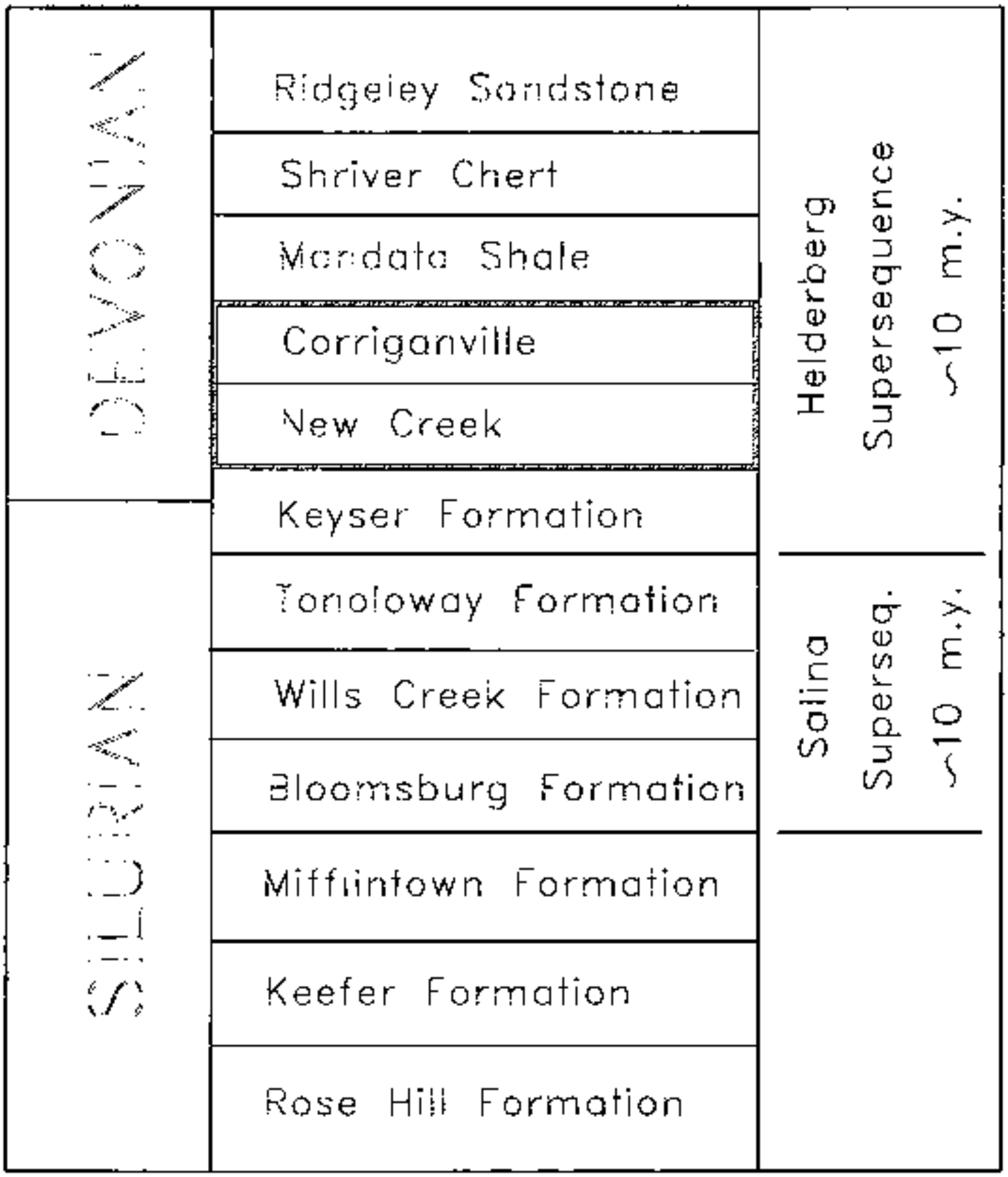


Figure 2. <u>Silurian and Devonian stratigraphy.</u>

The Lower Devonian New Creek and Corriganville Formations are part of the Helderberg 2nd-order Supersequence.

In addition to outcrop work, polished slabs and thin-sections were prepared. The slabs contained varied combinations of chert and limestone. On the observation that the chert is replaced limestone, it was decided to use typical limestone terminology for chert description. Each chert sample was described in detail by recording all features possibly linked to the stratigraphic occurrence of chert in this interval, including diagenetic features. The description included texture, structure, chert or limestone composition, and other features, including matter composing the structure, exotic minerals, replacement type, organic matter and degree of fossil preservation (Appendices 2 and 3).

Photography included outcrops, slabs and thin-sections displaying features relevant to a particular magnification. The purpose of outcrop photography was to show cyclicity and the position of chert in relation to cycle boundaries. Slabs and thin-sections were photographed and photomicrographed, respectively. Thin-sections were photomicrographed with an Olympus camera attached to a Leitz petrographic microscope with 200 ASA Kodak film. In order to see the most of sedimentary structures, the least magnification was used. The features showed various microcrystalline quartz-carbonate relationships in the host matrix of replaced limestone. Extra thick thin-sections were photographed on a Wild microscope stand with a Nikon camera to show various sedimentary structures in the scale of a few inches and less (less than 5 cm).

CHAPTER 2
STRATIGRAPHIC MODELS
PAC HYPOTHESIS AND MILANKOVITCH THEORY

Stratigraphy is the study of spatial and temporal relationships of rocks. Traditional stratigraphy was done at the scale of formations which are units interpreted as representing ancient environments. According to stratigraphic gradualism, depositional environments migrate gradually and continuously through time; laterally adjacent facies of formations were superimposed vertically, as the crust subsided or sea level rose. For example, in the classical stratigraphic study of the Helderbergian Group in New York State, the paleoenvironments were interpreted to be time-transgressive, migrating through time to form the vertical sequence of successively deeper formations (Rickard, 1962; Laporte, 1969).

Today, however, the stratigraphic record is viewed by an increasing number of investigators as accumulating episodically in response to high-frequency eustatic sea-level changes. According to this allostratigraphic view, the stratigraphic record consists of cycles or units produced by an allogenic mechanism, which often is attributed to Milankovitch orbital forcing of sea level. For example, in sequence stratigraphy, the rock record consists of sequences, which are bounded by unconformities (van Wagoner *et al.*, 1988). Sequences are composed of parasequences and parasequence sets, which form the vague hierarchy of sequence stratigraphy. This hierarchy is not scale-specific nor is it process-connected. The building block of the hierarchy is the parasequence, a shallowing-upward rock cycle bounded by marine flooding surfaces.

Lack of specificity with regard to scale and process has permitted the broad use of the sequence stratigraphy model in many different ways. For example, Strasser (1994) combined the model with the orbital forcing (Milankovitch) model to interpret Jurassic peritidal sequences as a hierarchy of 20 ky, 100 ky and 400 ky cycles. Goodman and Brett (1994) described high-frequency allostratigraphic sequences in the Silurian Appalachian Basin, whose mechanism they ascribed to both eustatic sea-level change and tectonic signatures in the basin morhpology (*i.e.* movement of the basin axis, flexure of the craton and basin margin). The sequences (3^{rd}-order) and subsequences (4^{th}-order) were subdivided into parasequence sets (5^{th}-order) and parasequences (6^{th}-order). The parasequences were equated with PACs, and formed the basic stratigraphic unit of correlation. They were traceable basinwide unless truncated by unconformities at basin margins. The Goodman and Brett (1994) hierarchy was not linked to specific processes but the 5^{th}- and 6^{th}-order cycles were ascribed to climatically controlled eustasy.

The Punctuated Aggradational Cycle (PAC) hypothesis is a comprehensive model which relates allogenic cycles as fundamental units of stratigraphy to glacial eustasy. A PAC is internally gradational, and laterally correlative by basin-wide surfaces of discontinuity, which denote geologically abrupt deepening events (Anderson *et al.*, 1984; Goodwin and Anderson, 1985; Goodwin *et al.*, 1986; Anderson and Goodwin, 1990). The surfaces of discontinuity, or cycle boundaries (Figure 3), are distinct surfaces marking disjunct changes from shallower (top of cycle below) to deeper (base of next cycle) facies. By matching the degree of environmental change across cycle boundaries lateral correlation of cycles can be established. These laterally correlative cycles form slices,

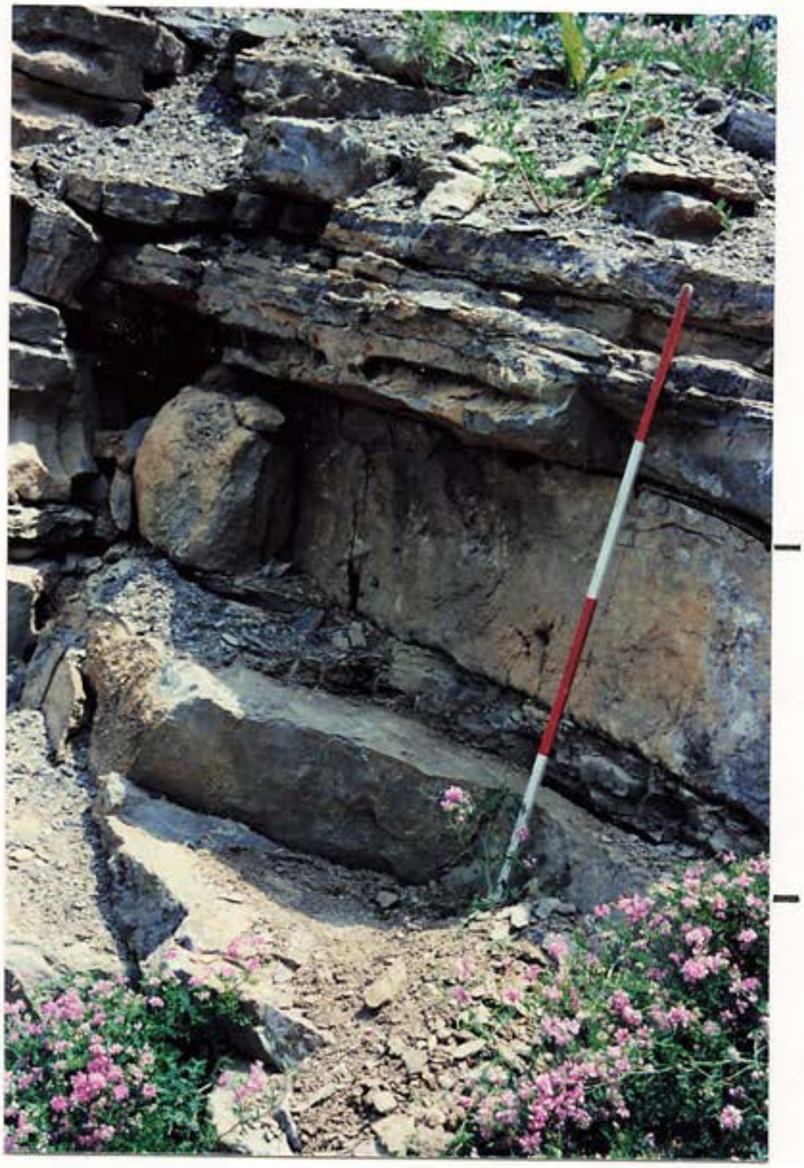


Figure 3. PAC 4, Corriganville Formation, Altoona Bypass.

