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**Sr<sup>87</sup>/Sr<sup>86</sup> Isotopic Age Determination of Upper Cretaceous Santonian,  
Campanian and Maastrichtian Chondrichthyan Teeth of the Atlantic and  
Eastern Gulf Coastal Plains: Implications for Sea Level Cyclicity and  
Macrofossil Time-Averaging in Depositional Sequence Lag Deposits**

by

**Martin Becker**

A dissertation submitted to the Graduate Faculty in Earth and  
Environmental Sciences in partial fulfillment of the requirements for the  
degree of Doctor of Philosophy, The City University of New York

1997

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This manuscript has been read and accepted for the Graduate Faculty in Earth and Environmental Science in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

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## Abstract

Unconformities and fossil rich layers are common elements in the stratigraphic architecture of upper Cretaceous sediments exposed on both the Atlantic and Eastern Gulf Coastal Plains. Contacts between the Eutaw Formation and Tombigbee Sands Member in Alabama, the Blufftown Formation and Cusseta Sands in Georgia and the Wenonah-Mt. Laurel and Navesink Formations in New Jersey are marked by erosional surfaces with overlying blankets and lenses of macrofossil residuum. These contacts correspond to bounding unconformities and transgressive lags separating Santonian-Campanian, lower Campanian-upper Campanian and Campanian-Maastrichtian depositional sequences.

Regression and subsequent transgression of sea level at the top of these depositional sequences resulted in hydrodynamic sorting of sediments and fossils that had previously accumulated in shelf and lower shoreface paleoenvironments. Remobilization of sediments by shoreface retreat reworked fossil hard-parts which became concentrated above erosional surfaces as sea level rose. Because of the abundance of chondrichthyan, pelecypod and ammonite fossils, these lags have great biostratigraphic significance and provide a basis for examining time averaging in macrofossil zonation.

Chondrichthyan teeth are composed of extremely durable and highly insoluble, biogenic apatite. This tooth apatite accurately records the

$\text{Sr}^{87}/\text{Sr}^{86}$  isotopic signature of seawater, from which the numerical age of the teeth can be calculated using published age/concentration data. Teeth (e.g. *Squalicorax kaupi*, *Scapanorhynchus texanus*) from Santonian-Campanian lag deposits at the contact of the Eutaw Formation and Tombigbee Sands Member in Alabama yield approximate ages of 85-81 Ma. Teeth from lower-upper Campanian lag deposits at the contact of the Blufftown Formation and Cusseta Sands in Georgia yield approximate ages of 83-75 Ma. Teeth from Campanian-Maastrichtian lag deposits at the contact of the Wenonah-Mt. Laurel and Navesink Formations in New Jersey yield approximate ages of 80-76 Ma. Isotopic age determination from these chondrichthyan teeth indicate average hiatus of approximately 3-7 million years occur during the development of lag accumulations and transgressive unconformities.

Santonian, Campanian and Maastrichtian macrofossils analyzed in this study are hydrodynamically stable components representing time-averaged fossil assemblages sorted together by physical processes and are not life cohorts. Abrupt appearance and disappearance of organisms found in upper Cretaceous lag deposits of the Atlantic and Eastern Gulf Coastal Plains are artifacts of a physical sorting processes associated with sea-level cyclicity.

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## **Introduction**

The Atlantic and Eastern Gulf Coastal Plains provide excellent localities for studying the effects of relative sea level cyclicity on lag deposit formation. The unconsolidated sediments which comprise these coastal plains contain a rich fossil fauna, particularly of chondrichthyan teeth. This paper focuses on the biostratigraphic and chronostratigraphic value of chondrichthyan teeth contained in coastal plain lag deposits.

Within coastal plain sediments, individual depositional sequences have been identified and correlated to global sea level changes (e.g. Olsson, 1991 and King and Skotnicki, 1994). Furthermore, the geologic history and biostratigraphic zonations of the Atlantic and Eastern Gulf Coastal Plains are well known (Weller, 1907; Stephenson et al., 1942; Richards et al., 1958; 1962; Petters, 1976; 1977; Sohl and Smith, 1980; Reinhardt, 1981; Watts, 1981; Gohn, 1985; Kiltgord and Huchinson, 1985; Owens and Gohn, 1985; Olsson, 1988; Raymond et al., 1988; Kennedy et al., 1992; King and Skotnicki, 1994; and Kennedy et al., 1995). This familiarity provides a framework in which to: 1) assess the utility of chondrichthyan teeth in time-averaging and taphonomy studies; and 2) interpret the taphonomy of fossil deposits, such as chondrichthyan teeth lags, in terms of third order relative sea level changes.

A five year field sampling in New Jersey, Georgia and Alabama suggests that upper Cretaceous chondrichthyan lag deposits have some

important common attributes: 1) chondrichthyan lag deposits occur at the boundaries between major facies changes of clay dominated to sand dominated conditions; 2) few chondrichthyan fossils occur above and below lag deposits; 3) chondrichthyan lag deposits occur as transgressive surfaces above disconformities; 4) chondrichthyan fossils are associated in these lags with other vertebrate fossils and mollusks; and 5) chondrichthyan fossils are associated with pebbles, wood, organics, glauconite and siderite concretions. These associations occur across approximately 1000 miles of the Atlantic and Eastern Gulf Coastal Plains.

This project describes a detailed study of Santonian, Campanian and Maastrichtian outcrops in New Jersey, Georgia and Alabama. It addresses the following questions: 1) can chondrichthyan lag deposits that accumulated during the Santonian, Campanian and Maastrichtian provide a key to tracing Depositional Sequences 3, 4, and 5 of Owens and Gohn, 1985, in outcrop; 2) are chondrichthyan lag deposits present in New Jersey, Georgia and Alabama created by similar regressive-transgressive mechanisms; 3) are chondrichthyan teeth in conjunction with other macrofossils useful biostratigraphic indicators; 4) do chondrichthyan teeth give accurate  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ages; 5) can  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic age determination for chondrichthyan teeth indicate these lag deposits are time-averaged fossil assemblages and not contemporaneous life-cohort assemblages; and 6) can estimates of the amount of temporal stratigraphic

mixing at the Santonian-Campanian; lower-upper Campanian and Campanian-Maastrichtian boundaries be made by  $\text{Sr}^{87}/\text{Sr}^{86}$  dating chondrichthyan representatives?

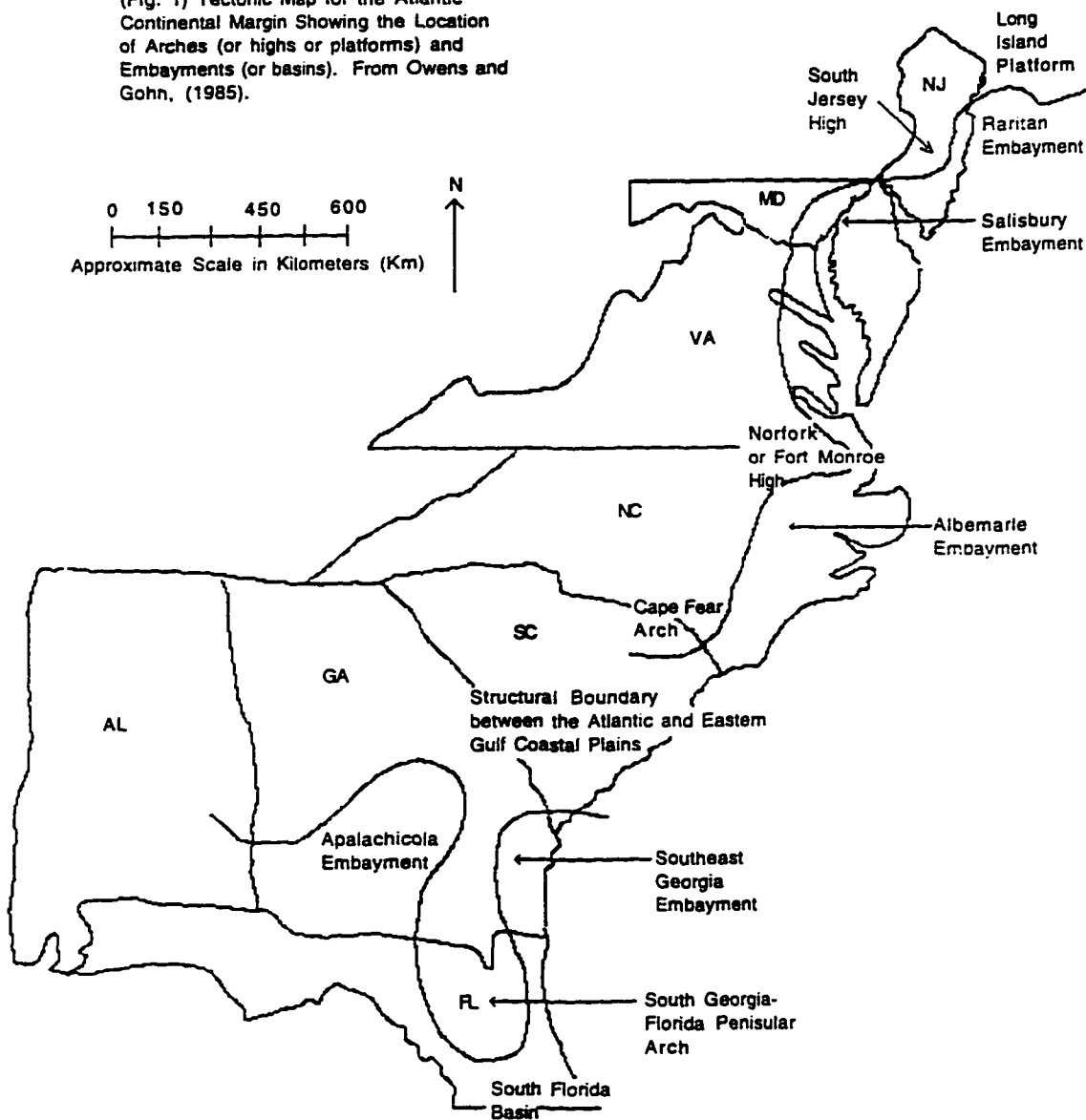
## **Geologic Setting**

### **Atlantic and Eastern Gulf Coastal Plains**

Upper Cretaceous sediments of the Atlantic and Eastern Gulf Coastal Plains record a complex history of tectonism, sea level cyclicity and basin development (Owens and Gohn, 1985). The basement framework for the Atlantic Coastal Margin was investigated by Brown et al., 1972 and Sheridan, 1974. The Atlantic Coastal Margin is described in their work as a series of arches (highs or platforms) alternating with a series of embayments (or basins). As noted in figure 1, the platforms, highs and arches, from north to south include the Long Island Platform, the South Jersey High, the Norfolk or Ft. Monroe High, the Cape Fear Arch, and the South Georgia-Florida Peninsular Arch. The embayments and basins, from north to south include the Raritan, Salisbury, Albemarle, Southeast Georgia and Apalachicola Embayments and the South Florida Basin (Owens and Gohn, 1985).

Highs along the Atlantic Coastal Plain characteristically show thinner sedimentary thickness due to thinning or non-deposition of sediment. Greater thickness of sedimentary deposits occurs in embayment or basin regions. Petters, 1976, and Olsson et al., 1988, attribute sediment thickness

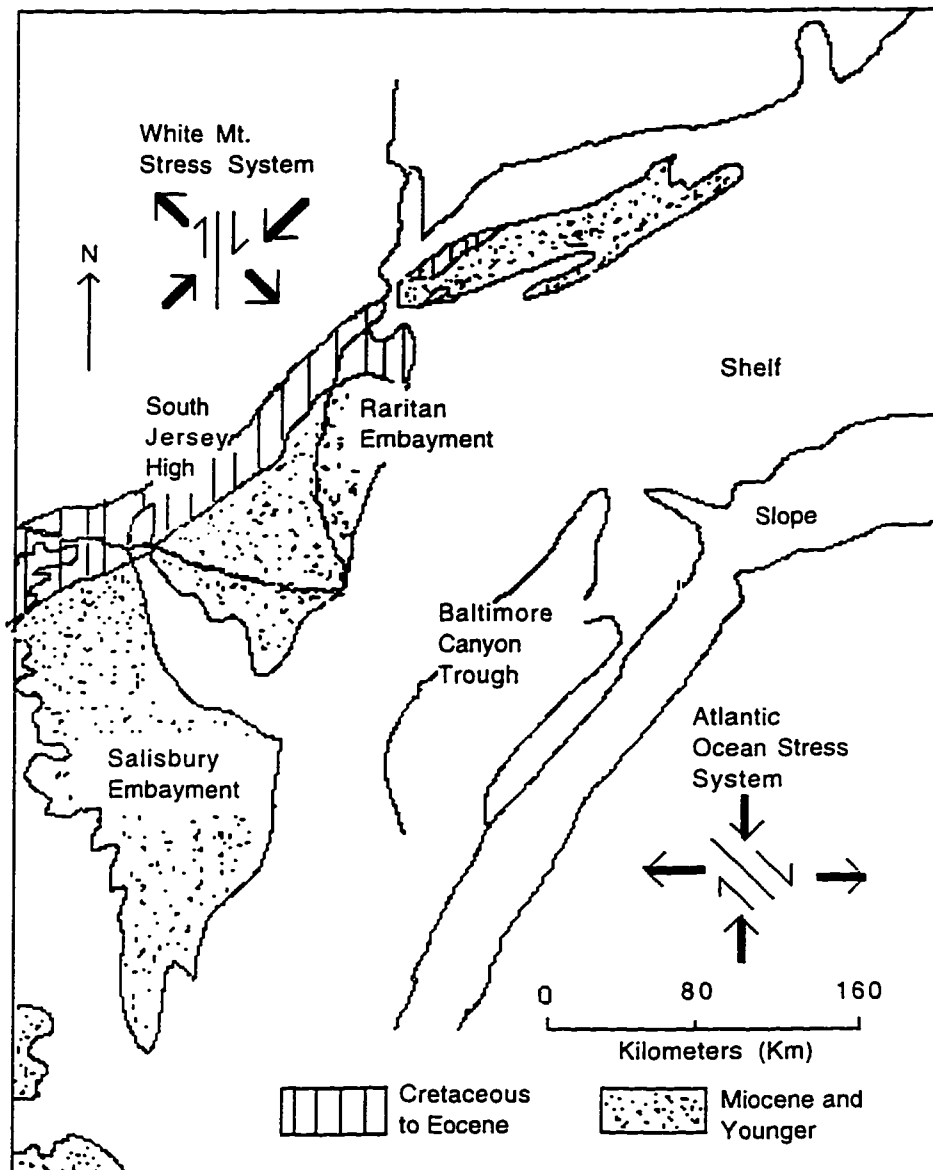
(Fig. 1) Tectonic Map for the Atlantic Continental Margin Showing the Location of Arches (or highs or platforms) and Embayments (or basins). From Owens and Gohn, (1985).



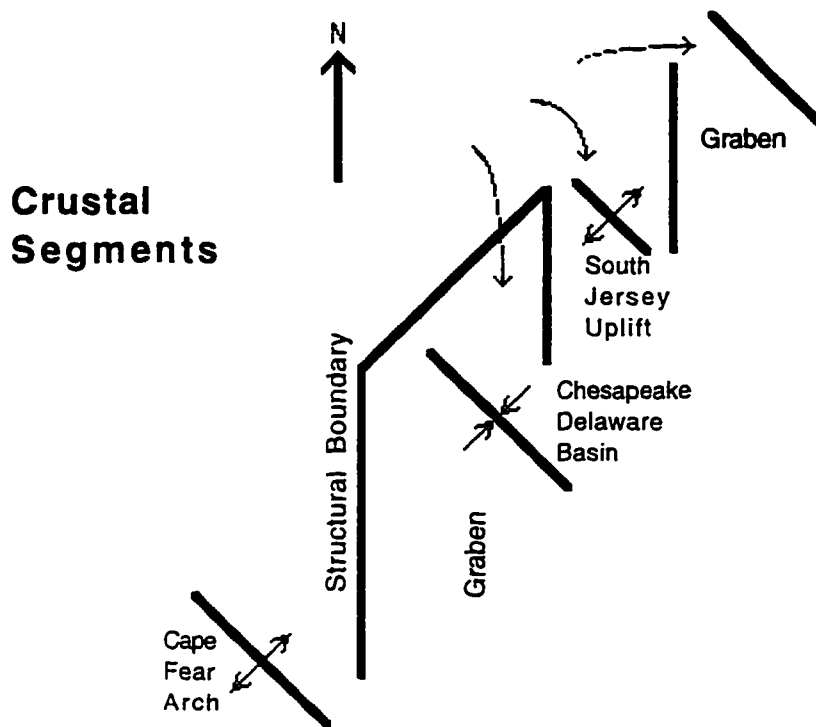
variations along strike in the Atlantic Coastal Plain to structural controls associated with the development of the arch and embayment systems.

The formation of the arch and embayment system in the Atlantic Coastal Plain is related to extensional mechanisms that operated during Triassic and Jurassic times. Brown et al., 1972, and Sheridan, 1974, conceptualized a clockwise rotation for the entire North American continental margin in response to differential opening of the Atlantic Ocean Fracture Zones and Labrador Sea Fracture Zone. The White Mountain Stress System served as a tension release hinge of these two stress systems and was created in response to the migration of the Great Meteor Hotspot (Sheridan, 1974 and Crough, 1981). Brown et al., 1972, describe the clockwise rotational motion of the individual basement blocks of the Atlantic Continental Margin as "Wrench-Fault Tectonism" (Figs. 2 and 3).

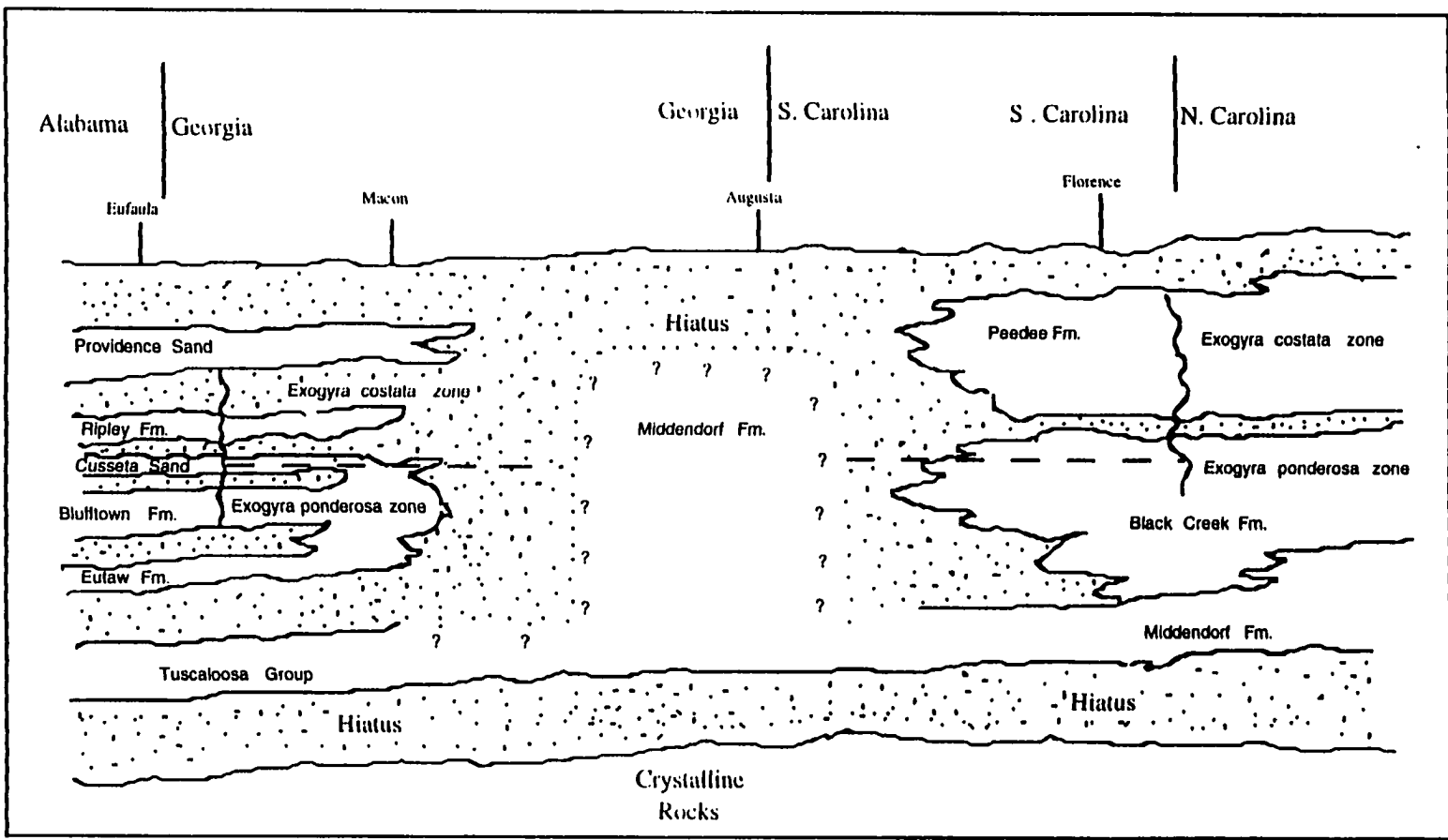
Brett, 1967, indicates the boundary between Atlantic and Eastern Gulf Coastal Plains is a broad low arch or platform on top of crystalline rocks extending southeastward between Georgia and South Carolina. This platform divides the southern portion of the Atlantic Coastal Plain from the Eastern Gulf Coastal Plain. Outcrop patterns show Eastern Gulf Coastal Plain and southern Atlantic Coastal Plain sediments to be separated by a narrow band of fluvial sediments running from eastern Georgia to western South Carolina (Fig. 4). In Alabama, Mesozoic and



(Fig. 2) Stress systems in the North Atlantic Coastal Plain responsible for the development of the archs and embayments. Redrawn from Olsson et al., (1975).



(Fig. 3) Wrench Fault Tectonism associated with the development of the Atlantic Coast Plain. Thick lines indicate boundaries between structural segments. Curved arrows indicate direction of block rotation while straight arrows indicate extensional and compressional mechanisms across individual structural segments. Redrawn from Brown et al., (1972).



(Fig. 4) Stratigraphic relationships of Cretaceous sediments from the Eastern Gulf Coastal Plain to lower Atlantic Coastal Plain. Redrawn from: Brett, (1967).

Cenozoic sediments cap hills and plateaus of remnant Paleozoic and Mesozoic volcanoclastic rocks (Raymond et al., 1988).

According to Owens and Gohn, 1985, sedimentation began in the eastern Gulf of Mexico and migrated up the Atlantic Coast. With the breakup of Pangea, a complex wedge of Cretaceous sediments which comprises the Eastern Gulf and Atlantic Coastal Plains was deposited. Erosion of the Appalachian Mountains provided the sediment which was transported by river systems, reworked, and then deposited along the margins of the continents under the influence of cyclical fluctuations of sea level (Owens and Gohn, 1985).

### **Sequence Stratigraphic Principles**

#### **Sequence Stratigraphy of Atlantic and Eastern Gulf Coastal Plains**

Sea level fluctuation has long been recognized as the dominant process controlling Atlantic and Eastern Gulf Coastal Plain deposition (Weller, 1907; Stephenson et al., 1942; Sloss, 1963; Vail et al., 1977; Haq et al., 1987; 1988). Modern day interpretation of sea level changes in marine stratigraphy has led, in part, to the development of a branch of geology called sequence stratigraphy (e.g. Sloss, 1963; Mitchum et al., 1977; Vail et al., 1977; Owens and Gohn, 1985 and Posamentier et al., 1988). A complete cycle of sea level change is recorded in the stratigraphic record by a depositional sequence. A depositional sequence is a relatively conformable succession of genetically related stratigraphic

units (Vail et al., 1977). Ideally, each sequence is bounded by unconformities which can be traced basinward to their correlative conformities. A complete cycle of sea level change includes two relative sea level falls separated by a point of maximum relative sea level rise (Mitchum et al., 1977); (Fig 5).

In the Atlantic Coastal Plain, Owens and Gohn, 1985, have identified five major late Cretaceous depositional sequences based on the occurrence of transgressive unconformities that can be traced across the entire Atlantic Coastal Plain. Each complete depositional sequence coarsens and shoals upward with vertical transition between marine shelf facies to nearshore marine facies to non-marine facies (Owens and Gohn, 1985 and Sugarman et al., 1995). Sugarman et al., 1995, indicate that sequence boundaries are represented in coastal plain outcrops as distinct surfaces of erosion, characterized by considerable relief, overlying gravel lags, bioturbation, and diagenetic cementation by groundwater.

The upper surfaces of sequences three, four and five of Owens and Gohn, 1985, are late Cretaceous coastal plain successions bounded by upper Santonian-lower Campanian, lower and upper Campanian and upper Campanian to lower Maastrichtian transgressive unconformities. Outcrop exposures in New Jersey, Georgia and Alabama have laterally discontinuous chondrichthyan lag deposits at the upper Santonian-lower Campanian, lower Campanian-upper Campanian and at the upper



Campanian-lower Maastrichtian boundaries (Schwimmer, 1986; Case and Schwimmer, 1988; Robb, 1992; King and Skotnicki, 1994 and Becker and Slattery, 1995); (Fig. 6).

### History and Development

The original concepts which led to the development of sequence stratigraphy are related to the work of Sloss, 1963. Sloss, 1963, recognized five major unconformity bound sequences developed over the North American Craton during the Phanerozoic: Sauk, Tippecanoe, Kaskaskia, Absaroka and the Zuni. These sequences were created by regressive-transgressive events which alternate with periods of orogenic activity on the eastern and western margins of the craton.

The concept of sequences was further developed by Vail et al., 1977, and Mitchum et al., 1977, through analysis of seismic profiles utilized for petroleum exploration. According to these authors, a sequence is defined as a stratigraphic unit composed of genetically related strata, bounded at the top and bottom by unconformities which can be traced basinward to correlative conformities. Unconformities, which define sequence boundaries, are created by erosion associated with fluctuations in relative sea level across a basin. Correlative conformities occur along the same surface and basinward of the sequence bounding unconformity. Basinward, in deeper water, the correlative conformity has not been

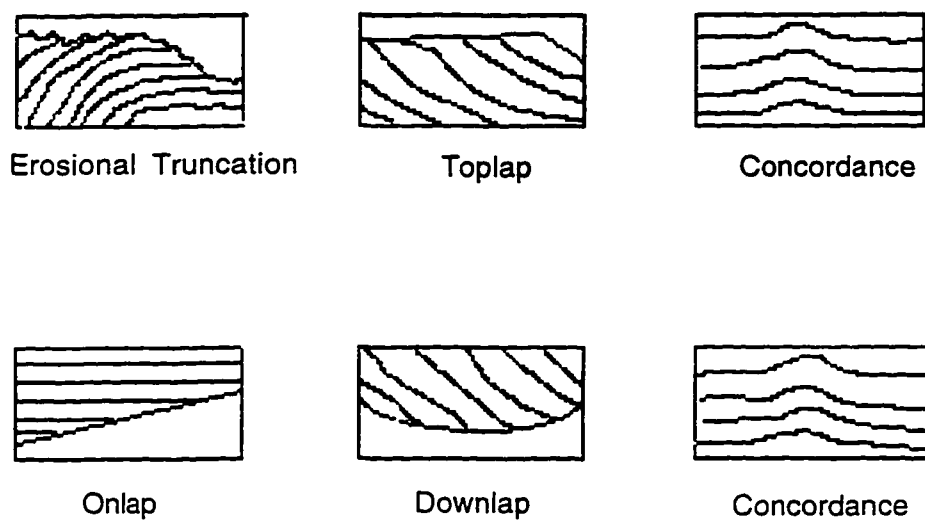


subjected to the erosive action of relative sea level fluctuation experienced by landward, shallower water environments.

Vail et al., 1977, suggest that sequences are correlated with coastal onlap resulting from eustatic sea level changes. This view of coastal onlap led to the development of global sea level curves. These curves have a characteristic saw tooth shape, with abrupt sea level falls and gradual sea level rises. The original interpretations of Vail et al., 1977, were modified during the 1980's as the role of tectonics and its influence on sea level processes in sequence deposition was clarified (Wilgus et al., 1988).

### Stratal Relationships

Discordant relationships are a key to the identification of sequences. Discordances are reflection terminations of strata along surfaces located at the bottom or top of sequences and are especially useful for finding sequence boundaries in seismic profiling (Vail et al., 1977). Basal onlap, or terminations at the bottom of sequences, may occur as onlap or downlap (Fig. 7). Onlap occurs when an originally horizontal unit overlaps an inclined surface, usually indicating a relative sea level rise. Downlap occurs when an originally inclined stratum terminates down dip against an older surface, usually indicating relative sea level fall. Terminations at the top of sequences may occur as toplap or erosional truncations (Fig. 7); (Vail et al., 1977). Toplap is the updip termination of inclined units and is characteristic of the unconformable part of the top of a sequence. Toplap,



(Fig. 7) Stratal relationships used in the identification of seismic sequences  
From: Vail et al., (1977).

characteristically occurs during relative sea level fall. Erosional truncation, which can also occur at the tops of sequences, is represented by stratal units whose upper surfaces are irregular due to erosion and relative sea level fall.

In the sequence stratigraphic model discordant relationships are the key to interpretation of relative sea level change. These principles have been modified to allow for the interpretation of sequences in seismic well log and outcrop data. Furthermore, the modern global sea level curve of Haq et al., 1988, is a product of the integration of seismic profiles, well log data and outcrop data for contemporaneous time intervals.

#### Depositional System Tracts

Sequences occur as packages of sediment whose deposition is the product of changes in sea level (Vail et al., 1977). Packages of deposited sediment are referred to as a depositional systems tracts. Three different types of depositional systems tracts can be identified: highstand, lowstand and transgressive. Highstand systems tract deposits develop when sea level rise progressively slows and sediments prograde basinward. Progradation takes place over earlier systems tracts and usually results in a downlapped surface at the base of the highstand systems tract. Deposition of fluvial sediments and erosion of underlying sediments occur during the later stage deposition of this systems tract.

The highstand systems tract usually terminates with a type one or type two unconformity. Type one unconformities result from relative sea level falls which expose the entire shelf to erosion while type two unconformities result from small relative sea level falls in which the shelf remains submerged (Vail et al., 1977). When type one unconformities occur, a lowstand systems tract develops. Lowstand systems tracts are formed when the shelf is subaerially exposed allowing rivers to cut into and bypass the shelf. River sediments feed directly to the continental slope allowing for the development of submarine fans, deltas, debris flows and turbidites. These genetically related lowstand deposits are typically interpreted from seismic profiles as continental slope wedges of sediment (Vail et al., 1977).

Transgressive systems tracts develop during relative sea level rise. A retrograding set of parasequences are deposited during the relative sea level rise. Parasequences comprise the building blocks of depositional systems and are defined as a relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces or their correlative conformities (Vail et al., 1977). Although each individual parasequence coarsens and shallows upward, successive parasequences begin in deeper and deeper water. The maximum advance of onlap is referred to as the maximum flooding surface and indicates the highest advance of relative sea level during the deposition of the entire sequence.

This surface marks the beginning of the highstand systems tract. After the maximum flooding surface has been deposited, relative sea level begins to fall and the entire cycle of highstand, lowstand and transgressive depositional systems tracts are repeated (Vail et al., 1977).

### Identification of Sequences in Outcrop

Outcrop interpretation of sequence boundaries are compiled from sediment stacking patterns of parasequences. The marine flooding surfaces separating parasequences indicate an increase in depth of deposition across the surface, and sometimes contain minor subaerial erosion or non-deposition. Stacking patterns associated with parasequences can show progradation, aggradation or retrogradation, allowing for the interpretation of sea level cyclicity.

### Parasequence Sets: Aggrading, Prograding and Retrograding

Prograding parasequence sets step basinward resulting in individual parasequences which show an increase in the amount of coarse grained sediments. These parasequence sets are characteristically deposited during falling relative sea level and are components of a highstand system tract.

Aggrading parasequence sets are deposited as sediment packages which show no apparent shift either landward or basinward. Individual parasequences, comprising an aggrading sequence, show no significant change in the amount of coarse or fine grained sediment. These parasequence sets are deposited when the rate of sea level rise is in

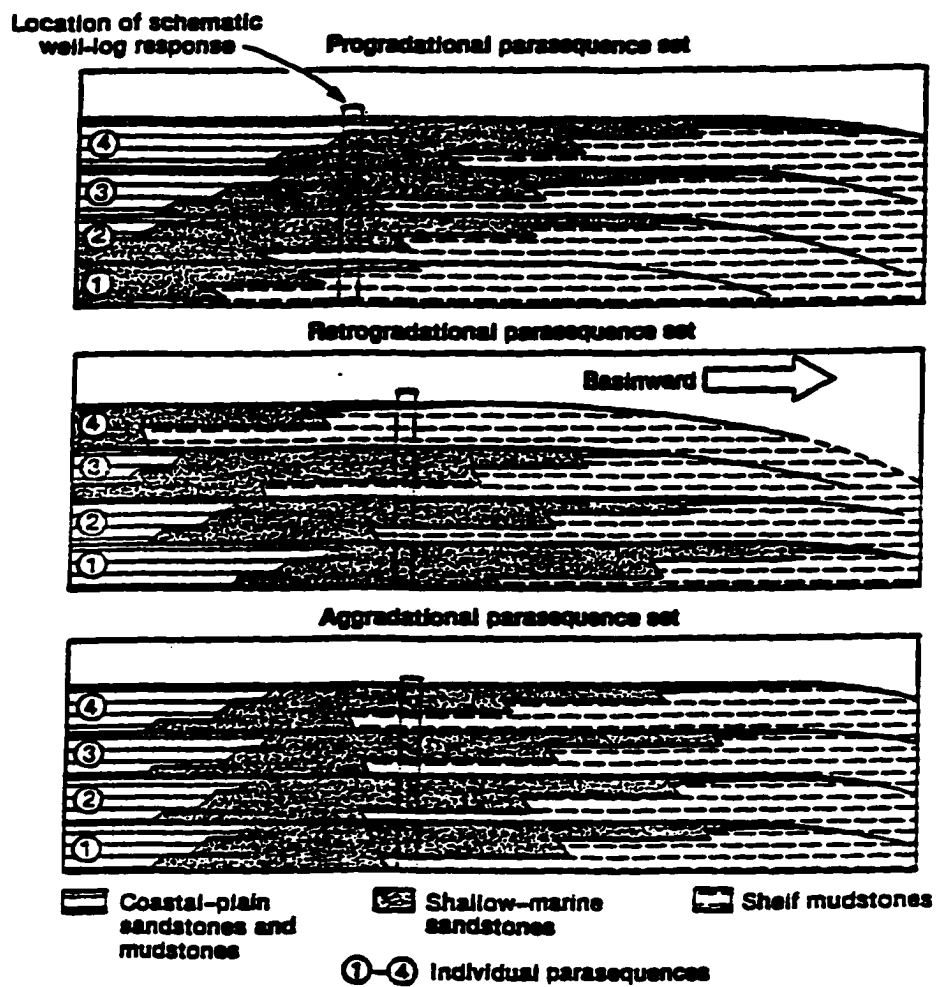
equilibrium with basin subsidence and sediment supply. Parasequence sets are usually deposited during the late highstand systems tract.

Retrograding parasequence sets step landward resulting in individual parasequences which show a decrease in the amount of coarse grained sediments. These parasequence sets are characteristically deposited during rising relative sea level and are products of the transgressive systems tract (Vail et al., 1977); (Fig. 8).

## **Sea Level Changes**

### **Relative Sea Level**

Vail et al., 1977, defines a relative change of sea level as an apparent rise or fall of sea level with respect to the land surface. Either the sea level alone, the land surface or sea floor, or both in combination may rise and fall during a relative cycle. Relative sea level change operates on a local, regional or global scale and is controlled by tectonics, eustasy and sediment influx parameters. Global or eustatic changes in sea level are defined as relative changes in three or more widely spaced regions which occur at the same time. Because such regions are influenced by different tectonic and depositional histories, eustatic sea level change is tectonic and sediment influx independent (Vail et al., 1977). Cycles of relative sea level change consist of a rise, a period of standstill and a fall. Individual, complete relative sea level cycles are responsible for the development of



(Fig. 8) Diagram of prograding, aggrading and retrograding parasequences comprising depositional sequences. From Vail et al., (1977).

parasequences, the fundamental building blocks of sequence stratigraphic packages, sequences and systems tracts.

