FINAL TECHNICAL REPORT
DEPARTMENT OF ENERGY AWARD
DE-FG02-92ER14251
TO THE PENNSYLVANIA STATE UNIVERSITY
PROJECT TITLE: CRETACEOUS SHALLOW DRILLING, U.S. WESTERN INTERIOR: CORE RESEARCH

DOE/ER/14251--T1

P.I.: Michael A. Arthur, Department of Geosciences

Date Submitted: July 8, 1998

DISCLAIMER

EXECUTIVE SUMMARY

The major accomplishment of the DOE-funded Project "Cretaceous Shallow Drilling, U.S. Western Interior: Core Research" is a synthesis volume, edited by Walter E. Dean (USGS) and Michael A. Arthur (PennState) published by SEPM (Society for Sedimentary Geology) as SEPM Concepts in Sedimentology and Paleontology No. 6, *Stratigraphy and Paleoenvironments of the Cretaceous Western Interior Seaway, USA*, 1998, 255 pages. This volume presents the the results of the coordinated, multidisciplinary study of Cretaceous carbonate and clastic rocks in cores collected along a transect across the old Cretaceous seaway that extended from the Gulf Coast to the Arctic by a team of academic, industry, and U.S. Geological Survey scientists funded largely by DOE. Our overall goal was to construct a subsurface transect of mid-Cretaceous strata that were deposited in the U.S. Western Interior Seaway (WIS), ranging from pelagic, organic-carbon rich, marine hydrocarbon source rocks in Kansas and eastern Colorado to nearshore, coal-bearing units in western Colorado and Utah. This transect of cores has provided the basis for paleoenvironmental interpretation of organic-carbon burial in an epicontinental, foreland basin setting. In part, the objectives of our study were motivated by the research emphases outlined by the Cretaceous Rhythms, Events and Resources (CRER) Project of the Global Sedimentary Geology Program. A table of contents of the volume is appended; all papers published in the volume were authored or coauthored by members of the research team who received some funding from the DOE contract. Some of these (5) were graduate students (at PennState, UNC and UMass) who benefitted from the interdisciplinary collaborative framework in their thesis work.

The papers in this volume focus on the Graneros Shale, Greenhorn Formation, Carlile Shale, and Niobrara Formation and equivalents in cores from six drillholes from western Kansas, southeastern Colorado, and eastern Utah. This series of cores provides unweathered samples and continuous smooth exposures required for geochemical studies, mineralogical investigations, and biostratigraphic studies. Major objectives of the project, covered in the collected papers include:

1. establishing the precise timing of sealevel change, rates of subsidence, and facies changes; 2. determination of controls on the accumulation, burial, and diagenesis of organic matter; 3. calibration of depositional cycles using high-resolution stratigraphy; and 4. determining the paleogeography, paleoclimatology, and paleoceanography of the Western Interior Seaway and immediately adjacent landmasses.

We gratefully acknowledge the many sources of funding and materials for these studies. Much of the research was funded by the Continental Scientific Drilling Program through the U.S. Geological Survey and by the Department of Energy through a contract to Penn State (DE-FG02-92ER14251). A core from an AMOCO drillhole from western Kansas was released to the USGS in 1992, and description and analysis of this core plus that from a previously acquired well (Schock-Errington #1) in northwestern Kansas constitute the data base for the eastern end of the transect. Three holes that form the western end of the transect, funded by USGS energy programs, were drilled and continuously cored in June, 1991 in the Kaiparowits basin near Escalante, Utah. In June, 1992, a 700-foot hole, funded by DOE, was drilled and continuously cored near Portland, Colorado east of the Florence oil field. This sequence, deposited in relatively deep water on the west side of the WIS, includes cycles of terrigenous-clastic and pelagic-marine sediments to contrast with the pelagic carbonate-dominated cycles of Kansas, and the clastic-dominated cycles of western Colorado and Utah. A second, 800-foot hole, also funded by DOE, was drilled in July, 1992 about 10 miles southwest of the Portland hole in Pierre Shale that is the reservoir for hydrocarbons in the Florence field. Formal descriptions of the cores are available in a computer data base published as USGS Open-File Reports. All tabulated data from the project are available through the National Geophysical Data Center, Boulder, Colorado. (NGDC: http://www.ngdc.noaa.gov/paleo/paleo.html).

