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Evolution of the Cretaceous calcareous nannofossil genus *Eiffellithus* and its biostratigraphic significance

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ABSTRACT

The calcareous nannofossil genus *Eiffellithus* is an important taxon of mid- to Upper Cretaceous marine sediments in biostratigraphy and paleoceanography. The definition of species within *Eiffellithus* have been both broadly interpreted and variably applied by nannofossil workers. This is particularly true for the *Eiffellithus eximius* plexus. While the taxonomy of mid-Cretaceous *Eiffellithus* species has recently been well-defined, the remaining 35 m.y. history of the genus has not been closely examined. Our investigation of Cenomanian to Maastrichtian sediments from the Western Interior Seaway, Gulf of Mexico, and Western Atlantic gives rise to six new species of *Eiffellithus* that can be reliably differentiated. In this paper the hitherto used biostratigraphic markers (*E. turriseiffelii* and *E. eximius*) have been redefined in a more restricted sense to increase their utility. These refinements in taxonomy reveal an obvious shift in abundance both within the genus and within the nannofossil assemblage as a whole through the Late Cretaceous. In the Cenomanian and Maastrichtian the genus is composed exclusively of coccoliths bearing an X-shaped central cross, such as *E. turriseiffelii,* while in the Coniacian through Campanian axial-cross forms such as *E. eximius* comprise more than 60% of the genus. Within the nannofossil assemblage the genus has low abundances in the Cenomanian but increases to >15% of the assemblage in well-preserved samples in the Santonian. In addition, the pattern of diversification of this genus, whereby a x-shaped, diagonal cross repeatedly gives rise to an axial cross by rotation about the central axis, is an excellent example of iterative evolution that may be related to repetitive shifts in Late Cretaceous climatic and paleoceanographic regimes.

1. Introduction

Since the original description of the genus *Eiffellithus* by Deflandre and Fert (1954), various nannofossil workers have noted the obvious, often striking, interspecies variation within its most prominent species (Verbeek, 1977; Perch-Nielsen, 1968, 1973, 1979, 1985; Watkins and Bergen, 2003). This morphological variability is linked both to the construction of the coccolith itself and to a poorly defined taxonomy. These inconsistencies have generated a wealth of literature that debates and refines the morphological characteristics that distinguish two historical end-members: *Eiffellithus turriseiffelii* (Deflandre and Fert, 1954) Reinhardt, 1965 and *E. eximius* (Stover, 1966) Perch-Nielsen, 1968. There has been little consensus within the nannofossil community with respect to discrete morphotypes, species descriptions, and evolutionary lineages (Gartner, 1968; Perch-Nielsen, 1968, 1973, 1979, 1985; Hill, 1976; Verbeek, 1977; Hill and Bralower, 1987; Watkins and Bergen, 2003).

The type-species for this genus, *E. turriseiffelii*, was one of the first calcareous nannofossil markers used in biostratigraphy. Both *E. turriseiffelii* and *E. eximius* are currently used as biostratigraphic datums in the Roth (1978) NC Zonation, Perch-Nielsen (1985) CC Zonation, and the Burnett and Whitham (1999) UC Zonation for calcareous nannofossils. Species within the genus display key characteristics of strong index fossils: *Eiffellithus* is dissolution resistant (Thierstein, 1980) and shows a rapid rate of evolution after its first appearance datum (FAD) in the upper Albian. The genus *Eiffellithus* is an abundant and ubiquitous component of Late Cretaceous nannofossil assemblages, reaching maximum abundances of up to 15–20% in well-preserved Santonian samples.

Previous work on the early diversification by Perch-Nielsen (1985) and Watkins and Bergen (2003) provide a well-defined taxonomy for the genus for the late Albian - middle Cenomanian. Despite the high abundance of this genus throughout the Late Cretaceous, these later forms remain largely undefined. The current study develops a more refined taxonomy for this period and defines

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the morphological diversity and variability present in these *Eiffellithus* assemblages. This taxonomic framework aids in biostratigraphy, particularly when one considers the likelihood of polytaxic markers in current *Eiffellithus* datums.

In this study, over 9000 specimens of *Eiffellithus* from the Upper Cretaceous were examined to verify the ranges of current biostratigraphic markers, to define the taxonomic relationships between discrete morphotypes, and to examine the potential source of variability expressed by these forms. This study identifies numerous new species and potential biostratigraphic datums and gives an excellent demonstration of iterative evolution.