Boundaries of PAC 4 are at facies changes to deeper facies (marked by black lines). PAC 4 consists of distinct high-stand and low-stand parts separated by a sea-level-fall surface. The high-stand part is characterized by shale and nodular micrite, and the low-stand part by calcarenitic, shallower facies. The stick for scale is in feet.

which record "small-scale episodic changes in paleogeography" (Goodwin and Anderson, 1988). The accumulation of sediments within a cycle is enhanced or dampened by different rates of subsidence and sedimentation, but the abrupt change to a relatively deeper environment is caused by a rapid sea-level change (Anderson *et al.*, 1984; Goodwin and Anderson, 1988).

An individual PAC has a distinct pattern consisting of cycle bounding surfaces and internal shallowing-upward fabric (Figure 4). This morphology of a cycle is attributed to changes in sea-level forced by the precessional cycle. In an ideally defined PAC the internal fabric is divided into high-stand and low-stand portions, which are separated by a sea-level-fall surface. Cycle boundaries and sea-level-fall surfaces are produced at times of rapid sea-level rise and fall, respectively, when the rate of sea-level change is the greatest. At times of lower rates of change deposition occurs, the lower portion of the cycle at highest sea-level stand and the upper portion at the lower stand of sea level.

In most allostratigraphic studies, the driving force of eustasy is attributed to Milankovitch orbital variations. The variables of Milankovitch astronomical forcing theory are the cyclic changes in precession, obliquity and eccentricity, or the varying positions of the Earth in relation to the Sun. Precession refers to cyclical change in the direction of Earth's tilted axis in relation to the perpendicular plane of the ecliptic orbit (Fig. 5). The axis makes a cone-shaped path within 20 000 years (20 ky), though it may fluctuate between 19 ky and 23 ky (Berger, 1988). The degree of the axial tilt is obliquity, which fluctuates between 23 and 25 degrees. One obliquity cycle has a duration of about 40 ky, but its effect is less prominent especially in low latitude carbonate

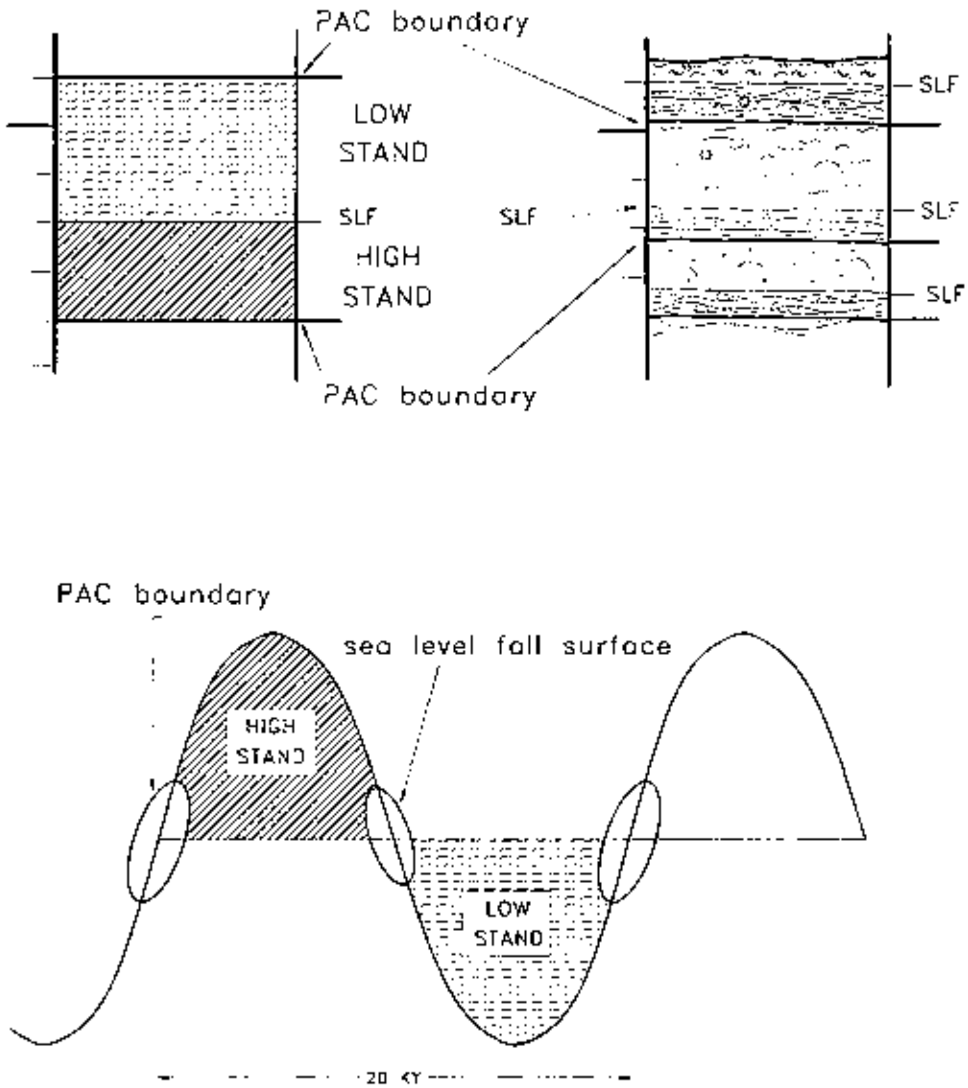


Figure 4. PAC dynamics.

Cycle boundaries are at abrupt changes to deeper facies. The high-stand and low-stand parts of a PAC are separated by a sea-level-fall surface (SLF), which marks a sudden change to shallower facies. PAC boundaries are produced during rapid rises of sea level, at the inflection point on the rising eustasy curve; sea-level-fall surfaces are produced at the inflection point on the falling limb of the eustasy curve.

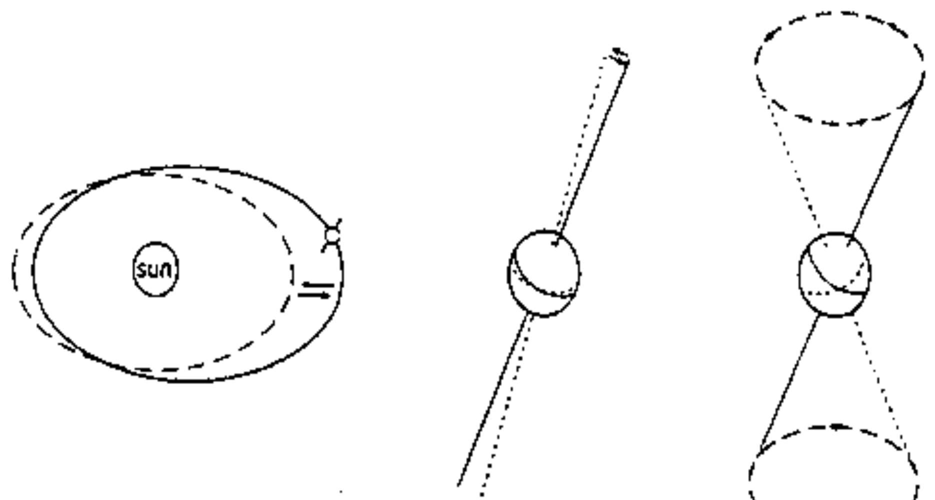


Figure 5. Milankovitch orbital forcing theory.

Orbital parameters, precession, obliquity and eccentricity, affect climate and sea level and thus control stratigraphic patterns. The precessional cycle is a 20,000 year (20 ky) cycle of the changing direction of the tilt of the Earth's orbit. The obliquity (degree of tilt) cycle has a period of approximately 40 ky. Eccentricity, change in the shape of the Earth's orbit around the Sun, occurs in two cycles of 100 ky and 400 ky periods. (Modified from de Boer, 1983).

environments (Schwarzacher, 1994). There are two sequences of eccentricity, with periods of 100 ky and 400 ky. The shape of the earth's orbit varies from a long ellipsoid with the sun in one end to a more circular ellipsoid. The effect of eccentricity modulates the effect of precessional change and hence creates bundling of cycles.

The variations in orbital parameters cause changes in the Earth's climate. Although climate is a result of complex variables such as oceanic and atmospheric currents and location and shape of landmasses the only energy source to drive climate is insolation. Hence anything that causes changes in insolation and thus in energy budget, will also cause climatic changes (Schwarzacher, 1994). These changes are thought to induce the amount of global continental glaciation, which would lower or raise the sea level by trapping or releasing water and thus indirectly affects sedimentation supply and patterns. The direction of the axial tilt of precession determines whether the northern or the southern hemisphere is directed toward the Sun at perihelion, which will affect the intensity of summer and winter. Obliquity controls the northern and southern extent of latitudes that will receive sun, thus modulating, in part, the duration and intensity of summer and winter. The eccentricity cycle, coupled with the direction of the tilt of the axis, modulates further the duration and intensity of insolation received by the hemispheres. Because landmasses are needed for the accumulation of continental ice sheets, the positions of the continents are crucial in relation to build-up of glaciers.

According to the PAC Hypothesis, the precessional cycle (20 ky) causes 6^{th}-order PACs while eccentricity acts as a modulator affecting the amplitude of precessional rises and falls and produces bundles of PACs. The characteristic stacking pattern is as follows:

there are five 6^{th}-order cycles or building blocks, in a 5^{th}-order sequence (Figure 6). Four 5^{th}-order sequences (100 ky) constitute a 4^{th}-order sequence (400 ky). Fifth-order sequences are generally asymmetric (shallowing-upward) following one or two eccentricity-enhanced precessional cycles (Figure 7). The 4^{th}-order sequence, though it is composed of 5^{th}-order sequences, follows the same pattern, in which the general trend is from deeper to shallower facies. The only fundamental cycle, however, is the 6^{th}-order PAC, whose sharp boundaries are precession-induced. The degree of facies change across each PAC boundary is modulated by eccentricity in cycles of 100 ky and 400 ky. In this model, all cycle boundaries are produced by the precessional forcing mechanism (Anderson and Goodwin, 1992).

In this study I will be applying the PAC Hypothesis and its mechanism of orbital forcing. Building on Orzechowski's (1995) initial finding of Milankovitch forcing, I will divide the interval into correlative allocycles, and document the occurrence of chert in this allostratigraphic fabric. This project is a test of the hypothesis that stratigraphic processes play a primary role in the origin and positioning of chert beds and nodules in carbonate rocks.