Cycles of relative sea level change are classified as first, second, third or fourth order by the duration in which the relative sea level change takes place (Vail et al., 1977). First order relative sea level changes represent durations on the order of  $10^8$  years. Second order relative sea level changes represent durations on the order of  $10^7$  years. Third and fourth order relative sea level changes represent durations ranging on the order from  $10^6$ - $10^5$  years (Vail et al., 1977).

#### Eustacy as a Control for Sea Level

Late postrift deposition on the Atlantic Coastal Plain occurred during reduced subsidence rate conditions (Gohn, 1988). Although there is a great degree of structural variability across the Atlantic and Eastern Gulf Coastal Plains, third order eustatic sea level cyclicity has been cited as the major controlling mechanism for coastal onlap (Cooper, 1977; Haq et al., 1987; Haq et al., 1988; Kendall and Lerche, 1988; Olsson 1988; Posamentier et al., 1988; Olsson, 1991; Olsson, 1989 and Dott, 1992). These researchers suggest that third order sea level cycles are changes that take place on the order of 0.5 to 5 million years.

Cooper, 1977, discussed eustacy during the Cretaceous and noted thirteen transgressive episodes between the late Valanginian and early Maastrichtian. His works suggest that significant volumetric changes in

the mid-ocean ridge system resulted from episodic plate motion on the one to several million year time scale. In his model, upward displacement of ocean water and sea level transgression onto the continent resulted from increase in the volume of the mid-ocean ridge system associated with periods of rapid rifting. This would be followed by a period of low spreading activity lasting for several million years and by regression. Five causes for eustatic changes in sea level cited by Cooper, 1977, which include third order changes, are: glaciation, volumetric changes in the mid-ocean ridge systems, orogenic events on continents, differences between the rate of consumption at subduction zones and the rate of accretion under the continents.

#### Eustatic Model For Sea Level Cyclicality

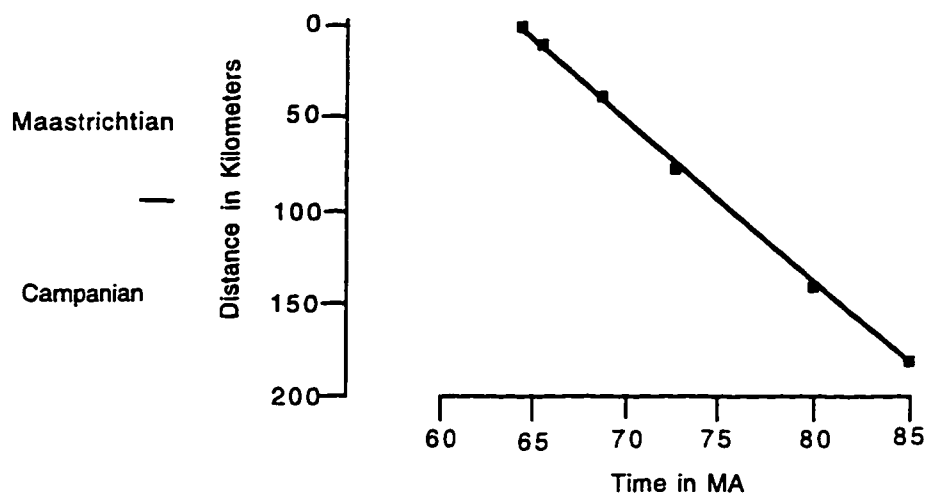
Haq et al., 1988, discussed Mesozoic sea level chronostratigraphy and associated mechanisms of sea level change. These authors generated a sea level cycle chart for the Mesozoic by compiling known biostratigraphy, magnetostratigraphy and radiometric dates for the Mesozoic. By comparing the age of magnetic anomalies to the distance from the mid-ocean ridge spreading centers, Haq et al., 1988, have determined the spreading rates in the Western North Atlantic at latitudes 25-32 degrees north and 37-45 degrees north. The data show that spreading rates in these two areas differed during the Santonian, Campanian and Maastrichtian stages. More southern latitudes show an approximate

spreading rate of 1.5 centimeters per year, while the northern latitudes show an approximate spreading rate of 0.8 centimeters per year (Figs. 9 and 10).

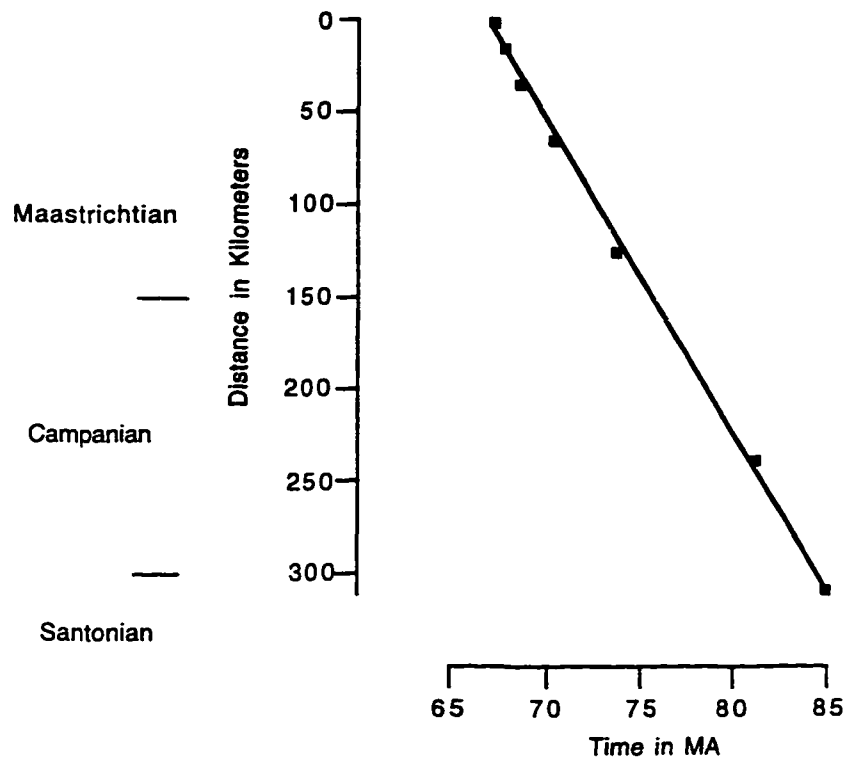
### Tectonism as a Control for Sea Level

The role of tectonic controls on sea level fluctuation, basin development and sedimentation along the Atlantic Coastal Plain are well discussed in the works of Gibson, 1970; Brown et al., 1972; Dewey and Burk, 1974; Sheridan, 1974; Watts, 1981; Cloetingh et al., 1985; Kiltgord and Hutchinson, 1985; Cloetingh, 1988; Crough, 1988; Sheridan et al., 1988 and Steckler et al., 1988.

Watts, 1981, believes subsidence of the Atlantic continental margin is controlled by two components. One component includes extension and thinning of the crust during rifting and postrift thermal contraction of the lithosphere. The second component includes loading of sediment and ocean water onto the continental crust. This model predicts that downwarp of the lithosphere by sediment loading controls relative sea level fluctuation and onlapping of progressively younger geologic sediments. Additionally, this model explains why postrift Jurassic and lower Cretaceous sediments are located in offshore regions and why upper Cretaceous and Cenozoic sediments are systematically and chronologically organized in the landward direction (Owens and Gohn, 1985).



(Fig. 9) Approximate mid ocean ridge spreading rates for the Western North Atlantic between latitudes 37 and 45 degrees north during the Campanian and Maastrichtian. Average rate is calculated as 0.8 cm per year. From Haq et al., (1988).

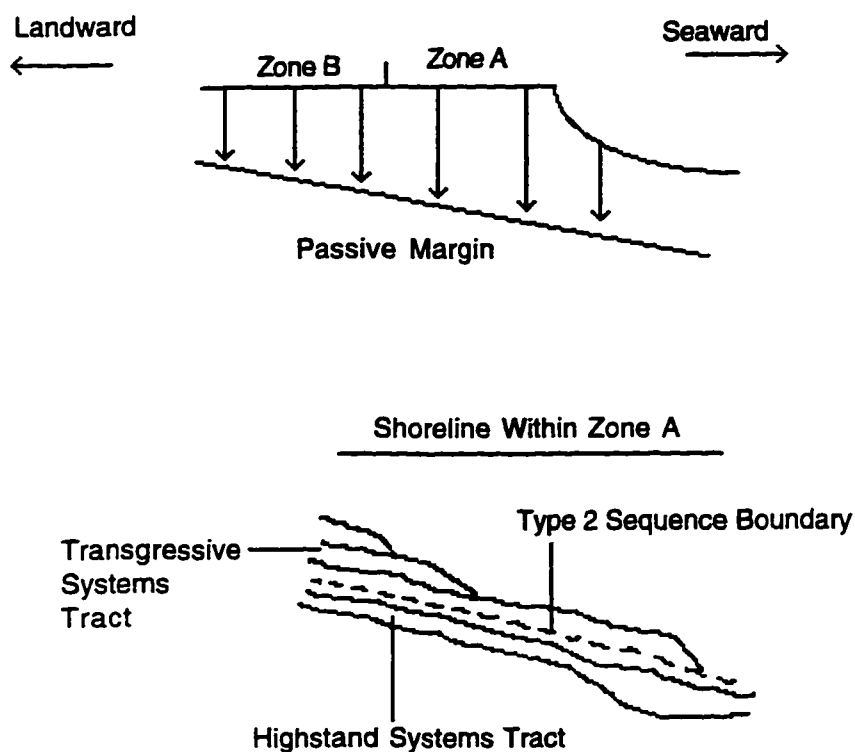


(Fig. 10) Approximate mid-ocean ridge spreading rates for the Western North Atlantic between latitudes 25 and 37 degrees north during the Santonian, Campanian and Maastrichtian. Average rate is calculated as 1.5 cm per year. From Haq et al., (1988).

Cloetingh, 1988, states that stress variations of a few hundred kilobars associated with local adjustments of stress at passive margins can explain apparent short-term variations in sea level. These sea level variations are on the order of tens of meters and can control a significant part of local stratigraphic record. This view is supported by the work of Steckler et al., 1988, and their interpretation of basement and coastal plain development. Steckler et al., 1988, suggest that basin subsidence resulted from variations in lithosphere rigidity and downward flexure where coastal plain development resulted from periodic onlapping in response to sea level fluctuations. Larger apparent sea level fluctuations on the order of fifty meters or more require stresses greater than a few hundred kilobars and are related to major reorganization of lithospheric stress fields due to rifting and plate fragmentation or convergent plate processes (Cloetingh, 1988).

#### Tectonic Model For Sea Level Cyclicity

The mechanics of tectonism controlling sea level on passive margins are well documented in the study of Posamentier and Allen, 1993. Their analysis of the relationship between eustacy and subsidence suggests the existence of two stratigraphic zones, zone A and zone B. As shown in figure 11, zone A is defined as the region where the rate of subsidence always exceeds eustatic fall. This results in constant sea level rise in zone A during the eustatic cycle. Zone B is defined as the region where the rate



(Fig. 11) Tectonic model for the development of sequence stratigraphic deposits along Passive Margins. Zone A is the site of maximum subsidence. Zone B is the region where the rate of eustatic sea level fall periodically exceeds subsidence rate. If the shoreline remains in Zone A during a relative sea level cycle, type two unconformities develop, separating highstand deposits from transgressive deposits. Shorelines within zone B result in type one unconformities in which the entire shelf is exposed and subjected to reworking. After Posamentier and Allen, (1993).

of eustatic fall periodically exceeds the subsidence rate. This results in an interval of eustatic fall in zone B during a complete sea level cycle (Fig. 11).

The boundary between zones A and B is marked by an equilibrium point where the rate of subsidence is equal to the rate of eustatic change. The equilibrium point separates the zone of relative sea level rise from the zone of relative sea level fall. As eustatic fall accelerates, the equilibrium point migrates to the direction of higher subsidence (Posamentier and Allen, 1993). Stratal patterns and bounding unconformities which develop are the product of the position of the shoreline at the time of maximum sea level fall (Posamentier and Allen, 1993).

If the ancient shoreline is located in zone A, a type two sequence boundary will develop and the stratigraphic succession will represent only a slowing then accelerating of relative sea level rise. Progradational, aggradational and retrogradational stacking patterns in outcrop will develop. If the ancient shoreline is located within zone B, where relative sea level falls can occur, a type one sequence boundary will develop. An unconformity generated by subaerial exposure, fluvial incision and the possibility of lowstand systems tract deposition can occur.

The Atlantic and Eastern Gulf Coastal Plains have been interpreted as relatively passive during the upper Cretaceous (Watts, 1982; Olsson, 1991; Posamentier and Allen, 1993). In the Posamentier and Allen, 1993,

model for passive margin settings, the site of maximum subsidence is located basinward of the shoreline and zone A would lie seaward of zone B. Coastal onlap cycles identified in the upper Cretaceous sea level curve of Haq et al., 1988, indicate that the majority of unconformities are type 2 during the upper Cretaceous based on compilation outcrop, bore hole and seismic data studies (Olsson, 1991 and King and Skotnicki, 1994). Posamentier and Allen, 1993, indicate subsidence during the upper Cretaceous has created sequence boundaries in which packages of transgressive and highstand systems tract deposits are separated from other transgressive and highstand systems tract deposits by type 2 unconformities and sequence boundaries.

Lowstand systems tract deposits are not expressed in type 2 sequence boundaries due to the magnitude of sea level regression with respect to the shelf margin. Lowstand systems tract deposits have not been identified in the Coastal Plain sediments of New Jersey or the Eastern Gulf Coastal Plain (King and Skotnicki, 1994 and Sugarman et al., 1995). However, King and Skotnicki, 1994, state that gravel lags and fluvial incisions occurring at the tops of highstand and bases of transgressive systems tract deposits in coastal plain sediments may be erosional remnants of the lowstand systems tract.

#### Sea Level Estimates

Evidence for major glaciation during the Cretaceous is not preserved in the rock record (Watts, 1982). Throughout most of the late Cretaceous,

sea level stood as high as any other time in the Phanerozoic, resulting in continents that were blanketed with marine sediments (Stanley, 1989).

Estimates for relative sea level change during the Cretaceous are included in the works of Pitman, 1978; Watts and Steckler, 1979 and Olsson, 1991. Pitman, 1978; Watts and Steckler, 1979 and Olsson, 1991, estimate a sea level regression ranging between 120 and 350 meters over the last 70 million years. Estimates were obtained from benthic foraminifera, paleoslope studies, mid-ocean ridge spreading data and through analysis of borehole records along the eastern margin of North America.

### **Lag Deposits**

#### **Taphonomy**

Taphonomy is the study of transport and burial processes associated with the creation a fossil deposit. Taphonomic information has practical application in paleoenvironmental, paleoecological, and biostratigraphic studies and has been the subject of much recent literature (e.g. Allison and Briggs, 1991; Donovan, 1991; Brett and Baird, 1993; Kidwell and Behrensmeyer, 1993 and Becker et al., 1996). The abrupt appearance and disappearance of organisms may be artifacts of transport, differential destruction and time averaging (Kidwell and Behrensmeyer, 1993). Time averaging is defined as the process by which organic remains from different time intervals are mixed and preserved together. Time averaging

generally refers to remains which accumulate from a local living community during the time required to deposit the sediment which contains this material (Kidwell and Behrensmeyer, 1993).

Transport studies on fossil assemblages address the question of allochthonous and autochthonous burial (Fursich, 1977; Kidwell, 1988; Fursich and Aberhan, 1990; Banerjee and Kidwell, 1991 and Brett and Baird, 1993). The criteria suggested by Brett and Baird, 1993, for analyzing whether or not fossils were buried in situ or transported in from external sources include: 1) the taxonomic composition of a fossil deposit as compared to the fossil content of adjacent beds; 2) the diversity of the fossil assemblage; 3) the completeness or fragmentary nature of the fossils; 4) the orientation of fossils; and 5) fossil assemblages showing exceptional preservation. Exceptional preservation in a fossil assemblage may imply instantaneous burial from catastrophic sources or suppressed oxygen conditions. Either condition limits the amount of predation as well as chemical and physical break down.

Differential destruction refers to the nature of fossil materials preserved in terms of hard and soft body parts (Brett and Baird, 1993 and Kidwell and Behrensmeyer, 1993). Hard parts tend to be preferentially preserved over soft parts in the fossil record. Preserved soft parts suggest conditions such as anoxia in the accumulation zone or rapid burial. Very resistant fossils such as teeth and bones tend not to show wear and can

suggest a unique set of paleoenvironmental conditions if found in large accumulations (Flessa, 1993). Kidwell, 1986, and Kidwell and Behrensmeyer, 1993, suggest that conditions required for large accumulations of fossil hard parts are related to sea level reworking effects, condensed sections under suppressed sedimentation rates or nearshore storms.

Time averaging involves the degree of mixing in environments where fossils are preserved (Fursich and Aberhan, 1990 and Kidwell and Behrensmeyer, 1993) . Flessa, 1993, conducted a time averaging and temporal resolution study in recent marine shelly faunas from sixty-six nearshore localities and one hundred twenty-six shelf localities. His results indicate that average mixing in nearshore habitats before burial and preservation within an horizon, is approximately  $10^3$  years, while shelf environments average approximately  $10^4$  years. These time durations represent compilations from the Cenozoic fossil record. Time durations calculated by these modern time averaging studies may or may not be analogous to the upper Cretaceous chondrichthyan lags analyzed in this study.

#### Types of Skeletal Concentrations

Skeletal lag deposits are residual accumulations of coarse sediments and fossils which are deposited on irregular, erosive surfaces.

Concentration of fossils in lag deposits may be the products of erosion and

hydrodynamic sorting associated with waves and/or currents or the result of slow, net sediment accumulation. Kidwell and Behrensmeyer, 1993, have identified three basic types of skeletal lag accumulations which include: 1) event or storm lag concentrations; 2) deep sea condensed sections or hiatal lag concentrations; and 3) sea level cyclicity lag concentrations.

#### Event or Storm Lag Concentrations

Morton, 1988, studied the effects of nearshore responses to great storms in both, modern and ancient environments. His research identified the following characteristics of storm deposits and their effect on sediments: 1) storms can accomplish in hours the same sedimentological work that normally takes years; 2) most coarse-grained, nearshore sediment is deposited during episodic events such as storms; and 3) differences in environmental response to the same event make recognition and stratigraphic correlation difficult.

An increase in global temperatures occurred during the Cretaceous (Stanley, 1987). Morton, 1988, states that this would have shifted the zone of tropical cyclones, tropical storms and hurricanes further north providing greater opportunity for the Cretaceous Atlantic and Eastern Gulf Coastal Plains to be impacted by the effects of storms. However, large storms also rely on a strong temperature gradient between the poles and the equator for their development. These offsetting effects suggest that the

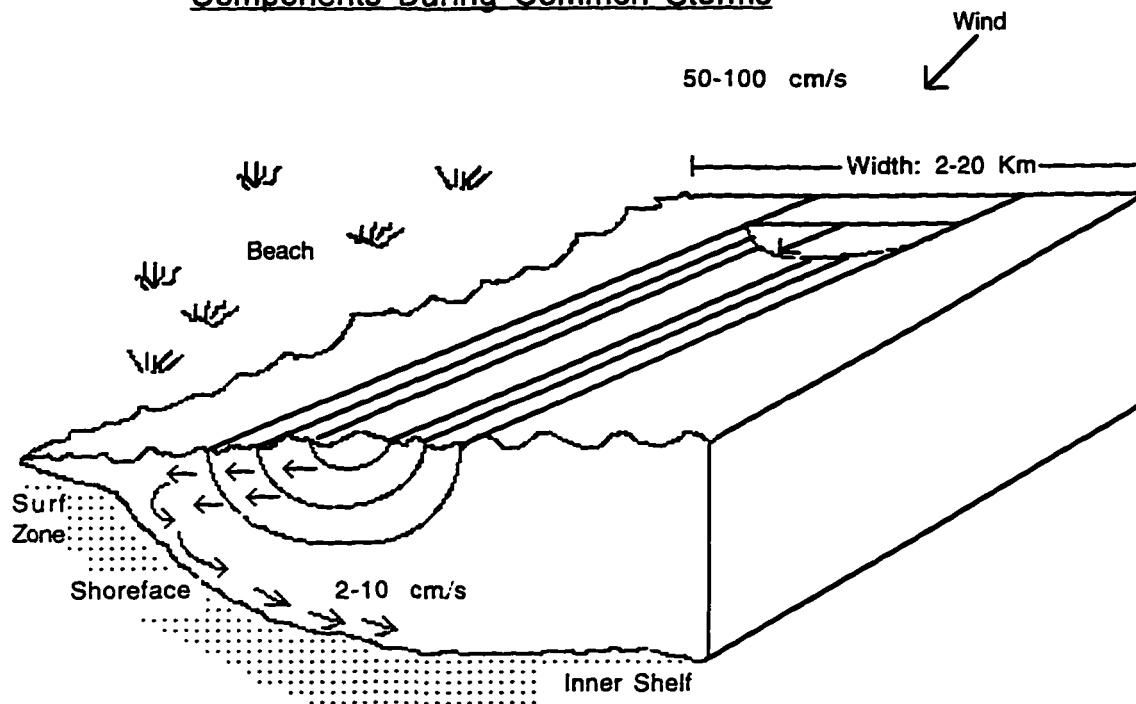
frequency of storms and their effect on the coastal environments during the Cretaceous is uncertain at best.

Morton, 1988 and Cartmell, 1978, compiled some storm and normal bottom current data for the Northern Hemisphere. Hurricane Camille's storm waves created bottom velocities under wave crests of 500 cm/s in 20 meters of water and about 300 cm/s in 45 meters of water. Morton, 1988, noted that near bottom velocities of 50 to 100 cm/s in as much as 80 meters of water are not that uncommon. Stronger waves regularly develop seaward moving currents that have velocities ranging from 2-20 cm/s (Fig. 12).

Comparison of these measured storm current velocities to a Hjulstrom Diagram provides some interesting suggestions about the initial accumulation of fossil lag deposits during storm events. At an average velocity of 100 cm/s, grain sizes up to 10 millimeters undergo transportation (Fig. 13). This would include all grains (and available materials such as macrofossils with a similar density to that of quartz; approximately  $2.65 \text{ g/cm}^3$ ) up through pebble sizes on the Wentworth grain-size scale.

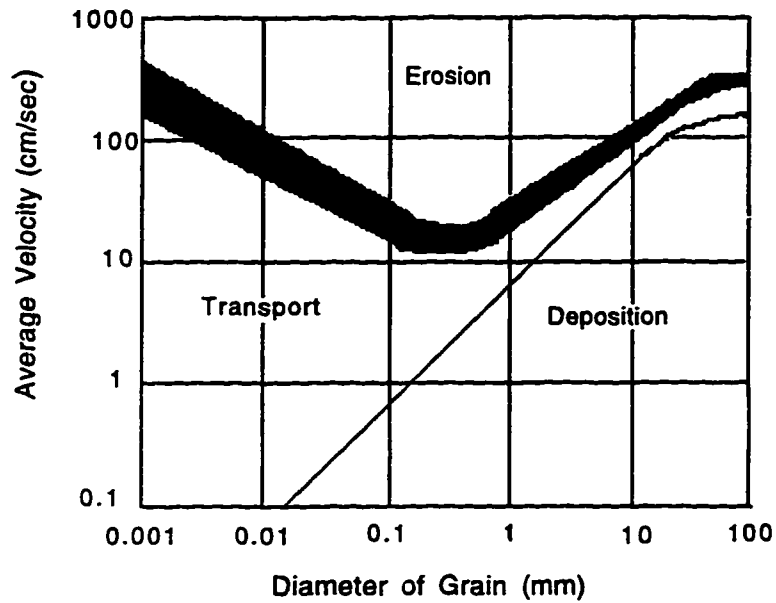
Cartmell, 1978, describes the process of event or storm lag formation as follows: The highest energy in the nearshore setting occurs as shoaling waves pass over the breaker bar, crest and break. The energy from the wave is then transferred into the bottom sediment. Some of the

Longshore and Cross-Shore Velocity Components During Common Storms



(Fig. 12) Wind blowing at an oblique angle to shoreline generates currents responsible for initial lag deposit accumulation in longitudinal troughs occurring within the shoreface and inner shelf and running parallel to the beach.

### Hjulstrom's Curve



(Fig. 13) Hjulstrom's Curve showing the relationship between current velocity, and grain size with respect to erosion, transportation and deposition of sediment. Thick black line represents a zone of both erosion and transport.

sediment and hard parts they contain are broken down into small sizes and transported away, while some larger and/or more dense sediment and hard parts begin to accumulate as a residuum. If later sedimentation buries the accumulated deposit, there is a potential for preservation. Many of the lags preserved in this type of setting are buried and exhumed repeatedly under the influence of coastal storms. Hard parts may be broken or destroyed during exhumation. Storm lag deposits characteristically occur in nearshore to outer shoreface environments as pods or lenses within formations or homogenous facies (Fig. 14).

In general, event or storm lags record a single episode of hard part concentration across a time span ranging from days to decades. Hard part concentrations represent reworking and time averaging of materials which accumulated in nearshore or inner shelf environments and are preserved within similar sediment type.

#### Sea Level Cyclicity Lags

Third order sea level regression-transgression can also result in fossil lag deposit formation (Banerjee and Kidwell, 1991, Brett and Baird, 1993, Kidwell and Behrensmeyer, 1993 and Becker et al., 1996). At the interface between regressive and transgressive sea level events, erosion, reworking and redistribution mechanisms are in operation. Regression and subsequent transgression of sea level, through eustatic and/or tectonic

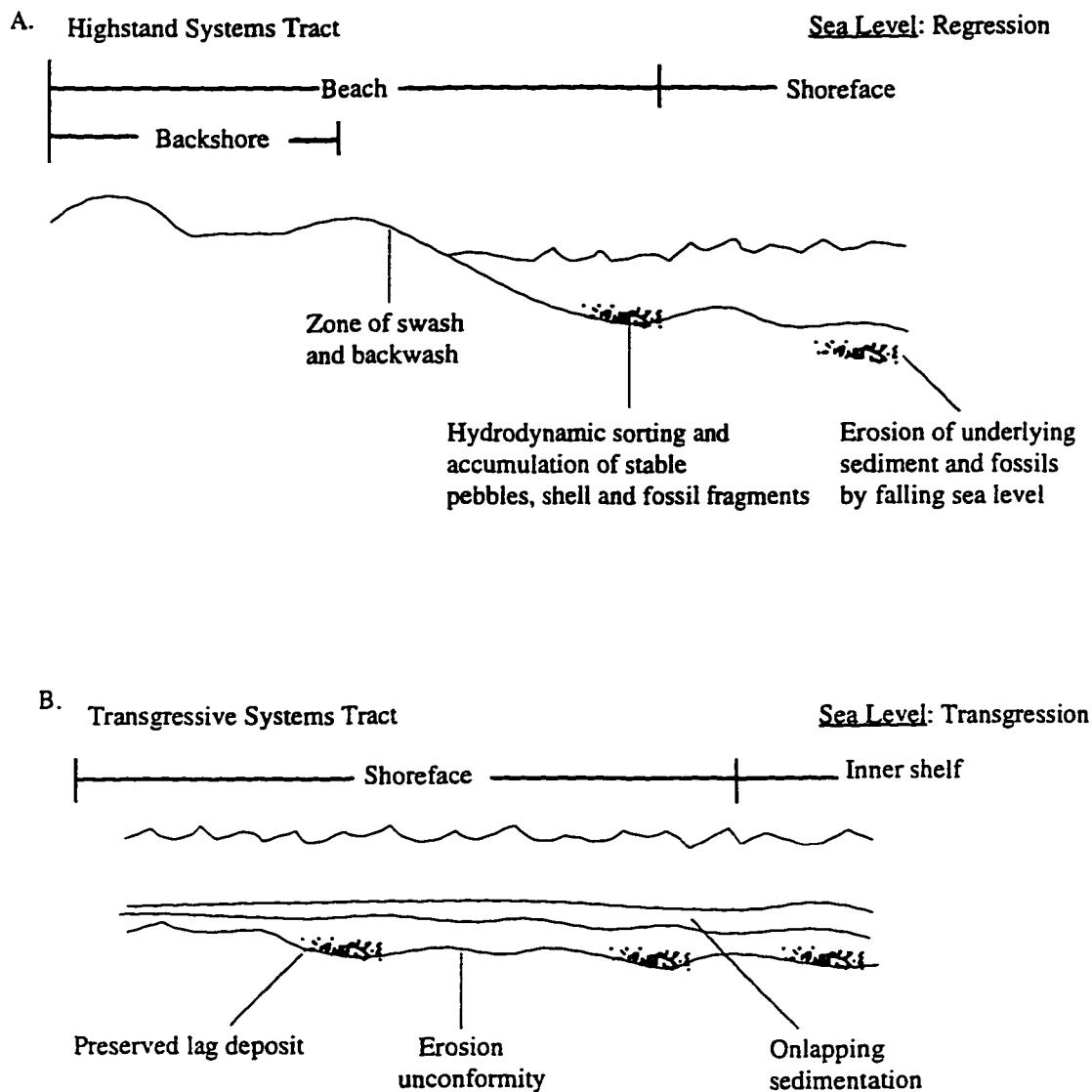
Lag Type	General Characteristics	Duration Range
Event or Storm Concentration	<p>Record a single episode of concentration by storms, gravity flows or biological processes</p> <p>Typically occur within similar sediment or formation</p> <p>Minor within habitat time averaging</p> <p>Typically associated with nearshore and inner shelf environments</p>	days-decades
Deep Sea Condensed Section or Hiatal Concentration	<p>Stratigraphically condensed concentration relative to coeval strata</p> <p>Created by slow net sediment accumulation</p> <p>Typically associated with outer shelf, slope or deeper marine environments</p>	$10^4 - 10^7$ years
Sea Level Cyclicity Lag Concentration	<p>Occur as blankets and lenses of highly durable material left as a residium from erosion</p> <p>Associated with major truncation events</p> <p>Typically occur at the boundary between facies and/or formations</p> <p>Typically associated with nearshore to outer shoreface environments</p>	$10^4 - 10^7$ years

(Fig. 14) Types of common skeletal concentrations found in marine environments. General characteristics from Kidwell and Behrensmeier, (1993), and duration ranges from Kidwell, (1993).

mechanisms, results in hydrodynamic sorting of sediment and fossils that accumulate in inner shelf and lower shoreface paleoenvironments (Fig 15). As transgression occurs, reworked fossil hard parts are deposited at the bases of the subsequent sequences due to a reduction in hydrodynamic sorting energy associated with progressively deepening water (Becker et al., 1996).

Kidwell, 1986, identified the following characteristics for sea level cyclicity lags: 1) destruction and removal of less durable and more easily transported hard parts; 2) a residuum of fossil hard parts deposited directly above an erosional surface; 3) incorporation of allochthonous elements delivered by relatively high energy eroding currents or waves; and 4) exhumation and admixing of significantly older hard parts with younger remains.

Cartmell, 1978, studied the formation of fossil shark teeth lags along the western coast of Florida. This author observed areas of extensive reworking in inner to outer shoreface environments where the impact of wave energy was applied to the underlying sediment. Larger hydrodynamic equivalents accumulate in longshore troughs parallel to the present beach. Hydrodynamic equivalents are sediments or fossils with roughly equivalent sizes and/or densities. Haq et al, 1988, cite a similar example of fossil shark teeth concentrated by third order sea level processes in the lower Lutetian stage at St. Leu d'Esserent in the Paris



(Fig. 15) Schematic model for lag deposit formation as described in text. After Becker et al., (1996).

A: Highstand Systems Tract. Previously deposited skeletal debris is exhumed and sorted hydrodynamically as sea level falls.

B: Transgressive Systems Tract. Reworked skeletal debris is re-deposited and preserved by sedimentation associated with sea level rise.

Beach Profile redrawn from: Friedman et al., (1992), p. 405.

Basin. At St. Leu d'Esserent, the lowest sequence boundary of 49.5 Ma is placed along an unconformity which separates micaceous sands of the Cuisian stage and coarse glauconitic sands of the lower Lutetian stage. The transgressive surface of the onlapping coarse glauconitic sands contains bryozoans and chondrichthyan teeth (Haq et al., 1988).

In longshore troughs, buried fossils can be exposed, reworked, and incorporated with more recent biological material. Reworking and sorting effects can be compounded if sea level regressive-transgressive mechanisms are operative (Vail et al., 1991). Sea level fall would allow for the effects of nearshore wave reworking on environments previously undisturbed by wave activity. In this newly created higher energy environment, only the largest materials would remain. Subsequent transgression would continue to rework the accumulating lag and distribute the contents as thin, discontinuous lenses. Continued transgression and sedimentation would eventually preserve the lag below the reworking effects of wave base. Lag deposits created by sea level fluctuation characteristically occur in shoreface to shelf environments at the interface between facies changes and/or formation contacts (Fig. 14).

#### Deep Sea Condensed Section Lags (Hiatal Concentrations)

Deeper water lag deposits arise due to sediment starvation and/or sediment bypass processes. Sediment starvation occurs when the siliciclastic sediment source is cut off and the only sediment supply coming

into the area of deposition is bioclastic in origin. This usually occurs in basins which experience rapid deepening (Kidwell and Behrensmeyer, 1993). In sediment bypass, the sediment is transported beyond a possible site of deposition. This occurs during turbidity flows or rapid motion sedimentation events. The result of both of these processes are condensed sections containing bioclastic lag deposits. In the absence of siliciclastic sedimentation, osteichthyans, chondrichthyans, and other marine vertebrates contribute distinct hard parts to the bottom sediments. Common hard parts preserved in such settings include fish scales, ear bones of whales, shark teeth, and other bones resistant to dissolution (Brunner and Normark, 1985; Twichell, 1985). Deep sea condensed section lag deposits characteristically occur in outer shelf and slope environments within fine-grained oxygen depleted sediments (Fig. 14).

In general, deep sea condensed sections or hiatal lags record concentration of hard parts across a time span of  $10^4$ - $10^7$  years. Hard part concentrations represent reworking and time averaging of materials which accumulated in outer shelf, slope or deep marine environments and are preserved within similar sediment type.

## Santonian, Campanian and Maastrichtian Stage

### Boundary Definitions

#### Santonian-Campanian Boundary

#### Index Fossils

The Santonian-Campanian type area is located in the Grande et Petite Champagne, Falaises de la Gironde in Northern Aquitaine, France (Birkelund et al., 1984). According to Birkelund et al., 1984, the base of the Campanian can be defined in terms of ammonites as: 1) the appearance of *Placenticerias bidorsatum*, the index species for the classic zonation in Europe; 2) the appearance of *Submortonicerias spathi* in North America, South Africa, Madagascar and Spain; and 3) the appearance of the *Scaphites hippocrepis* lineage in North America and Europe.

Other cited possibilities for the placement of the Santonian-Campanian boundary include: 1) the appearance of the calcareous nanofossil, *Goniotoothis granulataquadrata* in West Germany; 2) the extinction of the crinoid, *Marsupites testudinarius* in Northern Germany; 3) the appearance of the coccolith, *Aspidolithus parvus* in Europe, North Africa and North America; and 3) the appearance of the foraminiferans, *Bolivinooides strigillatus* and *Globotruncana arca* which have a Tethyan distribution (Birkelund et al., 1984); (Fig 16).