2. Site localities

Samples were selected from five localities: three in the Western Interior Basin (Washington Co., KS; Smoky Hill type area; Sisseton, SD) and two North American deep water localities (DSDP Leg 10–95; ODP Leg 171b-1049A/1050C) (Fig. 1). Sites were selected based on good average preservation of calcareous nannofossils and best stratigraphic coverage (Fig. 2). Due to the variation in both depositional and recovery thickness, samples were taken at regular intervals at each locality in order to maximize sampling from the available materials while generating a regular sample spacing throughout the column with respect to time. A total of 201 samples were used in final analysis. Samples with very low nannofossil abundance ($\leq$ 5% sediment volume) were excluded, as well as samples with poor preservation, where over-growth or dissolution obscures key morphological characteristics.

Greenhorn Limestone samples were collected from outcrop in North-central Kansas (Washington Co.) at Localities 6–7 of Hattin (1975), whose work provides a detailed lithologic description of each locality. Samples were collected at 10–20 cm intervals through 16.35 m of section, and consisted primarily of chalky limestone from the top of the Lincoln Member (Mbr) through the Pfeiffer Member. This site contains the oldest sediments examined in this study, from the base of the middle Cenomanian through the lower Turonian, with good coverage of the Cenomanian-Turonian boundary. Due to varying preservation, 69 of 115 samples were used in final analysis. First appearance datums from this section have been dated by correlation of marker units of Sageman et al. (1998). Dates are tentative and are given to estimate the timing of evolutionary events.

The Niobrara Chalk Formation (Fm) was sampled from outcrop at the Smokey Hill type area of Hattin (1982) in west central Kansas. The type area consists of a series of localities that spans the entire lithologic section, with Hattin's study (1982) providing very detailed stratigraphic and lithologic descriptions of each type locality. The section was sampled over 191 m at 1 m intervals, and consists of nannofossil rich chalks, for which the formation is named. This sample set includes the Fort Hayes and Smoky Hill Mbrs, with good coverage from the Coniacian -lower Campanian. From the 191 original samples, 103 were closely examined for their excellent preservation and stratigraphic distribution.

Deep Sea Drilling Program (DSDP) Leg 10, Site 95 is located on the Campeche Scarp face of the Yucatan Shelf in the Gulf of Mexico. Sediments consist of nannofossil chalk and foraminifera-nannofossil chalk to ooze, with thin intervals of chert clasts. Reports from DSDP Leg 10 by Worzel et al. (1973) give lithologic descriptions and stratigraphic distributions for this site. Cores were sampled through the entire 42 m of Late Cretaceous sediments. Cores 13–18 were sampled with as regular a spacing as possible;

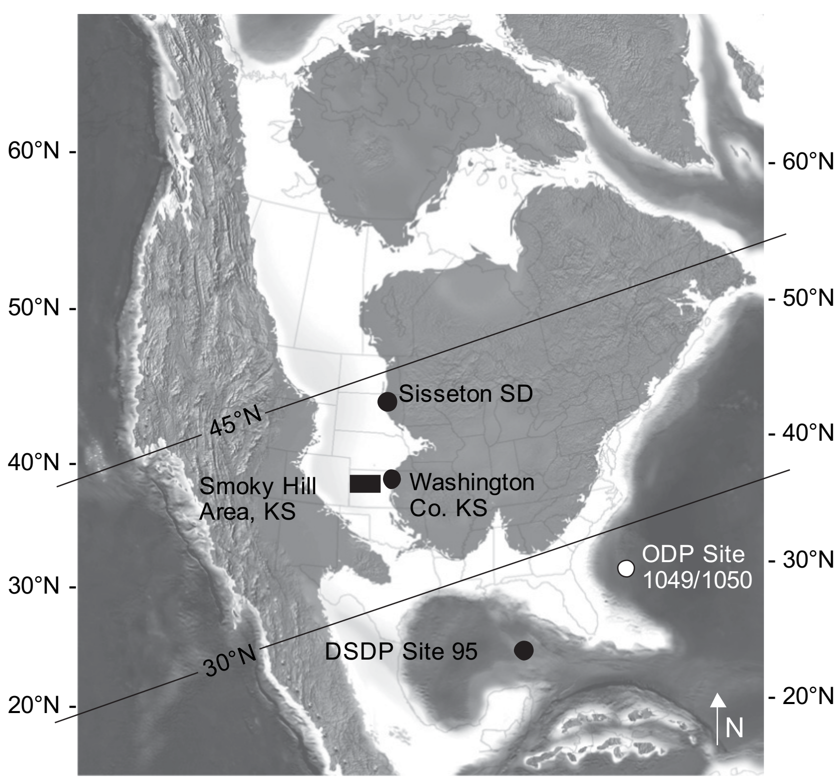

Fig. 1. Geographical distribution of the five localities examined in this study, three in the Western Interior Basin (Washington Co., KS; Smoky Hill type area; Sisseton, SD) and two North American deep water localities (DSDP Leg 10–95; ODP Leg 171b-1049A/1050C). Sites were correlated to create a composite Late Cretaceous section. Paleolatitudes lines at 30° and 45° are also shown.