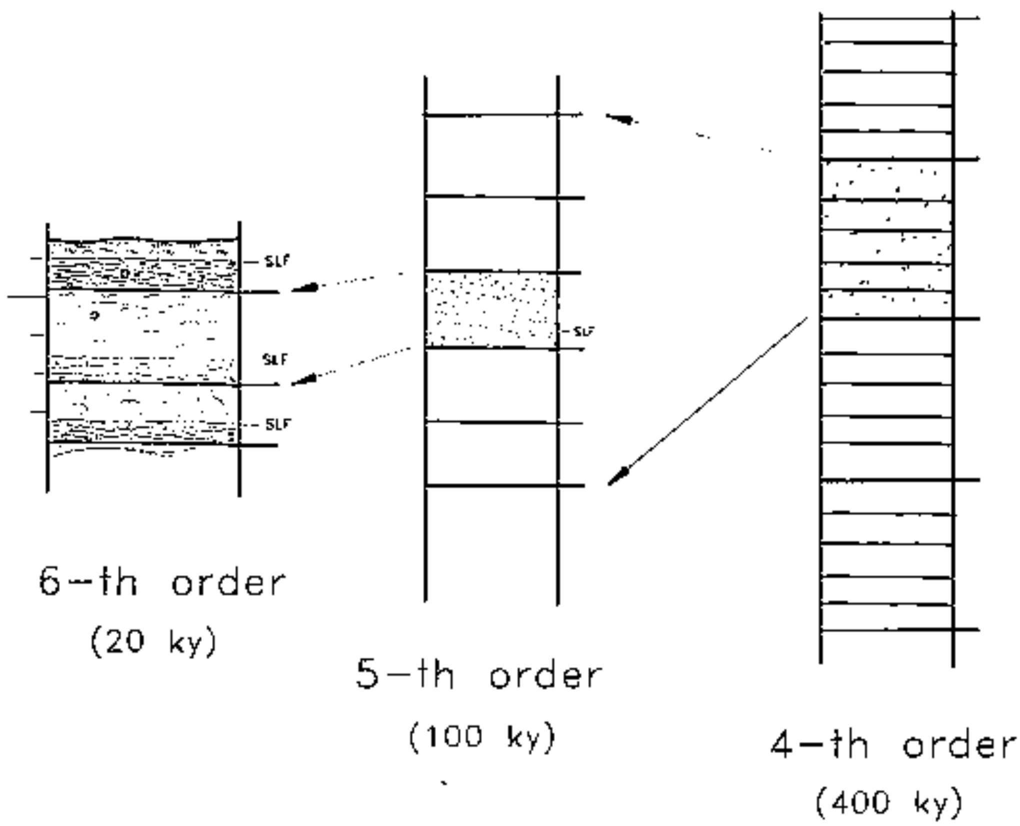


Figure 6. Stacking patterns of Punctuated Aggradational Cycles.

The predicted stacking patterns of PACs assuming Milankovitch forcing mechanisms of 4^{th}-order, 5^{th}-order and 6^{th}-order cycles. Precessional PACs should occur in eccentricity-modulated 5^{th}-order bundles of five; groups of four 5^{th}-order sequences constitute a 4^{th}-order (400 ky) sequence.

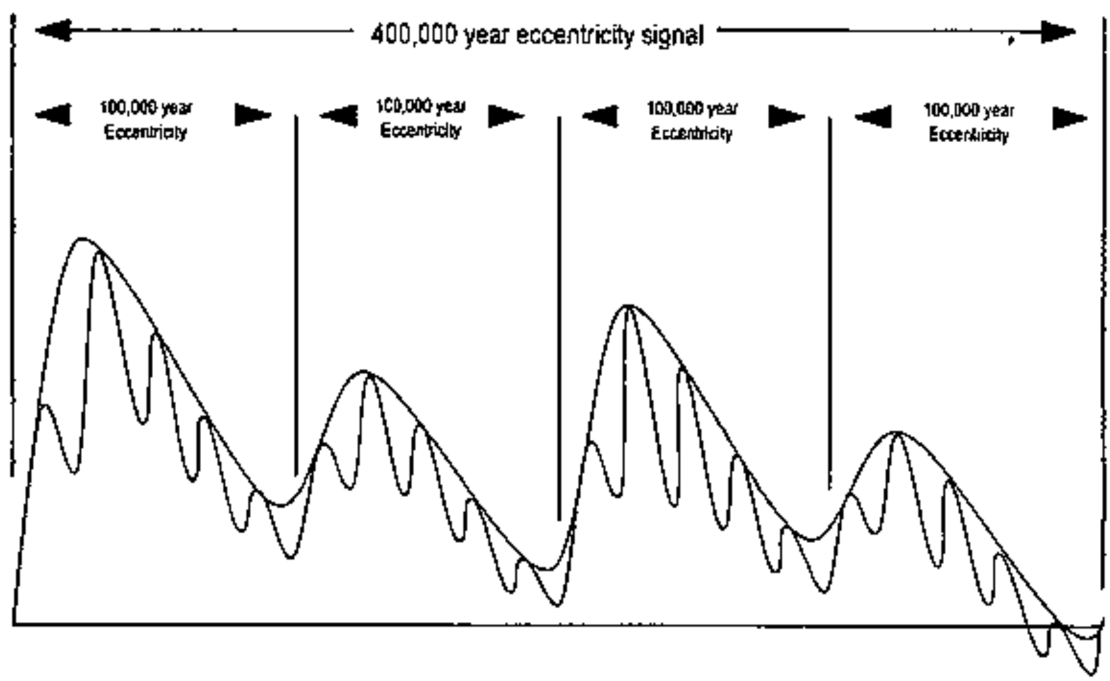


Figure 7. Fifth-order sequence dynamics.

A 5^{th}-order sequence is ideally composed of five or six 6^{th}-order cycles (PACs). Eccentricity modulates the pattern of PACs (6^{th}-order) in the sequence enhancing the first two precessional rises and dampening the last three or four. The result is an asymmetric shallowing-upward sequence containing one or two "transgressive" PACs. The second PAC tends to be of the deepest facies. (Modified from Chadwick, 1994).

CHAPTER 3
CHERT AND CHERTIFICATION

Introduction

Siliceous sediments which are composed largely of cryptocrystalline, authigenic silica (SiO_2) are called chert. In chert, SiO_2 can occur as various authigenic polymorphs (opal-A, opal-CT and quartz) as well as in different grain sizes. Mineralogical classification is based on the characteristics of powder X-ray diffraction patterns and corresponds with the internal atomic and crystallographic ordering of the polymorphs. The polymorphs are arranged from disordered with higher water content to internally ordered forms without water, an arrangement which roughly corresponds to the three main categories of SiO_2 (*e.g.* see discussion on the structural integrity of the polymorphs: Frondel, 1978, 1985; Heaney, *et al.*, 1994). These categories, which follow a precipitation-dissolution and maturation sequence of SiO_2, are: opal-A or amorphous silica (opal); opal-CT or cristobalite and tridymite interlayered; and α-quartz (α-quartz is stable below 573 °C). This authigenic quartz occurs in several grain shapes and sizes, which are: chalcedony or fibrous α-quartz (fiber length less than 1 mm), microcrystalline quartz (grain-size <20 μm; Hesse, 1989), and megaquartz (grain-size >20 μm; Hesse, 1989). More recently, experimental work has shown that the opal-A to opal-CT transformation is time- and depth-dependent; the proportion of opal-A to opal-CT, as well as the degree of ordering, seem to correspond to depth below the sediment-water interface and the amount of time elapsed since burial (Rice *et al.*, 1995).

Although some authors (*e.g.*, Baltuck, 1986) have suggested differences in the terms "silicification" and "chertification", these differences seem inconsequential in relation to the processes that produce silicified rock. Silicification is a general term which refers to the overall processes of transformation of originally non-siliceous sediments or fossils to partially or fully silicified rocks (Hesse, 1989); this transformation occurs in carbonate rocks, evaporites, fossil wood, and shale. Chertification is the making of silicified beds and nodules in limestone and other sedimentary rock sequences. In this process, pores are filled with silica and the original rock components are partially or totally replaced. Thus, the end-member processes of silicification are the filling of a void by a silica polymorph, whether the void was created a fraction of an instant ago or has been there as a natural void between grains, and the replacement of host rock "molecule by molecule". The replacement of host rock may occur through various steps and stages of dissolution and precipitation, each event of silicification preserving concurrent diagenetic features (Meyers, 1977). Thus, the complexity of silicification is due to different types or processes ranging from void filling to "molecular" replacement, different kinetic factors resulting in precipitation of a particular polymorph, and the multi-staged sequence of the process.

In outcrop, chert forms bands or variously sized and shaped nodules. For example, in the study interval chert morphology varies from nodules to convoluted, partially silicified beds to laterally extensive, fully silicified beds. Traditionally it has been thought that 'nodular', 'tabular' and 'bedded' chert correspond to different processes of genesis or sources of silica (Maliva and Siever, 1989). For example, it has been suggested that 'nodular' chert formed from sponge spicules at relatively shallow depths, bedded chert (more than 50-60% silica) from radiolarian ooze in deeper water, and tabular chert from sediment containing less than 50% silica. However, the problems with this classification are that the composition of precursor sediment may be nearly impossible to determine because of dissolution (Maliva and Siever, 1989), and the source of silica, any combination of radiolarians, sponge spicules, volcanic glass and inter- or intra-formational silica in solution, may be indeterminable.

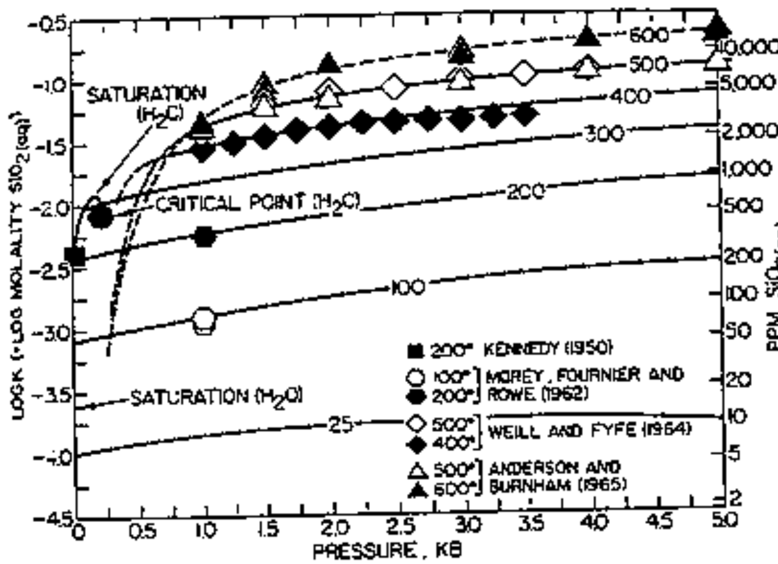
According to some authors (*e.g.* Bromley and Ekdale, 1986; Clayton, 1986) nodular chert has been related to burrowing activity by arthropods and worms. These burrows can form complicated three-dimensional networks, which served as conduits for fluid-carried silica. Increased permeability and organic matter content within the conduits create an environment which favors preferential silicification by trapping free silica (Chanda *et al.*, 1976). Thus, this particular type of nodular chert is a direct result of textural and compositional variations in the host rock and not a function of a unique source of silica.

In this study chert occurs in a range from nodules to completely silicified beds expressing a continuum of degrees of a single process, chertification by replacement and void filling in carbonates. These morphological differences are not thought to represent differences in kind of process or in source of silica. Even though there may be intricacies of chert genesis and source, these are embedded in the crystalline structure of chert and require kinds of observations and analysis beyond the scope of this project.