Of noteworthy mention to this research project is the Lagerdorf section in Northern Germany. This Santonian-Campanian section has been

Upper Cretaceous Stage Boundary	Last Appearance or Extinction			First Appearance		
	Ammonites	Foraminifera	Others	Ammonites	Foraminifera	Others
Campanian-Maastrichtian Boundary		<i>Glogotruncana calcarata</i>	<u>Coccolith</u> - <i>Quadrum trifidum</i>	<i>Hoploscaphites constrictus</i> <i>Pachydiscus neubergicus</i>	<i>Globotruncana falsostuarti</i>	<u>Belemnite</u> - <i>Belemnella lanceolata</i>
Santonian-Campanian Boundary	<i>Placenticerias bidorsatum</i> <i>Scaphites hippocrepis</i>	<i>Dicarinella asymmetrica</i>	<u>Crinoid</u> - <i>Marsupites testudinarius</i>	<i>Submortonicerias spathi</i>	<i>Gonioteachis granulataquadrata</i> <i>Bolivinooides strigillatus</i> <i>Globotruncana arca</i>	<u>Coccolith</u> - <i>Aspidoithus parvus</i>

(Fig. 16) Proposals for the Santonian-Campanian and Campanian-Maastrichtian boundaries of the upper Cretaceous based on ammonites, foraminifera, coccoliths, belemnites and crinoids. Biostratigraphic data compiled from Birkelund et al., (1985).

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proposed as a type section based on the appearance of *Goniotoothis granulataquadrata* and extinction of *Marsupites testudinarius* (Birkelund et al., 1984). Here, sedimentary facies changes indicate a regression and period of non-deposition across the Santonian-Campanian boundary.

#### Radiometric Ages of the Santonian-Campanian Boundary

Dating the Santonian-Campanian boundary has proved problematic. Hallam et al., 1985, suggest a date of 84 million years. They argue that this is consistent with: 1) Obradovich and Cobban's, 1975, age of  $84.4 \pm 1.6$  Ma for the *Desmoscapites bassleri* zone in the Western interior; 2) William and Baadsgaard's, 1975, dates of  $85-86 \pm 1.2$  Ma for the lower zones of *Scaphites hippocrepis* in Saskatchewan, Canada; 3) Kennedy and Odin's, 1982, date of  $81.5 \pm 3$  Ma for a basal Campanian lava flow in Texas; and 4) Hallam et al.'s, 1985, date of 83.5 Ma from a well drilled in the lower Campanian of Europe (Fig. 17). To this point, no international agreement exists as to the precise radiometric age for the Santonian-Campanian boundary (Birkelund et al., 1984 and Obradovich, 1993).

#### Campanian-Maastrichtian Boundary

##### Index Fossils

The Campanian-Maastrichtian type area is located in the Maastricht area of southeast Netherlands (Birkelund et al., 1984). According to Birkelund et al., 1984, the Campanian-Maastrichtian boundary can be

Upper Cretaceous Stage Boundaries	Basis for Placement	Age Determination (in Ma)	Author(s)	Commonly Accepted Age
Campanian-Maastrichtian Boundary	<i>Didymoceras nebrascence</i> zone	74	(Obradovitch and Cobban, 1975)	71.5 Ma (Hallam et al., 1985)
	<i>Exiteloceras jenneyi</i> zone	73.8	(Obradovitch and Cobban, 1975)	
	<i>Baculites grandis</i> zone	70.2	(Obradovitch and Cobban, 1975)	
	Foraminifera successions from Texas to Arkansas	74	(Pessagno, 1969)	
	Glauconite from Atlantic Coastal Plain	71.6 + 2.7	(Owens and Sohl, 1973)	
	Glauconite from lower Maastrichtian: Belgium/Netherlands	71.5 + 2.5	(Kennedy and Odin, 1982)	
Santonian-Campanian Boundary	<i>Didymoceras bassleri</i> zone	84.4 + 1.6	(Obradovitch and Cobban, 1975)	84 Ma (Hallam et al., 1985)
	<i>Scaphites hippocrepis</i> lower zone	85-86 + 1.2	(William and Baadsgaard, 1975)	
	Basal Campanian lava flow in Texas	81.5 + 3	(Kennedy and Odin, 1982)	
	Lower Campanian well in Europe	83.5	(Hallam et al., 1985)	

(Fig. 17) Radiometric age determinations for the Santonian-Campanian and Campanian-Maastrichtian stage boundaries. Radiometric age data compiled from Hallam et al., (1985).

defined in terms of ammonites as: 1) the appearance of *Hoploscaphites constrictus* a boreal European representative and; 2) *Pachydiscus neubergicus* which occurs in Europe, North America and the Indo-Pacific Region.

Other possibilities for the placement of the Campanian-Maastrichtian boundary include the appearance of the belemnite, *Belemnella lanceolata* in Russia and boreal western Europe, planktonic foraminifera *Globotruncana calcarata* in the Tethyan Realms and planktonic foraminifera, *Globotruncana falsostuarti* in North Africa (Birkelund et al., 1984); (Fig. 16).

Of noteworthy mention to this research project is fact that the boundary between the Campanian and Maastrichtian in the Northern Europe type section is marked by a major hiatus created by a sea level regressive-transgressive event.

#### Radiometric Ages of the Campanian-Maastrichtian Boundary

Dating of the Campanian-Maastrichtian boundary has also proved problematic. Hallam et al., 1985, suggest a date of 71.5 Ma based primarily on: Obradovich and Cobban's, 1975, dates for the Western Interior of 74 Ma for the *Didymoceras nebrascense* zone, 73.8 Ma for the *Exiteloceras jenneyi* zone, 73.3 Ma for the *Baculites compressus* zone, all occurring in the upper Campanian, and 70.2 Ma for the *Baculites grandis* zone from the lower Maastrichtian. Other evidence includes:

1) foraminifera successions in Texas to Arkansas placing the boundary at 74 Ma; (Pessagno, 1969); 2) glauconite from the Atlantic Coast suggests a maximum age of  $71.6 \pm 2.7$  Ma; (Owens and Sohl, 1973); and 3) glauconite for the base of the Maastrichtian in Belgium and the Netherlands suggests a date of  $71.5 \pm 2.5$  Ma; (Kennedy and Odin, 1982); (Fig. 17).

Study of the Campanian-Maastrichtian Boundary in the coastal plain of New Jersey by Sugarman et al., 1995, suggest that the isotopic age of the Campanian-Maastrichtian is even younger than previously suggested. Their work places the Campanian-Maastrichtian boundary using  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic measurements on *exogyra* and *pyncnodonte* shells and foraminifera tests at approximately  $70.5 \pm 1.2-2.0$  Ma. To this point, no international agreement exists as to the precise radiometric age of the Campanian-Maastrichtian boundary (Birkelund et al., 1984 and Obradovich, 1993).

For the Santonian-Campanian and Campanian-Maastrichtian boundaries, none of the microfossils or macrofossils used to define these boundaries has a well developed, cosmopolitan distribution. In general, these representatives are boreal, provincial, or tethyan in their European or North American type areas. The end result of the restricted distribution of important marker fossils is problematic biostratigraphic correlations.

## Chondrichthyan Teeth as Biostratigraphic Indicators

### Previous Studies

Santonian, Campanian and Maastrichtian chondrichthyan teeth have been collected and described from New Jersey, Delaware, Maryland, North Carolina, Georgia and Alabama (Fowler, 1911; Heron and Wheeler, 1964; Cappetta and Case, 1975; Case, 1982; Sohl and Christopher, 1983; Lauginiger, 1984; Hartstein and Decina, 1986; Lauginiger, 1986; Schwimmer, 1986; Case and Schwimmer, 1988; Robb, 1992; and Welton and Farish, 1993 and King and Skotnicki, 1994).

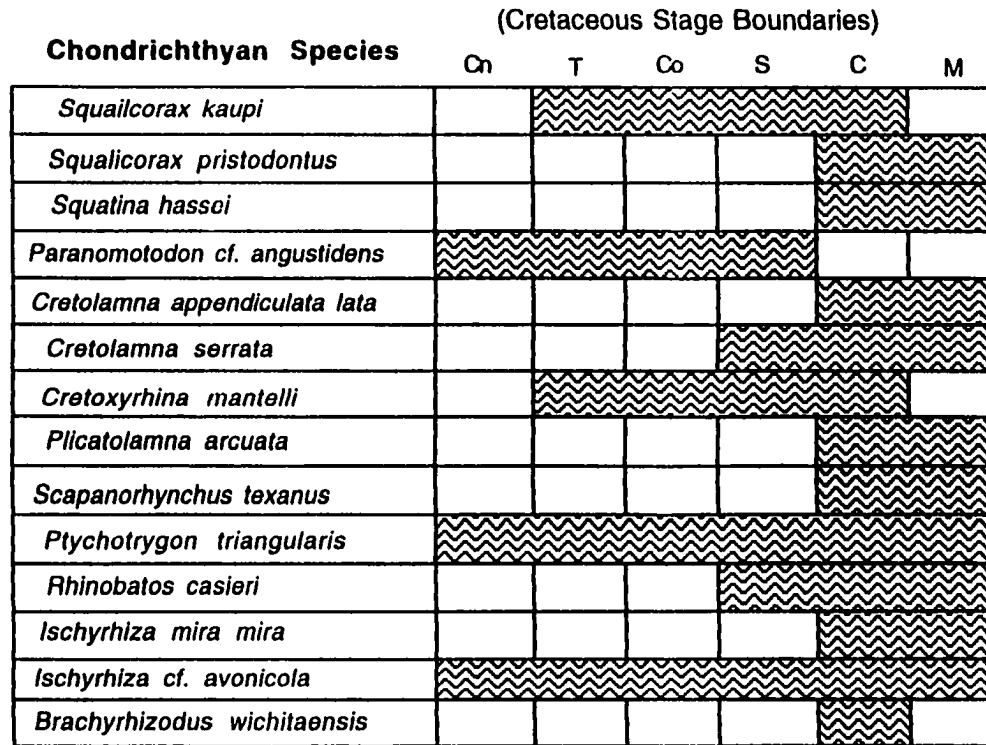
The morphology of chondrichthyan teeth has changed extensively, from their first appearance in the fossil record during the Devonian (Welton and Farish, 1993). During the Cretaceous, the stratigraphic range of many chondrichthyan species is restricted to a few stages or less. This provides excellent stratigraphic resolution if the teeth are found *in situ* (Cappetta and Case, 1975; Kolodny and Raab, 1988; Welton and Farish, 1993 and; Kent, 1994). Because many chondrichthyan representatives were, and still are today, cosmopolitan, their biostratigraphic usefulness is considerable. In general, most chondrichthyans are regarded as nektonic animals, that inhabited both open ocean and coastal regions. Examples of Cretaceous cosmopolitan representatives include: *Squalicorax*, *Scapanorhynchus*, *Cretolamna*, *Carcharis* and *Paranomotodon*. These Cretaceous chondrichthyans have been found in the central, southern and

eastern United States, northern Brazil, eastern Iraq, northern Africa, and northern France (Armbourg and Signeux, 1952; Pivetau, 1955; Armbourg et al., 1959; Goody, 1969; Cappetta and Case, 1975; Welton and Farish, 1993; Kent, 1994).

Cappetta and Case, 1975; Welton and Farish, 1993 and Kent, 1994, have compiled range zones for upper Cretaceous chondrichthyans of New Jersey, Maryland and Texas respectively. Cappetta and Case, 1975, have cross-checked their age assignments against Potassium-Argon dates on glauconites found in the same formations as the chondrichthyan teeth (Fig. 18). Welton and Farish, 1993, have cross-checked their age assignments on chondrichthyan teeth which were collected from formations assigned ages based ammonite biostratigraphy. Kent, 1994, cross-checked his age assignments on chondrichthyan teeth collected from formations whose biostratigraphy had previously been compiled using planktonic foraminifera.

Other criteria making chondrichthyan biostratigraphy useful include the following: 1) chondrichthyan teeth are extremely durable and resistant to erosion; 2) chondrichthyan teeth are common to marine shelf deposits; 3) chondrichthyan teeth are readily identifiable in the field and; 4) the insolubility of the biogenic apatite component comprising teeth makes it possible to cross-check biostratigraphy against absolute dating techniques

## Chondrichthyan Biostratigraphy



(Fig. 18) Original biostratigraphic age assignments for New Jersey upper Cretaceous chondrichthyan teeth. The Campanian-Maastrichtian boundary is placed on top of the Wenonah-Mt. Laurel Formation by Sugarman et al., 1995. (See page 147.) In the Cappetta and Case, 1975, study, the Wenonah Formation is assigned a maximum absolute age of 72.3 Ma while the Mt. Laurel Formation is assigned a maximum absolute age of 70.3 Ma using K-Ar dates compiled from glauconites. Figure redrawn from Cappetta and Case, 1975. Cn= Cenomanian, T= Turonian, Co= Coniacian, S= Santonian, C= Campanian and M= Maastrichtian.

(Kolodny and Raab, 1988; Case and Schwimmer, 1988; Schmitz et al., 1991; Welton and Farish, 1993; and Kent, 1994).

Most recently, Sereno et al., 1996, utilized nine species of chondrichthyan teeth, four which are exclusive to the Kem Kem beds and the Bahariya Formation of Morocco, Africa to confirm a Cenomanian age for the theropod dinosaurs *Carcharodontosaurus* and *Bahariasaurus* discovered in this region. Additionally, one of the sharks' teeth, *Serratolamna amonensis*, found with these dinosaurs has a world-wide distribution and is restricted to the Cenomanian. This provided a boundary age determination for the theropod dinosaur remains (Cappetta and Case, 1975 and Sereno et al., 1996).

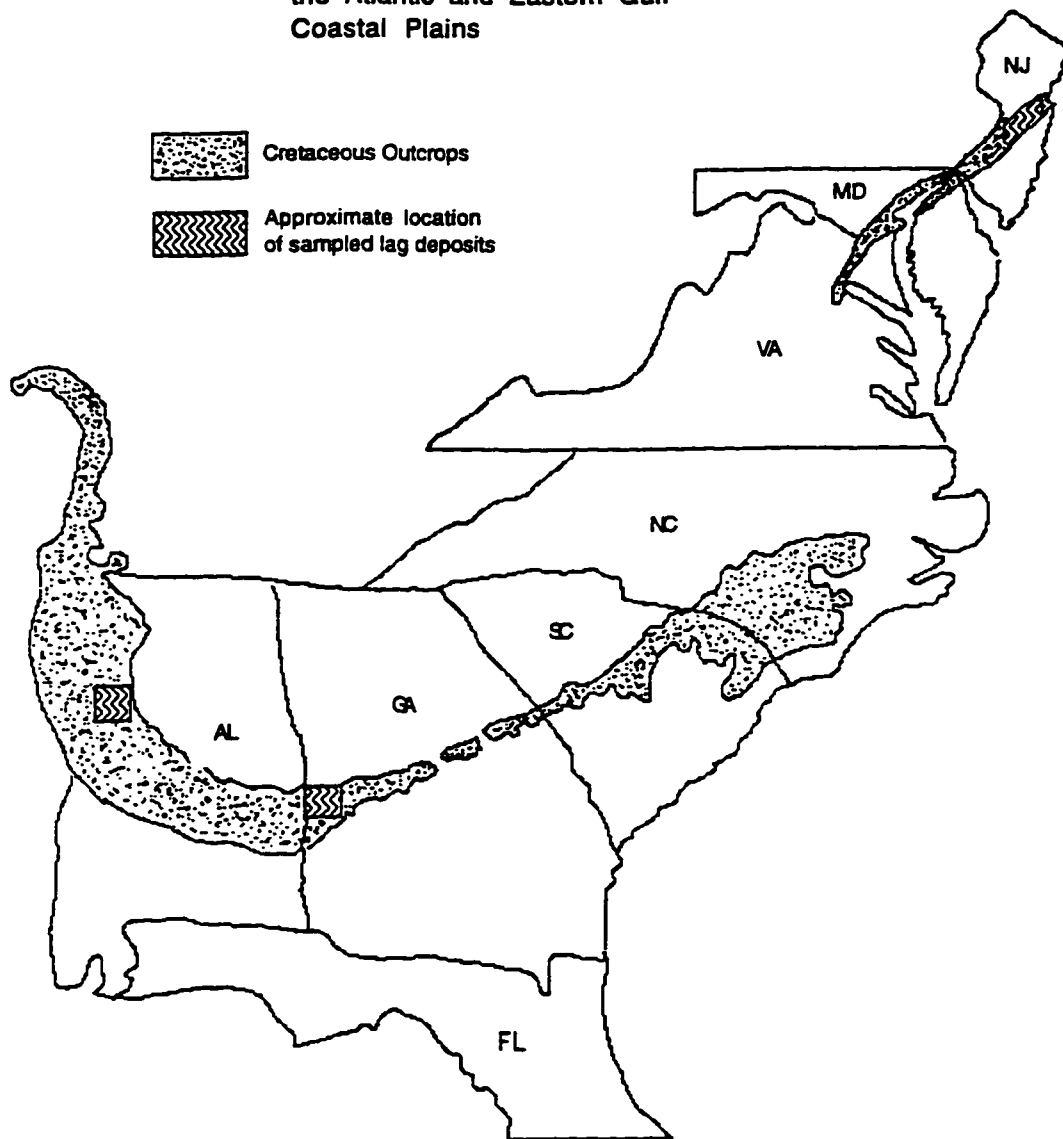
### **Background Stratigraphy, Sedimentology and Paleontology in the New Jersey, Georgia and Alabama Field Areas**

Upper Cretaceous outcrops in the Atlantic Coastal Plain trend northeast-southwest in New Jersey, Delaware, Maryland, Virginia, North Carolina, South Carolina, and Georgia. In western Alabama, Atlantic Coastal Plain deposits interfinger with Gulf Coastal Plain deposits of the Cretaceous Interior Seaway. Extensive Cretaceous outcrops occur in the central and northwestern corner of Alabama (Fig. 19).

#### New Jersey

New Jersey's Cretaceous strata outcrop in a diagonal belt running northeast to southwest through the center of the state. This belt is roughly

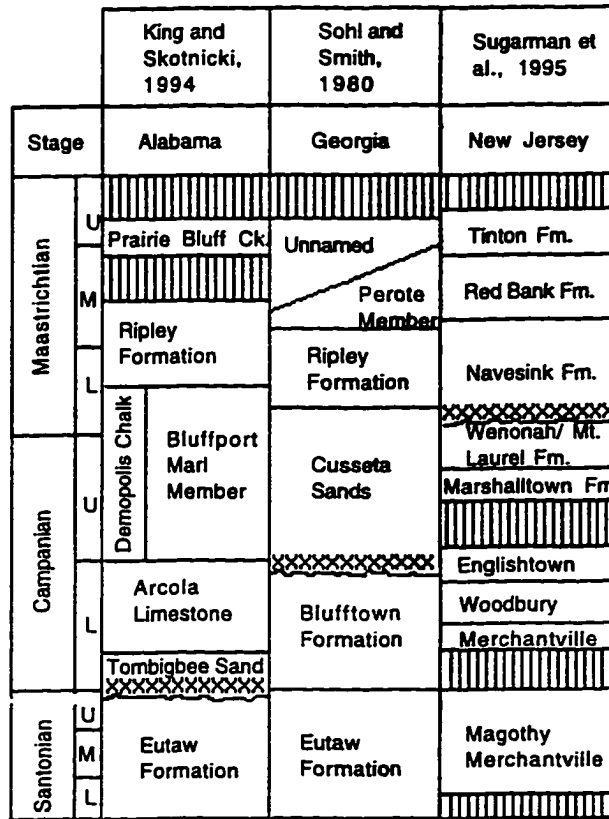
(Fig. 19) Distribution of Cretaceous Outcrops in the Atlantic and Eastern Gulf Coastal Plains



20 kilometers wide and 125 kilometers long. The majority of late Cretaceous sediments within this belt including the Merchantville, Magothy, Woodbury, Englishtown, Marshalltown, Wenonah, Mt. Laurel, Navesink, Red Bank and Tinton Formations, were deposited under inner-to mid-shelf conditions when warm shallow seaways invaded the eastern edge of the North American continent. These formations all dip to the southeast, averaging about 5 meters per kilometer (Johnson and Richards 1952 and Olsson, 1978; 1989). Characteristic deposits include sands, silts and muds in association with glauconite. Monmouth County, which is located within this belt, contains outcrop exposures of the Wenonah, Mount Laurel, and Navesink Formations. These formations can be observed in cross-section along Big, Ramanessin and Willow Brooks.

#### Stratigraphy and Sedimentology

The Campanian-Maastrichtian boundary in New Jersey outcrops has been placed between the Wenonah-Mt. Laurel and Navesink Formations and is marked in outcrop by a regionally extensive unconformity (Richards et al., 1958; Kennedy and Cobban, 1994; Becker and Slattery, 1995; and Sugarman et al., 1995); (Fig. 20). Sugarman et al., 1995, indicate that the Campanian-Maastrichtian boundary in New Jersey is equivalent to the boundary between depositional sequences 5 and 6 of Owens and Gohn, 1985 (Fig. 6).



(Fig. 20) Regional stratigraphy for the Alabama, Georgia and New Jersey outcrops. Stratigraphic position of regional unconformities and lag deposits analyzed during this study indicated by xxxxxx.

In the northern and central coastal plain of New Jersey, outcrop exposures of the contact between the Wenonah-Mt. Laurel and Navesink Formations contain a hydrodynamically sorted lag deposit with chondrichthyan, osteichthyan, reptile, ammonite and mollusk fossils (Becker and Slattery, 1995 and Becker et al., 1996).

The stratigraphic position and formation of this localized lag deposit, as well as its macrofossil contents, were carefully documented and studied by Kennedy and Cobban, 1994; Becker and Slattery, 1995; Kennedy et al., 1995 and Becker et al., 1996.

Lithological descriptions of the Wenonah, Mt. Laurel and Navesink Formations are included in the studies of Johnson and Richards, 1952; Minard et al., 1961; Owens and Sohl, 1969; Olsson, 1975 and Martino and Curran, 1990. Variations in the thickness along strike and dip of these formations occur in response to structural variability across the Raritan Embayment and South Jersey High, location with respect to the sediment source region and third order sea level cyclicity in the depositional environment. In general, the Wenonah, Mt. Laurel and Navesink Formations are thinnest in the northwest and achieve a maximum thickness in the subsurface near the present day shoreline (Petters, 1976 and Martino and Curran, 1990).

The Wenonah Formation contains bioturbated and mottled gray muds with fine- to very fine-grained quartz sands with fossil casts and

molds of bivalves and gastropods. Additional sedimentary materials include glauconite, feldspar, muscovite and carbonaceous detritus. The thickness of the Wenonah Formation ranges between 5 and 19 meters (Martino and Curran, 1990).

Owens and Sohl, 1969, have identified two lithofacies that comprise the Mt. Laurel Formation. These include a thin bedded sand and mud and a massive sand. The massive sand lithofacies occurs in the central and southern parts of the New Jersey Coastal Plain outside the study area. In the Northern Coastal Plain, the Wenonah Formation is conformably overlain by the thin bedded sand and mud lithofacies. Martino and Curran, 1990, describe this lithofacies as consisting of muddy, fine to medium quartz sands interbedded with clean fine to medium quartz sands. Additional sediments include glauconite, feldspar, muscovite and carbonaceous detritus. The maximum thickness of this lithofacies is about 9 meters, but is much thinner at some locations within its outcrop belt, and is absent altogether at some sites .

The wide variability in thickness and the occasional absence of the thin bedded sand and mud lithofacies can be explained by an erosional disconformity. This disconformity marks the boundary of the upper contact between the Mt. Laurel and Navesink Formations (Olsson, 1987; Martino and Curran, 1990; Becker and Slattery, 1994 and Sugarman et al.,

1995). Where the thin sand and mud lithofacies is absent, the Wenonah Formation is disconformably overlain by the Navesink Formation.

The Navesink Formation has been separated into two lithofacies by Martino and Curran, 1990. Above the erosional disconformity is a lithofacies that contains a pebbly, muddy, medium to coarse quartz sand with glauconite, organics and apatite. The basal 30 centimeters of this lithofacies is a lag which contains abundant macrofossils including steinkerns of pelecypods, gastropods, cephalopods and brachiopods, and teeth from reptiles, chondrichthyans and osteichthyans. Above the macrofossil rich unit are highly bioturbated, poorly sorted, medium- to coarse-grained quartz sands with extensive bioturbation and mica-rich dark mud containing glauconite. Maximum thickness for this lithofacies is 4 meters. The upper lithofacies of the Navesink Formation contains dark gray mud, silt, glauconitic-rich sands with burrows and mottling, and some minor planar bedding. Maximum thickness of this lithofacies is 8 meters (Martino and Curran, 1990).

#### Stratigraphic Placement of the Wenonah-Mt. Laurel and Navesink Formations in New Jersey

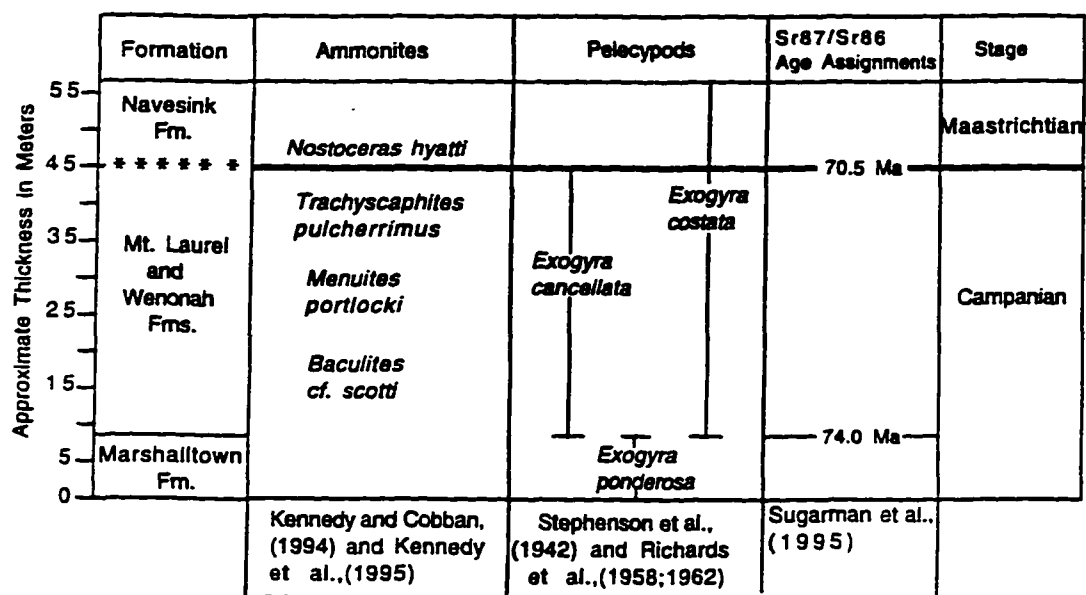
Using subsurface well data, Olsson, 1963 and Petters, 1976; 1977, place the Campanian-Maastrichtian boundary between the Marshalltown and Wenonah/Mt. Laurel Formations. These authors base the boundary upon the location of the *Globotruncana calcarata* and the *Rubotruncana*

*subcircumnodifer* zones. Cobban, 1974 and Kennedy and Cobban, 1994, place the Campanian-Maastrichtian boundary using outcrop data. These authors place the boundary between the Wenonah and Navesink Formations based on the last occurrence of the ammonites *Menuites portlocki*, *Trachyscaphites pulcherrimus* and *Baculites* cf. *B. scotti*. Stephenson et al., 1942 and Richards et al., 1958, place the Campanian-Maastrichtian boundary at the top of the *Exogyra cancellata* zone in the Mt. Laurel Formation. This coincides with the boundary based on ammonite zonation.

Macrofossil Evidence:

Ammonites: Kennedy and Cobban, 1994, have identified the following ammonites from the Wenonah Formation in Monmouth County: *Menuites portlocki*, *Placenticerias placenta*, *Placenticerias minor* n. sp., *Nostoceras puzosiforme* n. sp., *Nostoceras* aff. *N. colubriformis*, *Didymoceras* n. sp., *Didymoceras* spp., *Parasolenoceras* sp., *Baculites* cf. *B. scotti*, *Baculites* sp., and *Trachyscaphites pulcherrimus*.

Based on the occurrence of *Menuites portlocki* and *Trachyscaphites pulcherrimus*, Kennedy and Cobban, 1994, give the Wenonah an upper Campanian age. The occurrence of *Baculites* cf. *B. scotti* in the Wenonah Formation suggests an uppermost middle Campanian age (Kennedy and Cobban, 1994); (Fig 21). The occurrence of *Menuites portlocki* is equivalent to the *Baculites reduncus* and *Baculites scotti* zones of the Western Interior. Bentonites associated with the occurrence of these two



(Fig. 21) New Jersey ammonite and pelecypod biostratigraphy and placement of the Campanian-Maastrichtian boundary. Ammonite and pelecypod biozones were compiled from outcrop data. Asterisks indicate the stratigraphic position of the New Jersey lag deposit described in this study. Isotopic ages from Sugarman et al., (1995).

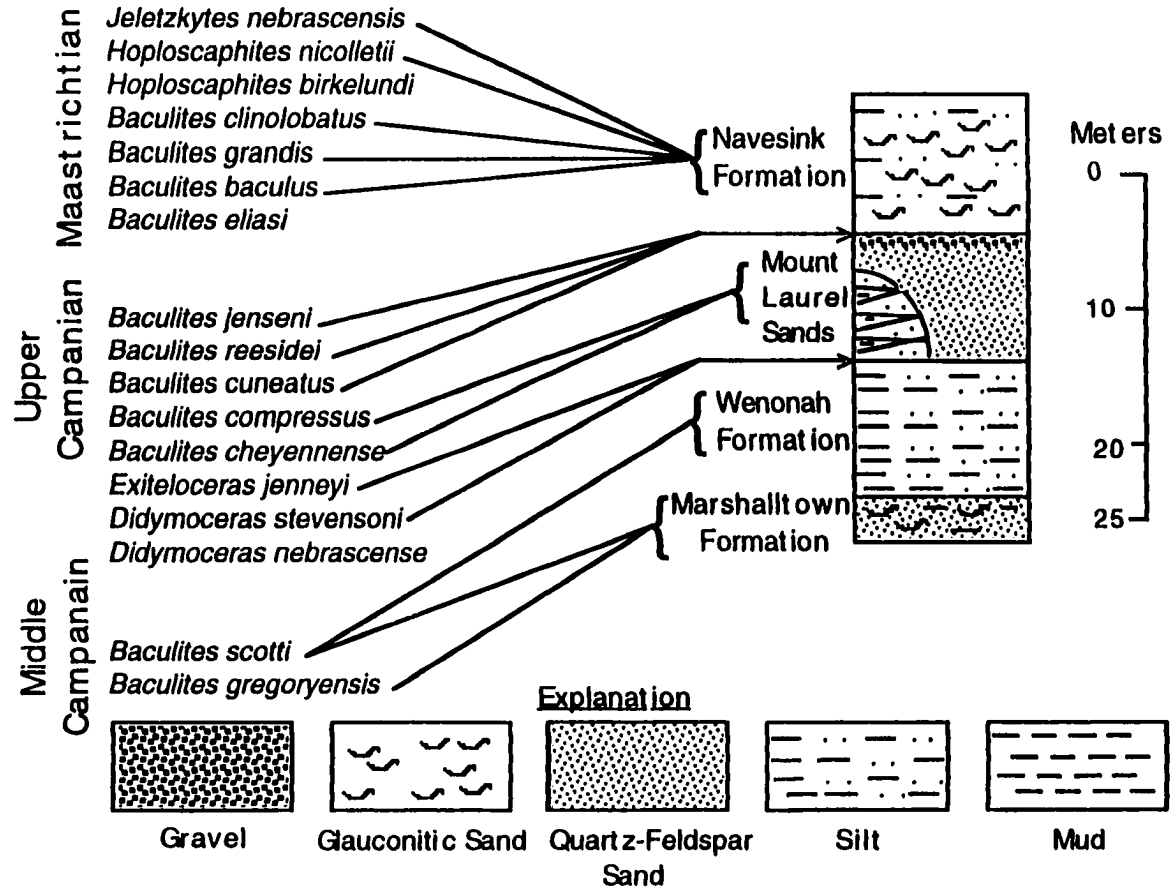
ammonite zones in the Western Interior give radiometric ages of  $75.5 \pm 0.6$  Ma (Obradovich, 1988).

In support of this age assignment, Cobban, 1974; Kennedy and Cobban, 1994 and Kennedy et al., 1995, have identified the occurrence of the following ammonites at Atlantic Highlands, New Jersey:

*Pseudophyllites indra*, *Kitchinites* sp., *Baculites ovatus*, *Baculites claviformis*, *Nostoceras helicinum*, *Nostoceras hyatti*, *Nostoceras pauper*, *Nostoceras approximans*, *Axonoceras* cf. *A. angolanum*, *Lewyites oronensis*, *Cirroceras conradi*, *Hoploscaphites pumilis*, *Jeletzkytes nodosus* and *Jeletzkytes* sp. All these ammonite representatives were collected in a 15 to 20 centimeter horizon separating the Wenonah-Mt. Laurel and Navesink Formations. Kennedy et al., 1995, indicate this assemblage is upper Campanian (Fig. 22).

Additional ammonites from this horizon include *Pachydiscus neubergicus* and *Nostoceras alternatum* (Kennedy et al., 1995). *Pachydiscus neubergicus* and *Nostoceras alternatum* are Maastrichtian ammonites and indicate the mixing of Campanian and Maastrichtian representatives in this horizon (Kennedy et al., 1995).

Sugarman et al., 1995, cite the occurrence of *Nostoceras hyatti* in the basal Navesink Formation. The *Baculites jenseni* zone of the Western Interior Seaway contains *Nostoceras hyatti* and is assigned the latest Campanian age (Kennedy and Cobban, 1994). Bentonites associated with



(Fig. 22) Correlation of the Campanian-Maastrichtian succession in New Jersey with the Western Interior ammonite zonation. Redrawn from Kennedy et al., (1995).

the occurrence of this ammonite zone gives radiometric age ranges between  $73.2 \pm 0.7$  and  $70.1 \pm 0.7$  Ma. (Obradovich, 1988 and Kennedy et al., 1992).

Chondrichthyan Teeth: Shark's teeth collected from Ramanessin, Willow and Big Brooks by Cappetta and Case, 1975; Lauginiger, 1984 and Case, 1995, indicate an uppermost Campanian-lowermost Maastrichtian age for the boundary between the Wenonah-Mt. Laurel and Navesink Formations. This placement is based on the occurrence of *Squalicorax kaupi*, a Campanian representative, and *Carcharias* sp. B, a Maastrichtian representative (Cappetta and Case, 1975; Welton and Farish, 1993 and Becker et al., 1996); (Fig. 23).

Mollusks: Mollusk range zones occurring within the Wenonah-Mt. Laurel and Navesink Formations are: *Flemingostrea pratti*, *Flemingostrea subspatulata* (early form), *Exogyra ponderosa*, *Anomia tellinoides*, *Exogyra cancellata*, and *Exogyra costata*.

Richards et al., 1958, cite the occurrence of *Anomia tellinoides*, *Exogyra cancellata*, and *Exogyra costata* in the Mt. Laurel and Navesink Formations. Owens and Gohn, 1985, give an upper Campanian age range for *Exogyra cancellata* and an upper Campanian through Maastrichtian age range for *Exogyra costata*. Sugarman et al., 1995, indicate a maximum age of 71.0 Ma for the top of the *Exogyra cancellata* zone and a maximum age of 74.1 Ma for the base of the *Exogyra costata* zone in New Jersey using

## Chondrichthyan Biostratigraphy

(Cretaceous Stage Boundaries)

Chondrichthyan Species	SA	CA	MA
<i>Squalicorax kaupi</i>		▨	
<i>Squalicorax pristodontus</i>		▨	▨
<i>Cretolamna appendiculata</i>	▨	▨	
<i>Paranomotodon cf. angustidens</i>	▨		
<i>Carcharis sp. B</i>			▨
<i>Scapanorhynchus texanus</i>		▨	▨
<i>Brachyrhizodus wichitaensis</i>	▨	▨	
<i>Ptychodus mortoni</i>	▨		

(Fig. 23) Age ranges for fossil chondrichthyan teeth collected during this study from the New Jersey, Georgia and Alabama field areas. Age ranges compiled from Cappetta and Case, (1975) and Welton and Farish, (1993). SA= Santonian, CA= Campanian and MA= Maastrichtian.

the  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic dating method. Their work shows the Wenonah Formation to be time equivalent with the Mt. Laurel Formation in New Jersey (Fig. 21); (Sugarman et al., 1995).