PROJECT ACCOMPLISHMENTS AND PRODUCTS: SUMMARY

PROJECT SUMMARY

1. **Project Title:** Cretaceous Shallow Drilling, U.S. Western Interior: Core Research

2. **Principal Investigators:**

Dr. Walter E. Dean

U.S. Geological Survey, Climate Processes Program, MS 930 Federal Center, Denver, CO 80225; phone: (303)236-5760; FAX: (303)236-0459; E-Mail: dean@usgs.gov

A. Role in project: project coordination; sampling; sedimentology; cyclostratigraphy and spectral analysis; inorganic geochemistry; stable isotope geochemistry; organic geochemistry

Dr. Michael A. Arthur

Department of Geosciences, Pennsylvania State University, University Park, PA 16802; phone: (814)863-6054; FAX: (814)863-7823; EMAIL: arthur@geosc.psu.edu

A. Role in project: project coordination; sampling; cyclostratigraphy and spectral analysis; inorganic geochemistry; stable isotope geochemistry; organic geochemistry

3. **Additional Project Personnel:**

Dr. Timothy Bralower

Professor, Department of Geology, Univ. North Carolina

A. Role in project: paleontology (calcareous nannofossils)
B. Principal areas of research and expertise: micropaleontology; stratigraphy

Dr. Katherine Freeman

Asst. Professor, Department of Geosciences, Penn State Univ.

A. Role in project: organic geochemistry
B. Principal areas of research and expertise:

Mr. Robert Hettinger

Geologist, U.S. Geological Survey, Branch of Coal Geology

A. Role in project: coal geology; sedimentology; sequence stratigraphy
B. Principal areas of research and expertise:

Dr. Erle Kauffman

Professor, Department of Geological Sciences, Univ. Colorado

A. Role in project: paleontology (macrofossils); cyclostratigraphy and spectral analyses
B. Principal areas of research and expertise:

Dr. Mark Leckie

Professor, Department of Geology, Univ. Massachusetts

A. Role in project: paleontology (foraminifera)
B. Principal areas of research and expertise:
C. Education:

Dr. Elana Leithold

Asst. Prof., Department of Marine, Earth, and Atmospheric Sciences, North Carolina State Univ.

A. Role in project: sedimentology
B. Principal areas of research and expertise:

Dr. Michael Lewan

Chemist, U.S. Geological Survey, Branch of Petroleum Geology

A. Role in project: organic geochemistry
B. Principal areas of research and expertise: organic geochemistry

Dr. Peter McCabe

Geologist, U.S. Geological Survey, Branch of Coal Geology

A. Role in project: coal geology; sedimentology; sequence stratigraphy
B. Principal areas of research and expertise:

Dr. Phillip Nelson

U.S. Geological Survey, Branch of Geophysics

A. Role in project: logging and well-log analysis
B. Principal areas of research and expertise:

Dr. Douglas Nichols

Geologist, U.S. Geological Survey, Branch of Paleontology and Stratigraphy

A. Role in project: paleontoilogy (palynomorphs)
B. Principal areas of research and expertise:

Dr. John Obradovich

U.S. Geological Survey, Branch of Isotope Geology

A. Role in project: age dating
B. Principal areas of research and expertise:

Dr. Bradley Sagemen

Asst. Professor, Department of Geology, Northwestern University

A. Role in project: sedimentology; cyclostratigreaphy and spectral analyses; trace fossils
B. Principal areas of research and expertise:
C Education:

Dr. Charles Savrda

Professor, Department of Geology, Auburn Univ.

A. Role in project: trace fossils
B. Principal areas of research and expertise:trace fossils; stratigraphy

Ms. Oona White

Graduate Student, Department of Geology, Univ. Massachusetts

A. Role in project: paleontology (foraminifera)
B. Principal areas of research and expertise:

Mr. Timothy White

Graduate Student, Department of Geosciences, Penn State Univ.