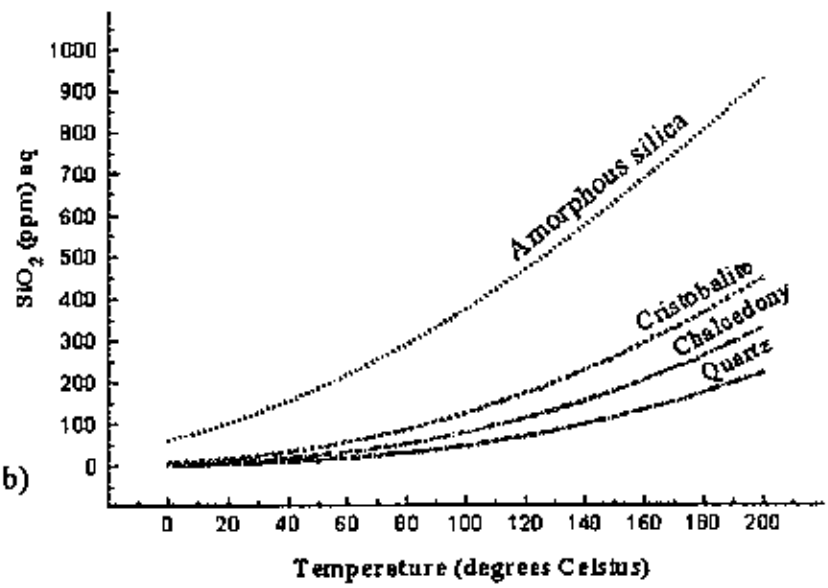
Geochemical Constraints

Silicification is controlled by the geochemical environment. Calcite and silica dissolve in different pH regions; calcite has higher solubility in acidic environments, whereas quartz has a higher solubility in basic solutions, at pH > 9 (Williams and Crerar, 1985a). The solubility of quartz is low (about 6 ppm SiO_2 at pH 7), whereas cristobalite and tridymite solubilities are greater and the solubility of amorphous quartz is the greatest. Sea water below 335-670 ft (100-200 m) is nearly saturated with respect to quartz, though amorphous silica, because of its greater solubility, will dissolve rapidly within the water column.

In addition to pH, temperature, pressure, organic matter and cations such as Mg^{2+}, Mn^{2+}, Fe^{2+}, and Al^{3+} affect the dissolution and precipitation of silica (*e.g.* Bennett and Siegel, 1987; Bohrmann *et al.*, 1994). The solubility of quartz and other polymorphs increases with increasing temperature, according to the Van't Hoff equation. Increasing temperature enhances the rate of diagenetic reactions as well. In diagenetic environments the range of temperature variations is small (Walther and Helgeson, 1977). Although the solubility of silica polymorphs increases with increasing pressure, the pressure does not change appreciably in diagenetic environments; therefore the effects of pressure are also small (Figure 8). However, at higher temperatures the effect of pressure is greater; for example, with an increase of 1 kb pressure at 25°C, the solubility of α-quartz increases from about 7 ppm to about 9 ppm, when at 100°C the increase of 1 kb pressure increases the solubility from 60 ppm to 100 ppm (Walther and Helgeson, 1977). Hence it appears



a)



b)

Figure 8. Pressure and temperature dependency of silica dissolution.

In low-pressure environments the effect of pressure is negligible (a). In low-temperature environments, the solubility of quartz is low; the solubility of amorphous silica is also low, but is more sensitive to changes in temperature than the solubility of quartz (b). (Modified from Walther and Helgeson, 1977).

appears that, within the diagenetic environment, temperature and pressure are less important than other geochemical and diagenetic factors.

Complexation has an important role in determining diagenetic pathways. Organic matter and some cations form soluble complexes with dissolved silica (H_4SiO_4). Thus, complexation may lower the concentration of free silica in solution and increase solubility (Williams and Crerar, 1985b). Through complexation and consequent lowered silicic acid content in solution, silica can be mobilized from its original site and transported in fluids at nearly neutral pH (Bennett and Siegel, 1987). The complex of silicic acid and a cation, which may be still electrically charged, attracts free silicic acid molecules, thus promoting further silica growth.

Silicic acid molecules may polymerize to form more complex configurations. Silicic acid may combine to form units that are repeated in the chains or globules in a polymer. The physical state of polymerized silica can be fluid, gel or short-range ordered solid. At $pH < 3$ or with salts present, the silica polymers form three-dimensional networks and gels; at higher pH and without salts, spherical silica particles grow in size (Williams and Crerar, 1985b). The polymers of a particular form may precede the precipitation of a particular silica polymorph, as the developing gel becomes more ordered and eventually crystallizes to form the type of polymorph closest in internal ordering.

Silicification is associated with organic decay through bacterial action and authigenic mineral precipitation and thus with diagenetic zones. The sediments immediately beneath the sediment-water interface are oxic, because they are being bathed by seawater. The concentration and preservation of organic matter, combined with the oxygen content of the sediments, will determine the extent of bacterial activity and where the environment will turn from oxidizing to reducing (*e.g.* Schulz *et al.*, 1994). Below the oxic zone, bacteria use nitrate, manganese and sulfate, in respective order, in the decomposition of organic matter. The roles of nitrate and manganese are not usually most significant in geological environments because their concentrations are usually low. Sulphate, however, seems to play a significant role in silicification.

The depth of the sulphate reduction zone usually varies from a few to 20 cm, depending on availability of oxygen, porosity and permeability (Berner, 1984). Within the sulphate reduction zone, remaining organic matter is converted, through many complex steps, to HCO_3^-, with the breakdown of SO_4^{2-} molecules to HS^-. The overall reactions may be summarized as:

$$2CH_2O + SO_4^{2-} \rightarrow 2HCO_3^- + H_2S \quad \text{at pH} > 7;$$

$$2CH_2O + SO_4^{2-} \rightarrow 2HCO_3^- + HS^- + H^+ \quad \text{at pH} < 7.$$

Pyrite will precipitate if adequate dissolved iron is available; otherwise dissolved sulfide will be transported toward the surface and oxidized by bacteria. The oxidation of H_2S releases H^+ ions, summmarized by the equation:

$$H_2S + 2O_2 \rightarrow 2H^+ + SO_4^{2-},$$

which lowers pH, which, in turn, induces dissolution of carbonate and allows precipitation of silica in the resulting void. Hence the initiation of silica precipitation, according to this model (Clayton, 1986), occurs in the vicinity of the oxic-anoxic boundary, and is connected through various steps to the conversion of organic matter and sulphate to pyrite. Thus there is a connection between organic matter, reducing conditions in the sulfate reduction zone, and the production of pyrite (*e.g.* Honigstein *et al.*, 1989), which can lead to the dissolution of carbonate (Hendry, 1993) and the precipitation of silica. Therefore, the presence of pyrite and organic matter in some chert suggests that chertification began under the same conditions and at the same time as the formation of pyrite.

Chertification of Carbonate Rock

The major steps to be considered in regard to chertification of carbonate rocks are: initial adequate concentration of silica; dissolution of silica; preservation of silica in the sediments; and nucleation of silica polymorphs. Each of these steps is affected by the composition, size and shape of the initial silica particles, which control solubility and precipitation (Williams and Crerar, 1985a). This pathway of silica from siliceous organisms through the different stages to chert depends on diagenetic processes, the depth of the diagenetic zones, and the time spent at each stage.

Maliva and Siever (1988) developed a detailed mechanism for silica replacement at the molecular level based on force of crystallization. This process involves the nucleation and growth of a single crystal, whether silicification is by replacement or by void filling. Although the theory was developed to explain silicified fossils, the same process operates in nodular chert as well. At a point within a fossil, a geochemical environment has been reached which induces dissolution of calcite and rapid nucleation of silica. The nucleated silica continues to grow with only a thin film of liquid between the authigenic mineral and the host mineral. The growing mineral exerts pressure on the host mineral; this additional and localized pressure increases the solubility of calcium carbonate, thereby causing dissolution. Once silica has precipitated it tends to withstand the pressure of a growing carbonate crystal and does not dissolve as easily. Replacement at this minute scale preserves details such as brachiopod shell fibers that could not have been preserved by a void filling process. Hence the diagnostic results of crystal growth as a result of force of crystallization are preservation of internal detail, the presence of euhedra of crystalline silica and no traces of dissolution in the surrounding host limestone (Maliva and Siever, 1988).

Silicification of this type has also been found in the silicificaton of ancient wood (Hesse, 1989), the similarity being the control of nucleation sites by organic acid molecules. Silicic acid permeates cell walls of wood, polymerizes, precipitates and dehydrates between cell walls and in cell openings. Structure is preserved in great detail, because organic molecules form the structure of cells and control grain boundaries; this control may still occur in the transformation from opal-CT to microcrystalline quartz (Hesse, 1989). Pore filling and replacement can be seen as end members of a dissolution and reprecipitation process; in pore filling, appreciable amounts of time may occur between dissolution and precipitation, whereas in replacement the time is very small (Hesse, 1989). For example, a calcareous fossil may dissolve entirely and leave a mold which will be filled later; or the fossil may be replaced molecule by molecule, in which case silicic acid will precipitate both by following and preserving the organic cell walls and structure of the fossil. Factors affecting the selective silicification are pH, dissolved ion activity and the extent of previous lithification (Hesse, 1989).

There appears to be a preferred chert occurrence in relation to microstructures, types of fossils, and host rock lithology (Meyers, 1977; see also Appendices 2 and 3). Various investigators have found a correlation of chert with particular parts of fossils (*e.g.* Watkins and Loope, 1994); some have constructed lists of silicification affinity (*e.g.* Elorza and Garcia-Garmilla, 1993); and some have found chert in particular types of rocks (*e.g.* Meyers, 1977). Further, certain chert polymorphs seem to have an affinity for particular sites; for example, chalcedony often fills pores or cavities within fossils or between particles. Hence the host-rock texture seems to control the type of silica precipitating out of solution (Maliva and Siever, 1989). Porosity, permeability and the presence of organic matter are thought to affect the preferred site of chertification or initial nucleation (*e.g.* Baltuck, 1986; Hein *et al.*, 1989; Gao and Land, 1991).

Laterally or vertically linked segments of permeable rock (*e.g.* burrows or bases of tempestites) would provide conduits for fluids bringing or removing ions in solution. Porosity and permeability are considered too low for pressure-gradient-driven advectional fluid movement in carbonate rocks (Heling and Giskow, 1994). Diffusion and compaction -driven advection require small quantities of fluid volume to provide enough silica, which is slightly soluble in interstitial waters (Aplin and Warren, 1994). Hence compaction-driven advection is a probable process, but in contrast to diffusion, operates at a larger scale than the slow, molecular-scale diffusion. Diffusional fluid movement is driven by concentration gradients of various species, and in contrast to advectional movement, is likely to operate at a scale of inches to feet (cm to dm) as opposed to the formational to basinal flow of advection (Heling and Giskow, 1994) or intraformational compaction-driven advection. Concentration gradients are driven by the geochemical environment (*e.g.* pH); thus inhomogeneities (*e.g.* silicified burrows or fossils) in the sediments can cause local centers of ion concentration. For replacement of rock, as opposed to cementation, in which ions are dissolved as well as precipitated and which probably involves two-directional movement, diffusion appears the viable alternative.