In general, the accepted stratigraphic position for the Campanian-Maastrichtian boundary in New Jersey outcrops is between the Wenonah-Mt. Laurel and Navesink Formations (Kennedy and Cobban, 1994; Sugarman et al., 1995 and Becker et al., 1996). Sugarman et al., 1995, assign an age of  $70.5 \pm 1.2-2.0$  Ma to the Campanian-Maastrichtian boundary in New Jersey outcrops by  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic dating of *Exogyra*, *Pycnodonte* and belemnite fossils contained above and below this boundary. This estimate is slightly younger than the Hallam et al., 1985, estimate of 71.5 Ma which was determined using radiometric dating of: 1) Western Interior ammonite zones; 2) foraminifera zones in Texas; and 3) glauconites from the Atlantic Coastal Plain, Belgium and the Netherlands. The lag deposit studied along Big, Willow and Ramanessin Brooks in New Jersey outcrops resides directly above an erosional disconformity located at the top of the Wenonah-Mt. Laurel Formations and contains the Campanian-Maastrichtian boundary (Becker et al., 1996).

### Georgia

The Cretaceous stratigraphy of Georgia outcrops in a diagonal belt running northeast to southwest through the center of the state. This belt is roughly 750 km long and 50-150 kilometers wide. Late Cretaceous

sediments, within this belt, included the Eutaw, Blufftown and Ripley Formations as well as the Cusseta Sands and Perote Member. These sediments were deposited under inner to mid-shelf conditions when warm shallow seaways invaded the southeastern edge of North America. Dip is approximately 1-3 meters per kilometer to the southeast. Characteristic deposits include sands, silts and muds in association with glauconite (Reinhardt et al., 1981).

Stewart County, which is located within this belt, contains outcrop exposures of the Eutaw and Blufftown Formations. These formations can be observed in cross-section along Hannahatchee Creek, a small tributary of the Chattahoochee River.

#### Stratigraphy and Sedimentology

In the Chattahoochee Valley Region, an unconformity separates the lower Campanian, Blufftown Formation from the upper Campanian, Cusseta Sands (Fig. 20). This unconformity is equivalent to the bounding unconformity separating depositional sequence 4 and 5 (Owens and Gohn, 1985); (Fig. 6).

Schwimmer, 1981, and Case and Schwimmer, 1988, identified fifteen chondrichthyan and eight osteichthyan taxa in the upper Blufftown Formation. Furthermore, their research noted a direct relationship between the abundance of vertebrate fossils and the erosional unconformity separating the upper Blufftown Formation from the lower Cusseta Sands.

The Blufftown Formation and Cusseta Sands of the Chattahoochee River Valley are described in the works of Reinhardt, 1981. The Blufftown Formation contains calcareous fine sand, micaceous mud, carbonaceous mud, silt, sand, highly fossiliferous mud, and glauconitic sand containing burrows. Total maximum thickness of the Blufftown Formation is given as 165 meters (Reinhardt et al., 1981).

The Cusseta Sands are described by Reinhardt, 1981, as coarse sands containing large scale crossbeds and locally abundant burrows with thin beds of carbonaceous mud toward the upper contact. Locally abundant pods of bivalve accumulations are also noted. The Cusseta Sands attain a maximum thickness of 60 meters (Reinhardt et al., 1981).

#### Stratigraphic Placement of the Blufftown Formation and Cusseta Sands in Georgia

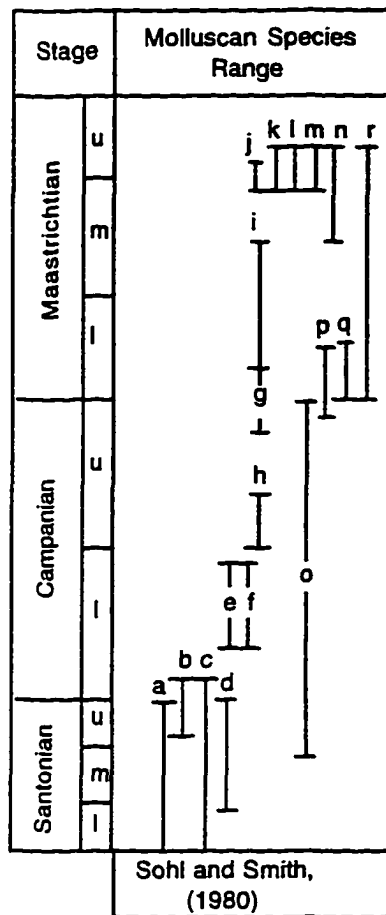
Sohl and Smith, 1980, place the base of the Blufftown Formation at the boundary between the Santonian and Campanian. The upper contact between the Blufftown Formation and overlying Cusseta Sand is placed at the boundary between the lower and upper Campanian. Schwimmer, 1981, notes the occurrence of a regional unconformity approximately 3 to 4 meters below the base of this contact in the uppermost Blufftown Formation. The upper contact of the Cusseta Sands extends into the lower part of the Maastrichtian (Sohl and Smith, 1980).

### Macrofossil Evidence

Ammonites: No ammonites were reported by Schwimmer, 1981; 1986 nor by Case and Schwimmer, 1988, from Hannahatchee Creek. Schwimmer, 1981, cites the occurrence of possible ammonite steinkerns. Along Hannahatchee Creek, this material shows complete shell and suture pattern loss due to dissolution. However, Owens and Gohn, 1985, cite the rare occurrence of *Delawaralle delawarensis* and *Scaphites hippocrepis* in the middle of the Blufftown Formation. Age ranges for these two important ammonite species are given as upper-lower Campanian to lower-upper Campanian (Owens and Gohn, 1985).

Chondrichthyan Teeth: Shark's teeth collected from Hannahatchee Creek by Schwimmer, 1981; 1986 and Case and Schwimmer, 1988, indicate a Campanian age based on the occurrence of abundant *Squalicorax kaupi*. The age range given for this species by Cappetta and Case, 1975 and Welton and Farish, 1993, is Campanian (Fig. 23).

Mollusks: The contact between the Blufftown Formation and Cusseta Sands occurs within the *Exogyra ponderosa* zone (Sohl and Smith, 1980). Schwimmer, 1981, also makes note of the following occurrence of mollusks along Hannahatchee Creek: *Crassostrea cusseta*, *Exogra ponderosa*, *Turritella vertebroides*, *Idonearca carolinensis* and *Crassatella roodensis*. The *Exogyra ponderosa* zone has a maximum range of upper Campanian (Sohl and Smith, 1980); (Fig. 24). In general, the accepted



(Fig. 24) Molluscan biostratigraphy for the upper Cretaceous Atlantic and Eastern Gulf Coastal Plains: Molluscan fossils include:  
 a-*Ostrea cretacea*; b-*Pycnodonte aucella*; c-*Exogyra upatoiensis*;  
 d-*Lopha knappi*; e-*Scaphites hippocrepis*; f-*Delawarella delawarensis*;  
 g-*Flemingostrea pratti*; h-*F. subspatulata* (early form);  
 i-*F. subspatulata* (normal form); j-*F. subspatulata* (late form);  
 k-*Haustator bilira*; l-*Scabrotrigonia angulicostata*; m-*S. cerulia*;  
 n-*Sphenodiscus* spp.; o-*Exogyra ponderosa*; p-*Anomia tellinoides*;  
 q-*Exogyra cancellata*; r- *E. costata*; From: Sohl and Smith, (1980).

stratigraphic position for the lower-upper Campanian boundary in Georgia outcrops is between the Blufftown Formation and Cusseta Sands (Reinhardt et al., 1981 and Donovan, 1993).

Donovan, 1993, assigned the lower-upper Campanian boundary an age of 80.0 Ma in eastern Alabama and western Georgia through the use of radiometrically dated glauconites. This numerical estimate is slightly older than the Kent and Gradstein, 1985, world-wide geochronological estimate of 78-79 Ma for the lower-upper Campanian boundary. The lag deposit studied along Hannahatchee Creek in Georgia outcrops resides directly above an erosional disconformity located just below the top of the Blufftown Formation and contains the lower-upper Campanian boundary (Schwimmer, 1986 and Becker et al., 1996).

### Alabama

Alabama's Cretaceous stratigraphy outcrops in a belt running east-west through the center of the state and north-south along the western edge of the state. This belt is roughly 1200 kilometers long and 150-300 kilometers wide. The majority of late Cretaceous stratigraphy within this belt was deposited when warm shallow seaways invaded the southern and interior parts of the North American continent. These formations all dip at approximately 1-5 meters per kilometer along both the central and western exposures. Characteristic deposits include sands, silts and muds in addition to limestones, marls and chalks (Raymond et al., 1988).

Greene County, which is located within this belt, contains outcrop exposures of the Eutaw Formation and Tombigbee Sands. These formations can be observed in cross-section along Trussels Creek, running north-south near the Alabama-Mississippi state line.

### Stratigraphy and Sedimentology

In central and western Alabama an unconformity separating upper Santonian and lower Campanian sediments occurs between the upper Eutaw Formation and Tombigbee Sands Member (Fig. 20). This unconformity is equivalent to the bounding unconformity separating depositional sequences 3 and 4 (Owens and Gohn, 1985); (Fig. 6).

The extensive Campanian and Maastrichtian vertebrate fauna in central and western Alabama are compiled and described in the works of Applegate, 1970 and Thurmond and Jones, 1981.

The Eutaw Formation is described as a light greenish-gray, fine to medium grained, well-sorted, micaceous, cross-bedded sand, silty mud, and carbonaceous mud containing abundant fossils (Raymond, et al., 1988). In western and central Alabama outcrop exposures can attain a thickness of 130 meters. Outcrop exposures thin to 30 meters in eastern most Alabama. Locally, the Eutaw Formation is capped by the Tombigbee Sands Member in west-central Alabama.

The Tombigbee Sands Member is described in these studies as a light-gray massive, highly glauconitic sand and mud containing abundant

burrows and mollusk shells. Raymond et al., 1988, state that the discontinuous outcrops of the Tombigbee Sands Member range in thickness from approximately 2 to 7 meters in outcrop.

### Stratigraphic Placement of the Eutaw Formation and Tombigbee Sands in Alabama

Sohl and Smith, 1980 and King and Skotnicki, 1994, cite the age of the Eutaw Formation and Tombigbee Sands Member as Santonian-Campanian. Raymond et al., 1988, place the base of the Eutaw Formation at the boundary between the Coniacian and Santonian on top of a regional unconformity. The lower contact of the Tombigbee Sands Member has been placed slightly below the Santonian-Campanian boundary. The upper, erosional contact of the Tombigbee Sands Member extends into the lower Campanian.

### Macrofossil Evidence

Ammonites: Ammonites occurring within the lag deposit separating the Eutaw Formation and Tombigbee Sands along the Trussels Creek field area include *Menuites* sp., *Baculites* sp., *Didymoceras* sp., *Placenticeras* sp., and *Eutrophoceras* sp. Overlapping age ranges of these ammonites indicate an upper Santonian to upper Campanian age for this lag deposit (Moore et al., 1962); (Fig 25).

Chondrichthyan Teeth: The occurrence of *Squalicorax kaupi* and *Ptychodus mortoni* within the lag deposit separating the Eutaw Formation



and Tombigbee Sands along the Trussels Creek field area suggests an age equivalent to the Santonian-Campanian boundary. *Ptychodus mortoni* is cited as a Santonian representative while *Squalicorax kaupi* is cited as a Campanian representative (Welton and Farish, 1993); (Fig 23).

Mollusks: The Upper Eutaw Formation and Tombigbee Sands Member occur within the age ranges of the following Molluscan species from Sohl and Smith, 1980: *Ostrea cretacea*, *Pycnodonte aucella*, *Exogyra upatoiensis*, *Lopha knappi* and *Exogyra ponderosa* (Fig. 24).

In general, the accepted stratigraphic position for the Santonian-Campanian boundary in Alabama outcrops is between the Eutaw Formation and Tombigbee Sands (Raymond et al., 1988; Donovan, 1993; King and Skotnicki, 1994 and Becker et al., 1996). King and Skotnicki, 1994, assign an age of 84.4 Ma to the Santonian-Campanian boundary in Alabama outcrops from a radiometrically dated bentonite contained in the lowermost Tombigbee Sands. This estimate is consistent with the Hallam et al., 1985, estimate of 84 Ma which was determined using radiometric dating of:

1) Western Interior and Canadian ammonite zones; 2) basal Campanian lava flows from Texas; and 3) well data from the lower Campanian of Europe. The lag deposit studied along Trussels Creek in Alabama outcrops resides directly above an erosional disconformity located at the top of the Eutaw Formation and contains the Santonian-Campanian boundary (Becker et al., 1996).

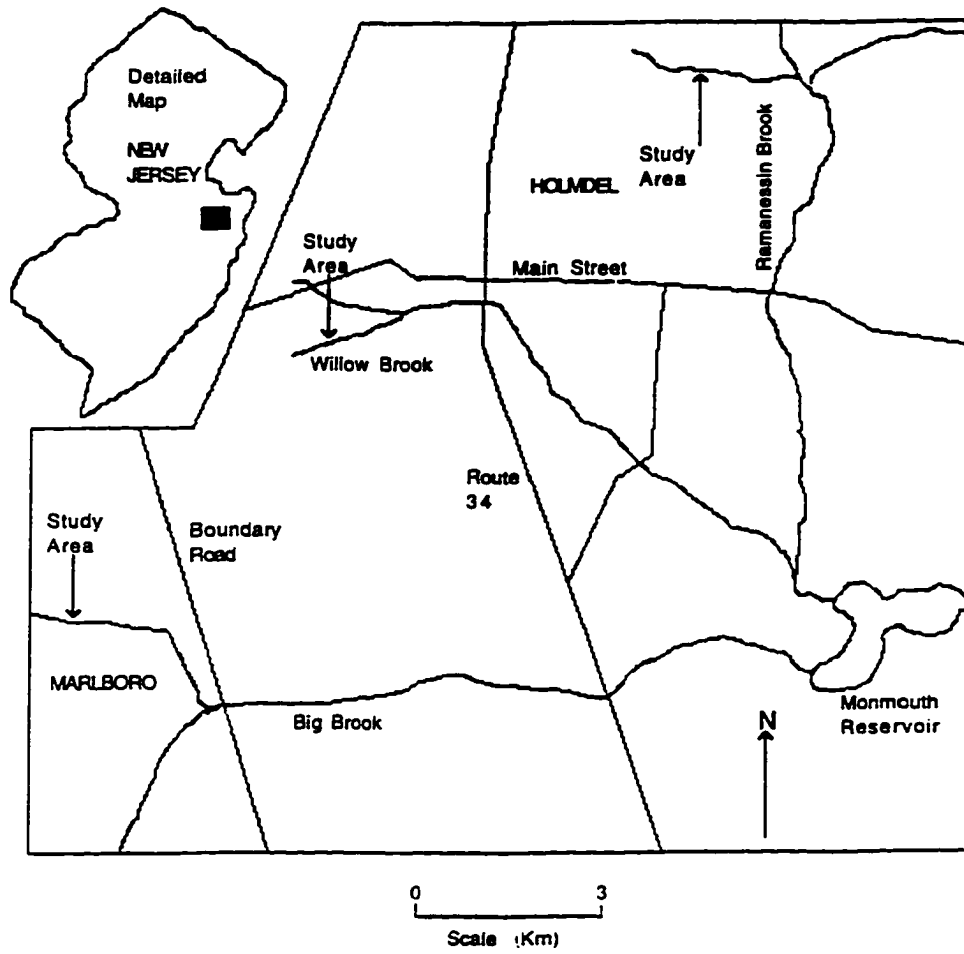
## **Field Methods**

### **Outcrop Selection**

The following outcrops were used for the compilation of measured sections and collection of macrofossils:

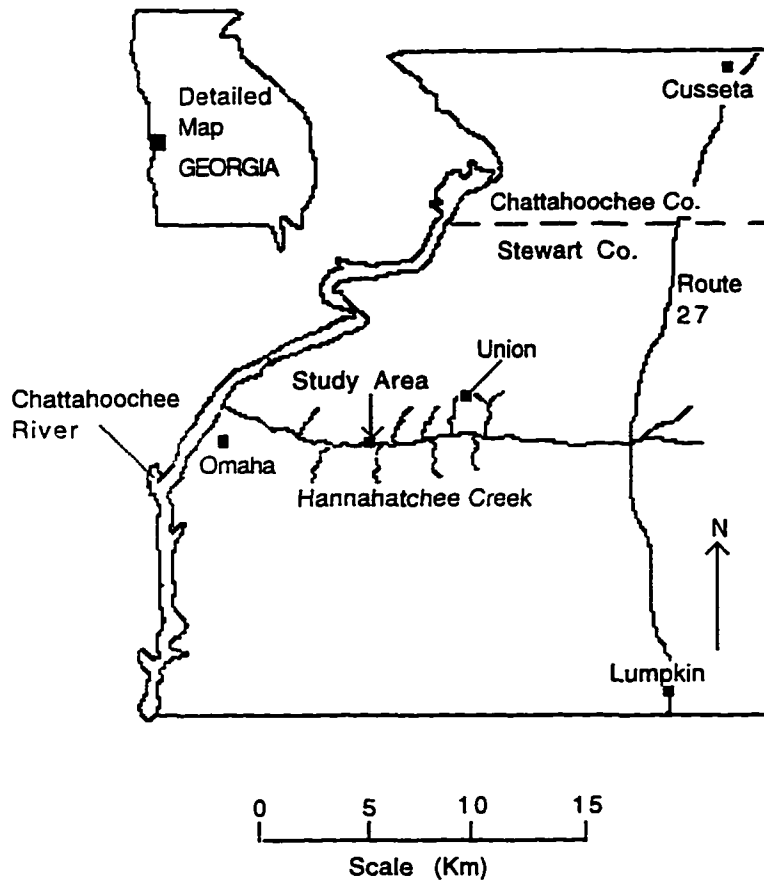
- 1) New Jersey: Ramanessin Brook, Willow Brook and Big Brook, Monmouth County; (Fig. 26); approximate locations N 40° 22' 00"/ W 74°10'30"; N 40° 21'00"/ W 74° 12' 20" and N 40° 19' 05" , W 74° 13' 55" respectively, exposures of the Campanian-Maastrichtian boundary;
- 2) Georgia: Hannahatchee Creek, Stewart County; (Fig. 27); approximate location N 32° 10' 00"/ W 84° 59' 00" exposure of the lower Campanian-upper Campanian boundary; and 3) Alabama: Trussels Creek, Greene County; (Fig. 28); approximate location N 32° 54' 00"/ W 87° 59' 00" exposure of the Santonian-Campanian boundary.

These areas were selected because erosion has downcut through the unconsolidated sediments providing for good cross-sectional exposure of formation contacts and accessibility to chondrichthyan lag deposits. Furthermore, chondrichthyan lag deposits in these three locations appear to correspond favorably to the Campanian-Maastrichtian, lower-upper Campanian and Santonian-Campanian stage boundaries. This is advantageous in that it provides: 1) a means for cross-checking chondrichthyan biostratigraphy against well defined, upper Cretaceous stage boundaries; and 2) a base for comparing calculated  $\text{Sr}^{87}/\text{Sr}^{86}$  ages for



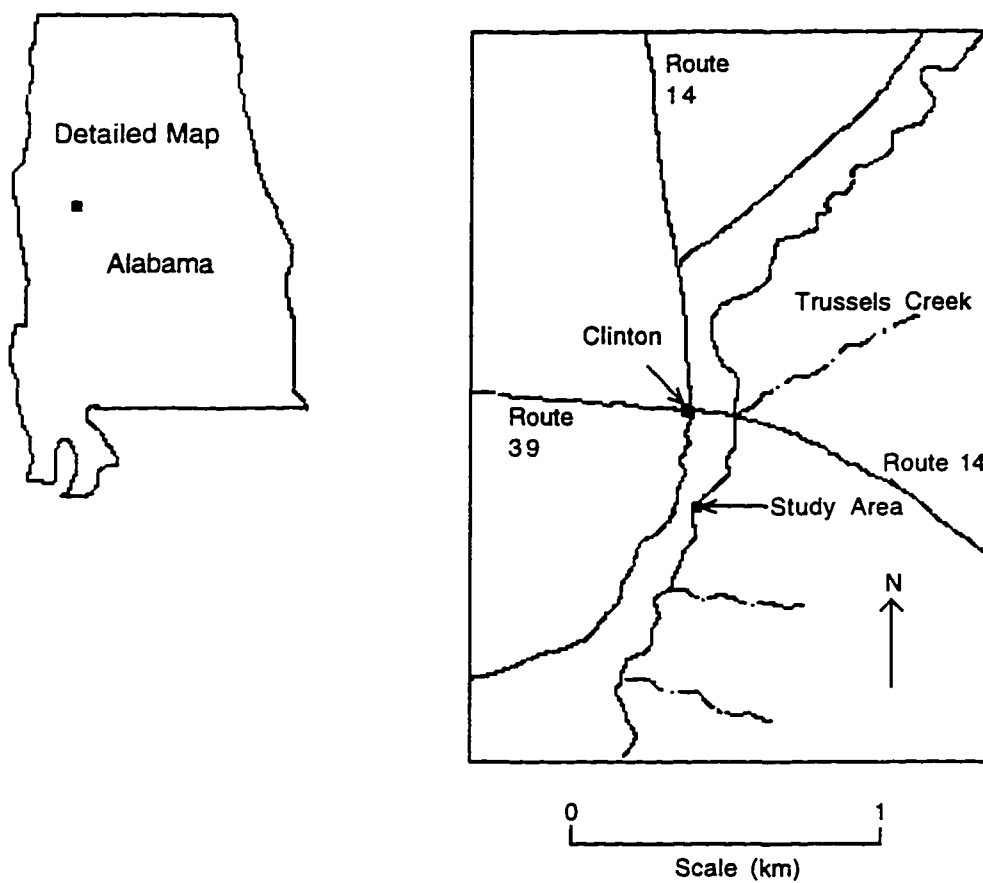
(Fig. 26) Location of study areas along Big, Willow and Ramanessin Brooks. Monmouth County, New Jersey.

## Hannahatchee Creek, Stewart County, Georgia



(Fig. 27) Location of study area along Hannahatchee Creek, East of Omaha, Georgia. Redrawn from Case and Schwimmer, (1988).

## Trussels Creek, Greene County, Alabama



(Fig. 28) Location of study area along Trussels Creek, due south of Clinton, Alabama.

chondrichthyan teeth with published isotopic ages for the Campanian-Maastrichtian, lower-upper Campanian and Santonian-Campanian stage boundaries.

At each of the three localities, the following procedures were done:

1) collecting lag deposit macrofossils for biostratigraphic and chronostratigraphic interpretation; 2) measuring and describing vertical thickness of exposed units containing chondrichthyan lag deposits; and 3) tracing the horizontal continuity of the chondrichthyan lag deposit outcrops.

#### Fossil Collection

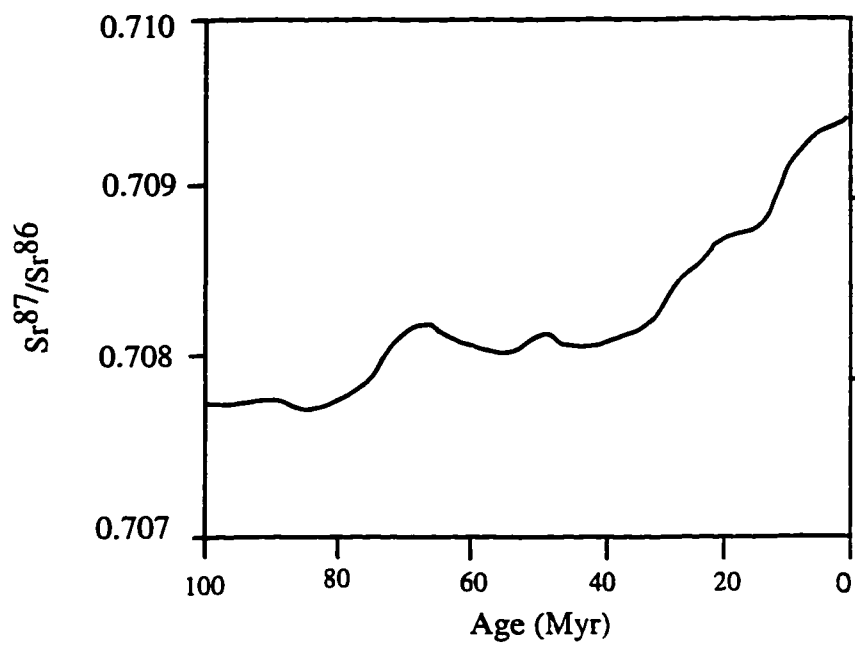
Fossils were collected by sieving outcrops with 0.5 centimeter screens. Only *in situ* material was collected and identified. Identified macrofossils were integrated with the known chondrichthyan and ammonite biostratigraphy for the Cretaceous Atlantic Coastal and Western Interior Seaways from: Fowler, 1911; Moore et al., 1958; Cobban, 1974; Cappetta and Case, 1975; Case, 1982; Lauginger, 1984; Hartstein and Decina, 1986; Lauginger, 1986; Schwimmer, 1986; Case and Schwimmer, 1988; Robb, 1982; Welton and Farish, 1993; Kennedy and Cobban, 1994; Kent, 1994 and Kennedy et al, 1995. Stage and substage age assignments for macrofossil lags collected in this field study were obtained from biostratigraphic zonations of chondrichthyans and ammonites. Some

specimens were randomly selected for isotopic age determination using strontium dating.

### **Strontium Dating: Chondrichthyan Teeth**

Recent advances in isotope geochemistry have led to a procedure in which the strontium isotopic ratio of chondrichthyan teeth can be accurately measured (e.g. Schmitz et al., 1991). Regardless of the exact mechanism driving the addition of strontium to seawater, the observed overall trend is that strontium shows a slow, unidirectional increase throughout the world's oceans over the last 100 million years (Fig. 29). These compositional differences in seawater make strontium a useful tool in absolute age determination studies. Conversion of isotopic ratio to absolute geologic age can be accomplished by comparing measured strontium in a chondrichthyan tooth sample to well documented, age versus strontium concentration in seawater data. The upper Cretaceous Atlantic and Eastern Gulf Coastal Plains are excellent localities to collect chondrichthyan teeth from well studied and documented stratigraphic boundaries. Therefore, any biostratigraphic or chronostratigraphic interpretation compiled from these areas using chondrichthyan teeth can be cross-checked and confirmed.

Natural strontium consists of four isotopes:  $\text{Sr}^{84}$ ,  $\text{Sr}^{86}$ ,  $\text{Sr}^{87}$  and  $\text{Sr}^{88}$ .  $\text{Sr}^{84}$ ,  $\text{Sr}^{86}$  and  $\text{Sr}^{88}$  are naturally occurring, while  $\text{Sr}^{87}$  is the non-radioactive daughter product produced by beta decay of  $\text{Rb}^{87}$ . As an ion,



(Fig. 29) Generalized trend of marine  $\text{Sr}^{87}/\text{Sr}^{86}$  ratio for the last 100 million years. Redrawn from Palmer and Elderfield, (1985) and Ingram et al., (1994).

strontium has an overall charge of plus two, electronegativity of 1.0 and approximate ionic radius of 0.113 nanometers. In terms of abundance, strontium is 21st among the elements occurring in the rocks of the earth's crust and 11th in terms of the content of seawater. It is estimated that 38,000 tons of strontium are present per cubic mile of seawater.

Strontium is thought to be delivered to the oceans of the world through a combination of erosion of siliciclastic rocks on the craton and hydrothermal activity at the mid-ocean ridge. Palmer and Elderfield 1985; Richter et al., 1992 and Clemens et al., 1993, cite the India-Asia collision in conjunction with episodic glaciation as the major driving mechanism affecting strontium isotopic composition in seawater over the last 100 Ma. Their research indicates that fluctuations in the  $\text{Sr}^{87}/\text{Sr}^{86}$  ratio correlate favorably to glacial and interglacial episodes as seen in  $\text{O}^{18}/\text{O}^{16}$  ratios of foraminifera. Interglacial episodes result in increased  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios from cratonic erosion while glacial episodes result in decreased  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios as ice protects the craton from direct chemical erosive processes. A similar model of fluctuating  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios in response to cratonic exposure and glaciation was originally proposed by Armstrong, 1971.

During the interglacial-glacial transitions,  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios change at a rate of approximately one part per million per thousand years. Mass-balance calculations proposed by Clemens et al., 1993, indicate that this rate of change cannot completely account for the observed rate of  $\text{Sr}^{87}/\text{Sr}^{86}$

increase over the last 100 million in the world's oceans. Additional mechanisms must be in operation. Clemens et al., 1993, postulate the possibility of: 1) the existence of strontium sinks created by groundwater run-off from Jurassic and Cretaceous carbonates during sea level lowstands; 2) glacial-interglacial changes in chemical weathering and; 3) variation in hydrothermal fluctuation at places such as the mid-ocean ridge.

In contrast to the models postulated by Palmer and Elderfield 1985; Richter et al., 1992; Clemens et al., 1993 and Jones et al., 1994, believe hydrothermal activity at the mid-ocean ridge, occurring as changing intensity of mid-ocean ridge crustal generation rates, plays a crucial role in the  $\text{Sr}^{87}/\text{Sr}^{86}$  variation in seawater. In their model, the hydrothermal activity of seawater circulating through newly forming mid-ocean ridge basalts is the major driving mechanism in the observed strontium isotopic composition of seawater. Changing intensity of mid-ocean ridge crustal generation rates are well supported during the Santonian, Campanian and Maastrichtian stages of the Cretaceous in the Haq et al., 1988, study. The Haq et al., 1988, data indicate that spreading rates have varied as much as 0.7 cm/yr in the North Atlantic during the upper Cretaceous.

The  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic dating method is utilized in this research project to determine whether: 1) chondrichthyan teeth are accurate  $\text{Sr}^{87}/\text{Sr}^{86}$  age indicators (or have they been subjected to significant diagenetic alteration; 2) chondrichthyan teeth in conjunction with other macrofossils

are useful biostratigraphic indicators; 3)  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic age determination on chondrichthyan teeth can prove that the lag deposits discussed here are time-averaged fossil assemblages and not contemporaneous life-cohort assemblages; and 4) estimates of stratigraphic mixing at the Santonian-Campanian; lower-upper Campanian and Campanian-Maastrichtian boundaries can be made by  $\text{Sr}^{87}/\text{Sr}^{86}$  dating chondrichthyan representatives.

### The Origin of Strontium in Chondrichthyan Teeth

Embryonic shark teeth are generated internally and move outward to the jaw margin where they erupt fully formed. Individual teeth function for a short time either for crushing, grasping, swallowing, cutting or gouging. Teeth are continuously replaced during the shark's lifetime in a conveyor belt fashion in which a new tooth rotates into position to replace a lost tooth (Welton and Farish, 1993).

Chondrichthyan teeth are composed primarily of biogenetically secreted apatite,  $\text{Ca}_3(\text{PO}_4)_2\text{F}$ , but may also contain a minor carbonate component (Welton and Farish, 1993 and Kent, 1994). During the growth phase, chondrichthyans extract calcium ions from food sources and seawater which are utilized in tooth and cartilage construction.

Staudigel et al., 1985, indicate diffusion of strontium from seawater incorporates minor amounts of strontium in chondrichthyan teeth. Vital effects do not take place in the concentration of strontium in fossils such as

mollusks, ammonites, foraminifera, bones and teeth. Concentration of strontium is a diffusion process and is not actively selected for by the organism in skeletal construction (Staudigel et al., 1985, Toyoda and Tokonami, 1990 and Krueger, 1996) .

Ingram et al., 1994, noted that fish tooth apatite contains a much higher concentration of strontium than marine calcite. Average estimates indicate chondrichthyan and osteichthyan teeth are comprised of 1000 to 6000 p.p.m. strontium while marine carbonates typically contain 600 to 1500 p.p.m.. In an analysis of forty-seven chondrichthyan and osteichthyan teeth from the mid-Cretaceous, Ingram et al., 1994, noted minimal post-depositional recrystallization because of the high quantity of strontium concentrated in the teeth. These researchers further noted that minimal post-depositional recrystallization in chondrichthyan and osteichthyan teeth make them likely candidates for paleoceanographic and absolute age studies.

#### Strontium Isotopic Dating Technique: Use and Importance

The underlying principle in strontium isotopic dating is that minor amounts of strontium become concentrated in the mineralogical make-up of chondrichthyan teeth. Barring diagenetic alteration and vital effects, the  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratios measured in chondrichthyan teeth should reflect the  $\text{Sr}^{87}/\text{Sr}^{86}$  ratio of seawater at the time the organism was alive.

If strontium is isotopically homogeneous in seawater throughout the world's oceans at any given time,  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratios measured on chondrichthyan teeth should allow for absolute age determination.

Additionally, absolute ages generated from chondrichthyan teeth from known stratigraphic intervals should offer a means of regionally and possibly globally correlating stratigraphic events.

Strontium isotopic dating applied to mollusks and foraminifera has resulted in the development of many seawater strontium isotopic curves which have proved reliable in: 1) determining absolute ages of marine fossils; 2) globally correlating stratigraphic units and tectonic events; and 3) timing sea level fluctuation events (Martin and Macdougall, 1991; Richter et al., 1992; MacArthur et al., 1993;1994; Jones et al., 1994, Ingram et al., 1994; and Sugarman et al., 1995).

#### Possible Problems with $\text{Sr}^{87}/\text{Sr}^{86}$ Dating Method

##### Diagenetic Alteration

Two factors are known to affect strontium dating in samples. These include: 1) temperature effects due to metamorphism which cause diffusion of strontium; and 2) late post-depositional ion or isotopic exchange with waters circulating through unconsolidated sediments (Brownlow, 1979).

The chondrichthyan teeth studied in this project were collected from unconsolidated sediments of the Atlantic Coastal Plain in New Jersey and Eastern Gulf Coastal Plain of Georgia and Alabama.

The unconsolidated sediments of the Atlantic and Eastern Gulf Coastal Plains have not been subjected to deep burial, lithification or metamorphism so that the effects of such agents are not likely to be an important factor in this case. However, groundwater dissolution and ion or isotopic exchange in these unconsolidated sediments are potential problems affecting the absolute age determination using the  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic dating technique. Lag deposits, where fossil chondrichthyan teeth are commonly found, typically contain greater porosity and permeability than the surrounding sediments. This results in groundwater flow concentration within the lags and makes alteration of original tooth biogenic apatite a potential problem in using chondrichthyan teeth for isotopic age dating..

The importance of analyzing and addressing the possibility of diagenetic alteration in strontium isotope dating by ion exchange and recrystallization was carefully documented and addressed in the studies of DePaolo and Ingram, 1985; Hess et al., 1985; Palmer, 1985; Nelson et al., 1986; Kolodny and Raab, 1988; Schmitz et al., 1991; Ingram et al., 1994 and Sugarman et al., 1995. Their results conclude that all samples should be carefully inspected and treated for diagenetic alteration before  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratios are measured. Having done so, these researchers successfully utilized strontium dating in paleosalinity, paleoxygen, stratigraphic correlation and absolute age determination studies on:

foraminifera, mollusks, belemnites and teeth and bones from chondrichthyans, osteichthyans and reptiles.

Ingram et al., 1994, noted that in recrystallized foram and mollusk shells, the range of variation in the  $\text{Sr}^{87}/\text{Sr}^{86}$  ratio depends on: 1) the timing and rate of recrystallization; 2) the proportion of  $\text{Sr}^{87}/\text{Sr}^{86}$  ratio and the strontium content of the non-carbonate phase of sediment; and 3) the burial depth and temperature in proximity to ocean basement. These researchers further note that  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios are probably not significantly altered from their original composition if compaction and diagenesis takes place soon after burial.