A. Role in project: stable isotope geochemistry
B. Principal areas of research and expertise:

4. Project Overview:

A. Project Objectives:

The primary objective of the project is to construct a subsurface transect of Cretaceous strata that were deposited in the Kansas-Colorado-Utah corridor, going from marine sequences that contain organic-carbon-rich hydrocarbon source rocks in Kansas and eastern Colorado to nearshore coal-bearing units in western Colorado and Utah. This drilling transect will provide continuous, unweathered samples for inorganic, organic, and isotopic geochemical studies and mineralogical investigations to determine the characteristics of hydrocarbon source rocks. This transect also will provide information on the extent of thermal maturation and migration of hydrocarbons in organic-carbon-rich strata along a burial gradient. In addition, the eastern Colorado hole will provide characteristics of an important fractured reservoir (the Pierre Shale) in the Florence oil field, the oldest continuously producing field in the United States (>100 years; 600 wells; >14 Mbbls)

The scientific investigations based on materials recovered from these holes probably will continue for many years, but the overall scientific goals are :

1) Determine onshore-offshore facies patterns and amount, accumulation rate, type, and degree of preservation of organic matter.

2) Determine variations in faunal and floral components and sedimentary structures in order to evaluate the extent and intensity of oxygen deficiency during organic-carbon depositional episodes, and the relation between oxygen deficiency and the preservation of organic matter.

3) Determine the effects of organic-matter enrichment on the geochemical characteristics of the sediments, including cycling of redox sensitive elements.

4) Determine the effects of increasing burial depth on thermal metamorphism and other geochemical characteristics of the sediments and their contained organic matter in time (depth) and space along a gradient defined by the transect of drill cores.

5) Determine the effects of diagenesis on porosity and composition of carbonate, clastic, and organic components.

6) Determine the timing and rates of sea-level change, and their influence on lithology, sedimentation rate, and sediment geochemistry.

7) Examine rates of subsidence, apparent sea-level change, and facies migration in light of global tectonic-eustatic events.

8) Provide a unique high-resolution time sequence to calibrate possible Milankovitch cyclicity. This unique time series will be possible for the Western Interior Seaway because of the high diversity of micro- and macro-faunal and floral assemblages, together with abundant volcanic ash layers for absolute dating.

9) Elucidate trends in geochemical properties and organic-carbon accumulation rates and compare them to global trends.

10) Provide data for validation of climate models (e.g. GCMs).

11) Provide explanations for the significance of bioevents and substantial changes in global biotic diversity during the Cretaceous and document rates and timing of biotic extinction and evolution in detail.

12) Investigate the possibility that such shallow Cretaceous seas were the sources of oxygen-depleted oceanic deep-water masses.

B. Project Relation to DOE Mission:

The project addresses both DOE and USGS interests in the U.S. Continental Scientific Drilling Program (USCSDP) with the stated goal of an improved understanding of the continental crust from which we derive our energy and mineral resourcers. DOE's mission in the USCSDP is to focus on thermal regimes, sedimentary basins, and energy resources of the earth's crust. The goals of the project, as stated above, clearly relate to the DOE mission in that the focus of the project is on a sequence of strata that contain major hydrocarbon source and reservoir rocks as well as major coal-bearing sequences deposited and preserved under a wide variety of depositional, diagenetic, and thermal regimes.

C. Project Relation to Other DOE Projects:

Most other projects supported by DOE under the USCSDP have focused on geothermal energy systems. This project differs from these projects in that the primary focus is on fossil fuels, namely source and reservoir rocks for oil and gas in eastern Colorado and Kansas, and coal in western Colorado and Utah.