Because of the shortness of distance travelled by ions in diffusion, the developing silica center will be in close proximity to the initial silica source, which would support the observation of chert occurring near cycle boundaries, the loci of silica accumulation. The presence of chert in less permeable micritic facies, in which fluid movement is slow, further supports the idea that ion movement is driven by concentration gradients and not pressure gradients. Further, all different lithologies near cycle boundaries may silicify, which indicates that proximity to the source of silica is the principal controlling factor. Since cycle boundaries are a result of hiatus, there is an additional component of increased time for diagenetic reactions, and slow diffusion, to occur resulting in preferential silicification of tops and bottoms of beds and cycles. This conclusion removes the apparent contradiction, that porous and permeable rocks are more likely to chertify but micritic rocks silicifiy as well, indicating that grain-size and porosity are not the sole determining factors of silicification.

Chert-rich Facies

Although chert occasionally occurs in peritidal and evaporitic facies, the preponderance of chertified carbonates are below-wave-base shelf facies (*e.g.* Maliva and

Siever, 1989; Loope and Watkins, 1989; Lawrence, 1994) and deeper shelf turbiditic facies (*e.g.* Bustillo and Ruiz-Ortiz, 1987; Hesse, 1987; Haas *et al.*, 1994). These paleoenvironments are characterized by intermittent deposition, abundant supply of siliceous organisms, influx of argillaceous material and accumulation of organic matter. Common lithologies are packstones, grainstones and wackestones. Intermittent deposition permits the concentration of siliceous matter during times of non-deposition and the subsequent preservation of the accumulated silica by burial during times of rapid sedimentation. Organic matter contributes toward anoxic conditions, and the iron content of argillaceous material toward pyrite precipitation in the sulphate reduction zone. Therefore, the conditions prevalent in below-wave-base environments create the optimal chemical environment for silicification.

Often rhythmic patterns of chert beds and nodules occur in a thick interval within otherwise non-cherty facies. For example, in the Onondaga Formation of New York State, chert falls within predictable environmental intervals in generally shallow platform carbonates corresponding to the four Onondaga members Edgecliff, Nedrow, Moorehouse and Seneca (Oliver, 1956; Brett and Ver Straetten, 1994; Ver Straetten and Brett, 1995). Chert occurs mostly in the top half of the micritic argillaceous wackestone of the Edgecliff Member and in the similar facies of the Moorehouse Member (Brett and Ver Straeten, 1994). The deeper facies of the Nedrow Member, which consists of calcareous shales and argillaceous micrite, are devoid of chert, as are the finer-grained limestone and shale facies of the Seneca Member. The generally coralline, crinoidal, coarse- to finer-grained limestone of the Edgecliff Member is suddenly overlain by the particularly shaly beginning of the Nedrow Member. As the content of shale decreases, some chert is observed occasionally in the top section (Oliver, 1956). The Moorehouse Member is fine- to medium-grained limestone with nearly black chert and coarse fossils at the top part (Oliver, 1956; Ver Straeten and Brett, 1995). The facies of the Seneca Member are similar to those of the Moorehouse Member, but the predominant fossil population is different and there are additional shaly partings increasingly toward the top of the member suggesting a different environment of deposition. Hence, chert is encountered in the impure limestones but nearly absent within the particularly muddy intervals. Curiously, within the Edgecliff Member, corals do not occur in association with chert (Oliver, 1956), which may be indicative of limiting environmental conditions.

In the Lower Devonian Helderberg Group (New York State) chert occurrence follows a similar pattern. For example, the Kalkberg Formation in New York State contains chert within its two members. In general, the Kalkberg environment is stable, open marine, low energy, with good circulation and low influx of argillaceous matter (Laporte, 1969). The general facies are brachiopod- and bryozoa-rich, fine-grained calcarenites and calcisiltites with some minor crinoids. The chert-rich facies occur in the lower portion of the Hannacroix Member and in the upper portion of the Broncks Lake Member (Connor, 1983). In contrast, within the Helderberg Group, chert is absent or rare in the formations representing above-wave-base, high-energy environments, and quiet but peritidal to supratidal and very deep basinal environments (Maliva and Siever, 1989).

Similar trends of chert distribution are observed in many other ancient rock intervals. In some occurrences one chert-formation parameter may be stronger than some other parameter; but it is the combination of all the sedimentologic and geochemical factors within an environment, that determines whether or not chert will form. For example, the deeper water chert beds of the Toril Formation, Jurassic, Spain, (Bustillo and Ruiz-Ortiz, 1987), are interpreted to be calcareous turbidites, in which chert occurs in a predictable location within the structure of the turbidite beds. The origin of the turbiditic sediments is from the rims of the shallow shelf from where they were transported to a deeper basinal environment. The turbidites are divided into three differing facies according to lithology and the morphology of chert. The occurrence of chert is associated with a particular sedimentary process (*i.e.*, turbidite/intermittent deposition). Silica preservation is thought to be due to rapid burial by finer sediments, which inhibits silica diffusion back to sea water. Thus chert is found only in turbiditic pelagic biomicrites and not as much in autochthonous, presumably deeper water, background biomicrites.

Thus, in chert-bearing facies the important parameters appear to be intermittency of deposition, source of silica, and a supply of modifying parameters within the correct environmental zone. The modifying parameters are constituted from the components of the lithology, including carbonate particles, argillaceous matter and organic remains. In addition, kinetics of both geochemical/diagenetic reactions and sedimentation rate affect silicification.

Allostratigraphic Controls of Chert Distribution

On a large scale, chert-rich intervals which can be correlated for great distances have been associated with long-term periodic fluctuations in sea level. On a small scale, individual beds of chert or cycles containing chert have been traced for great distances, again suggesting a stratigraphic control of their origin. Chert occurrence is sometimes described as cyclic or rhythmic or is connected to a particular stratigraphic phenomenon, *e.g.* an unconformity.

For example, at a fourth-order scale the alternation of chert-rich members of the Onondaga Formation with chert-poor members is considered by Brett and Ver Straeten (1994) to be caused by long-term sea-level fluctuation. The Onondaga Formation of the New York State contains two third-order depositional sequences, as defined by sequence stratigraphers (Brett and Ver Straeten, 1994), each comprising 2-3 million years. The first third order sequence contains the Edgecliff, Nedrow and Lower Moorehouse Members, which are time-stratigraphic units correlative throughout the state. This is a deepening-shallowing sequence, which has an erosional lower boundary. In this third-order sequence the Edgecliff and Moorehouse Members contain abundant chert; the deeper Nedrow Member between them is chert-free. The Upper Moorehouse and Seneca Member comprise the second third order sequence, which denotes a return to coarser wackestone, similar to the lower part of Edgecliff Member, and likewise contains chert. This second third order sequence is in general upward-deepening toward the Marcellus Shale, though it contains smaller-scale cycles. The top of the sequence denotes a major deepening event. There is some chert found in the beginning of this third-order sequence, which corresponds to the Upper Moorehouse Member. Hence it seems that chert occurrence is correlative with large-scale stratigraphic events, and in more particular, with 4th-order sea-level fluctuations (Anderson and Goodwin, 1992).

Within the cherty members of the Onondaga Formation there is some evidence of smaller-scale stratigraphic control on the distribution of chert, which can be observed in the pattern of the cycles. Parasequences of the Edgecliff Member consist of cherty and non-cherty, submeter-scale couplets, which are traceable from eastern to western New York State. In the Nedrow Member, the parasequences are cycles consist of regular alternations of more argillaceous and less argillaceous limestone. Comparing these chert-bearing couplets to small-scale cycles in the Schoharie Formation, Ver Straeten and Brett (1995) interpreted them as possibly orbitally forced.

In the Kalkberg Formation (Lower Devonian, New York State) chert has long been used as a stratigraphic indicator. For example, Rickard (1962) defines the formational boundary with the Ravena Member of the Coeymans Formation at a surface corresponding to the first chert bed. Anderson *et al.* (1984) documented that the formation boundary is actually a series of surfaces, each marking a separate allocycle boundary. Therefore the chert associated with each cycle is allostratigraphically controlled, probably by precesssional sea-level fluctuations (Anderson *et al.*, 1984).

The Cretaceous Chalk of England, studied stratigraphically for more than a century, contains evidence that chert sequences are time-stratigraphic. The Chalk was divided into the Lower, Middle and Upper Chalks on the basis of flint content. This rough division was further separated into a lithostratigraphical framework (Mortimore and

Wood, 1986), which is correlatable throughout the Northern and Southern Provinces regardless of lithological and faunal differences. At the base of the Upper Chalk there is a stratigraphically significant occurrence of maximum flint development, also called the high Turonian flint maximum (Mortimore and Wood, 1986).

Flint horizons have been used as correlative tools for establishing a stratigraphic framework (*e.g.* Bromley and Ekdale, 1986; Mortimore, 1986). For example, the Ferruginous Flint in the Northern Province denotes a stratigaphically important marker horizon, which appears to be correlative with the flint of Akers Steps, at Dover, in the Southern Province. The high Turonian flint maximum, which is clearly correlative throughout the two provinces, shows a small-scale cyclic structure at Dover. This 'Basal Complex' is composed of nodular limestone, nodular flint, marl seams and chalk arranged in a cyclic fashion. Hence the flinty successions of English Chalk show the use of flint in large-scale stratigraphic correlation, of which the correlated lithostratigraphic framework of the Lower, Middle and Upper Chalk between the Provinces is an example, and smaller-scale correlation, of which the cyclic structure of the high Turonian flint maximum is an example.

Similarly, occurrences of red chert within Pennsylvanian cyclothems in Utah and Nebraska (Loope and Watkins, 1989) suggest a small-scale allostratigraphic control on the origin of the chert and a large-scale control on its color. Within the high-stand portion of the 4^{th}-order cyclothems chert occurs in sharply bounded, 2-5 m thick intervals resembling 5^{th}- and 6^{th}-order allocycles. This pattern is repetitive in a vertical sense and laterally correlative, suggesting an allostratigraphic control. At the 4th-order scale chert became red as pyrite within chert was oxidized to hematite during 4th-order low stands.

The examples above have shown that chert occurrence is not random but is dependent on strict environmental, or rather cyclic, variabilites which are allogenic in origin. Chert-rich intervals are laterally correlative (Onondaga and High Turonian flint maximum); chert is connected to cycle boundaries (Kalkberg); within a lithostratigraphic framework, individual chert bands are time-stratigraphic (English Chalk); and chert is found in sharply bounded small-scale cycles within the high-stand part of cyclothem (Pennsylvanian cyclothems). However, none of these examples shows chert in a hierarchic cyclic framework, laterally correlated cycle by cycle over hundreds of kilometers, and connected to a eustatic curve at a resolution of the precessional signal. Thus, the significance of this study lies in demonstrating the small-scale cyclic occurrence of chert in a precessional/eccentricity allogenic framework.

CHAPTER 4
CHERT AND CYCLICITY IN THE NEW CREEK AND CORRIGANVILLE FORMATIONS

Introduction

The Lower Devonian New Creek and Corriganville Formations are below-wave base, shallow shelf deposits. In Pennsylvania, the formations comprise about 20 ft (6.1 m) of medium- to fine-grained crinoidal calcarenite. These formations have been studied in a large-scale cyclic context by Dorobek and Read (1986) who interpreted the Helderberg Group to be a third-order Vail sequence. In that study the whole of Helderberg Group consisted of three 2-3 m.y. transgressive-regressive sequences. The New Creek Formation was seen as a shallowest unit of one of these large sequences, whereas the Corriganville Formation was interpreted as the beginning of the next transgressive trend. Thus the New Creek-Corriganville contact was considered the sequence boundary.