In order to address the importance of diagenetic alteration in  $\text{Sr}^{87}/\text{Sr}^{86}$  age dating of fish teeth, Schmitz et al., 1991, analyzed the rare earth element, lanthanum. Skeletal debris including teeth, contains insignificant amounts of lanthanum and other rare earth elements. The concentration of rare earth elements in fossil fish apatite was used in their study to investigate the extent to which apatite had been exposed to ion carrying pore waters. Of the forty-one teeth samples analyzed by Schmitz et al., 1991, only two samples showed an increase in lanthanum, suggesting diagenetic alteration with circulating pore waters.

Additionally, iron and manganese concentrations have been cited as reliable indicators of the extent of diagenetic alteration (Jones et al., 1994).

These two elements are present in very low concentrations in seawater, yet are abundant in crustal rocks and pore waters. Therefore, authigenic calcite contains much more iron and manganese compared to calcite precipitated directly out of seawater. Higher iron and manganese concentrations in fossil samples may then be linked to diagenetic alteration affecting the  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios measured by isotopic analysis. Jones et al., 1994, analyzed belemnites and oysters for iron and manganese in a  $\text{Sr}^{87}/\text{Sr}^{86}$  dating study of Jurassic and Cretaceous oceans. Diagenetic alteration was observed in samples which contained iron in abundances greater than 150 p.p.m. and manganese in abundances greater than 50 p.p.m..  $\text{Sr}^{87}/\text{Sr}^{86}$  dates from this study, which had been diagenetically altered, yielded ages approximately 5-10 million years younger than predicted, indicating a diagenetic impoverishment of  $\text{Sr}^{87}$ .

### Identification Techniques for Diagenetic Alteration

#### Plain/cross-polarized Light

In order to address the possibility of diagenetic alteration occurring in chondrichthyan teeth collected from the selected lag deposit outcrops, thin sections of five teeth were prepared. The teeth selected are from the following species: *Ptychodus mortoni* and *Squalicorax kaupi* from Alabama; *Paranomotodon angustidens* and *Carcharis* sp. B from New Jersey and *Scapanorhynchus texanus* from Georgia. These teeth were

selected because these species comprise the sampling population for  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratios measured during this study.

All thin sections were examined under plain and cross-polarized light at both low (4X) and high (40X) magnification with respect to: 1) the mineralogy of the biogenic apatite comprising the teeth; 2) overgrowths on any of the biogenic apatite; and 3) pore and void spaces where authigenic mineral growth could have occurred.

### Cathodoluminescence

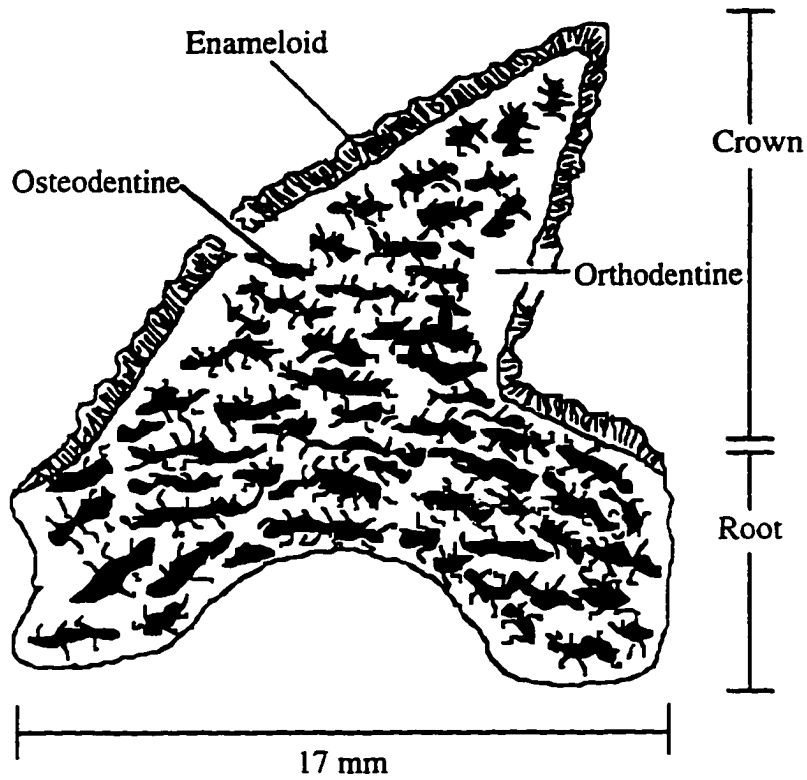
Additionally, because of the extremely fine grained nature of the biogenic apatite, each thin section was subjected to cathodoluminescence. Any authigenic calcite obscured by the biogenic apatite could then be detected by its luminescent properties.

Cathodoluminescence is visible light emitted from a specimen when it is bombarded with electrons. By carefully examining the color patterns produced by crystalline mosaics under a microscope, determination of recrystallization, growth banding, zonation, nondeposition, corrosion or erosion is possible (Kopp, 1981). Luminescence is affected by the nature of the host lattice which contains activators and quenchers, the degree of surface preparation, the voltage applied to the cathode, and the beam power density.

Luminescence is thought to occur as a result of activator ions present in a sample. The luminescence effect is offset by the number of quencher

ions present in the same sample. Activators are impurities which form centers for easy excitation. Manganese and rare earth elements are common activators in geologic materials. Excitation of these ions results in transition from inner atomic orbitals to outer orbitals with the emission of energy observed as characteristic colors. Quenchers produce excited electron states which have radiationless transitions of electrons and offset the luminescence effects of the activators. The most common quencher is iron. In general, 10-50 p.p.m. of manganese may be sufficient for activation in iron free samples. Typically, samples require about 100 p.p.m. of manganese or rare earth elements to compensate for iron or other quencher that may be present (Marshall, 1988).

Chondrichthyan teeth are comprised of biogenic apatite,  $\text{Ca}_5(\text{PO}_4)_3\text{F}$ , which occurs in two calcified tissue types, dentine (osteodentine and orthodentine), which surround the pulp cavity and enameloid which coats the outer surface of the crown (Fig. 30). *Squalicorax kaupi*, *Carcharis* sp. B, *Scapanorhynchus texanus* and *Ptychodus mortoni* are osteodonts which contain osteodentine in the central tooth portion and root structure (Welton and Farish, 1993). Orthodentine surrounds the osteodentine while enameloid is located along the outer edge of the tooth crown (Welton and Farish, 1993 and Kent, 1994). Non-mineralized portions of the tooth contain cavities, canals and tubules that in life allow for movement of body fluids and blood.



(Fig. 30) Mineralized tissue diagram of a cross-section of *Squalicorax kaupi*. Enameloid coating tooth crown is much less porous and less permeable than osteodentine or orthodentine. Tooth and tissue diagram redrawn from Welton and Farish, (1993).

## Luminescence Properties of Common Minerals

### Apatite

Apatite and fluoroapatite are noted as luminescing in a wide variety of colors including yellow, brown, lavender and green (Marshall, 1988). Activators common to apatite and fluoroapatite are  $\text{Ce}^{3+}$ ,  $\text{Eu}^{2+}$ ,  $\text{Sm}^{3+}$ ,  $\text{Mn}^{2+}$  and  $\text{Dy}^{3+}$  while  $\text{Fe}^{2+}$  or  $\text{Fe}^{3+}$  serves as a quencher. Hagni, 1984, cited the benefits of cathodoluminescence techniques applied to collophane. His study indicates that the fine grained fibrous nature of apatites contained in collophanes make detection of authigenic minerals under plain and cross-polarized light difficult. Applying cathodoluminescence techniques, along with a presumed abundant manganese activator, resulted in easy detection of fluoroapatite contained in a collophane-rich iron ore from Birmingham, Alabama (Hagni, 1984).

### Calcite

Typical colors of cathodoluminescence seen in calcite are orange-red, yellow-orange and orange (Marshall, 1988).  $\text{Mn}^{2+}$ , or in more rare instances  $\text{Pb}^{2+}$ , act as the activator while  $\text{Fe}^{2+}$  acts as the quencher. Dolomite, is thought to behave similarly to calcite, but luminesces in the darker reds or yellows. Authigenic calcite or dolomite can be seen using cathodoluminescence petrography as well defined euhedral grains that are intergrown within void regions of analyzed samples. Zoning,

overgrowths, erosions and corrosion are readily identified by notable color changes along euhedral edges of mineral grains (Kopp, 1981).

Diagenetic calcite and dolomite are cited as the most common minerals resulting from recrystallization and alteration by pore water ion exchange (Brownlow, 1979).

### Siderite and Authigenic Feldspar

Other common authigenic minerals that could interfere with the strontium isotopic dating procedures are siderite and authigenic feldspar. These two minerals occur in the sediments where the New Jersey, Georgia and Alabama lag deposits exist (Reinhardt, 1981; Raymond et al., 1988 and Martino and Curran, 1990). Neither of these minerals luminesce, rendering this technique ineffective in their identification. Siderite lacks luminescent properties because of the abundance of iron in its chemistry, approximately 48 % ferrous iron in pure samples. Siderite must be identified through the application of alternative techniques such as x-ray diffraction or x-ray fluorescence.

Lack of luminescent properties in authigenic feldspars is much less understood. Marshall, 1988, lists the following reasons for non-luminescence in authigenic feldspars: 1) absence of necessary activator ions in the environment of formation; 2) the incorporation of quenching elements; 3) the temperature of formation associated with authigenic

feldspar formation; and 4) the crystal structure lacking the capacity to take up necessary activators allowing for luminescent properties.

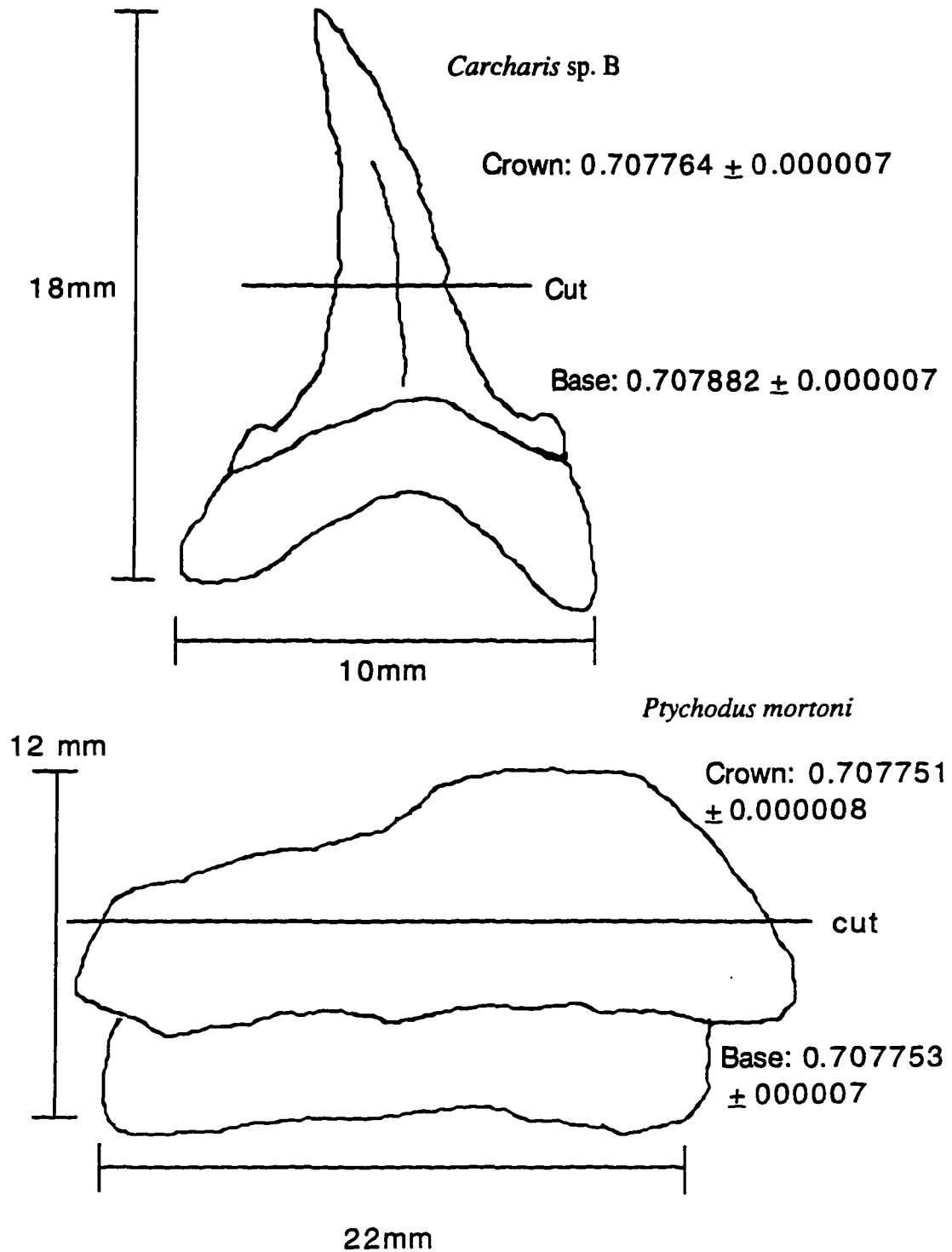
#### Sr<sup>87</sup>/Sr<sup>86</sup> Isotopic Comparison: Identification of Diagenetic Alteration

A total of four teeth were randomly selected from a population of New Jersey, Georgia and Alabama specimens in order to compare the isotopic nature of the enameloid, osteodentine and orthodentine within each individual tooth. Cuts were made separating the crowns and bases in *Carcharis* sp. B, *Ptychodus mortoni*, *Squalicorax kaupi* and *Paranomotodon angustidens* (Figs. 31 and 32). The Sr<sup>87</sup>/Sr<sup>86</sup> isotopic ratio of crowns verses bases were measured for each tooth sample at the Institut für Geologie, Ruhr-Universitaet Bochum, in Germany by Dr. Dieter Buhl.

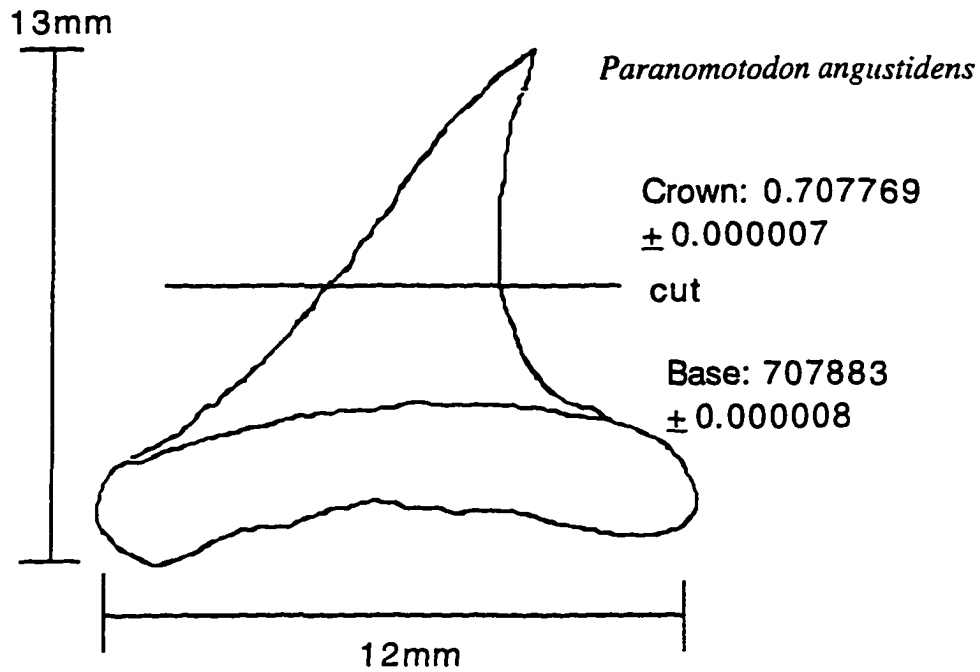
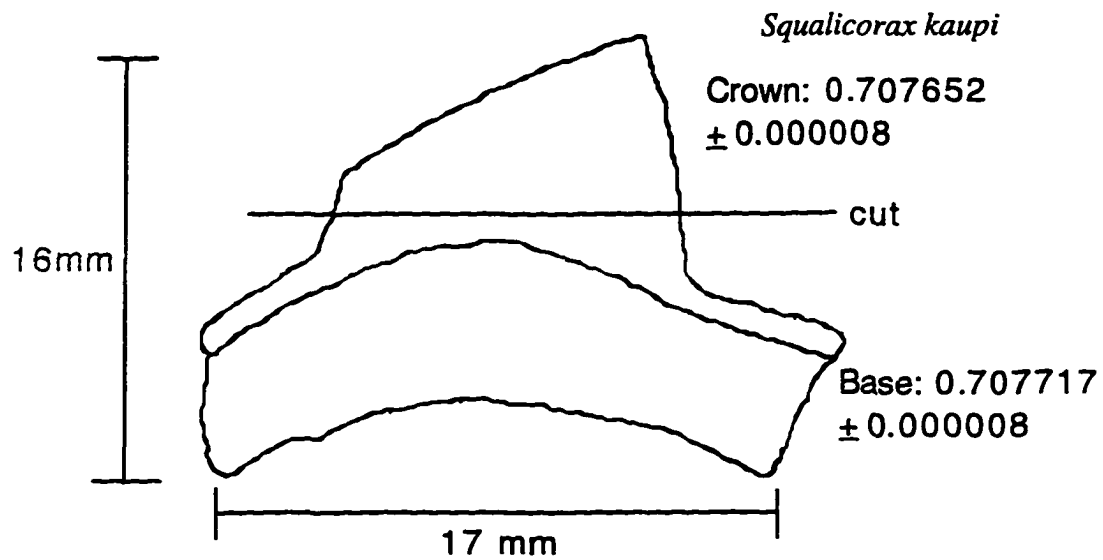
If results proved homogeneous Sr<sup>87</sup>/Sr<sup>86</sup> isotopic ratios in the crowns and bases of each tooth sample, any diagenetic alteration that occurred would have affected each tooth sample uniformly. Alternatively, if differences in the Sr<sup>87</sup>/Sr<sup>86</sup> isotopic ratios were observed in crowns and bases of individual teeth, diagenetic alteration must have preferentially occurred in zones within a tooth sample.

The enameloid, located along the outer edge of the tooth crown, is the most likely material for preserving the original Sr<sup>87</sup>/Sr<sup>86</sup> isotopic signature. Thin section analyses identified this portion of the tooth as the least porous and permeable and thus, least susceptible to the effects of groundwater diagenetic alteration. (For procedures related to treatment

(Fig. 31) Comparison of  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratios for the crowns and bases of *Carcharis* sp. B and *Ptychodus mortoni*.



(Fig. 32) Comparison of  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratios for the crowns and bases of *Squalicorax kaupi* and *Paranomotodon angustidens*

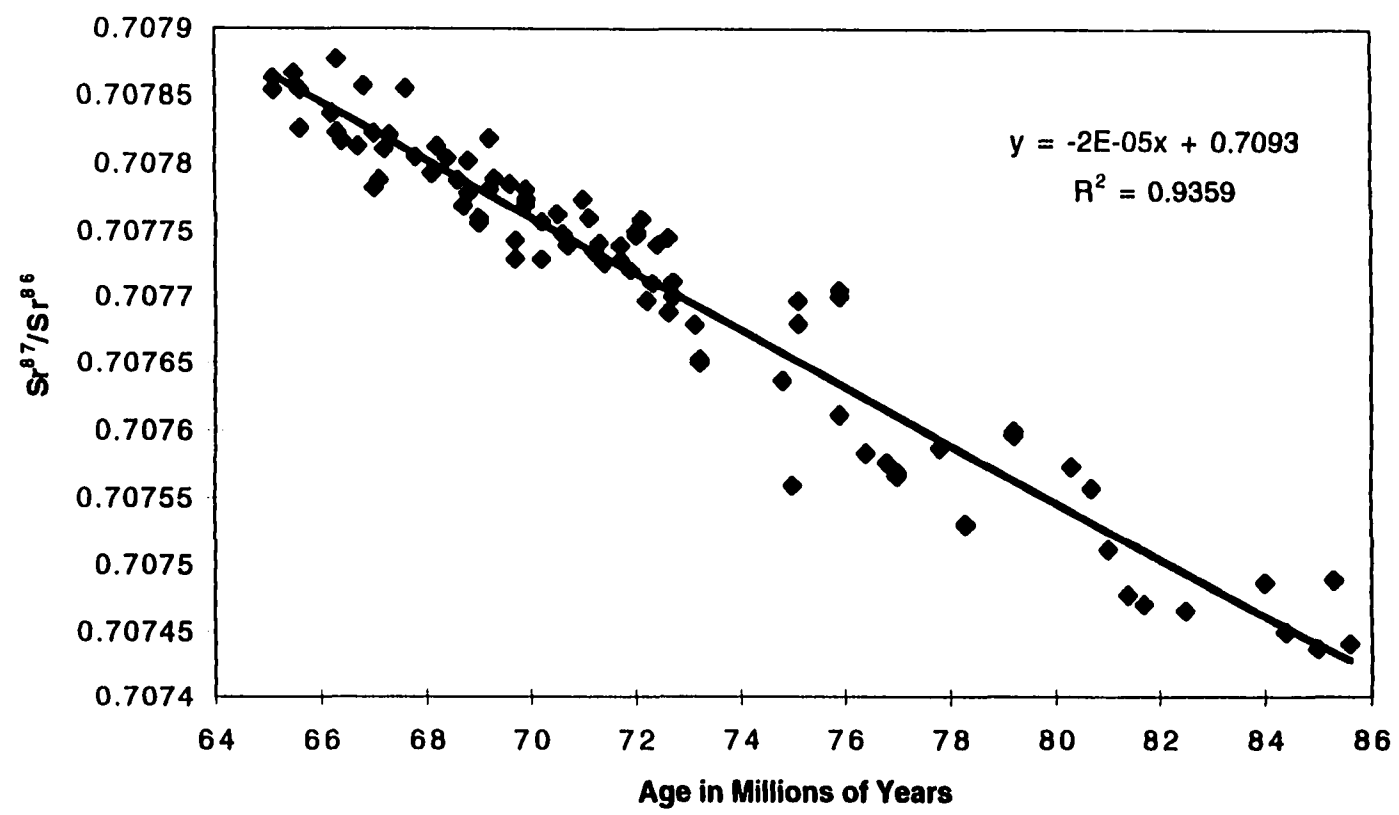


of authigenic mineral growth, acid dissolution techniques and strontium isolation techniques, see appendix 1).

Absolute Age Determination:  $Sr^{87}/Sr^{86}$  Procedure

All strontium analyses conducted at the Geochron Laboratories and the Institut für Geologie, Ruhr-Universität on chondrichthyan teeth were normalized to  $Sr^{86}/Sr^{88} = 0.11940$ . Analyses of NBS 987 and EN-1 averaged 0.710241 (15) (n= between 65 and 71) during the period of these analyses. Errors on  $Sr^{87}/Sr^{86}$  are given as 2 sigma (95%) in the last two digits. Measured isotopic ratios were converted into absolute ages through the use of a composite age versus  $Sr^{87}/Sr^{86}$  diagram compiled from age versus concentration data published in the studies of Hess et al., 1986; MacDougall, 1988; MacArthur et al., 1994; and Sugarman et al., 1995 (Fig. 33). Strontium isotopic ratios in these researchers' analyses were measured on foraminifera, oysters, belemnites and ammonites.

A linear trendline was selected between all plotted data points ranging in age between 85 and 69 Ma covering a  $Sr^{87}/Sr^{86}$  ratio of 0.707400 to 0.707900. The resulting equation of this plot is  $Sr^{87}/Sr^{86}$  (Measured) =  $2 \times 10^{-5}$  (Age in Ma) + 0.7093. The selected linear regression on these data provides an excellent fit to the data points, and yields a correlation coefficient of  $R = 0.94$ . Correlation coefficients exceeding  $R = 0.90$  are an indication of a highly significant relation between plotted parameters (Devore, 1995).



(Fig. 33) Composite Age Vs  $Sr^{87}/Sr^{86}$  ratio for the Santonian, Campanian and Maastrichtian stages of the upper Cretaceous. Compiled from age Vs concentration measurements of Hess et al., (1986); MacDougall, (1988); MacArthur et al., (1994); and Sugarman et al., (1995).

### Confidence Interval and t-distribution

In order to model the amount of time averaging occurring in chondrichthyan lag deposits, a confidence interval analysis was conducted on three separate populations of chondrichthyan teeth from New Jersey, Georgia and Alabama. Each confidence interval analysis assumed a t-distribution for the three separate populations of teeth.

A t-distribution is a common statistical method for modeling an approximation of population statistics based on sample statistics and is used for statistical analyses with low sample numbers (Devore, 1995). (For confidence interval formula, see appendix 2). Assumptions necessary to validate the use of a t-distribution in modeling time averaging in chondrichthyan lag deposits include: 1) teeth are randomly sampled from the lag horizon; and 2) teeth represent a normal distribution within lag deposits.

The validity of these assumptions are based on: 1) teeth contained in lag deposits are covered in clays when sampled. The author did not preferentially select certain individuals from the lag horizon; and 2) paleobathymetry controls the accumulation of teeth. Sharks as well as other organisms have a range of desirable water depths. Altering water depth will more than likely cause sharks and other nektonic organisms to migrate to more acceptable depth conditions.

During sea level regressive-transgressive events, a greater abundance of sharks would have been living in specific areas and losing teeth during optimum paleobathymetric conditions. The majority of teeth, with the potential for becoming fossils, would have accumulated during this time. Less teeth would have been accumulating in these specific areas during the highest and lowest stands of a sea level regressive-transgressive event. Reworking all of the deposited teeth into a lag would create a normal distribution in teeth age ranges.

The confidence interval analysis will be used to substantiate the approximate number of years of reworking and hydrodynamic sorting within each lag deposit. The general assumptions that the confidence interval analysis will work under are: 1) the reworking process can be no older than the youngest tooth contained in the lag deposit. In other words, final hydrodynamic sorting by sea level cyclicity has to have occurred after the youngest  $\text{Sr}^{87}/\text{Sr}^{86}$  dated representative for each lag had been deposited; and 2) the oldest dated tooth in the lag deposit approximates how far back in time the erosion and exhumation processes operated. Therefore, the minimum and maximum range in values achieved through the application of a confidence interval analysis should approximate how much reworking and time averaging has taken place during the formation of each lag deposit. The calculated range for the New Jersey, Georgia and Alabama lag deposits can then be compared to the Busch and Rollins, 1984; Kidwell,

1993; Van Wagoner et al., 1988 and Vail et al., 1991, estimate of 0.5 to 5.0 million years for lag deposits which occur as products of third sea level cyclicity.

### Sample Size

All confidence interval analyses were conducted at 99% with a sample size of ten samples from each of the three field area lag deposits. At a confidence interval of 99%, only one out of one hundred of the teeth, whose absolute age was determined using the  $\text{Sr}^{87}/\text{Sr}^{86}$  dating methodology described above, would fall outside the calculated maximum and minimum age range for each lag deposit. Therefore, calculated maximum and minimum age ranges are statistically representative of chondrichthyan teeth populations from each lag deposit. Confidence interval results are compiled in Table 5 of results section.

### Stratigraphic Position and Sea Level

In order to assess the role of sea level cyclicity in macrofossil lag deposit formation, the stratigraphic positions and age of lag outcrops were compared to sea level studies of Sohl and Smith, 1980; New Jersey paleobathymetric and sea level studies by Olsson and Nyong, 1984; Depositional Sequences Boundary 3, 4, and 5 of Owens and Gohn, 1985; and the third order sea level curve of Haq et al., 1988.

## **Results**

### **Stratigraphy and Sedimentology of Lag Deposits**

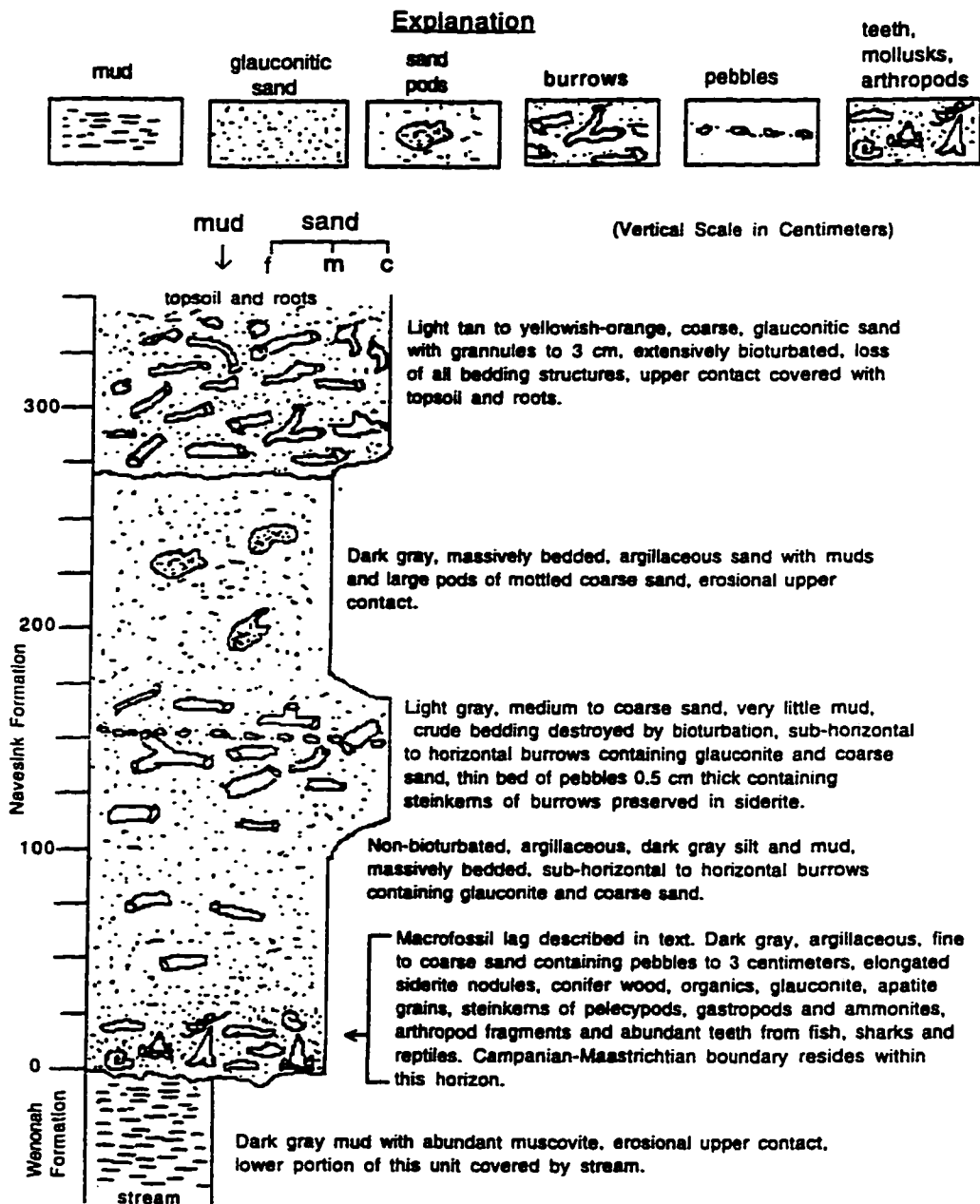
Five measured sections of New Jersey, Georgia and Alabama lag deposits were compiled for this project. These particular sections were selected because they represent the most complete, accessible, cross-sectional exposures of the Santonian-Campanian, lower-upper Campanian and Campanian-Maastrichtian boundaries which contain chondrichthyan teeth along the Atlantic and Eastern Gulf Coastal Plains. Furthermore, these sections were selected because the regional stratigraphy and paleontology is well-documented, providing a framework in which to evaluate any interpretations and conclusions on the formation of chondrichthyan lag deposits.

#### **New Jersey**

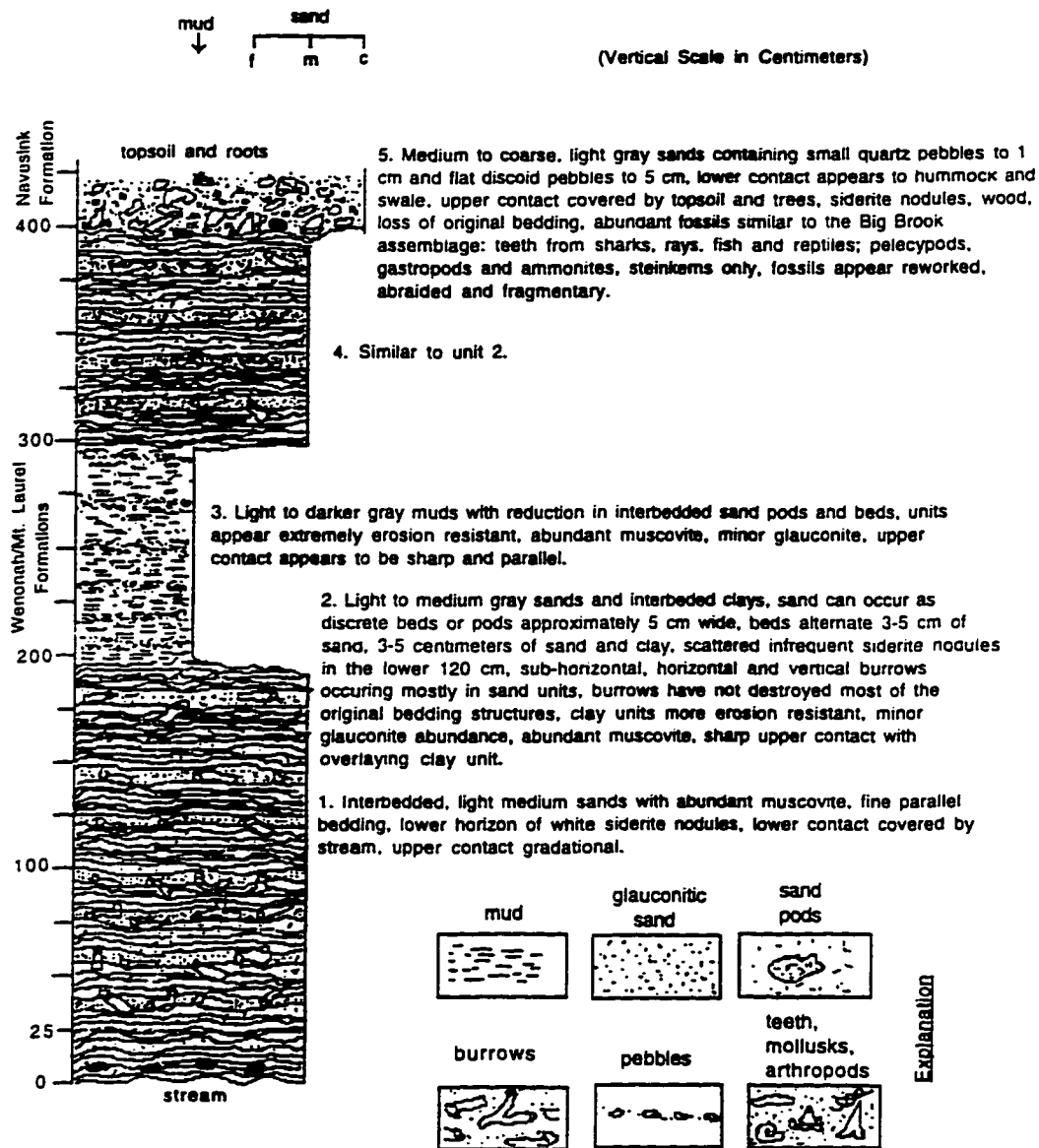
Three detailed measured sections of the lag deposit separating the Wenonah/Mt. Laurel and Navesink Formations and the Campanian-Maastrichtian boundary along Big, Willow and Ramanessin Brooks in Monmouth County, New Jersey were compiled (Figs. 34, 35, 36). Careful attention was given to the following parameters: 1) sediment grain size, color and mineralogical make-up; 2) bedding structures and erosion 3) unit and formation contacts; 4) fossil type; and 5) areas of fossil concentration.