D. Project History:

Summary

This is a project that began in FY 1991 and ended in 1994. As stated above, the primary objective of the project is to construct a subsurface transect of organic-rich Cretaceous strata across the Western Interior Seaway (WIS) based on continuously cored material. We initially concluded that cores from four relatively shallow (<1000m) reference holes from western Kansas to eastern Utah would be required at a minimum. in order to construct this transect. The first two holes (western Kansas and southeastern Colorado) would be the most economical because of the proximity to Denver and shallow depth. The first hole would be drilled in eastern Kansas, where the middle to Upper Cretaceous strata are largely pelagic and have not experienced deep burial. The second hole in the transect would be drilled to the west, in the southern Denver Basin near Florence or Cañon City, Colorado to obtain cores of more deeply buried offshore pelagic-hemipelagic strata. The first two cores should contain well preserved marine organic matter in the Niobrara and Greenhorn Formations deposited during maximum transgression of the WIS. A third hole, or, more likely, a series of overlapping holes, would be drilled in the northern San Juan Basin in southwestern Colorado to sample mid-Turonian to lower Campanian nearshore coal-bearing strata of the Mesa Verde Group and Mancos Shale (Fig. 4). A fourth hole, or a series of overlapping holes, would be drilled on the Kaiparowits Basin in Utah to sample upper Turonian to lower Campanian nearshore and terrigenous coal-bearing strata of the Straight Cliffs Formation, and the underlying marine Tropic Shale.

During FY 1991 three holes were cored in the Kaiparowits Basin of south central Utah by a drilling rig and crew from the USGS Branch of Coal Geology. All three holes were about 900 feet deep, and continuously cored with 98%+ recovery. Two holes (USGS-CT1-91 and USGS-SMP1-91) were drilled on top of the Kaiparowits Plateau and collected the coal-bearing sequences of the Upper Cretaceous Straight Cliffs Formation. A third hole (USGS #1 Escalante) was drilled at the base of the Kaiparowits Plateau near the town of Escalante, Utah and collected all of the marine Tropic Shale and the top of the Dakota Sandstone. These three holes were funded by the USGS Coal, Onshore Oil and Gas, and Evolution of Sedimentary Basins Programs, and the cores are presently in the USGS Core Research Center in Denver. They constitute the western end of the transect.

Two cores of the Mesa Verde Group from the Southern Ute Indian Reservation (SUIT #1 and #2) in the northern San Juan Basin were collected as part of a BIA-funded project. These cores are presently on hand in the USGS-Core Research Center in Denver, and are available to the project. The lower part of the desired section, the Mancos Shale, has been sampled in detail by Mark Leckie (University of Massachusetts) and colleagues in a series of trenches near Mesa Verde National Park. Although it would be desirable to have core coverage of the Mancos, we feel that the combination of the Mesa Verde cores and Leckie's trenched section for the time being give us the desired coverage in southwestern Colorado.

In January, 1992, the Cretaceous part (about 1000 feet) of the AMOCO #1 Rebecca K. Bounds core from Greeley Co., Kansas was released by AMOCO and shipped to the USGS Core Research Center in Denver. The section from the middle of the Upper Cretaceous Niobrara Formation to the top of the Upper Jurassic Morrison Formation was continuously cored with better than 90% recovery. This hole constitutes the eastern end of the transect. All that remained was a key core from ther southern Denver Basin in southeastern Colorado.

During June, 1992, a 700-foot hole (USGS #1 Portland), funded by DOE, was drilled and continuously cored in Cretaceous strata east of the Florence oil field near Cañon City, Colorado on the property of the Ideal Cement Company (Holnam, Inc.), Portland, Colorado. The drilling was done by a rig and crew from the USGS Branch of Coal Geology with core recovery of essentially 100%. The section recovered includes the lower half of the Niobrara Formation, the Carlile Shale, the Greenhorn Formation, the Graneros Shale, and the top of the Dakota Sandstone. Of particular note was the excellent recovery of very distinct limestone-marlstone cycles of the Greenhorn and Niobrara. Both of these pelagic carbonate units contain abundant marine organic matter that may be sources of petroleum in the Florence field as well as in the Denver basin. A second, 800-foot hole, also funded by DOE, was drilled in July, 1992 about 10 miles southwest of the Portland hole in Pierre Shale that is the reservoir for hydrocarbons in the Florence field. Because the Pierre Shale in the Florence basin is highly fractured, coring was attempted on only 250 feet of the drilled 800-foot section with 96% recovery. Most of the material recovered was homogeneous dark gray claystone with closely spaced high-angle fractures, but parts of the section contain multiphase layers or concretions of limestone, siderite, and (or) phosphate.