More recently, a small-scale cyclic analysis was conducted in order to determine and correlate Milankovitch-induced cyclic patterns (Orzechowski, 1995). In that study, Orzechowski determined that the cyclic pattern of the two formations consists of two 5th-order (100 ky) eccentricity-modulated sequences each corresponding to a formation, the cyclic framework consisting of "vertically consistent and laterally correlative" precession-induced PACs. The New Creek Formation consisted of three and the Corriganville Formation of five PACs. Orzechowski concluded that the two 5th-order sequences comprised an incomplete 4th-order (400 ky) sequence and thus formed a very condensed

Figure 9. New Creek and Corriganville Formations, Hollidaysburg.

The New Creek and Corriganville Formations are bounded by the Keyser Formation below and the Mandata Shale above (black lines denote formational boundaries). The New Creek Formation is massively bedded. The PACs of the Corriganville Formation begin with a shaly interval and extend up to the top surface of a light calcarenite bed. The measuring stick is in feet.

Figure 10. New Creek Formation, Allegheny Furnace.

The New Creek Formation extends from below the bed under the hammer to under the highest bed behind the measuring stick, a total of 7 ft. The boundary between the lower New Creek and the upper New Creek is a shaly surface behind the one foot mark on the measuring stick. The chert in PAC 2 is seen as a blue-gray bed behind the handle of the hammer.

Figure 11. New Creek Formation, Limestoneville.

The Keyser-New Creek formational boundary is located under the lowest chert-containing one foot-thick bed at the black line. The upper line is at the New Creek-Corriganville boundary. The measuring stick rests on the boundary between the lower and upper divisions of the New Creek Formation, between New Creek PACs 3 and 4.

interval. Orbital forcing affected the stratigraphic fabric at two levels, precession and eccentricity. Precession caused cycle boundaries by rapid sea-level rises, while the role of eccentricity was to modulate the cyclic framework by enhancing 5th-order boundaries and then dampening the precessional effect, thereby producing a generally shallowing trend internal to a 5th-order sequence (Figure 7).

In this current study I have utilized the Orzechowski (1995) framework as a starting point, and have modified it by defining additional cycles. In the New Creek I recognized six cycles averaging 1.5 ft (.46 m) in thickness and nine cycles in the Corriganville Formation likewise averaging 1.4 ft (.43 m) (Figures 9 and 13-19). All of the cycles are sharply bounded, but not obviously upward-shallowing as stated in the original PAC hypothesis. The cycles are composed of clearly distinguishable beds or combinations of beds which correlate throughout the nearly 130 miles (300 km) outcrop belt. Typically the cycles in the Corriganville Formation are divided by sea-level fall surfaces into high- and low-stand portions, the deeper high-stand portion being shaley and the shallower low-stand portion calcarenitic. Sea-level-fall surfaces are absent in the New Creek Formation. The presence of additional allocycles in each formation requires a modification of Orzechowski's (1995) Milankovitch interpretation.

A definite relationship occurs between stratigraphic fabric and the occurrence of chert in the New Creek-Corriganville interval. Instead of chert occurring sporadically throughout the interval, nodules and discontinuous beds are located at specific horizons, generally at cycle boundaries or in the high-stand portion of a cycle. These patterns suggest a genetic relationship between the occurrence of chert and the stratigraphic processes that produced the cyclic fabric of the interval.

Cycles and Chert in the New Creek Formation

General Characteristics

The general facies of the New Creek Formation is fine-grained to medium-grained, crinoidal, shallow-shelf calcarenite. This interval averages 8.5 ft (2.59 m) in thickness in the study area and is bounded by peritidal calcareous mudstone of the Keyser Formation below and the deeper, thinner-bedded unit (shale-calcarenite couplets) of the Corriganville Formation above (Figure 9). The lower half of the New Creek Formation is in general thicker-bedded than the thinner-bedded, finer-grained and more argillaceous upper half (Figures 9,10 and 11); this division corresponds to the boundary between PACs 2 and 3 of the Orzechowski interpretation. As opposed to the three PACs defined by Orzechowski (1995) I have defined a total of six, averaging 1.5 ft (0.46 m) in thickness. These cycles are bounded by surfaces, which mark a sharp lithological contrast between either a thin layer of clay or a fossil lag and the medium-grained intra-cycle lithology. In addition, as a cycle shallows upward, there are coarse fossil particles within the otherwise fine calcarenite. Especially in the upper half of the formation, surfaces are often denoted by a layer of fossils or a thin layer of clay. Chert in the New Creek Formation is usually associated with cycle boundaries.

Figure 12. Legend for columnar sections

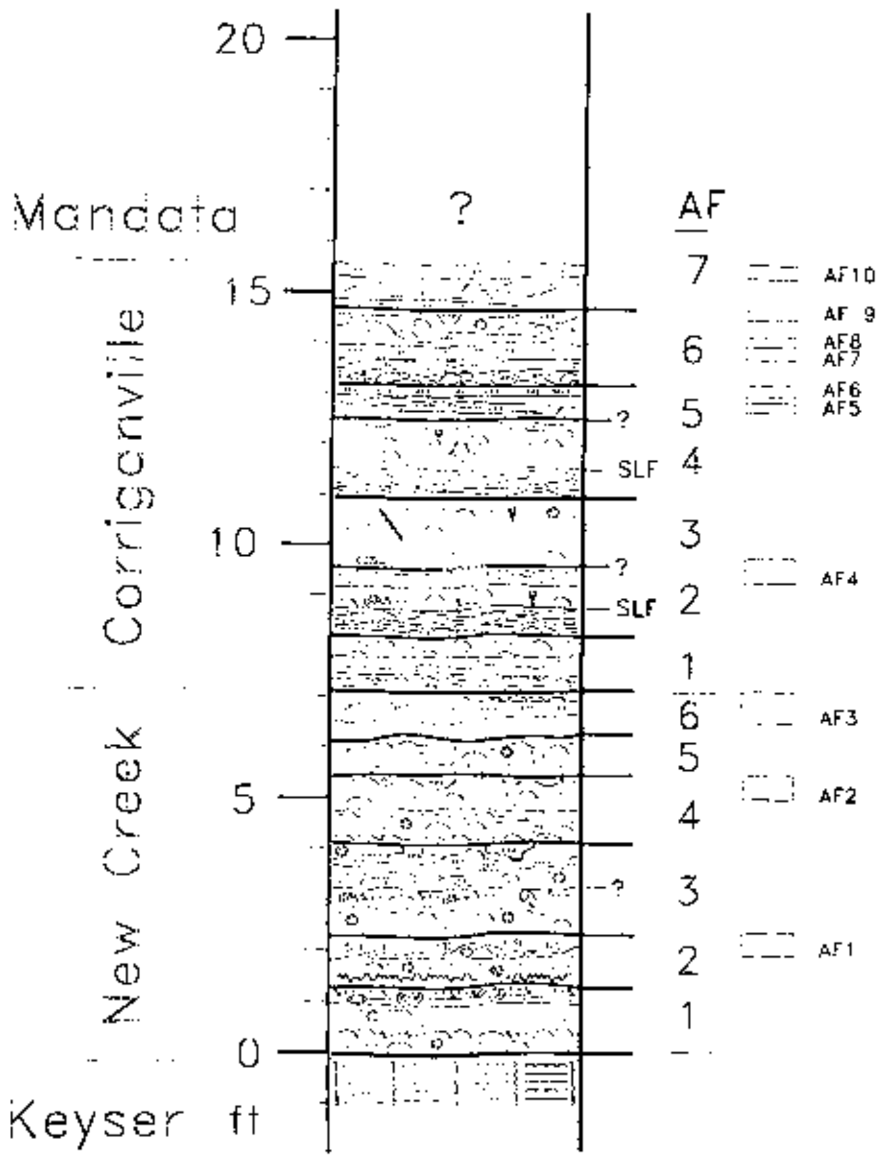


Figure 13. Columnar section, New Creek and Corriganville Fms., Allegheny Furnace.

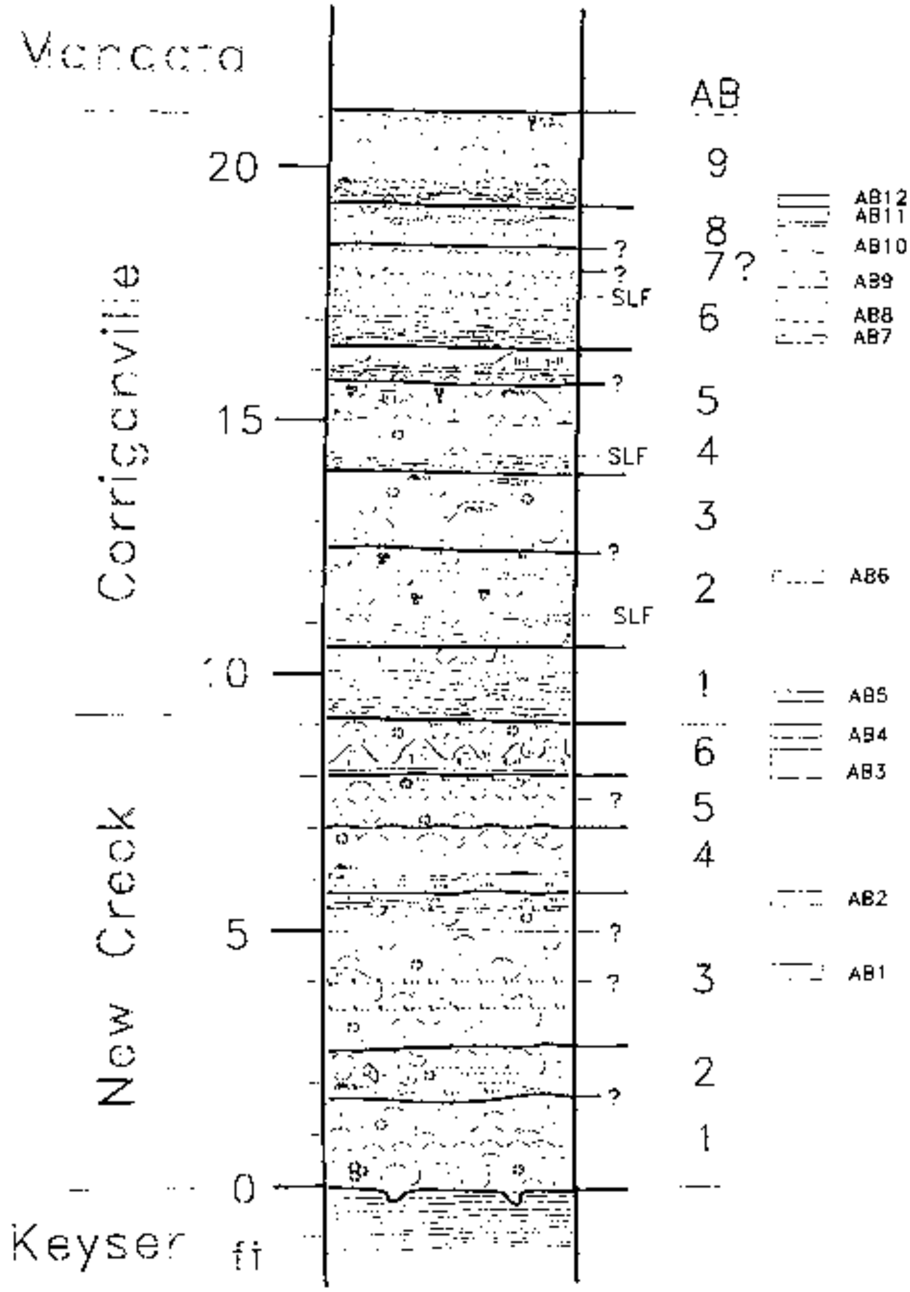


Figure 14. Columnar section, New Creek and Corriganville Fms., Altoona Bypass.