The upper Wenonah Formation along Big, Willow and Ramanessin Brooks contains dark gray muds with fine grained quartz sands, abundant

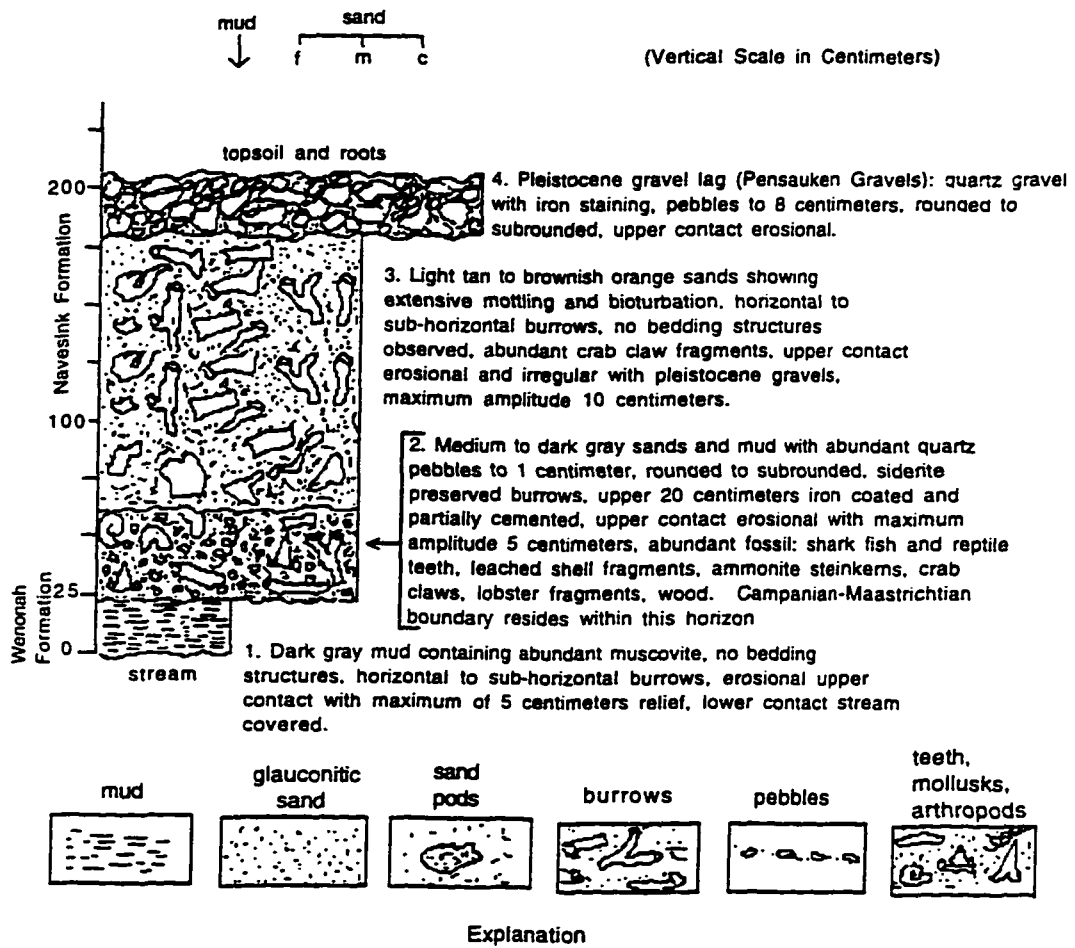
(Fig. 34) **Measured Section: Big Brook, Marlboro, New Jersey**  
by: M. Becker, 1994



(Fig. 35) **Measured Section: Willow Brook**  
**Marlboro, New Jersey**  
 by: M. Becker, 1995



(Fig. 36) **Measured Section: Ramanessin Brook, Homdel, New Jersey**  
By: M. Becker



muscovite and sparse macrofossil evidence. Sedimentary structures include a high degree of bioturbation resulting in many instances in loss of original bedding structures. The upper contact of the Wenonah Formation along these brooks is erosional with a maximum of 5 centimeters of relief. The lower contact has not been exposed by stream erosion. Exposures of the upper Wenonah Formation along Big, Willow and Ramanessin Brooks range from 1 to 4 meters thick.

The upper Mt. Laurel Formation appears to be thin or absent along Big and Ramanessin Brooks. This is perhaps related to the formation of the erosional disconformity identified by Olsson, 1987; Martino and Curran, 1990; Becker and Slattery, 1995 and Sugarman et al., 1995. Willow Brook outcrops contain some of the thin bedded sand and mud lithofacies identified by Martino and Curran, 1990. Along Willow Brook, outcrops contain light to medium gray sands and interbedded clays. Beds of sand, 3-5 centimeters thick, alternate with 3-5 centimeter thick beds of mud. Siderite nodules and burrows of *orphimorphia* are also scattered throughout the Mt. Laurel Formation. The upper contact of the Mt. Laurel Formation along Willow Brook is similar to that of the Wenonah Formation observed along Big and Ramanessin Brooks. The Mt. Laurel Formation along Big, Willow and Ramanessin Brooks varies from approximately 0-2 meters thick.

Directly above the erosional disconformity at the top of the Wenonah Formation, (or Mt. Laurel Formation along Willow Brook), is the macrofossil lag deposit comprising the basal Navesink Formation. The general characteristics of the lag deposit located along Big, Willow and Ramanessin Brooks are muddy, medium to coarse quartz sands with glauconite, pebbles to 3 centimeters, elongate siderite nodules, conifer wood, organics and apatite grains. Maximum thickness of the lag deposit is approximately 30 centimeters. Abundant and diverse assemblages of macrofossils occur in this lag including mollusks steinkerns, fragments of arthropods and teeth from reptiles, chondrichthyans and osteichthyans. Macrofossils are fragmentary and show signs of transport and reworking (For a description of macrofossils collected from this lag see results section).

The upper Navesink Formation, exposed along Big and Ramanessin Brooks, consists of sands and mud in which original bedding structures have been lost due to bioturbation. (The upper Navesink Formation along Willow Brook is buried under topsoil and roots). Preserved burrows are horizontal to sub-horizontal. The upper contact of the Navesink Formation along Big Brook is covered by topsoil and roots. Along Ramanessin Brook the upper contact can be seen as an erosional disconformity capped by the Pensauken gravels of Pleistocene age. Maximum thickness of the upper

Navesink Formation observed along Big Brook is approximately 3.5 meters.

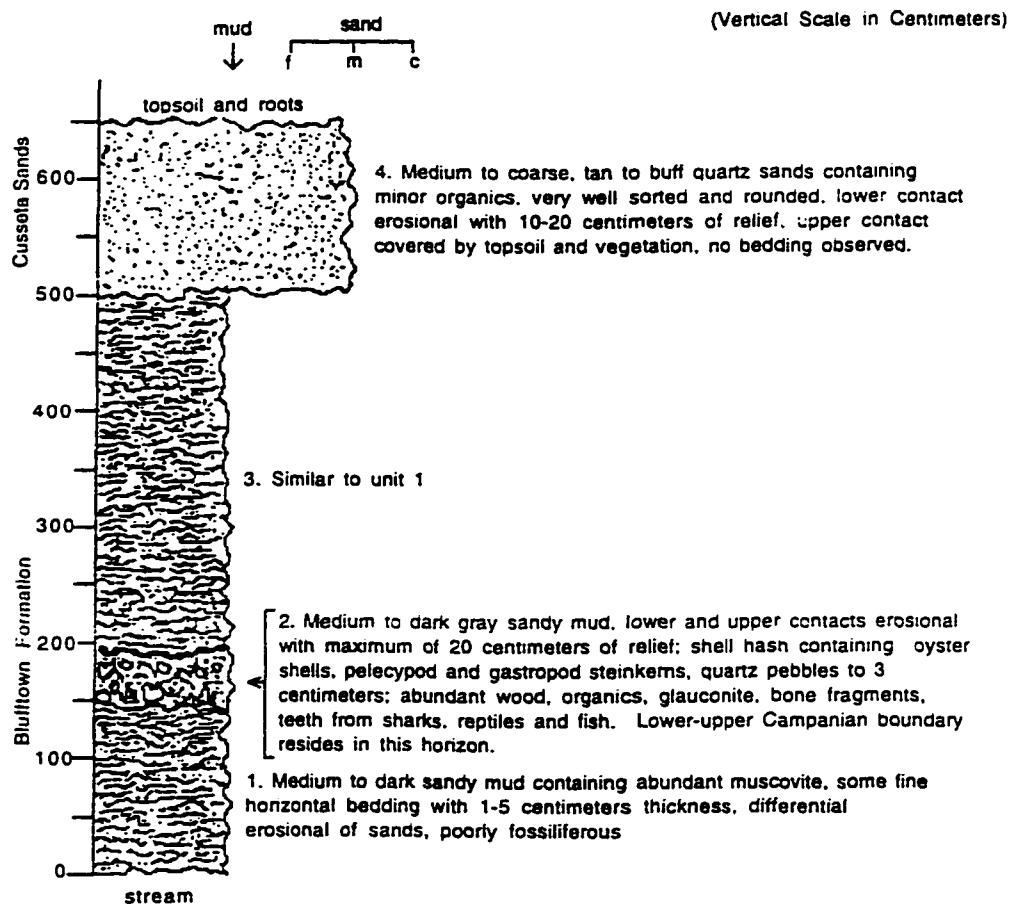
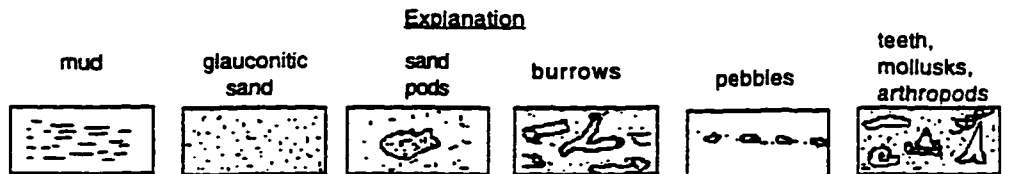
### Georgia

A detailed measured section of the lag deposit separating the Blufftown Formation and Cusseta Sands and the lower-upper Campanian boundary along Hannahatchee Creek in Stewart County, Georgia was compiled (Fig. 37). The same parameters were examined here as in New Jersey.

The upper Blufftown Formation along Hannahatchee Creek consists of medium to dark gray, sandy mud containing abundant muscovite and sparse macrofossil evidence. Some minor horizontal bedding ranging in thickness from 1-5 centimeters exists in the lower Blufftown Formation. Vertical burrows approximately 5-10 centimeters long are scattered throughout the upper part of this formation. The lower contact of the Blufftown Formation has not been exposed by stream erosion. The approximate thickness of the upper unit of the Blufftown Formation along Hannahatchee Creek is 1.25 meters.

Near the upper contact of the Blufftown Formation is an erosional surface with approximately 20 centimeters of relief. Directly above this erosional disconformity is the macrofossil lag studied in this project. The lag deposit consists of medium to dark gray sandy mud with pebbles to 3 centimeters, abundant wood, organics and glauconite. Abundant and

(Fig. 37) **Measured Section:** Hannahatchee Creek, Stewart County, 3.1 miles east of Omaha, Georgia  
By: M. Becker, 1995



diverse assemblages of macrofossils occur in this lag including mollusk steinkerns, fragments of arthropods and teeth from reptiles, chondrichthyans and osteichthyans. Macrofossils, in particular pelecypods, occurring in this lag, are fragmentary and show signs of transport and reworking. (For a description of macrofossils collected from this lag see results section). Directly above the lag deposit is approximately 3 meters of sediments similar to the upper Blufftown Formation described above. The upper contact of this unit is erosional with approximately 10-20 centimeters of relief.

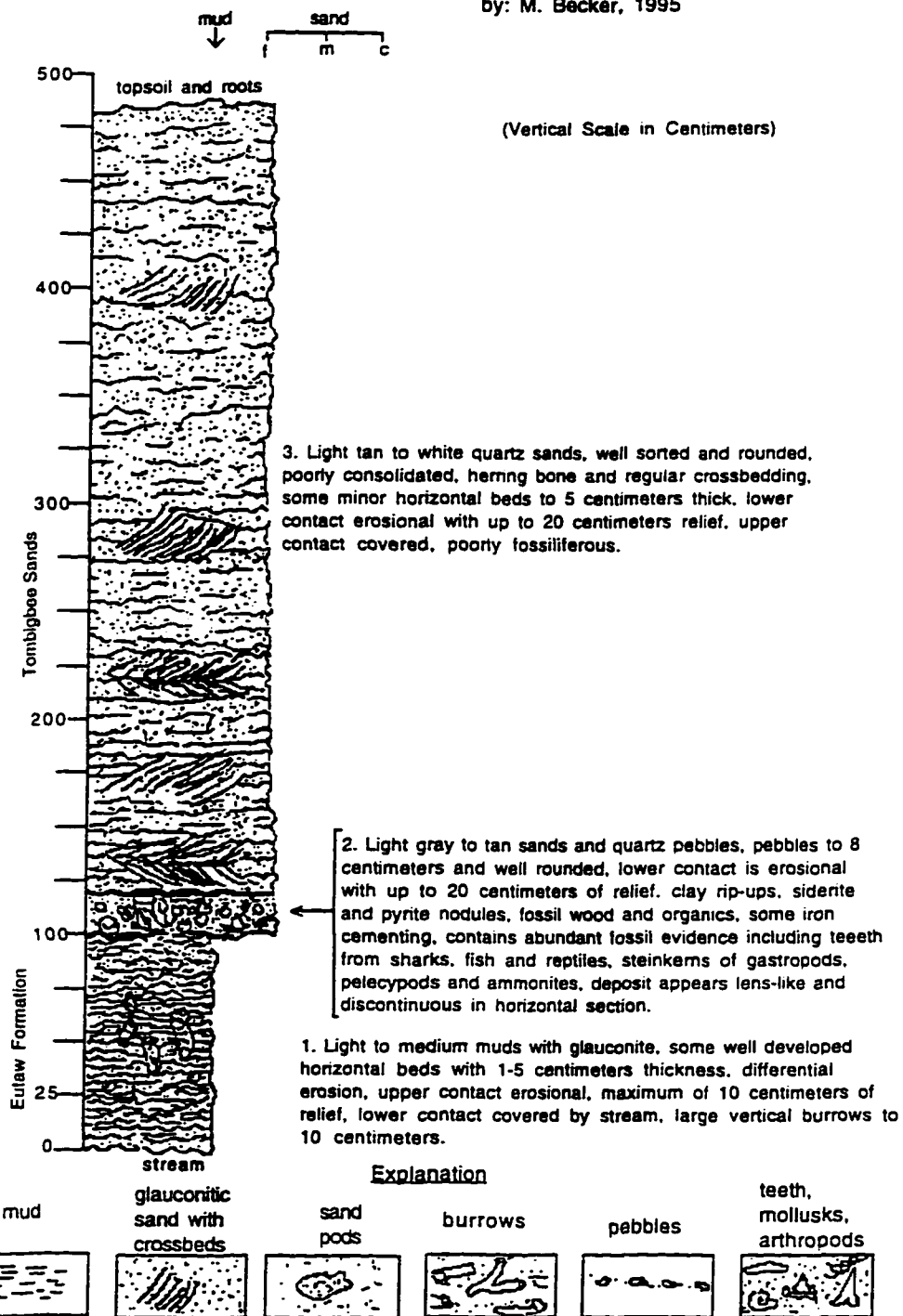
Directly above this contact is approximately 1.5 meters of the Cusseta Sands which contains medium to coarse, tan to buff sands containing minor organics. No fossil evidence or bedding structures were observed in the Cusseta Sands along Hannahatchee Creek. The upper contact of the Cusseta Sands was covered by topsoil and vegetation.

### Alabama

A detailed measured section of the lag deposit separating the Eutaw Formation and Tombigbee Sands and the Santonian-Campanian boundary along Trussels Creek in Greene County, Alabama was compiled (Fig. 38). The same parameters were examined here as in New Jersey and Georgia.

The upper Eutaw Formation along Trussels Creek consists of light to medium muds containing fine sands, glauconite, vertical burrows to 10 centimeters and sparse macrofossils. Horizontal beds show thicknesses of

(Fig. 38) **Measured Section: Trussels Creek**  
 Greene County, Alabama  
 by: M. Becker, 1995



1-5 centimeters and contain small numbers of large vertical burrows. The lower contact of the Eutaw Formation has not been exposed by stream erosion along Trussels Creek. The upper contact of the Eutaw Formation is erosional with a maximum of 20 centimeters of relief. Maximum thickness of the upper Eutaw Formation observed along Trussels Creek is approximately 1 meter.

Directly above the erosional upper contact of the upper Eutaw Formation is the macrofossil lag comprising the basal 25-30 centimeter of the Tombigbee Sands. The lag deposit consists of light gray muds with tan sands and well rounded quartz pebbles to 8 centimeters. Additional sedimentological components include clay rip ups, siderite and pyrite nodules, fossil wood and organics. The upper contact of the lag deposit is erosional with 20 centimeters of relief. A diverse macrofossil assemblage occurs in this lag and includes mollusk steinkerns, fragments of arthropods and teeth from reptiles, chondrichthyans and osteichthyans.

Chondrichthyan teeth are extremely abundant in this horizon and comprise the majority of the fossil assemblage. Macrofossils occurring in this lag, are fragmentary and show signs of transport and reworking. (For a description of macrofossils collected from this lag see results section).

The upper portion of the Tombigbee Sands exposed along Trussels Creek contains light tan to white quartz sands, which are well sorted and rounded. Some minor horizontal beds, approximately 1-5 centimeters

thick, with crossbedding occurs in this lithofacies. No fossils were discovered in this lithofacies. Maximum thickness of the upper portion of the Tombigbee Sands along Trussels Creek is approximately 4 meters.

### Chondrichthyan and Ammonite Paleontology and Biostratigraphy

#### New Jersey

Ammonites: Ammonites collected from the Ramanessin, Willow and Big Brooks during this study include the following species: *Trachyscapites pulcherrimus*, *Baculites* sp., *Placenticeras minor*, *Placenticeras placenta*, *Menuites portlocki*, and *Didymoceras bindosium*. Ammonites are preserved as fragmentary siderite steinkerns where dissolution has removed all original shell material. Siderite steinkerns suggest a significant amount of groundwater percolation through the lag deposit while the fragmentary nature of the ammonites suggests active transport and reworking.

Chondrichthyans: Chondrichthyans collected from Ramanessin, Willow and Big Brooks during this study include the following species: *Squalicorax kaupi*, *Squalicorax pristodontus*, *Cretolamna appendiculata*, *Scapanorhynchus texanus*, *Paranomotodon angustidens*, *Carcharis* sp. B and *Brachyrhizodus wichitaensis*. The majority of chondrichthyan teeth are fragmentary and show signs of abrasion. The fragmentary, abraded nature of chondrichthyan teeth suggests active transport and reworking.

Age of the New Jersey Lag Deposit Based on Macrofossil Biostratigraphy:

Compilation of chondrichthyan and ammonites age ranges, based on specimens collected from lag deposit outcrops separating the Wenonah-Mt. Laurel and Navesink Formations indicate preservation of remains from different stages. The formation of the unconformity separating these deposits, (see section on New Jersey stratigraphy and sedimentology), has resulted in the mixing of Campanian-Maastrichtian ammonite and chondrichthyan biozones.

*Menuites portlocki* is upper Campanian and occurs in the Western Interior in the *Baculites gregoryensis* and *Baculites reduncus* zones (Kennedy and Cobban, 1994). *Didymoceras binodosum* is restricted to the upper-middle Campanian *Baculites scotti* zone of the Western Interior (Kennedy et al., 1995). These fossils, along with *Trachyscaphites pulcherrimus*, *Placenticerus placenta* and *Placenticerus minor*, were collected from the lag deposit separating the Wenonah-Mt. Laurel and Navesink Formations, suggesting mixing of Campanian ammonite zones.

Chondrichthyan teeth *Squalicorax kaupi*, *Paranomotodon angustidens* and *Brachyrhizodus wichitensis* are Campanian age (Cappetta and Case, 1975; Welton and Farish, 1993). These teeth co-occur with teeth of *Carcharis* sp. B, a Maastrichtian representative in the lag separating the Wenonah-Mt. Laurel and Navesink Formations (Cappetta and Case, 1975; Welton and Farish, 1993).

Because six different species of chondrichthyans and six different species of ammonites are found in the lag deposit separating the Wenonah-Mt. Laurel and Navesink Formations, erosion and hydrodynamic sorting must account for their juxtaposition. Furthermore, the lag deposit, which has an average thickness of thirty centimeters and lies directly above an erosional disconformity, contains both Campanian and Maastrichtian fossils. This suggests that the Campanian-Maastrichtian boundary in the Big, Willow and Ramanessin Brook outcrops has been condensed within the thirty centimeters that comprises the macrofossil lag (Becker and Slattery, 1995).

### Georgia

Ammonites: No ammonites were collected from the Hannahatchee Creek locality during this study. Biostratigraphic resolution is provided by the rare occurrence of *Delawaralle delawarensis* and *Scaphites hippocrepis* in the middle of the Blufftown Formation (Owens and Gohn, 1985). Owens and Gohn, 1985, indicate an upper-lower Campanian to lower-upper Campanian age for the middle of the Blufftown Formation based on these occurrences.

Chondrichthyans: Chondrichthyans collected from the Hannahatchee Creek field areas include: *Squalicorax kaupi*, *Squalicorax pristodontus*, *Cretolamna appendiculata*, *Scapanorhynchus texanus*, *Paranomotodon angustidens* and *Brachyrhizodus wichitaensis*. The majority of

chondrichthyan teeth are fragmentary and show signs of abrasion. The fragmentary, abraded nature of chondrichthyan teeth suggests active transport and reworking. However, chondrichthyan teeth from the Hannahatchee Creek field area appeared to be the most pristine of the three lag locations studied.

Age of the Georgia Lag Deposit Based on Macrofossil Biostratigraphy:

Compilation of chondrichthyan age ranges, based on specimens collected from lag deposit outcrops separating the Blufftown Formation and Cusseta Sands, indicate preservation and mixing of Campanian fossils. The formation of the unconformity separating these deposits, (see section on Georgia stratigraphy and sedimentology), has resulted in the mixing of Campanian chondrichthyan biozones.

Chondrichthyan teeth *Squalicorax kaupi*, *Paranomotodon angustidens* and *Brachyrhizodus wichitaensis* collected from this lag make their last appearance during the Campanian (Cappetta and Case, 1975; Welton and Farish, 1993).

Six different species of chondrichthyans were found in the lag deposit separating the Blufftown Formation and Cusseta Sands along Hannahatchee Creek. Erosion and hydrodynamic sorting must account for the juxtaposition of these Campanian fossils. Furthermore, the lag deposit, which contains these Campanian fossils, lies directly above an erosional

disconformity, suggesting mixing of lower and upper Campanian fossil representatives (Becker et al., 1996).

### Alabama

Ammonites and Nautiloids: Ammonites collected from Trussels Creek during this study include the following genera: *Menuites* sp., *Baculites* sp., *Didymoceras* sp., *Placentoceras* sp. In addition, specimens of the nautiloid *Eutrophoceras* sp. were also collected. Ammonites and nautiloids are preserved as highly fragmentary siderite steinkerns where dissolution has removed all original shell material. Siderite steinkerns suggest a significant amount of groundwater percolation through the lag deposit. The fragmentary nature of the ammonites and nautiloids suggest active transport and reworking.

Chondrichthyan Teeth: Sharks teeth collected from Trussels Creek during this study include: *Squalicorax kaupi*, *Cretolamna appendiculata*, *Ptychodus mortoni*, *Scapanorhynchus texanus* and *Brachyrhizodus wichitaensis*. The majority of chondrichthyan teeth are fragmentary and show signs of abrasion. The fragmentary, abraded nature of chondrichthyan teeth suggests active transport and reworking.

Compilation of chondrichthyan and ammonites age ranges, based on specimens collected from lag deposit outcrops separating the Eutaw Formation and Tombigbee Sands indicate preservation of remains from different stages. The formation of the unconformity separating these

deposits, (see section on Alabama stratigraphy and sedimentology), has resulted in the mixing of Santonian-Campanian ammonite and chondrichthyan biozones.

Age of the Alabama Lag Deposit Based on Macrofossil Biostratigraphy:

An age interpretation obtained by overlapping the first and last appearance of ammonite genera indicates an upper Santonian to upper Campanian age. The chondrichthyan *Ptychodus mortoni* is Santonian age (Welton and Farish, 1993). This species co-occurs with teeth of *Squalicorax kaupi*, *Paranomotodon angustidens* and *Brachyrhizodus wichitensis* which make their last appearance in the Campanian. This suggests mixing of Santonian and Campanian fossils (Cappetta and Case, 1975; Welton and Farish, 1993).

Because five different species of chondrichthyans, four different species of ammonites and one species of nautiloid can be found together in lag deposits separating the Eutaw Formation and Tombigbee Sands, erosion and hydrodynamic sorting must account for the juxtaposition of these fossil representatives. Furthermore, the lag deposit, which has an average thickness of thirty centimeters and lies directly above an erosional disconformity, contains both Santonian and Campanian fossil representatives. This suggests that the Santonian-Campanian boundary in Trussels Creek outcrops must reside within the thirty centimeters that comprise the macrofossil lag (Becker et al., 1996).

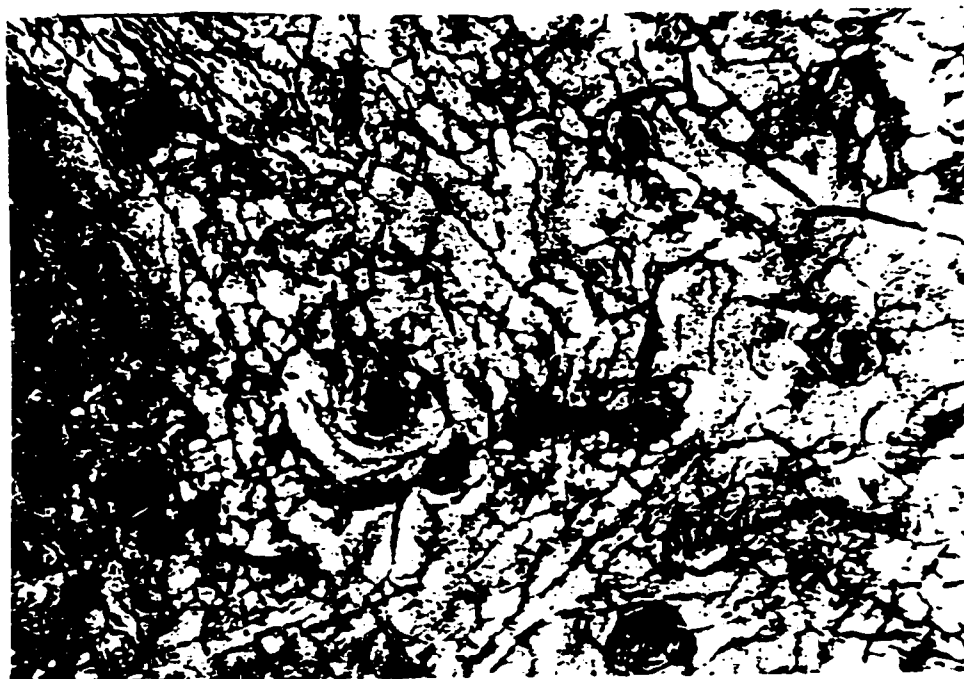
### Thin Section Petrography: Plain and Cross Polarized Light

Thin section analyses with a petrographic microscope and cathodoluminescence were performed on the following teeth: *Ptychodus mortoni* and *Squalicorax kaupi* from Alabama; *Paranomotodon angustidens* and *Carcharis* sp. B from New Jersey and *Scapanorhynchus texanus* from Georgia.

Figure 39 shows the appearance of chondrichthyan tooth osteodentine and orthodentine under plain-polarized light at high (40X) magnification. The composition of these teeth appeared to consist primarily of biogenic apatite. Optical properties of biogenic apatite observed in these thin sections are included in the following: 1) Indices of Refraction:  $E=1.630-1.645$ ,  $W=1.632-1.649$ ; 2) Birefringence:  $0.003-0.005$ , with maximum interference color = gray-white of the first order; 3) Color: colorless, pale green, black or brown as seen in collophane; 4) Form: hexagonal, poor basal (0001) cleavage; and 5) Crystal Habit: apatite, common to teeth and bones typically is spherulitic, oolitic, plumose, radiating or cryptocrystalline in structure (Heinrich, 1965).

No authigenic siderite, calcite, aragonite or dolomite overgrowths were observed on any of the thin sections of the teeth under plain and cross polarized microscope techniques.

Crowns of teeth *Carcharis* sp. B, *Squalicorax kaupi*, *Squalicorax pristodontus* and *Paranomotodon angustidens* appeared to consist primarily



(Fig. 39) *Squalicorax kaupi*, showing collophane minerals, plain polarized light, 40X magnification.

of enameloid with lesser amounts of orthodontine and osteodontine (Fig. 40). Roots in these species consisted exclusively of osteodontine and orthodontine. A molar tooth from the upper Cretaceous shell crushing shark, *Ptychodus mortoni*, had a more homogeneous composition. In this species, both crown and root consist primarily of orthodontine and osteodontine with limited enameloid coating the apical portion of the tooth.

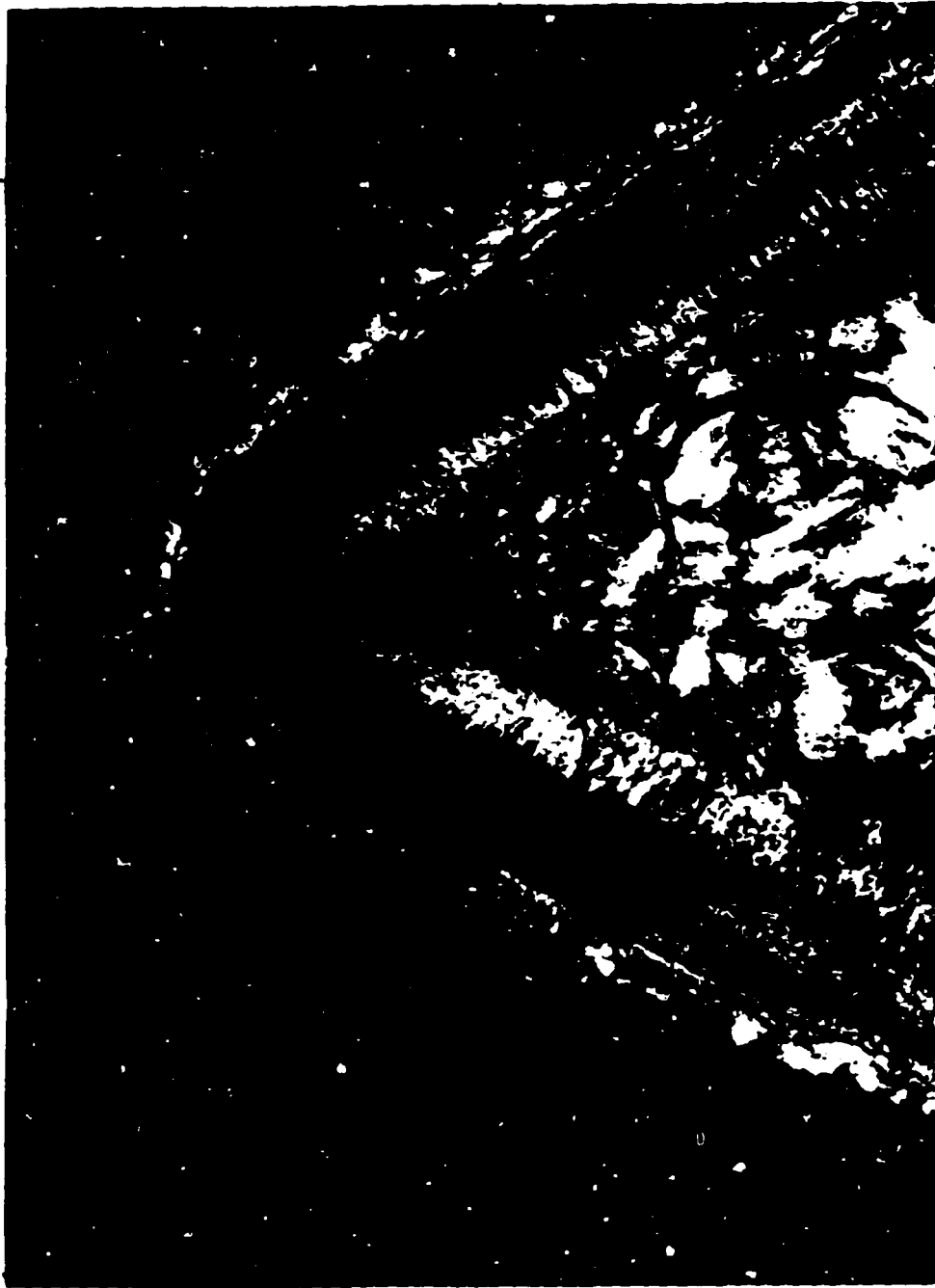
### Cathodoluminescence

Cathodoluminescence techniques isolated a few larger euhedral mineral grains within the osteodontine of tooth roots (Fig. 41). These mineral grains luminesced bright reddish-orange under (4X) magnification on *Squalicorax kaupi* from Trussells Creek Alabama and *Carcharis* Sp. B from New Jersey.

Comparison of these larger euhedral mineral grains using the identification techniques outlined by Marshall, 1988, indicate that these reddish-orange grains are authigenic calcite. These grains appeared as small areas of mineral growth within the osteodontine root structure of *Squalicorax kaupi* and *Carcharis* sp. B. (Removal of authigenic mineral growth and possibility of diagenetic alteration are discussed in methodology section.)

### Sr<sup>87</sup>/Sr<sup>86</sup> Isotopic Comparison and Identification of Diagenetic Alteration

Table 1 summarizes the Sr<sup>87</sup>/Sr<sup>86</sup> isotopic comparison data for *Carcharis* sp. B, *Squalicorax kaupi*, *Paranomotodon angustidens* and



(Fig. 40) *Squalicorax kaupi* crown showing enameloid and osteodentine, cross polarized light, 4x magnification.



(Fig. 41) Euhedral calcite grains infilling void space in *Carcharis* sp. B. Cathodoluminescence conditions were approximately 15kV, 1mA and a beam diameter approximately 3 mm, 40x magnification.

*Ptychodus mortoni*. The crowns of teeth *Carcharis* sp. B, *Squalicorax kaupi* and *Paranomotodon angustidens* showed lower  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratios than bases. *Ptychodus mortoni* showed no significant difference in  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratio from crown to base (Table 1). Differences in isotopic ratio in teeth *Carcharis* sp. B, *Squalicorax kaupi* and *Paranomotodon angustidens* indicate some diagenetic alteration must have taken place in the burial site.

The most probable cause for this differential uptake in strontium is groundwater percolation. Lag deposits contain the coarsest and most permeable material of outcrop exposures, resulting in preferred groundwater flow concentration. Illites and other clays can contain minor amounts of strontium. Groundwater in contact with these clays could have incorporated minor amounts of this strontium and then percolated through the more porous and permeable portions of the chondrichthyan tooth apatite. Diagenetic alteration may have occurred if strontium from this groundwater source was deposited into the tooth apatite (Krueger, 1996, personal communication).

Thin section analysis and cathodoluminescence indicate the root structures in *Carcharis* sp. B, *Squalicorax kaupi* and *Paranomotodon angustidens* to contain greater porosity and permeability and therefore, greater susceptibility to diagenetic alteration. Isotopic results in each of these species indicate the tooth bases all contain higher  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios.