Funding ($k)

Funding	FY1991			FY1992			FY1993		
Source	Science	Drilling	Overhead	Science	Drilling	Overhead	Science	Drilling	Overhead
USGS		$80	$26	$200		$66	$200		$66
total		$106			$266			$266	
DOE				$91	$66	$72	$99		$40
total					$229			$139	

Previous and Current Contracts

DOE to USGS for drilling and logging	$100k	3/92 to 3/93
DOE to Penn State for academic science	$269k	3/92 to 3/94

5. Scientific and Technical Content:

A. Relation to other Research in Field:

Because of the importance of the Cretaceous to so many different disciplines of the geosciences, the new Global Sedimentary Geology Program (GSGP) has identified "Cretaceous Resources, Events and Rhythms" (CRER) as its first major international project. Under this project are five Working Groups: 1) Sequence stratigraphy and sea level change ; 2) Black shales and organic-carbon burial; 3) Cyclostratigraphy; 4) Carbonate platform evolution; and 5) Paleogeography, paleoclimatology and sediment fluxes. The CRER program presently has no funding and no focus on the international level, and it will depend on the activities of national committees to assure success and recognition for it. The present project under the U.S. Continental Scientific Drilling Program is the first major research effort under the objectives of CRER. Marine sedimentary units deposited in the Cretaceous Western Interior Seaway provide an exciting opportunity to develop and integrate the research efforts under the 5 working group themes listed above in one project. The seaway was situated such that it was a very environmentally sensitive region as the NW arm of the Tethys Ocean. The strata of interest therefore, in part, monitor global change during the Cretaceous and include a number of petroliferous and coal-bearing units, are characterized by well-developed cyclicity in the Milankovitch band, pose a variety of interesting paleoclimatic, paleoceanographic and sediment flux problems, and are dominated by sequences produced by marked transgressive-regressive cycles.

B. Schedule of Research Activities:

Synthesis volume completed and published in 1998.

C. Scientific Issues Being Addressed:

1. **Issue:** What was the effect of large-scale changes in sea-level during the Cretaceous on lithology, sedimentation rate, geochemistry, and organic productivity in the Western Interior Seaway? **Significance:** The proposed drilling will provide sampling of strata deposited during two major transgressive-regressive cycles that reflect global changes in sea level. The origin of these sea-level changes is puzzling because much of the Cretaceous is thought to have been ice-free and characterized by warm, latitudinally equable climates and, therefore, ice-volume changes could not have induced much variation in sea level. On the other hand, the Cretaceous was a time of unusually active sea-floor spreading and plate-margin and mid-plate volcanism so that tectonically induced changes in sea level should be expected. Key issues are the precise timing and rates of sea-level change, and their influence on lithology, sedimentation rate, and sediment geochemistry. Of particular interest will be the amount, type, and degree of preservation of organic matter, and their relationships to sea-level variations whether tectonic or eustatic. In addition, rates of subsidence, apparent sea-level change, and facies migration will be closely examined in light of global tectonic-eustatic events.
2. **Issue:** What paleoenvironmental conditions cause the enhanced preservation of organic matter, and what are the effects of organic-matter enrichment on the geochemical characteristics and hydrocarbon potential of the sediments? **Significance:** The sequences to be drilled encompass several episodes of enhanced burial of organic carbon that have importance both within the WIS and globally. These periods of widespread oxygen deficiency in oceanic deep-water masses (so-called "Oceanic Anoxic Events"), marked by widespread organic-carbon-rich sequences, loosely called "black-shales", include several hydrocarbon source-rock sequences as well as economically important coal sequences. These episodes provide the opportunity to examine the extent to which local vs. global factors influence organic matter production and accumulation. Of particular interest will be comparison of the onshore-offshore facies patterns, rates of organic-matter accumulation, and changes in organic-matter type and degree of preservation to water mass properties predicted by ocean-circulation and oxygen-exchange models. In addition, variations in faunal and floral components and sedimentary structures will be used to evaluate the extent and intensity of oxygen deficiency during black-shale episodes for comparison with the model results. The effects of organic-matter enrichment on the geochemical characteristics of the sediments also will be examined, particularly as they relate to the cycling of Fe, Mn, S, N, P, and trace elements. Finally, the transect of cores will provide fresh, unweathered samples for the study of the effects of thermal maturation and other geochemical characteristics with increasing burial depth.