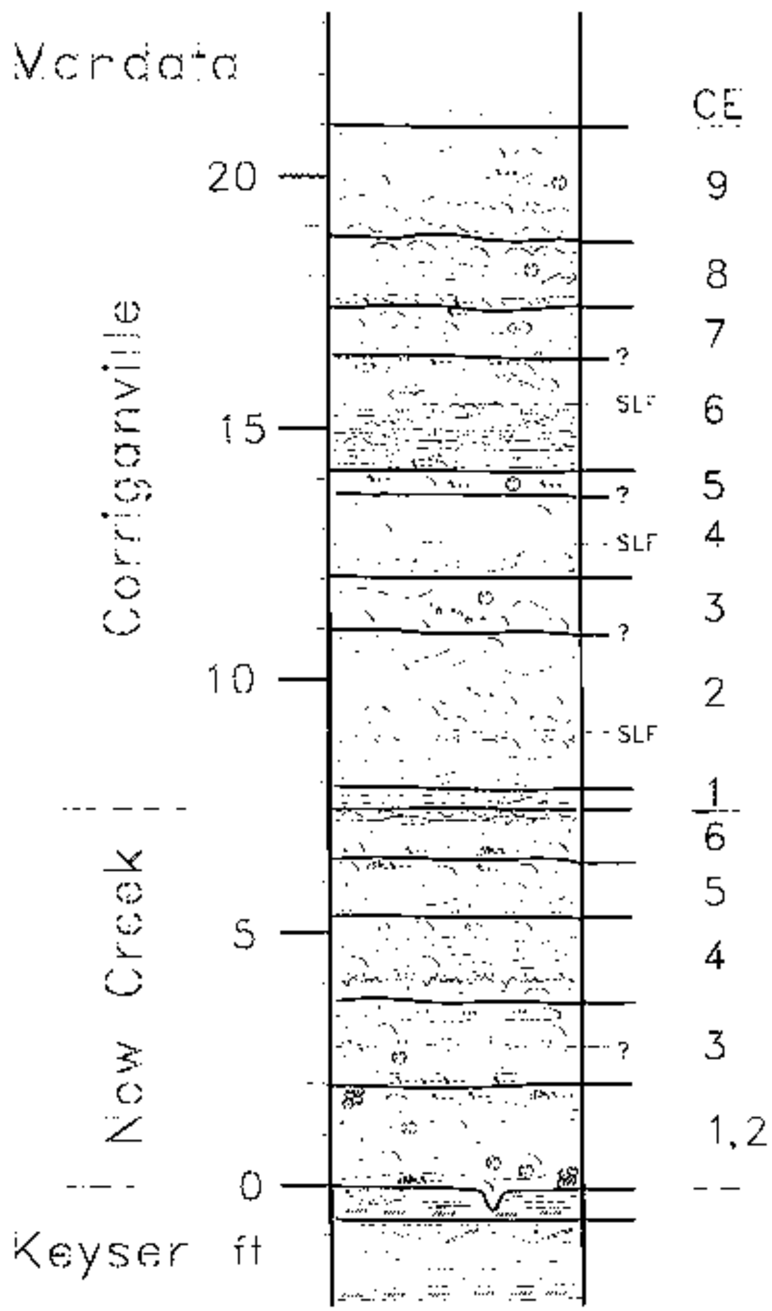


Figure 15. Columnar section, New Creek and Corriganville Fms., Cessna.

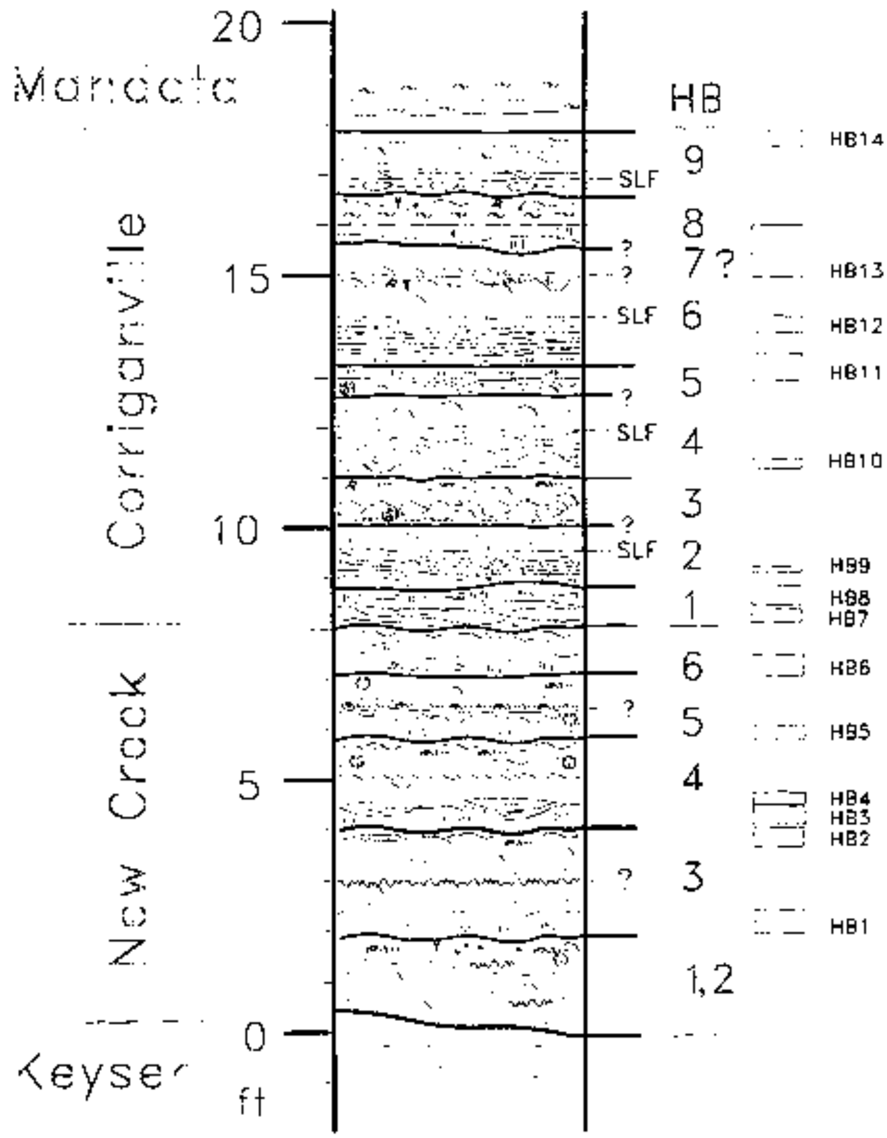


Figure 16. Columnar section, New Creek and Corriganville Fms., Hollidaysburg.

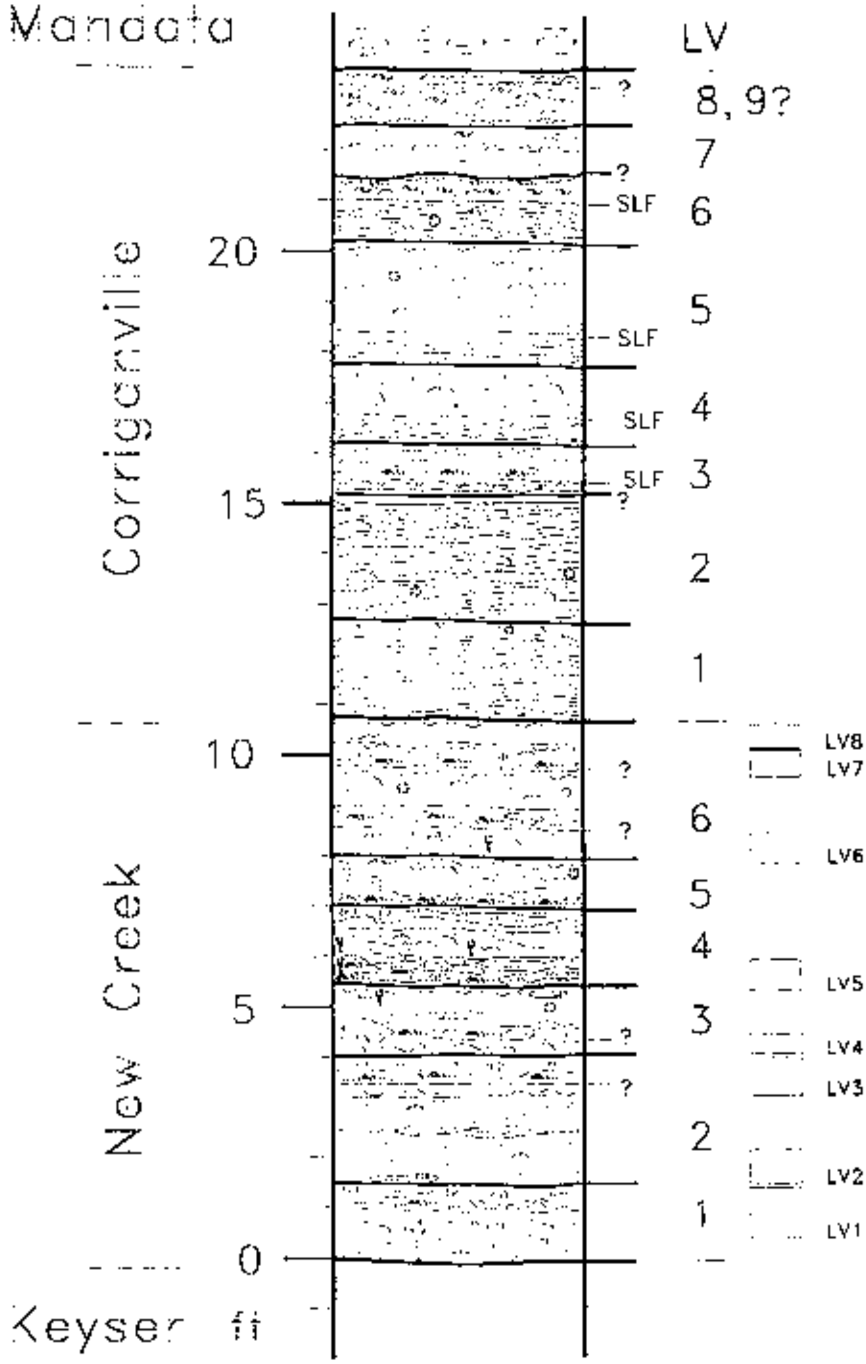


Figure 17. Columnar section, New Creek and Corriganville Fms, Limestoneville.