Table 1: Measured  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios in Crowns Vs Bases

<u>Chondrichthyan Species</u>	<u><math>\text{Sr}^{87}/\text{Sr}^{86}</math> (Tops)</u>	<u>Error (+/- 2 S.D.)</u>	<u>Calculated Age (in Ma)</u>
1. <i>Carcharis</i> sp. B	0.707764	7	76.8
2. <i>Squalicorax kaupi</i>	0.707658	8	82.1
3. <i>Paranomotodon angustidens</i>	0.707769	8	76.6
4. <i>Ptychodus mortoni</i>	0.707751	8	77.5
<u>Chondrichthyan Species</u>	<u><math>\text{Sr}^{87}/\text{Sr}^{86}</math> (bases)</u>	<u>Error (+/- 2 S.D.)</u>	<u>Calculated Age (in Ma)</u>
1. <i>Carcharis</i> sp. B	0.707882	7	65.9
2. <i>Squalicorax kaupi</i>	0.707717	8	70.9
3. <i>Paranomotodon angustidens</i>	0.707883	8	65.9
4. <i>Ptychodus mortoni</i>	0.707753	7	77.4

Absolute ages were calculated from the equation:  $(\text{Sr}^{87}/\text{Sr}^{86}) = -2 \times 10^{-5}(\text{age in Ma}) + .7093$   
 From: Composite Age vs.  $\text{Sr}^{87}/\text{Sr}^{86}$  Concentration linear trendline. Based on age vs. concentration measurements of MacAuthur et al.(1994); Hess et al. (1986); MacDougall (1988) and Sugarman et al. (1995).

The Strontium analyses are normalized to  $\text{Sr}^{88}/\text{Sr}^{86} = 0.11940$

Analysis of National Bureau of Standards (NBS) 987 averaged 0.710241 (15) (n= between 65 and 71) during the period of these analyses.

Errors on  $\text{Sr}^{87}/\text{Sr}^{86}$  are given as 2 sigma (95%) in the last two digits.

Absolute ages were calculated from the equation:

$$(\text{Sr}^{87}/\text{Sr}^{86}) = -2 \times 10^{-5}(\text{age in Ma}) + 0.7093$$

Sample analyses done at the Institut fuer Geologie, Ruhr-Universitaet Bochum, in Germany by Dr. Dieter Buhl.

Percolation of Sr<sup>87</sup> into osteodentine and orthodentine root structures from groundwater and a surrounding clay source could have resulted in higher measured isotopic ratios. The much less porous and permeable enameloid located along the tooth crown did not incorporate significant additional strontium from groundwater sources.

*Ptychodus mortoni* has a more homogeneous composition of crown and root structure. Moreover, *Ptychodus mortoni* lacks the thick, exterior enameloid coating seen along the crowns of *Carcharis* sp. B, *Squalicorax kaupi* and *Paranomotodon angustidens*. This would have rendered *Ptychodus mortoni* uniformly susceptible, from crown to base, to groundwater percolation. Groundwater percolation would have uniformly raised the Sr<sup>87</sup>/Sr<sup>86</sup> isotopic ratio across the entire tooth structure, resulting the observed insignificant difference in Sr<sup>87</sup>/Sr<sup>86</sup> isotopic ratio between crown and root (see Fig. 31).

#### Absolute Age Determination and Confidence Interval Analyses

All absolute age determinations were compiled from the formula  $Sr^{87}/Sr^{86}(\text{Measured}) = 2 \times 10^{-5}(\text{Age in Ma}) + 0.7093$  (Tables 2, 3 and 4). (See methodology section, for justification). The maximum error on all dated samples occurred in a specimen of *Carcharis* sp. B from New Jersey with error of  $\pm 0.000014$  Sr<sup>87</sup>/Sr<sup>86</sup> or  $\pm$  approximately 700, 000 years.

Larger error bars ranging from  $\pm 1.2$ - 2.0 Ma were cited in the study of Sugarman et al., 1996, in the development of strontium reference

Table 2: Measured  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios in Monmouth County, New Jersey Chondrichthyan Teeth

<u>Chondrichthyan Species</u>	<u><math>\text{Sr}^{87}/\text{Sr}^{86}</math> (<math>\pm</math> 2 S.D.)</u>	<u>Error</u>	<u>Age (in Ma)</u>
1. <i>Carcharis</i> sp. B	0.707727	14	78.7
2. <i>Brachyrhizodus wichitaensis</i>	0.707763	13	76.9
3. <i>Squalicorax kaupi</i>	0.707766	11	76.7
4. <i>Squalicorax kaupi</i>	0.707764	11	76.8
5. <i>Cretolamna apendiculata</i>	0.707743	11	77.9
6. <i>Cretolamna apendiculata</i>	0.707736	08	78.2
7. <i>Scapanorhynchus texanus</i>	0.707700	11	80.0
8. <i>Scapanorhynchus texanus</i>	0.707739	10	78.1
9*. <i>Carcharis</i> sp. B	0.707764	7	76.8
10*. <i>Paranomotodon angustidens</i>	0.707769	8	76.6

The Strontium analyses are normalized to  $\text{Sr}^{88}/\text{Sr}^{86} = 0.11940$

Analysis of National Bureau of Standards (NBS) 987 averaged 0.710241 (15) (n= between 65 and 71) during the period of these analyses.

Errors on  $\text{Sr}^{87}/\text{Sr}^{86}$  are given as 2 sigma (95%) in the last two digits.

Absolute ages were calculated from the equation:

$$(\text{Sr}^{87}/\text{Sr}^{86}) = -2 \times 10^{-5} (\text{age in Ma}) + 0.7093$$

From: Composite Age vs.  $\text{Sr}^{87}/\text{Sr}^{86}$  Concentration linear trendline. Based on age vs. concentration measurements of MacAuthur et al., (1994); Hess et al., (1986); MacDougall, (1988) and Sugarman et al., (1995).

\* Samples analysis done at the Institut fuer Geologie, Ruhr-Universitaet Bochum, in Germany by Dr. Dieter Buhl.

Table 3: Measured  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios in Hannahatchee Creek, Omaha, Georgia Chondrichthyan Teeth

<u>Chondrichthyan Species</u>	<u><math>\text{Sr}^{87}/\text{Sr}^{86}</math></u>	<u>Error (+/- 2 S.D.)</u>	<u>Age (in Ma)</u>
1. <i>Cretolamna appendiculata</i>	0.707663	08	81.9
2. <i>Cretolamna apendiculata</i>	0.707783	13	75.9
3. <i>Cretolamna apendiculata</i>	0.707758	11	77.1
4. <i>Scapanorhyncus texanus</i>	0.707611	11	84.5
5. <i>Scapanorhyncus texanus</i>	0.707667	13	81.7
6. <i>Scapanorhyncus texanus</i>	0.707707	10	79.7
7. <i>Scapanorhyncus texanus</i>	0.707645	11	82.8
8. <i>Squalicorax kaupi</i>	0.707774	10	76.3
9. <i>Squalicorax kaupi</i>	0.707767	08	76.7
10. <i>Squalicorax kaupi</i>	0.707800	10	75.0

The Strontium analyses are normalized to  $\text{Sr}^{88}/\text{Sr}^{86} = 0.11940$

Analysis of National Bureau of Standards (NBS) 987 averaged 0.710241 (15) (n= between 65 and 71) during the period of these analyses.

Errors on  $\text{Sr}^{87}/\text{Sr}^{86}$  are given as 2 sigma (95%) in the last two digits.

Absolute ages were calculated from the equation:

$$(\text{Sr}^{87}/\text{Sr}^{86}) = -2 \times 10^{-5} (\text{age in Ma}) + 0.7093$$

From: Composite Age vs.  $\text{Sr}^{87}/\text{Sr}^{86}$  Concentration linear trendline. Based on age vs. concentration measurements of Hess et al., (1986); MacDougall, (1988); MacAuthur et al., (1994) and Sugarman et al., (1995).

\* Samples analysis done at the Institut fuer Geologie, Ruhr-Universitaet Bochum, in Germany by Dr. Dieter Bulh.

Table 4: Measured  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios in Trussels Creek, Alabama Chondrichthyan Teeth

<u>Chondrichthyan Species</u>	<u><math>\text{Sr}^{87}/\text{Sr}^{86}</math></u>	<u>Error (+/- 2 S.D.)</u>	<u>Age (in Ma)</u>
1. <i>Cretolamna appendiculata</i>	0.707616	10	84.2
2. <i>Cretolamna appendiculata</i>	0.707681	11	81.0
3. <i>Scapanorhynchus texanus</i>	0.707601	10	85.0
4. <i>Scapanorhynchus texanus</i>	0.707633	11	83.4
5. <i>Squalicorax kaupi</i>	0.707674	11	81.3
6. <i>Squalicorax kaupi</i>	0.707686	11	80.7
7. <i>Ptychodus mortoni</i>	0.707760	11	77.0
8. <i>Ptychodus mortoni</i>	0.707587	10	85.7
9*. <i>Squalicorax kaupi</i>	0.707658	8	82.1
10*. <i>Ptychodus mortoni</i>	0.707751	8	77.5

The Strontium analyses are normalized to  $\text{Sr}^{88}/\text{Sr}^{86} = 0.11940$

Analysis of National Bureau of Standards (NBS) 987 averaged 0.710241 (15) (n= between 65 and 71) during the period of these analyses.

Errors on  $\text{Sr}^{87}/\text{Sr}^{86}$  are given as 2 sigma (95%) in the last two digits.

Absolute ages were calculated from the equation:

$$(\text{Sr}^{87}/\text{Sr}^{86}) = -2 \times 10^{-5} (\text{age in Ma}) + 0.7093$$

From: Composite Age vs.  $\text{Sr}^{87}/\text{Sr}^{86}$  Concentration linear trendline. Based on age vs. concentration measurements of Hess et al. (1986), MacDougall, (1988); MacAuthur et al., (1994) and Sugarman et al., (1995).

\* Samples analysis done at the Institut fuer Geologie, Ruhr-Universitaet Bochum, in Germany by Dr. Dieter Buhl.

section DSDP Site 525 A. These larger errors occurred in two foraminifera samples of Campanian age (Sugarman et al., 1995). Sugarman et al., 1995, achieved 2 sigma values as high as  $\pm 0.000026$  on  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratios measured on planktonic foraminifera in the strontium reference section established off the western coast of Africa. (Errors in this dating methodology are given as 2 sigma (95%) in the last two digits of the  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic measurement). These researcher's higher errors may be the product of instrumentation and measurement and/or the higher susceptibility of carbonate organisms to diagenetic alteration.

### New Jersey

The oldest dated sample from New Jersey was *Scapanorhynchus texanus* which yielded an age of 80.0 Ma while the youngest sample was *Paranomotodon angustidens* which yielded an age of 76.6 Ma. The mean age of ten dated samples was 77.7 Ma with a standard deviation of 1.1 Ma. Confidence interval analysis results indicate age ranges of 76.5 to 78.8 Ma for teeth from the New Jersey lag deposit. Reworking and time averaging of chondrichthyan teeth representatives in the New Jersey lag deposits is suggested to be approximately 2.3 Ma by these confidence interval results (Table 5).

**Table 5: Confidence Interval Analyses for New Jersey, Georgia and Alabama Chondrichthyan Teeth**

Number of Samples	Mean	Standard Deviation	Confidence Interval	Min./Max. Age (in Ma)	Range of Mixing (in Ma)
New Jersey 10	77.7	1.1	99	76.5/78.8	2.3
Georgia 10	79.2	3.4	99	75.7/82.7	7.0
Alabama 10	81.8	2.9	99	78.8/84.8	6.0

Formula:  $\bar{x} \pm t_{\alpha/2, n-1} \cdot s / \sqrt{n}$  where:  $\bar{x}$ = sample mean;  $t$ = value related to how closely sample population approximates the z or normal distribution;  $\alpha$  = 1- confidence interval;  $s$ = standard deviation for samples;  $n$ = number of samples. Formulas from Devore, (1995). Standard deviation can be calculated from formula:

$$s^2 = \sum_{i=1}^n \frac{(x_i - \bar{x})^2}{n-1}$$

## Georgia

The oldest dated sample from Georgia was *Scapanorhyncus texanus* which yielded an age of 84.5 Ma while the youngest sample was *Squalicorax kaupi* which yielded an age of 75.0 Ma. The mean age of ten dated samples was 79.2 Ma with a standard deviation of 3.4 Ma. Confidence interval analysis results indicate age ranges of 75.7 to 82.7 Ma for fossils in the Georgia lag deposit. Reworking and time averaging of chondrichthyan teeth in the Georgia lag deposits is suggested to be approximately 7.0 Ma by these confidence interval results (Table 5).

## Alabama

The oldest dated sample from Alabama was *Ptychodus mortoni* which yielded an age of 85.7 Ma while the youngest sample was also a *Ptychodus mortoni* tooth which yielded an age of 77.0 Ma. The mean age of ten dated samples was 81.8 Ma with a standard deviation of 2.9 Ma. Confidence interval analysis results interval indicate age ranges of 78.8 to 84.8 Ma for fossils in the Alabama lag deposit. Reworking and time averaging of chondrichthyan teeth in the Alabama lag deposits is suggested to be approximately 6.0 Ma by these confidence interval results (Table 5).

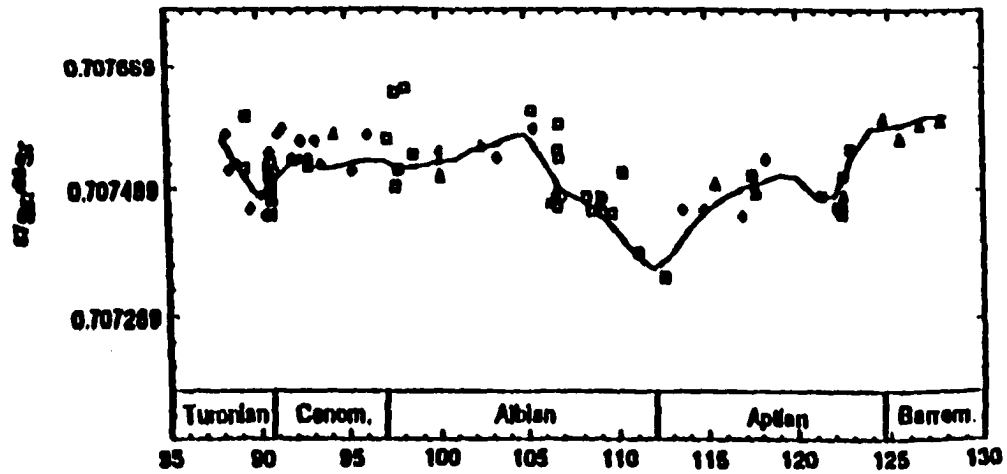
## **Discussion**

### Are Chondrichthyan Teeth Accurate $\text{Sr}^{87}/\text{Sr}^{86}$ Isotopic and Age Indicators?

Toyoda and Tokonami 1990, analyzed diffusion of rare earth elements in fish teeth from deep sea sediments in order to address the

utility of fish teeth as paleoceanographic indicators. Their results indicate that diffusion coefficients of rare earth elements from seawater into fish teeth before burial is too slow to account for the observed rare earth element enrichments. Instead Toyoda and Tokonami 1990, contend that the rare earth element concentrations found in fish teeth must be due to surrounding pore fluids in contact with buried teeth. Analysis of the rare earth element, lanthanum, in teeth from base towards crown showed a reduction from 1500 p.p.m. to 500 p.p.m. suggesting less susceptibility of the crowns of teeth to diagenesis.

Ingram et al., 1994, identified detrital clay minerals in contact with fossil fish teeth to be high in  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios and a possible candidate to alter the original isotopic  $\text{Sr}^{87}/\text{Sr}^{86}$  signature. For their study in comparing  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratio to mid-Cretaceous oceanic anoxic events, Ingram et al., 1994, selected the lowest  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratios measured in the fish teeth to provide the best estimate of original seawater. In support of this, a plot of  $\text{Sr}^{87}/\text{Sr}^{86}$  measured ratios, from forty-seven fish teeth samples from Aptian to Turronian age, was compared to previously published  $\text{Sr}^{87}/\text{Sr}^{86}$  measured ratios made on DSDP foraminifera and foraminiferal limestones (Fig 42). Maximum deviation from the averaged, interpolated best fit line was approximately plus 0.000160  $\text{Sr}^{87}/\text{Sr}^{86}$ , occurring in two teeth specimens from the Albian-Cenomanian boundary.



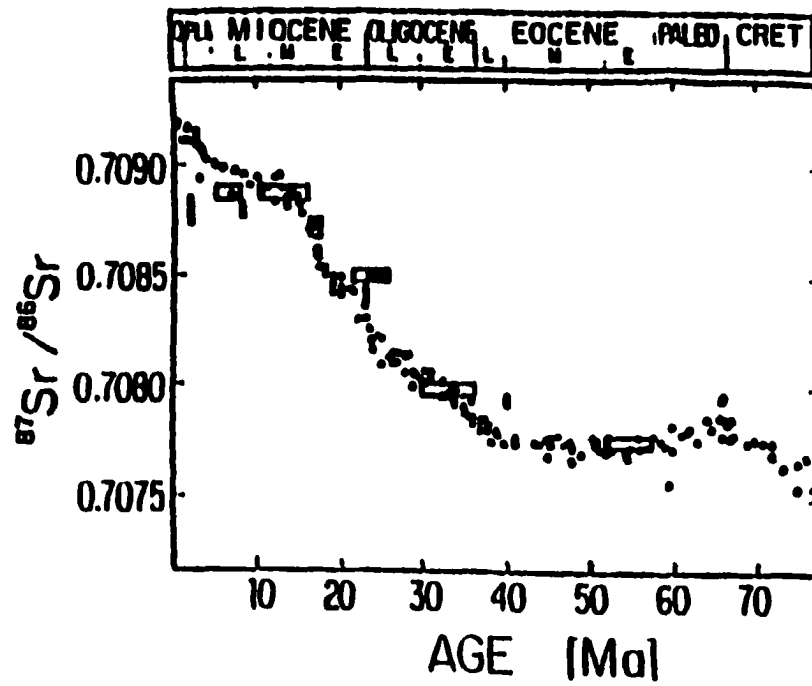
(Fig. 42)  $Sr^{87}/Sr^{86}$  isotopic ratios for the mid-Cretaceous plotted against fish teeth, (squares), DSDP foraminifer, (triangles), and foraminiferal limestones, (diamonds). Maximum deviation from the strontium sea level curve is approximately 0.000160  $Sr^{87}/Sr^{86}$  occurring at the Albian-Cenomanian boundary. From Ingram et al., (1994).

Staudigel et al., 1985, plotted the known Cretaceous to Quaternary  $\text{Sr}^{87}/\text{Sr}^{86}$  curve for marine carbonates against  $\text{Sr}^{87}/\text{Sr}^{86}$  measurements from fish teeth from the Indian, Pacific and Atlantic Oceans as well as from the Caribbean and Southern Seas. Age ranges for these teeth samples were cited from Recent to approximately 55 Ma (Fig. 43). Staudigel et al., 1985, indicate that deviations of the  $\text{Sr}^{87}/\text{Sr}^{86}$  ratios measured on fish teeth compared to the  $\text{Sr}^{87}/\text{Sr}^{86}$  seawater curve may be caused by diagenetic carbonate in the cavities of fish teeth and removal of this material may be necessary to achieve good agreement between samples and the  $\text{Sr}^{87}/\text{Sr}^{86}$  seawater curve.

MacArthur et al., 1994, applied thin section and cathodoluminescence analyses to ammonite thin sections to identify diagenetic alteration that had potential of adversely affecting  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic measurements in ammonites. To further support this, multiple  $\text{Sr}^{87}/\text{Sr}^{86}$  analyses were made on individual samples and used as a measure of preservation and diagenetic alteration. These techniques were also supported by Staudigel et al., 1985, who, having identified authigenic carbonate as a possible source of diagenetic alteration, treated separates from fish teeth with acetic acid prior to dissolution for isotopic analyses.

#### Diagenetic Alteration

The treatment procedures (e.g. plain and cross-polarized light analyses, cathodoluminescence, dual  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic analyses on single



(Fig. 43) Comparison of  $Sr^{87}/Sr^{86}$  isotopic ratios of Marine Carbonates, (dots), to Tertiary and Quaternary fish teeth, (rectangles). From Staudigel et al., (1985).

samples and acid cleaning) applied during this study identified and removed minor calcite before  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic analyses were conducted. This however, does not eliminate the possibility of additional strontium being added by adjacent clay minerals and groundwater percolation into teeth samples.

An independent measure of the value of using  $\text{Sr}^{87}/\text{Sr}^{86}$  analyses on chondrichthyan teeth is that the biostratigraphy of selected field areas are well known. Moreover, the known biostratigraphy of upper Cretaceous chondrichthyan teeth and ammonites from such sources as Cappetta and Case, 1975; Welton and Farish, 1993; Kennedy and Cobban, 1994; Kennedy et al., 1995; and Kent, 1994; allows for confirmation and cross-checking of calculated  $\text{Sr}^{87}/\text{Sr}^{86}$  ages made on chondrichthyan teeth.

A comparison of age calculations made from dual  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratio measurements on chondrichthyan teeth crowns verses bases, shows the  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratio of the crowns of teeth to conform better to the known biostratigraphy. All sections studied in the New Jersey, Georgia and Alabama field areas showed taphonomic mixing of Campanian macrofossils. Calculated ages 76.8, 82.1, 76.6 and 77.5 Ma for crowns of *Carcharis* sp. B, *Squalicorax kaupi*, *Paranomotodon angustidens* and *Ptychodus mortoni* respectively, fall well within the known age range of the Campanian (approximately 84-71.5 Ma); (See Tables 2, 3 and 4).

Bases of three teeth gives calculated of 65.9, 70.9 and 65.9 for *Carcharis* sp. B, *Squalicorax kaupi*, *Paranomotodon angustidens* respectively. These three ages are well above the known biostratigraphy and correspond better with late Maastrichtian-early Tertiary dates, (approximately 65.5 Ma for the K-T boundary); (Hallam et al., 1985). This is clearly not possible given the stratigraphic position from which these teeth were collected.

Microscopic analysis of chondrichthyan thin sections perhaps has identified the source of the differing isotopic measurements. Enameloid, osteodentine and orthodentine all consist of biogenic apatite. However, enameloid coating the crowns of teeth, is far less porous and permeable than root structures. The isotopic dates on root structures are higher in all four  $\text{Sr}^{87}/\text{Sr}^{86}$  measurements, suggesting the susceptibility of porous and permeable root structures to diagenetic alteration (Table 1).

#### $\text{Sr}^{87}/\text{Sr}^{86}$ Isotopic Dating of Chondrichthyan Teeth

Biogenic apatite which comprises fossil chondrichthyan teeth is far less soluble than calcite. Schmitz et al., 1991, cite the solubility product of apatite as  $2 \times 10^{-33}$  while calcite has a solubility product  $5 \times 10^{-9}$ . The higher solubility seen in organisms constructing their shells out of carbonate may render such organisms, and the fossils they leave behind, more susceptible to diagenetic alteration. The lower solubility of chondrichthyan teeth make them excellent candidates for  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic dating studies.

An additional advantage to using chondrichthyan teeth for  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic dating studies is the ability to remove authigenic calcite through acid cleaning procedures. Authigenic calcite can contain minor amounts of ionically substituted strontium. If the ionically substituted strontium is not removed, the possibility of interpreting this strontium as original isotopic signature exists. Biogenic apatite, comprising chondrichthyan teeth, is not susceptible to dissolution in weak acids. Preferential removal of authigenic calcite can be accomplished through application of weak acids and simple filtration techniques, without significantly affecting the biogenic apatite. Similar treatment procedures cannot be applied to calcitic organisms which contain strontium-contaminated, authigenic calcite. Both original and authigenic calcite are susceptible to dissolution in weak acids. Therefore, only the most pristine of calcitic samples can be selected for application of  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic dating.

Of the thirty chondrichthyan teeth isotopically analyzed during this study, only *Ptychodus mortoni* and *Carcharis* sp. B yielded  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ages which were younger than their known biostratigraphy. *Ptychodus mortoni* is cited by Welton and Farish, 1993, as Santonian. Of three absolute age determinations on this tooth, two teeth yielded 77.0 and 77.5 Ma. If the upper limit of the Santonian stage boundary is approximately 84 Ma as suggested by Hallam et al., 1985, it appears that *Ptychodus mortoni*, as indicated by the Alabama lag deposit, lived into the

lower Campanian. Alternatively, the two *Ptychodus mortoni* teeth which yielded lower Campanian ages may have experienced minor diagenetic alteration. As described above, *Ptychodus mortoni* lacks well developed enameloid surrounding the tooth crown. Additional strontium from outside sources may have been added to the original  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic signature of the enameloid by groundwater percolation. This would alter the original  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratios and result in the younger calculated ages.

The most probable cause for younger calculated ages on *Ptychodus mortoni* is diagenetic alteration through groundwater percolation. The Tombigbee Sands consist of highly unconsolidated, clean quartz sands of high porosity and permeability. The underlying Eutaw Formation consists of much less porous and permeable muds. The lag deposit where *Ptychodus mortoni* was collected from along Trussels Creek exists at the boundary between these two deposits. Groundwater flow along Trussels Creek percolates vertically downward through the more porous and permeable Tombigbee Sands until it reaches the less porous and permeable Eutaw Formation. Groundwater flow is then forced horizontally along the contact between the Eutaw Formation and Tombigbee Sands and directly through the lag deposit. Potentially, this groundwater flow contained minor amounts of strontium which percolated into *Ptychodus mortoni* and resulted in the younger calculated ages.

*Carcharis* sp. B is cited by Welton and Farish, 1993, as Maastrichtian in age. Two teeth yielded absolute ages of 78.7 and 76.8 Ma. If the lower limit of the Maastrichtian stage boundary is approximately 71.5 Ma as suggested by Hallam et al., 1985, it appears that *Carcharis* sp. B, as indicated by the New Jersey lag deposits, lived in the upper Campanian as well as the Maastrichtian.

Two alternative possibilities for the age discrepancy in *Carcharis* sp. B the identification of this tooth or diagenetic alteration. Welton and Farish, 1993, indicate the distinguishing characteristics for *Carcharis* sp. B are a: 1) much larger adult tooth size than other Cretaceous odontaspids; 2) wider crown bases; and 3) more extensive lingual crown ornamentation. Case, 1995, classifies the same tooth in a recently updated selachian faunal list from New Jersey as *Carcharis holmdelensis*. If *Carcharis holmdelensis* is the correct identification, potentially an older biostratigraphic assignment exists for this chondrichthyan.

The enameloid located along the crown of *Carcharis* sp. B appeared similar to that of *Squalicorax kaupi* and *Scapanorhynchus texanus* under plain and cross-polarized light. Both *Squalicorax kaupi* and *Scapanorhynchus texanus* yielded ages consistent with their known biostratigraphy. Additionally, no special circumstances were observed during the application of cathodoluminescence or during the  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratio comparison of tooth crown and base on *Carcharis* sp. B.

Therefore, the more probable explanations for the older than expected ages of *Carcharis* sp. B are related to the identification and biostratigraphy of this tooth.

Overall, twenty-six out of thirty (or approximately 87%) of the chondrichthyan teeth dated during this study, support the biostratigraphy and chronostratigraphy of the lag horizons from where they were collected (Fig. 44). (The four teeth whose absolute age fell outside the known biostratigraphy are discussed above). The implications for the accuracy of this data are: 1) chondrichthyan teeth yield accurate  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic ratios and absolute ages, barring diagenetic alteration and specimen identification discrepancies; and 2) chondrichthyan teeth provide an important means for studying the dynamics of sea level cyclicity and taphonomy of fossil deposits.

Additional field collecting from the Atlantic and Eastern Gulf Coastal Plain as well as European sections coupled with careful cross-checking against microfossil and macrofossil biostratigraphy; and  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic dating will more than likely: 1) improve upon the known Cretaceous chondrichthyan biostratigraphy; and 2) increase the use of chondrichthyan teeth in biostratigraphy and chronostratigraphic studies.

Strontium Dated Chondrichthyan Species	Chondrichthyan Biostratigraphy			# of individual teeth dated	# of teeth falling outside known age range	Range of Sr87/Sr86 Ages (in MA)
	SA	CA	MA			
<i>Squalicorax kaupi</i>				8	0	82.1-75.0
<i>Cretolamna appendiculata</i>				7	0	84.2-75.9
<i>Paranomotodon cf. angustidens</i>				1	0	76.6
<i>Carcharis sp. B</i>				2	2	78.7-76.8
<i>Scapanorhynchus texanus</i>				8	0	85.0-78.1
<i>Brachyrhizodus wichitaensis</i>				1	0	76.9
<i>Ptychodus mortoni</i>				3	2	85.7-77.0
		84.4 Ma	70.5 Ma	Total # of teeth	Total # of teeth falling outside known age ranges	Percentage of teeth confirming Biostratigraphy and Regional Stage Boundary Age Assignments
Regional Stage Boundary Age Assignments	King and Skotnicki, (1994)	Sugarman et al., (1995)	30			

(Fig. 44) Correlation diagram of chondrichthyan biostratigraphy from Cappetta and Case, (1975) and Welton and Farish, (1993) compared to: 1) regional stage boundary age assignments of King and Skotnicki, (1994) and Sugarman et al, (1995); 2) number of individual teeth dated; 3) number of of teeth falling outside known biostratigraphy and regional stage boundary age assignments; and 4) percentage of teeth confirming biostratigraphy and regional stage boundary age assignments. Maximum error on all strontium dated teeth is  $\pm 700,000$  Ma. (For justification: see text results: absolute age determination). SA= Santonian, CA=Campanian and MA=Maastrichtian.

## Role of Sea Level in Lag Deposit Formation

### New Jersey

In order to establish the Campanian-Maastrichtian stratigraphic framework of the New Jersey coastal plain, Sugarman et al., 1995, developed DSDP strontium reference site 525A from the western coast of Africa. Foraminifera, *Pycnodonte*, *Exogyra* and belemnite fossils collected from the Wenonah-Mt. Laurel and Navesink Formations in outcrop and land drilled wells of the New Jersey coastal plain were then compared to DSDP 525A in order to determine absolute ages. Using regression analysis on DSDP site 525A data, Sugarman et al., 1995, cite the isotopic age for the Campanian-Maastrichtian boundary in New Jersey outcrops to be 70.5 Ma. Stratigraphically, this boundary is placed between the Wenonah-Mt. Laurel and Navesink Formations in New Jersey outcrops (Kennedy and Cobban, 1994; Sugarman et al., 1995 and Becker et al., 1996).

Isotopic ages on ten New Jersey chondrichthyan teeth are Campanian age (Table 2). If the Sugarman et al., 1995, assignment of 70.5 Ma is correct for the boundary between the Wenonah-Mt. Laurel and Navesink Formations, chondrichthyan teeth must have been exhumed and reworked from the underlying Wenonah-Mt. Laurel Formation during third order sea level regression 3 of UZA 4 of Haq et al., 1988.  $Sr^{87}/Sr^{86}$  calculations indicate teeth from as far back as 80.0 Ma to be incorporated in this lag deposit. Reworking and exhumation of teeth from the Wenonah-Mt.

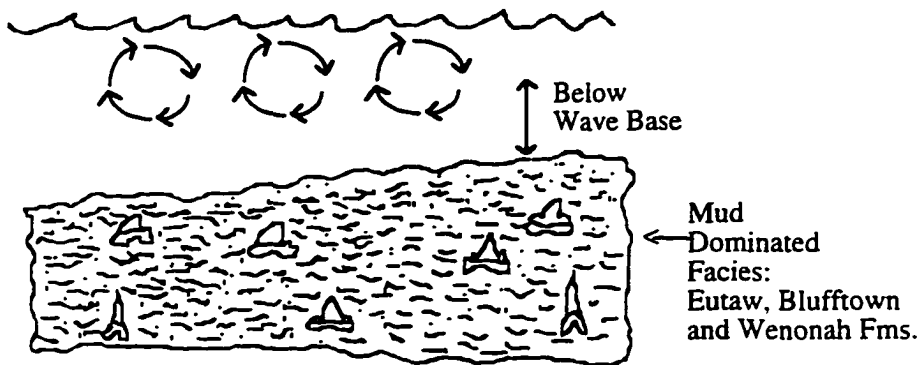
Laurel Formations ended sometime after 76.6 Ma as indicated by the youngest tooth in the lag deposit, during third order sea level transgression 4 of UZA 4 of Haq et al., 1988. Confidence interval analysis for this lag deposit suggest 2.3 million years of reworking and time averaging in the lag deposit separating the Wenonah-Mt. Laurel and Navesink Formations and therefore across the Campanian-Maastrichtian boundary in New Jersey outcrops.

Lack of teeth younger than 75 Ma in New Jersey lag deposits may reflect a preferred time period of teeth accumulation under optimum paleobathymetric conditions. Potentially, greater concentrations of sharks were living in offshore zones of inner shelf paleoenvironments approximately 76 to 80 Ma. As regressive sea level event 3 of UZA 4 of Haq et al., 1988, occurred, these sharks migrated seaward to more suitable water depths. Continuing regression would have exhumed and reworked the teeth these sharks left behind. Subsequent transgressive sea level event 4 of UZA 4 of Haq et al., 1988, would have continued to rework and transport these teeth landward. These teeth eventually were deposited and preserved stratigraphically higher in the section along Big, Willow and Ramanessin Brooks in New Jersey along the Campanian-Maastrichtian boundary (Fig. 45).

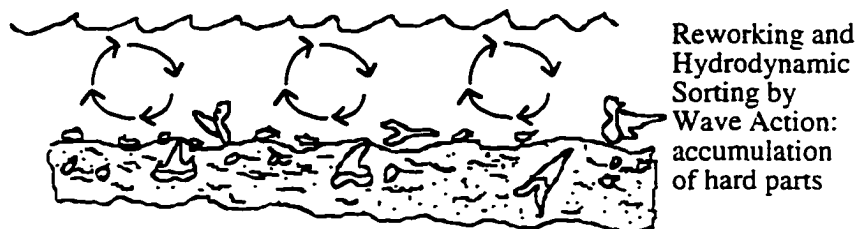
The stratigraphic position of the New Jersey macrofossil lag corresponds to third order regressive-transgressive event 3 and 4 of UZA

(Fig. 45) Taphonomic Model For Chondrichthyan Teeth Mixing

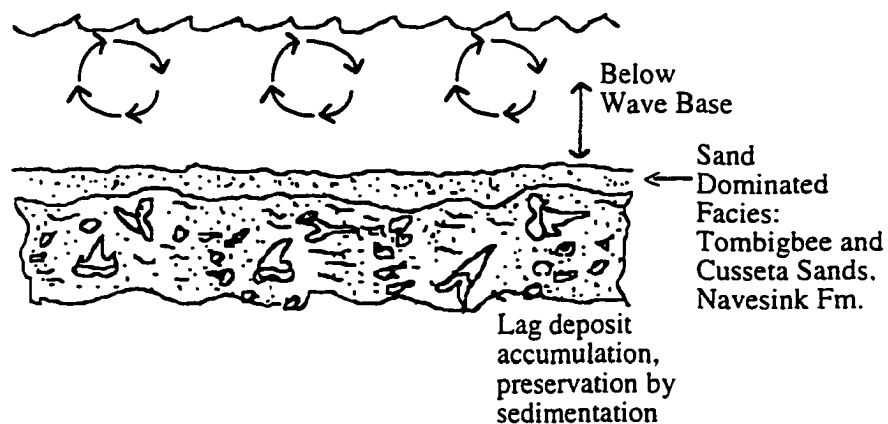
A. Initial sea level fall: middle to late highstand systems tract: initiates shark and nektonic organism movement to more favorable bathymetric conditions.



B. Sea level fall: late highstand systems tract: reworked hard parts can be: 1) deposited stratigraphically lower in section with geologically older material, (Georgia and Alabama); or 2) transported and deposited stratigraphically higher in section with geologically younger material (New Jersey). (See text).