3. **Issue:** Do Cretaceous sedimentary sequences really record solar-terrestrial orbital cycles, and, if so, what can they tell us about geochronology, sedimentology, and paleoclimates? **Significance**: The WIS Cretaceous sequences are renowned for their expression of small-scale bedding cyclicity, in which C_{org} and $CaCO_3$ contents vary on scales of 0.2 to 1.5m with estimated periodicities of 20-100 ky that commonly are attributed to Milankovitch orbital variations. In addition, longer-term cycles with periodicities of up to several million years, are defined on geochemical and geophysical logs and also may be related to orbital cycles or possibly to sea level changes that are correlated with Milankovitch forcing. However, the linkages of these presumed orbital variations to sedimentary processes in a supposed ice-free world are poorly understood in contrast to ice-volume-dominated Quaternary cycles with similar periodicities. The continuously cored sequences and a cross-basin transect will provide an opportunity to examine the sedimentary expression of orbital cyclicity in a geographically restricted part of the Cretaceous ocean that apparently was finely tuned to these orbital variations. The sequences of the WIS have the greatest diversity of faunal and floral assemblages of any Cretaceous sequence in the world. The detailed biostratigraphies provided by these assemblages, together with abundant volcanic ash layers, will provide a unique high-resolution time sequence to calibrate the rates and timing of sediment supply, organic productivity, and changes in water-mass characteristics that contribute to the sedimentary expression of Milankovitch orbital cycles.

4. **Issue:** What was the cause of the extreme increase in global temperature during the middle Cretaceous, and was the effect of this "ultrathermal" on paleoenvironmental conditions in the world ocean? **Significance:** The globally warm, equable, ice-free Cretaceous climate is generally viewed as having been about as far removed from our present glacially dominated climate as that of any other

geological period. However, the origins of this warm climate are poorly understood, but are presumed to be related to a major expression of a "greenhouse" phenomenon, such as might result from increased volcanic outgassing of carbon dioxide. However, even the warm, equable climate paradigm is being challenged, at least for some parts of the Cretaceous, as new data are obtained. The sedimentary sequences in the Western Interior Seaway are an important part of the global expression of high eustatic sea levels, tectonism, warm climate, and oxygen depletion because of the relative geographic isolation of the seaway and, therefore, its strong susceptibility to paleoclimatic and paleoceanographic change. As such, these sequences deserve a detailed study in order to: 1. elucidate trends in geochemical properties and organic-carbon accumulation rates and their potential global impact; 2. provide validation of climate models (e.g. GCMs); 3. provide explanations for the significance of bioevents and substantial changes in global biotic diversity during the Cretaceous; 4. document rates and timing of biotic extinction and evolution; and 5. investigate the possibility that such shallow Cretaceous seas were the sources of oxygen-depleted oceanic deep-water masses and anoxia.

D. Approaches Taken:

Obtain as much information as possible about the rocks and their contained organic matter and fossils. Fine tune the chrono- and biostratigraphies of the already best-dated Cretaceous section in the world.

E. Importance of Problem:

The Cretaceous Period (ca. 136-66 Ma) of earth history offers a significant opportunity for major contributions to understanding global processes and their variations. Cretaceous marine and terrestrial strata are extremely widespread in outcrop, subcrop, and in ocean basins. Many of the subcrop sections are available by shallow to intermediate (up to 1000 m) continental drilling, and ocean-basin sites are accessible by deep-sea drilling. Variable combinations of tectonism, volcanism, atmospheric and ocean chemistry, climate, sea level, and sediment supply helped to produce some of the largest phosphorite deposits and hydrocarbon reserves known on earth. In addition, Cretaceous strata contain major reserves of coal, kaolinite, bauxite, and manganese. Accurate prediction of the availability of such resources, and an understanding of their distribution requires models based on a comprehensive knowledge of the Cretaceous world. Understanding the Cretaceous is tantamount to understanding most of the world's hydrocarbon resources.