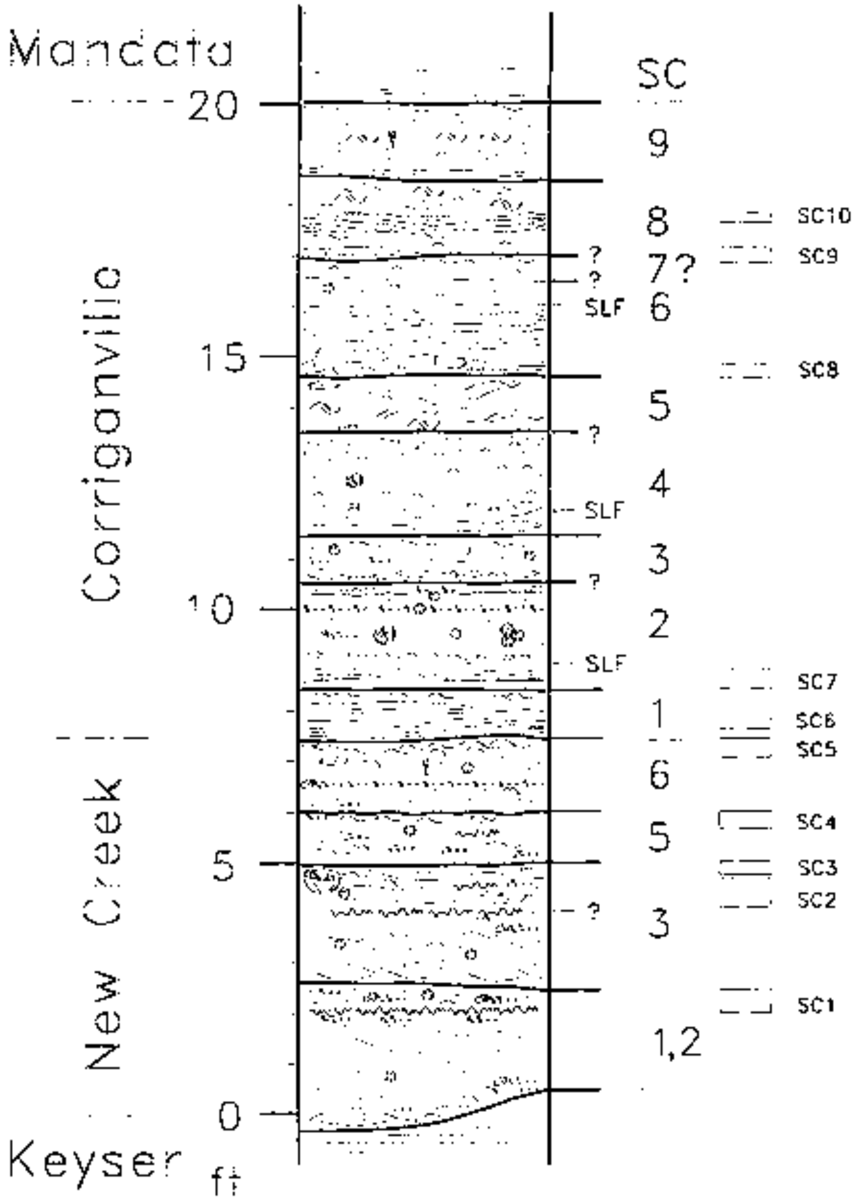


Figure 18. Columnar section, New Creek and Corriganville Fms., St. Clairsville.

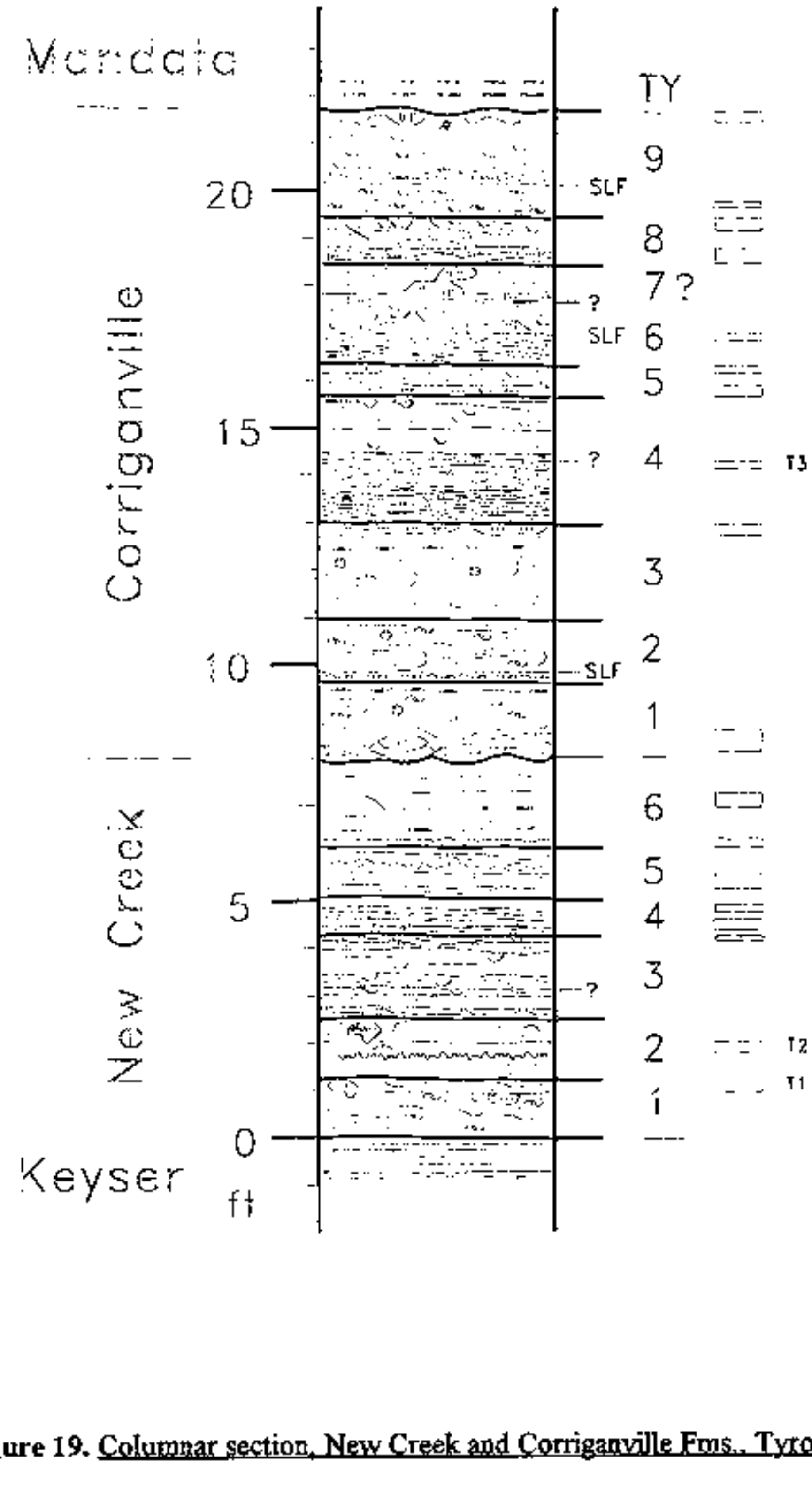


Figure 19. Columnar section, New Creek and Corriganville Fms., Tyrone.

Lower New Creek Formation

The lower New Creek is composed of thicker and less argillaceous cycles than the upper half of the formation. This interval, ranging in thickness from 3.5 ft (1.07 m) to 5.5 ft (1.68 m), consists of three cycles, which average 1.4 ft (0.43 m) in thickness. These cycles, which are composed of fine-grained to medium-grained calcarenite, coarsen upward. The three cycles and their bounding surfaces are recognized at all localities except Cessna, St. Clairsville and Hollidaysburg. At these localities PACs 1 and 2 are not distinguishable, but distinctive features of PAC 3 suggest that the lower interval encompasses both PACs or PAC 1 is missing at the unconformity with the Keyser Formation.

PAC 3 is a distinctive marker unit throughout the study area. The lower boundary of PAC 3 is denoted by an abrupt lithological change across a distinct surface from coarse, fossiliferous calcarenite or chert at the top of PAC 2 to fine calcarenite (*e.g.* Figures 13, 17 and 18) at the base of PAC 3. A prominent bed of chert characterizes the upper boundary of this PAC at all study localities; likewise, similar internal features of this PAC are found at all localities. For example, at Limestoneville there is a prominent 2" shell lag with some nodular chert in the middle of the PAC (Figure 11). In the same stratigraphic position at Tyrone, there is a coarse pink calcarenite bed; at Allegheny Furnace and Altoona Bypass there is a thin, but distinct fossil lag in the middle of the PAC. This internal feature is a potential PAC boundary because it is found at most localities; however, because this surface is not associated with a marked facies change, it remains questionable as a cycle boundary (Plate 1).

Most chert in the lower New Creek occurs as microcrystalline silica, incompletely replacing the host limestone; silica may rarely occur as chalcedony spheroids (*e.g.* in Figure 20; the chalcedony spheroids are in between calcareous mudstone and microcrystalline pod). In this lower New Creek Formation chert occurrence is related to cycle boundaries in the following manner. Chert occurs most consistently at the PAC 3-4 boundary and with less persistence at other cycle boundaries. Most commonly, chert occurs below the boundary but in some cases may be either above or both above and below it (Figures 12-19). Chert below the boundary at St. Clairsville (Figure 21) is prefentially located about an inch below the boundary, within a coarse, fossiliferous, organic-rich zone, indicating a lithologic control on the exact location of silicification. Occasionally chert is found within the internal sub-surface of PAC 3 and at Hollidaysburg at the bottom of PAC 3. Below PAC 3 chert occurs only north of Altoona Bypass.

The precise correlation of chert types, host lithology and microscopic features with stratigraphy is complicated. For example, the top of PAC 2 is characterized by a thick chert bed at Allegheny Furnace and Limestoneville (Figures 10, 11, 13 and 17) and correlates with a zone of minor nodular, fossiliferous chert at Tyrone. At the same horizon, macrocrystalline silica has filled the pores silica of the grainstone at Tyrone (Figures 22 and 23), while at that horizon in the section at Canoe Creek Quarry, the grainstone at top of PAC 2 is completely silicified to chert. This variation in the degree of silicification indicates that other controls than texture determine silicification patterns. For example, the type of silica polymorph precipitation is dependent on solution concentration

Figure 20. Thin-section from PAC 3, lower New Creek Formation, Hollidaysburg.

This thin-section is positioned between the micritic host-rock and a chert pod near the base of PAC 3. Yellowish-brown micrite is in the upper right corner, and chert is seen as nearly dark, pinpointed microcrystalline silica on the opposing corner. A calcite vein is at the contact, surrounded by chalcedony spherules. Most of the chert nodule is composed of microcrystalline silica. The few fossils present are replaced preserving detail, although the host micrite is devoid of fossils. Width of photomicrograph is 3.6 mm.