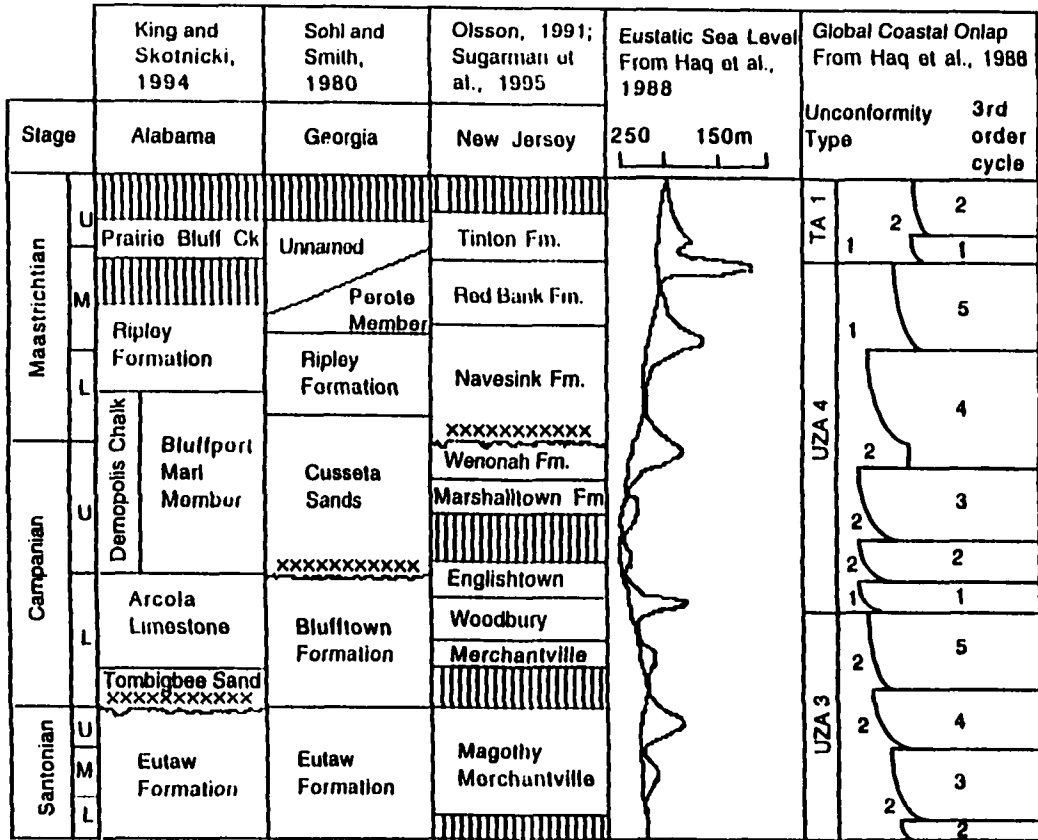


C. Sea level rise: early transgressive systems tract

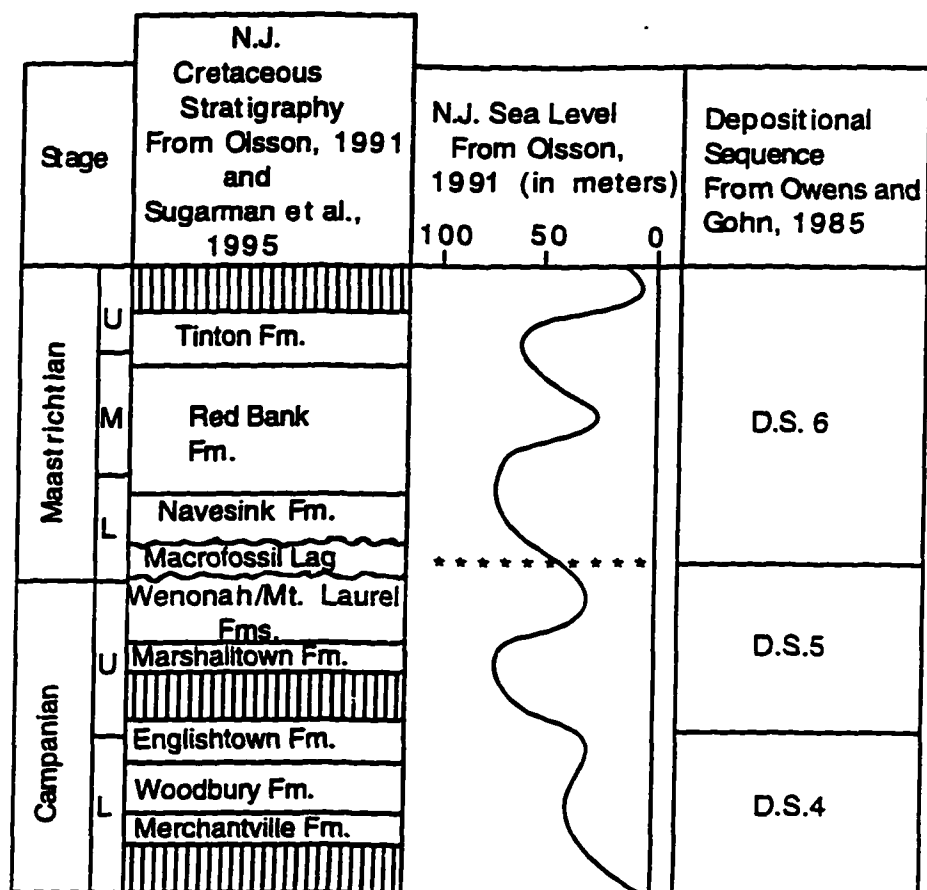


4 in the global sea level curve of Haq et al., 1988; Depositional Sequence Boundaries 5 and 6 of Owens and Gohn, 1985; and the boundary between the Marshalltown and Navesink Depositional Sequences (Martino and Curran, 1988; Olsson, 1991; Becker and Slattery, 1995 and Sugarman et al., 1995); (Figs. 46 and 47). Regression of sea level during the deposition of the Wenonah-Mt. Laurel Formations resulted in reworking and hydrodynamic sorting of sediment and macrofossils during the highstand systems tract. Subsequent sea level rise during the beginning of the overlying transgressive systems tract of the Navesink Formation re-deposited these reworked fossils directly above the erosional disconformity as a chondrichthyan tooth lag.

The Wenonah Formation was deposited along the offshore zones of New Jersey's inner shelf during a regressive phase in sea level. Olsson and Nyong, 1984, suggest a paleobathymetry ranging between 10 and 50 meters. The Mt. Laurel Formation, a lithofacies equivalent to the Wenonah Formation, was deposited along outer shoreface to inner shelf paleobathymetries of 10-30 meters during the same regressive phase. The Navesink Formation represents a transgressive shelf facies and a paleobathymetry of middle neritic conditions (30-100 meters); (Fig. 47); (Olsson and Nyong, 1984).



(Fig. 46) Approximate stratigraphic position of Alabama, Georgia and New Jersey lag deposits sampled during this study indicated by xxxx. The stratigraphic position of lag deposits corresponds favorably to: 1) facies changes between clay dominated and sand dominated sediments; 2) stage or substage boundaries in the upper Cretaceous; 3) third order regressive-transgressive events in the eustatic sea level curve of Haq et al., (1988); and 4) boundaries between coastal onlap depositional sequences.



(Fig. 47) New Jersey upper Cretaceous stratigraphy compared to paleobathymetric studies of Olsson, (1991) and depositional sequences from Owens and Gohn, (1985). Asterisks indicate the stratigraphic position of the lag deposit described in this study.

## Georgia

Donovan, 1993, assigned an age of 80.0 Ma for the lower-upper Campanian boundary in eastern Alabama and western Georgia through the use of radiometrically dated glauconites.

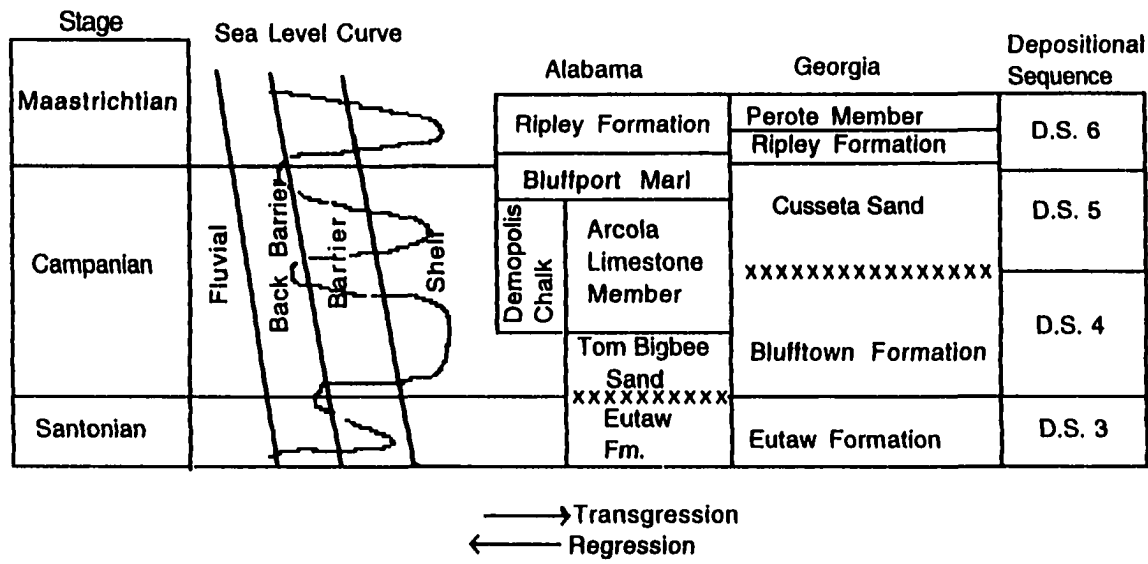
Calculated ages on ten chondrichthyan teeth, taken from Georgia lag deposits, are Campanian age (Table 3). If the Donovan, 1993, estimate of 80.0 Ma is correct, for the boundary between the Blufftown Formation and Cusseta Sands and the lower and upper Campanian boundary, chondrichthyan teeth must have been exhumed and reworked by third order sea level regression 3 of UZA 4 of Haq et al., 1988.  $Sr^{87}/Sr^{86}$  calculations indicate reworking of teeth as old as 84.5 Ma in the Blufftown Formation during this fall in relative sea level as indicated by the oldest dated tooth from this lag deposit. Reworking of teeth from the Blufftown Formation ended sometime after 75.0 Ma as indicated by the youngest tooth in the lag deposit, during third order sea level transgression 2 of UZA 4 of Haq et al., 1988. Confidence interval analysis for this lag deposit suggest 7.0 million years of reworking and time averaging must have taken place in the lag deposit separating the Blufftown Formation and Cusseta Sands.

The 75.0 Ma tooth from this lag is approximately 5 million years younger than the 80 Ma estimate of Donovan, 1993, for the lower-upper Campanian boundary. This suggests acceptable paleobathymetric

conditions for sharks occurred well above the lower-upper Campanian boundary in Georgia. Regressive sea level event 1 of UZA 4 of Haq et al., 1988, would have eventually forced these sharks to migrate seaward. Continuing regression would have exhumed and reworked teeth younger than the lower-upper Campanian boundary stratigraphically backwards where they were mixed with older teeth. Subsequent transgressive sea level event 2 of UZA 4 of Haq et al., 1988, would have continued to rework these teeth which were eventually deposited and preserved at the lower-upper Campanian boundary (Fig. 45).

The stratigraphic position of this macrofossil lag corresponds to third order regressive-transgressive event 1 and 2 of UZA 4 in the global sea level curve of Haq et al., 1988, sea level curve data compiled by Sohl and Smith, 1980 and Depositional Sequence Boundaries 4 and 5 of Owens and Gohn, 1985; (Figs. 46 and 48). Regression of sea level during the deposition of the Blufftown Formation would have resulted in reworking and hydrodynamic sorting of sediment and macrofossils during the fall in relative sea level at the end of the highstand systems tract. Subsequent sea level rise, during the beginning of the overlying transgressive systems tract of the Cusseta Sands, re-deposited these reworked fossils directly above the erosional disconformity as a chondrichthyan tooth lag.

Towards the middle of the Blufftown Formation, sea level regresses from a shelf to back barrier paleobathymetry. At approximately the



(Fig. 48) Georgia and Alabama stratigraphy for the Santonian, Campanian and Maastrichtian compared to the regional sea level curve, the stratigraphic position of depositional sequences 3,4,5 and 6 from Owens and Gohn, (1985). XXXXX indicates the approximate stratigraphic position of the sampled fossil lags in this research project. Sea level curve and stratigraphy information from Sohl and Smith,(1980).

lower-upper Campanian boundary, sea level begins to transgress rapidly from back barrier to barrier to shelf paleobathymetries (Sohl and Smith, 1980); (Fig. 48).

Donovan, 1993, also identified this regional unconformity separating the Blufftown Formation and Cusseta Sands in the Chattahoochee River Valley. His research and literature review indicate the boundary between the Blufftown Formation and Cusseta Sands, as well as other boundaries from the upper Cretaceous of Central Alabama and Western Georgia were originally defined based on regional surfaces marked by coarse grained lags, facies changes, major flooding events and biostratigraphic breaks.

#### Alabama

In an extensive study of the central and eastern Gulf Coastal Plains in Alabama, King and Skotnicki, 1994, reviewed the regional biostratigraphy of the Eutaw Formation and overlying Tombigbee Sands Member. Their research strongly indicates a late Santonian-early Campanian age for this boundary assignment based on: 1) calcareous nanoplankton, *Calculites obscurus*; 2) palynomorph zone: *Pseudodoplicapollis cuneata-Semioculopollis verrucosa*; 3) pelecypod biostratigraphy from Sohl and Smith, 1980; and 4) a radiometric age of a bentonite (84.4 Ma) from within the lowermost Tombigbee Sands Member of the Eutaw Formation.

Calculated ages on ten chondrichthyan teeth indicate Santonian and Campanian ages (Table 4). If 84.4 Ma is the correct age assignment for the

boundary between Eutaw Formation and Tombigbee Sands and the Santonian and Campanian boundary, as indicated by King and Skotnicki, 1994, chondrichthyan teeth must have been exhumed and reworked from the underlying Eutaw Formation during third order sea level regression 4 of UZA 3 of Haq et al., 1988.  $\text{Sr}^{87}/\text{Sr}^{86}$  calculations indicate teeth as old as 85.0 Ma are incorporated in this lag deposit. Reworking and exhumation of teeth from the Eutaw Formation ended sometime after 77.0 Ma as indicated by the youngest tooth in the lag deposit, during third order sea level transgression 5 of UZA 3 of Haq et al., 1988. Confidence interval analysis for this lag deposit suggest 6.0 million years of reworking and time averaging must have taken place in the lag deposit separating the Eutaw Formation and Tombigbee Sands and therefore across the Santonian-Campanian boundary.

The 77.0 Ma tooth from this lag is approximately 7 million years younger than the 84.4 Ma estimate of King and Skotnicki, 1994, for the Santonian-Campanian boundary. This suggests acceptable paleobathymetric conditions for sharks occurred well above the Santonian-Campanian boundary in Alabama. Regressive sea level event 4 of UZA 3 of Haq et al., 1988, would have eventually forced these sharks to migrate seaward. Continuing regression would have exhumed and reworked teeth younger than the Santonian-Campanian boundary stratigraphically backwards where they were mixed with older teeth. Subsequent transgressive sea level event

5 of UZA 3 of Haq et al., 1988, would have continued to rework these teeth which were eventually deposited and preserved at the Santonian-Campanian boundary (Fig. 45).

The stratigraphic position of this macrofossil lag corresponds to third order regressive-transgressive event 4 and 5 of UZA 3 in the global sea level curve of Haq et al., 1988, sea level curve data compiled by Sohl and Smith, 1980 and the boundary between Depositional Sequences 3 and 4 of Owens and Gohn, 1985 (Figs. 46 and 48). Regression of sea level during the deposition of the Eutaw Formation resulted in reworking and hydrodynamic sorting of sediment and macrofossils during the highstand systems tract of the Eutaw Formation. Subsequent sea level rise during the beginning of the overlying transgressive systems tract of the Tombigbee Sands Member re-deposited these reworked fossils directly above the erosional disconformity as a chondrichthyan tooth lag.

Towards the top of the Eutaw Formation, sea level regresses from a barrier to back barrier paleobathymetry. At approximately the Santonian-Campanian boundary sea level begins to transgress rapidly from back barrier to barrier to shelf paleobathymetries (Sohl and Smith, 1980); (Fig. 48).

### Time Averaging

Compilation of the known biostratigraphy for the New Jersey, Georgia and Alabama lags indicate placement of these lags at the

Campanian-Maastrichtian, lower-upper Campanian and Santonian-Campanian boundaries respectively. Occurring at these same boundaries are regressive-transgressive cycles 3 and 4 of UZA 4; 1 and 2 of UZA 4; and 4 and 5 of UZA 3 of Haq et al., 1988 (Fig. 49).

If sea level cyclicity is the responsible agent for lag deposit formation in the selected New Jersey, Georgia and Alabama field areas then  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic dating of shark teeth should produce a range of isotopic ages indicating time-averaging on a scale consistent with known sea level cyclicity patterns. Statistical confidence interval analyses of calculated  $\text{Sr}^{87}/\text{Sr}^{86}$  ages from these lag deposits indicate the chondrichthyan lags have time averaging ranges of 2.3 Ma in New Jersey, 6.0 Ma in Alabama, and 7.0 Ma in Georgia. The Georgia value of 7.0 Ma and Alabama value of 6.0 Ma fall slightly outside the Busch and Rollins, 1984, Kidwell, 1993 and Van Wagoner et al., 1988, estimate of 0.5 to 5.0 Ma for lag deposits which are products of third order sea level cyclicity.

The slightly larger Georgia and Alabama values may reflect the most modern available dating techniques such as the  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic system applied in this study to Mesozoic chondrichthyan teeth. The larger values may also be related to the highly durable and resistant nature of chondrichthyan teeth and their ability to survive exhumation, reworking, transport and re-deposition. Shelly fossils commonly used for time-averaging studies may have a shorter post-mortem life expectancies as

Lag Location	Biostratigraphic Age	Regional Absolute Age	Range of Numerical Mixing from Confidence Interval Analyses	Haq et al., 1988, Third Order Sea Level Cycles
New Jersey	Campanian-Maastrichtian	70.5 Ma (Sugarman et al., 1995)	2.3 Ma	3/4 of UZA 4
Georgia	lower-upper Campanian	80.0 Ma (Donovan, 1993)	7.0 Ma	1/2 of UZA 4
Alabama	Santonian-Campanian	84.4 Ma (King and Stocknicki, 1994)	6.0 Ma	4/5 of UZA 3

(Fig. 49) Stratigraphic position of Alabama, Georgia and New Jersey lag deposits compared to biostratigraphic age, regional absolute age, range of numerical mixing and third order sea level cycles of Haq et al., (1988).

recognizable entities and undergo destruction under similar conditions.

The principle composition of the Blufftown, Eutaw and Wenonah Formations are clay dominated facies. The upper contacts of these formations are marked in outcrop with erosional disconformities. Stratigraphically above these disconformities, are chondrichthyan lags which average thirty centimeters or less. Immediately above the lag deposits are the sand dominated facies of the Navesink Formation, Cusseta and Tombigbee Sands. The only feasible explanation for this prominent clay dominated to sand dominated facies change is a regressive event in relative sea level. Erosion, hydrodynamic sorting and reworking created by relative sea level change must account for the chondrichthyan fossil abundance and age diversity. As suggested by biostratigraphy and  $\text{Sr}^{87}/\text{Sr}^{86}$  analyses on individual chondrichthyan teeth, these lag deposit are products of physical sorting processes associated with third order sea level cyclicity. This is further supported by the fact that the stratigraphic position of these lags corresponds favorably to third order regressive-transgressive cycles 3 and 4 of UZA 4; 1 and 2 of UZA 4; and 4 and 5 of UZA 3 of Haq et al., 1988.

Storm or event lag deposits occur within similar sediment types and do not show the prominent facies change observed in the New Jersey, Georgia and Alabama lag deposits. Furthermore, the calculated ranges of mixing from confidence interval analyses for these three lag deposits

indicate durations much larger than can be anticipated for storm lag deposits.

Most chondrichthyans are nektonic organisms and represent paleobathymetries ranging from near shore to outer shelf depths. In the lags, chondrichthyan teeth have been mixed with molluscan assemblages representing mobile benthic, pelagic and nektonic life styles characteristic of shoreface to outer shelf paleoenvironments. It is highly unlikely that such an array of ecologically diverse fossil organisms would have shared the same paleocommunity or would have been co-deposited by storms or other one-time sedimentary events.

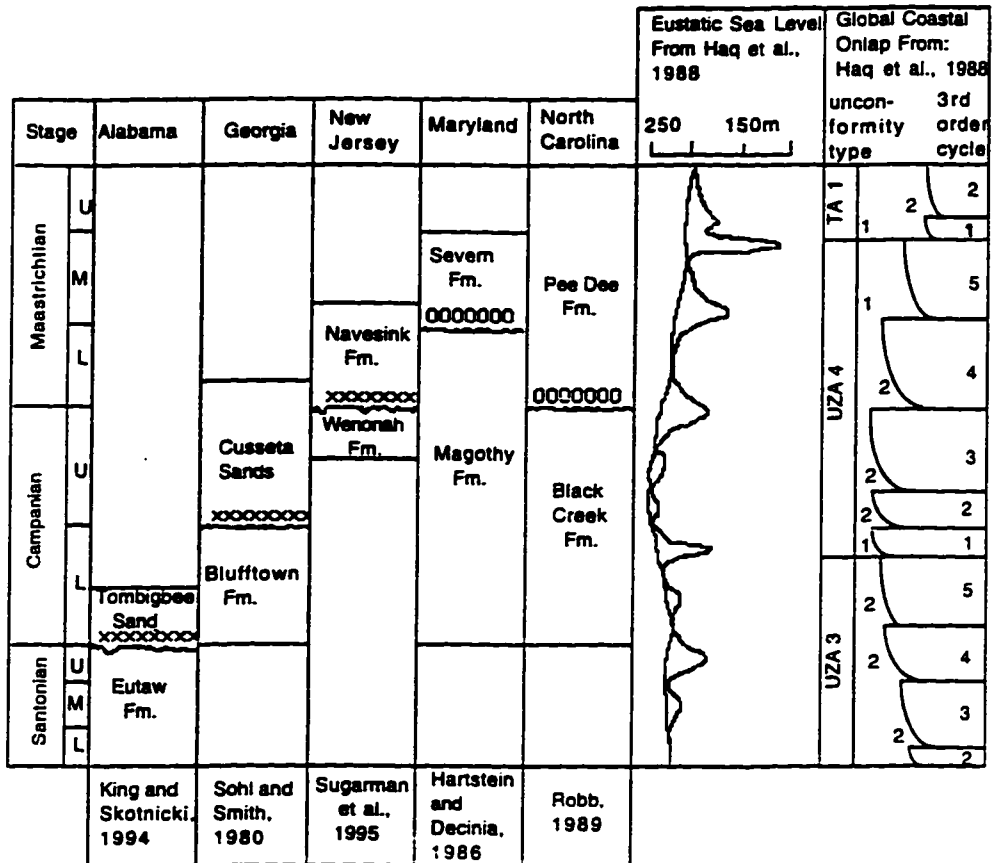
Deep sea condensed or hiatal lags also do not show the prominent facies change observed in the New Jersey, Georgia and Alabama lag deposits, and lack of mollusks and ammonites fossils which are characteristic of shallower water bathymetries. Moreover, paleobathymetric studies of Olsson and Nyong, 1984 and Sohl and Smith, 1980, indicate the Wenonah-Mt. Laurel, Navesink, Blufftown and Euatw Formations as well as the Cusseta and Tombigbee Sands were deposited in water depths ranging from back barrier, shoreface to inner shelf. This is not consistent with the paleobathymetries of outer shelf and slope depths characteristic of deep sea condensed or hiatal lags. Confidence interval analyses for the New Jersey, Georgia and Alabama lag deposits indicate durations equivalent to that of deep sea or hiatal lag deposits, ( $10^4$ - $10^7$

years, see figure 14). However, the observed facies change, paleobathymetries and fossil evidence are not consistent with general characteristics associated with deep sea or hiatal lag deposits.

#### Other similar lag deposits

Similar chondrichthyan lag deposits have been identified in the coastal plains of Maryland and North Carolina (Hartstein, and Decina, 1986 and Robb, 1989). The Maryland chondrichthyan lag occurs within the Severn Formation and has an early-middle Maastrichtian age while the North Carolina chondrichthyan lag occurs at the contact between the Black Creek and Peedee Formations and has an upper Campanian age (Hartstein, and Decina, 1986 and Robb, 1989). Thus, it appears that regressive-transgressive events defining the boundaries of third order eustatic cycles of Haq et al., 1988, during the upper Cretaceous had regional affects on the formation of macrofossil lags across the Atlantic and Eastern Gulf Coastal Plains (Fig. 50).

It is interesting to point out that in other parts of the geologic record, lag deposits identified as products of third or four order sea level cycles give estimates of duration similar to the New Jersey, Georgia and Alabama lag deposits. Busch and Rollins, 1984, studied transgressive-regressive units in Carboniferous strata and noted that lag accumulations represent durations of approximately 0.5 to 5.0 Ma. Brett and Baird, 1993, indicate lag accumulations in Paleozoic mudrocks represent between



(Fig. 50) Approximate stratigraphic position of Alabama, Georgia and New Jersey lag deposits sampled during this study indicated by xxxx. Similar lag deposits whose stratigraphic position is indicated by 0000 were identified by Hartstein and Decinia, (1986) and Robb, (1989) in Maryland and North Carolina. The stratigraphic position of the Maryland and North Carolina lag deposits also appears to correspond favorably to third order regressive-transgressive events 4 and 5 of UZA 4 and 3 and 4 of UZA 4 in the eustatic sea level curve of Haq et al., (1988) respectively.

$10^4$  and  $10^6$  years. Kidwell, 1993, states time averaging patterns in post-Paleozoic shallow marine fossils associated with hiatal concentrations indicate durations between  $10^3$  and  $10^6$  years. In comparison, the upper Cretaceous lag deposits of New Jersey, Georgia and Alabama, which indicate time averaging ranging from 2.3 - 7.0 Ma, seem typical of third or fourth order sea level cycles.

### Mechanisms of Formation

Research compiled during this project suggests that the mechanism of chondrichthyan lag deposit formation is independent of geologic time and location. If third order sea level cyclicity is the responsible agent for chondrichthyan lag deposit formation in New Jersey, Georgia and Alabama, as this research indicates, then: 1) chondrichthyan lag deposits provide an important means of identifying depositional sequences which characteristically occur at third order regressive-transgressive interfaces; and 2) chondrichthyan teeth contained in lag deposits provide meaningful biostratigraphic and chronostratigraphic information applicable to the understanding of geologic time and processes.

### **Conclusions**

The paleontological implications of this research are not limited to this study. Fossils are collected where you find them. This is trivial, but the possibility of erroneously interpreting the significance of a fossil assemblage exists if such an assemblage is removed from the context of

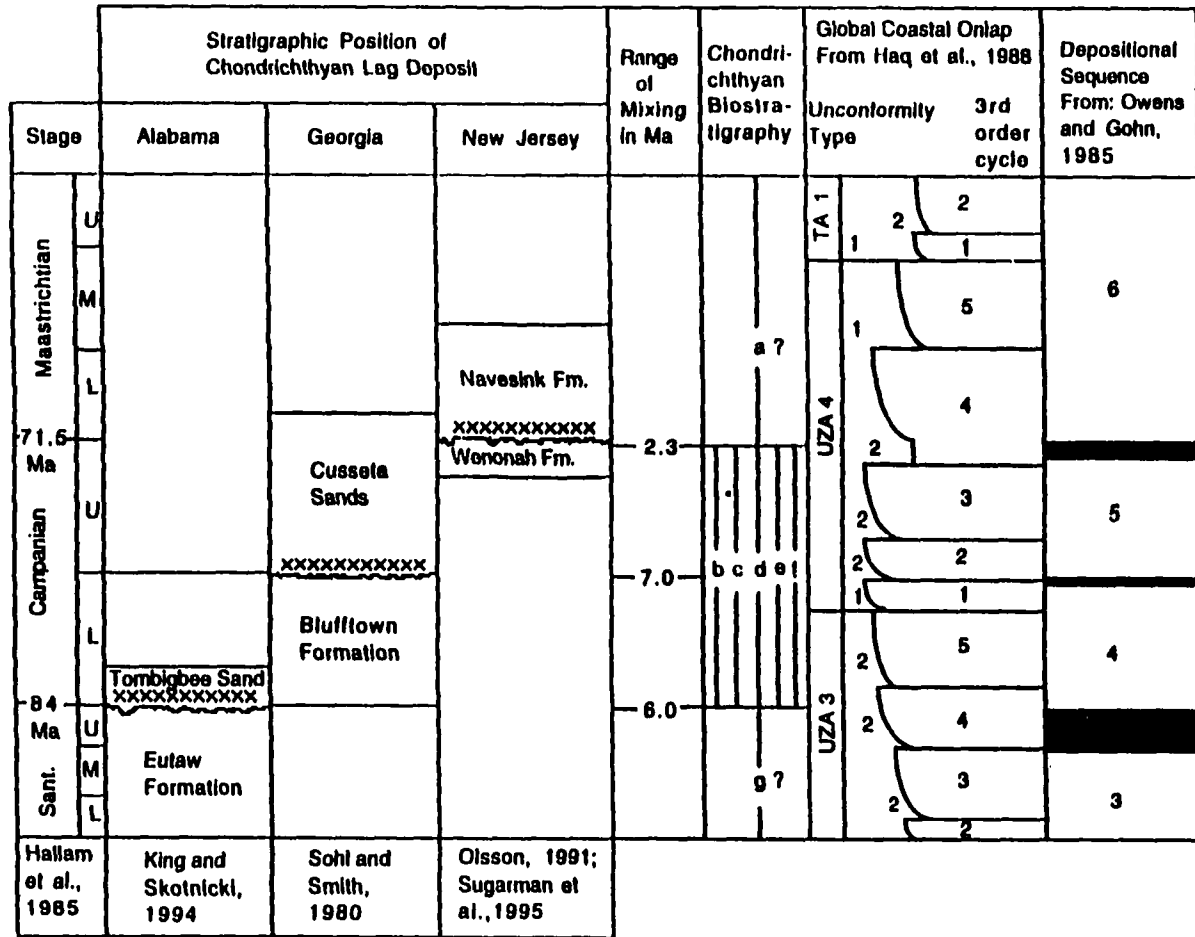
geological processes responsible for its formation. Many paleoecological studies are based on the assumption that if two fossils occur together, they were contemporaries. However, as is the case here, chondrichthyans and other co-occurring fossils lived in oceans separated in time by millions of years.

This research shows that third order fluctuation of relative sea level played a major role in the development of the unconformities bounding depositional sequences and the formation of chondrichthyan lag deposits of the Atlantic and Eastern Gulf Coastal Plains during the Santonian, Campanian and Maastrichtian. This is evident from the abundant vertebrate lag fauna occurring in New Jersey, Georgia and Alabama at unconformities and overlying transgressive deposits.

Confirming the utility of chondrichthyan teeth in  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic studies has important applications in stratigraphic, taphonomic and paleontological problems. The isotopic ages generated by measuring the  $\text{Sr}^{87}/\text{Sr}^{86}$  ratio in chondrichthyan teeth from New Jersey, Georgia and Alabama shows that: 1) the bounding unconformities of depositional sequence 3, 4 and 5 of Owens and Gohn, 1985, can be located and traced laterally by following chondrichthyan lag deposits; 2) chondrichthyan teeth are useful tools in biostratigraphic studies; 3) isotopic dating of chondrichthyan teeth provides important chronostratigraphic information in the placement of bounding unconformities; 4) the majority

chondrichthyan teeth crowns have retained their original  $\text{Sr}^{87}/\text{Sr}^{86}$  isotopic signature and have not been subjected to significant diagenetic alteration; and 5) chondrichthyan teeth concentrated at the boundary between regressive-transgressive depositional sequences have undergone approximately 2.3 to 7 Ma of reworking across the Santonian-Campanian, lower-upper Campanian and Campanian-Maastrichtian boundaries in New Jersey, Georgia and Alabama respectively (Fig. 51).

The concepts of remobilization of chondrichthyan teeth and subsequent deposition above unconformities during the formation of transgressive lags, which are developed in this study, have practical application in a variety of geologic issues: 1) differing biostratigraphic zonations for both macrofossil and microfossils; 2) the identification and placement of sequence boundaries; and 3) the selection field areas for paleontological, biostratigraphic and chronostratigraphic studies.



(Fig. 51) Diagram comparing Alabama, Georgia and New Jersey lag deposits (indicated by xxxxxx) to: 1) upper Cretaceous stage boundaries and absolute ages; 2) range of numerical mixing in lag deposits from Sr87/Sr86 dating of chondrichthyan teeth; 3) known chondrichthyan biostratigraphy; 4) global coastal onlap cycles of Haq et al., (1988); and 5) upper Cretaceous depositional sequences. (a= *Carcharis* sp. B; b= *Squalicorax kaupi*; c= *Cretolamna appendiculata*; d= *Paranomotodon angustidens*; e= *Scapanorhynchus texanus*; f= *Brachyrhizodus wichitaensis*; and g= *Ptychodus mortoni*).

## APPENDIX 1

### Treatment of Authigenic Mineral Growth:

#### Acid Dissolution Technique and Strontium Isolation

The laboratory procedure performed at Geochron Laboratories and the Institut für Geologie for chondrichthyan teeth cleaning and strontium extraction included the following:

1) To remove the dust and other particles from the surface of the shark teeth, the samples were cleaned using distilled water and an ultrasonic bath.

The crowns of chondrichthyan teeth were removed and cleaned of authigenic calcite by subjecting them to acetic acid cleaning and use of a vacuum pump to draw acid through the powdered specimens. Cleaning treatment was stopped when no significant release of CO<sub>2</sub> gas was detected.

2) A small portion of the powdered and acid cleaned tooth crowns were dissolved with 1-2 ml of suprapure 2.5 N HCL in sterilized beakers. The 2.5 N was directly used for the ion exchange procedure.

3) A spike material to determine the Sr content of the samples was not added.

4) Strontium was isolated by standard ion exchange techniques and analyzed at Geochron Laboratories in Cambridge, Massachusetts and the Institut für Geologie, Ruhr-Universität Bochum, in Germany. Sr was

extracted using quartz glass columns filled with 2.5 ml ion exchange resin type AG 50-W x 8 (Biorad) and 15 to 20 ml HCL 2.5 N.

5) The isotopic ratios were measured on a solid source mass spectrometer. The samples were loaded on Re-single filaments applying an activating agent. The data were collected in a so-called peak jumping mode (dynamic mode), using three faraday cups to detect five masses (Rb and Sr). The mass  $Rb^{85}$  was recorded as a monitor mass, but no Rb correction was applied. The thermal fractionation of Rb during a Sr measurement is unpredictably high so that a reliable natural  $Rb^{87}/Rb^{85}$  ratio can not be determined and can not be used to correct the mass  $Sr^{87}$  and  $Rb^{87}$ . However, the Rb signal during a Sr run is negligibly small. The upper tolerance limit for  $Rb^{85}$  was therefore  $2 \cdot 10^{-5}$  volt at about 4-5 volt signal for  $Sr^{88}$  of the same run.

6) The average total blank for Sr (chemical + ion exchange columns + loading blank) did not exceed  $8.5 \cdot 10^{-3}$  ng/g.

7) NBS 987 and USGS EN-1 were used as a standard reference material. The NBS 987 solution was loaded directly into the filaments and therefore represents the reproducibility of the mass spectrometry. The EN-1 carbonate powder underwent the same procedure as the samples and represents the reproducibility of the complete analytical procedure.

8) Strontium analytical procedures were compiled from personal communications with Dieter Buhl, Institut fuer Geologie, Ruhr-

Universitaet, Bochum, Germany and Harold Krueger, Krueger Enterprises Inc.. Geochron Laboratories Cambridge, Massachusetts.

## APPENDIX 2

### Confidence Interval Analysis

Formula:  $\bar{x} \pm t_{\alpha/2, n-1} \cdot s / \sqrt{n}$  where:  $\bar{x}$ = sample mean;  $t$ = value related to how closely sample population approximates the z or normal distribution;  $\alpha$  = 1- confidence interval;  $s$ = standard deviation for samples;  $n$ = number of samples. Standard deviation can be calculated from:

$$s^2 = \frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}$$

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