The Cretaceous is marked by substantial changes in extent of shelf and epicontinental seas and in regional and global patterns of marine sedimentation. These changes were the result of major fluctuations in global eustatic sea level. Much of the Cretaceous is also recognized as having had a globally warm, equable, mostly ice-free climate that is generally viewed as having been about as far removed from our present glacially dominated climate as that of any other geological period. The origins of this warm climate are not well understood, but are presumed to be related to a major "greenhouse" phenomenon, possibly the result of increased volcanic outgassing of carbon dioxide.

The middle Cretaceous between 120 Ma and 80 Ma is characterized by several globally widespread episodes of organic-carbon burial in marine sequences. These episodes represent periods of widespread oxygen deficiency in oceanic mid- and deep-water masses that have been termed "Oceanic Anoxic Events" (OAEs; Fig. 1). The widespread occurrence of OAEs in time and space within the middle Cretaceous may imply fundamental changes in oceanic circulation and (or) the rate and mode of delivery of organic matter to the deep sea. The origin of the OAEs is not known for certain, but available data suggest that such events resulted from some combination of higher phytoplankton productivity and enhanced preservation under oxygen-depleted deep-water masses.

6. **Project Output:**

A. Major Recent Accomplishments:

All cores for the project have been collected, have been processed and sampled in the USGS Core Research Center, in Denver, and scientific investigations are completed. A workshop involving most of the scientific collaborators was held in Denver during the week of August 10, 1992; a sample handling and curation protocol was a major result of that workshop (see Open-File Report listed below). An AAPG core workshop was held in 1994 in Denver featuring cores and scientific results from this project. A synthesis volume was publshed by SEPM in 1998 (see list).

Peer-Reviewed Publications

Slingerland, R., Kump, L.R., Arthur, M.A., Fawcett, P.J., Sageman, B.B., and Barron, E.J., 1996. Estuarine circulation in the Turonian Western Interior seaway of North America. *Geol. Soc. Amer. Bull.*, 108, 941-952.

Sageman, B.B., Rich, J., Arthur, M.A., Birchfield, G.E., and Dean, W.E., 1997. Evidence for milankovitch periodicities in Cenomanian-Turonian lithologic and geochemical cycles, Western Interior, U.S.A. *J. Sedim. Geol.*, 7, 286-302.

Dean, W.E. and Arthur, M. A., eds., 1998. Stratigraphy and paleoenvironments of the Western Interior Seaway. SEPM Concepts in Sedimentology and Paleontology, v. 6, 255 pages. (contains 13 papers summarizing scientific results of the Cretaceous Shallow Drilling Project).

Theses

The DOE-funded project contributed samples and some funding for all or part of the thesis research of the following graduate students:

Celeste E. Burns, University of North Carolina (M.S. Thesis), 1994
T.J. Bralower, advisor

Oona L. O. West, University of Massachusetts (M.S. Thesis), 1995
R. Mark Leckie, advisor

Richard D. Pancost, Pennsylvania State University (PhD Dissertation), 1998
K. H. Freeman, advisor

Timothy White, Pennsylvania State University (PhD Dissertation), 1998
M. A. Arthur, advisor

Open-File Reports

Dean, W.E., and Arthur, M.A., 1992. Sample handling and curation protocol for the Western Interior Seaway Shallow Drilling Project: U. S. Geological Survey Open-File Report 92-397, 6 p.

Dean, W.E., Arthur, M.A., Sageman, B.B., and Lewan, M.D., 1995. Core descriptions and preliminary geochemical data for the Amoco Production Company Rebecca K. Bounds #1 Well, Greeley County, Kansas: U. S. Geological Survey Open-File Report 95-209, 243 p.

SUMMARY OF DRILLCORE AVAILABILITY
U. S. CONTINENTAL SCIENTIFIC DRILLING PROGRAM
U.S. GEOLOGICAL SURVEY
CRETACEOUS WESTERN INTERIOR SEAWAY DRILLING PROJECT

o DRILLING AND LOGISTICS:

Location: Lat. 37°45'N, Long. 111°36'W
Locale: Near Escalante, Utah
Drilling: three holes, 3" diameter
Depth: 900 to 1000 ft (274 to 305 m) each
Completion Date: June 26, 1991
Cost: $80,000 (USGS)
Core Recovered: 98%+
Core Repository: USGS Core Research Center, Denver
Fluid Sampling: None
Drilling Management: USGS
Special Concerns: None
Hole Identification: USGS #1 Escalante, CT1-91, and SMP1-91
Status: samples are being collected for geochemical, sedimentologic, and biostratigraphic studies

Location: Lat. 38°23'N, Long. 105°01'W
Locale: Portland (near Florence and Canon City), Colorado
Drilling: one hole, 3" diameter
Depth: 700 ft (213 m)
Completion Date: June 28, 1992
Cost: $50,000 (DOE)
Core Recovered: 99%+
Core Repository: USGS Core Research Center, Denver
Fluid Sampling: None
Drilling Management: USGS
Special Concerns: None
Hole Identification: USGS #1 Portland
Status: Hole was cased to 700' with 11/8" steel pipe for heat-flow measurements; samples are being collected for geochemical, sedimentologic, and biostratigraphic studies

Location: Lat. 38°14'N, Long. 105°06'W
Locale: Wetmore (near Florence and Canon City), Colorado
Drilling: one hole, 3" diameter
Depth: 799 ft (244 m)
Completion Date: July 17, 1992
Cost: $50,000 (DOE)
Core Recovered: Of the 799 feet drilled, coring was attempted on 254.04 feet with recovery of 243.44 ft (96%).
Core Repository: USGS Core Research Center, Denver
Fluid Sampling: None
Drilling Management: USGS
Special Concerns: Problems associated with drilling in fractured shale
Hole Identification: USGS #1 Wetmore
Status: samples are being collected for geochemical, sedimentologic, and biostratigraphic studies

o SCIENTIFIC OBJECTIVE:

Construct a subsurface transect of Cretaceous strata that were deposited in Western Interior Seaway, going from organic-rich, marine hydrocarbon source rocks in Kansas and eastern Colorado to nearshore coal-bearing units in western Colorado and Utah.

o PRINCIPAL INVESTIGATORS:

Walter E. Dean, USGS, Denver; Michael A. Arthur, Penn State Univ.

o INSTITUTIONAL INVOLVEMENT:

Government Agencies: USGS; DOE

Universities: Penn State; Northwestern; North Carolina State; Univs. of Massachusetts, North Carolina, Colorado, & Rhode Island

ADDRESSES OF INVESTIGATORS CONTRIBUTING MANUSCRIPTS TO SYNTHESIS VOLUME WHO RECEIVED FUNDING FROM DOE CONTRACT FOR SALARY, TRAVEL OR SAMPLE ANALYSIS

Co-PIs:
Michael A. ARTHUR (PennState)
Walter E. DEAN (USGS)

Timothy J. BRALOWER
Department of Geology
University of North Carolina
Chapel Hill, NC 27599-3315

Bradley B. SAGEMAN
Department of Geological Sciences
Northwestern University
Evanston, IL 60208

Charles SAVRDA
Department of Geology
210 Petrie Hall
Auburn University
Auburn AL 36849

Mark PAGANI
Dept. of Geosciences
Penn State University
University Park, PA 16802

Elana L. LEITHOLD
Department of Marine, Earth and Atmospheric Sciences
North Carolina State University
Box 8208
Raleigh, NC 27695-8208

Celeste E. BURNS
Department of Geology
University of North Carolina
Chapel Hill, NC 27599-3315

R. Mark LECKIE
Department of Geology and Geography
University of Massachusetts
Amherst, MA 01003

Richard PANCOST
Dept. of Geosciences,
Penn State University,
University Park, PA 16802

Robert W. SCOTT
Precision Stratigraphy Associates
3734 S. Darlington
Tulsa, OK 74135

Oona WEST
Department of Geology and Geography
University of Massachusetts
Amherst, MA 01003

reprint removed.