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STRONTIUM ISOTOPE STRATIGRAPHY IN THE LATE CRETACEOUS: NUMERICAL CALIBRATION OF THE Sr ISOTOPE CURVE AND INTERCONTINENTAL CORRELATION FOR THE CAMPANIAN

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Abstract. The white Chalk exposed in quarries at Lägerdorf and Kronsmoor, northwestern Germany, provides a standard section for the European Upper Cretaceous. The $^{87}Sr/^{86}Sr$ values of nannofossil chalk and belemnite calcite increase upward through 330 m of section, from ≤ 0.70746 in the Upper Santonian to ≥ 0.70777 in the Lower Maastrichtian. The data define three linear trends separated by major points of inflection at stratigraphic heights in the section of 162 m (75.5 Ma) in the Upper Campanian *Galerites vulgaris* zone and at -6 m (82.9 Ma), just above the base of the Campanian in the *Inoceramus lingua/Gonioteuthis quadrata* zone. The temporal rate of change of $^{87}Sr/^{86}Sr$ was constant through each of the linear segments of our isotope "curve" when viewed at the resolution of our average sampling interval (0.15 m.y.). Fine structure, if real, may record brief (< 100 kyr) excursions of $^{87}Sr/^{86}Sr$ from values expected from the overall trends. In Lägerdorf, the boundary between the Santonian and Campanian stages, taken here as the level of first occurrence of the belemnite *Gonioteuthis granulataquadrata*, has an $^{87}Sr/^{86}Sr$ of 0.707473 ± 5. This is within error of the values of 0.707457 ± 16 for this boundary in the U.S. western interior (base of the *Scaphites leei* III zone) and 0.707479 ± 9 for this boundary in the English Chalk (top of the *Marsupites testudinarius* zone). In Kronsmoor, the boundary between the Campanian and Maastrichtian stages, taken here as the level of first occurrence of the belemnite *Belemnella lanceolata*, has an $^{87}Sr/^{86}Sr$ of 0.707723 ± 4. This is within error of the values of 0.707725 ± 20 for this boundary in the U.S. western interior (base of the *Baculites eliasi* zone) and 0.707728 ± 5 for this boundary in the English Chalk (defined as in Germany).

1. INTRODUCTION

Dating and correlation with Sr isotopes are now commonplace (for reviews and applications see Elderfield [1986], Miller et al. [1988, 1991], Veizer [1989], McArthur et al. [1990, 1992, 1993*a*, *b*] and references therein). For the method to be useful, $^{87}Sr/^{86}Sr$ in samples of unknown age must be matched to standard curves that are calibrated against well-documented biostratigraphy, magnetostratigraphy, and numeric age. As currently practiced, much strontium isotope stratigraphy assumes a high quality for this stratigraphic framework, but this quality, and the quality of accompanying assignments of numeric age, are generally overestimated. Some pointers to the real errors inherent in the stratigraphy, and numeric age assignment, used for Sr isotope work have recently been given by Miller et al. [1988, 1991].

Most extant Sr isotope curves are based on Deep Sea Drilling Project/Ocean Drilling Project (DSDP/ODP) sections that are calibrated against magnetostratigraphy and nannofossil and microfossil biostratigraphy, whereas the correlation and dating of most continental sequences is based on zonation with macrofossils. Integration of these different schemes is not straightforward and can be assisted by the use of Sr isotopes.

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This paper represents a step toward such integration by providing a detailed curve of $^{87}Sr/^{86}Sr$ through a standard section of the Upper Cretaceous European Chalk at Lägerdorf and Kronsmoor in northwestern Germany. We use this curve to correlate to the U.S. western interior, and to the United Kingdom.

2. SAMPLES ANALYZED

To define our $^{87}Sr/^{86}Sr$ curve, we have analyzed belemnites and bulk samples of nannofossil chalk from quarries near Lägerdorf and Kronsmoor, 40 km northwest of Hamburg, Germany [Schönfeld et al., 1993]. For the purposes of correlating other sections to Germany, we have analyzed nannofossil chalk and macrofossils (fragments of inoceramid bivalves, brachiopods, belemnites, and an oyster) from a borehole cored through the English Chalk at Trunch, Norfolk, United Kingdom [McArthur et al., 1993*a*], and fragments of aragonitic ammonites and calcitic inoceramid bivalves from the United States western interior [McArthur et al., 1993*b*].

3. STRATIGRAPHY

It is important to note that the boundaries between Upper Cretaceous stages and substages have not yet been defined by the International Commission on Stratigraphy and that boundaries vary widely in their position from author to author, as do boundaries defined by different fossil groups. For a general discussion of Upper Cretaceous stage boundaries, see the works by Birkelund et al. [1984] and Hancock [1991, 1993].

The section at Lägerdorf/Kronsmoor is one of the best available for the northwestern European Upper Cretaceous Chalk. Its stratigraphy is summarized by Schönfeld et al. [1993]; relevant details are briefly repeated here. Four meters of unexposed section separate the lowermost strata in Kronsmoor from the uppermost strata in Lägerdorf. The stratigraphy of the combined section is given in Figure 1. The difference in sedimentological detail shown in the upper (Kronsmoor) and lower (Lägerdorf) parts of Figure 1 are due to their derivation from different authors (see section 3.1 and 3.2). Nineteen macrofossil zones can be recognized, based on the distribution of ammonites, belemnites, inoceramid bivalves, echinoids and crinoids, together with 15 benthic foraminiferal zones (see sections 3.1 and 3.2). Stratigraphic levels are given in meters from a prominent Lower Campanian marl seam (M1) in Lägerdorf that is widely traceable in northwestern Europe. Bedding is picked out by layers of flint nodules, marl seams, marly chalk beds, and beds containing pyritized burrows. The chalk is friable and white and consists of >85% nannofossils, together with minor amounts of calcispheres, foraminifera, macrofossil debris (fragments of bryozoa, echinoids, bivalves, and brachiopods), and generally less than 10% clastic material [Schulz et al., 1984; Schönfeld et al., 1991]. Certain levels, such as the Santonian/Campanian boundary, locally contain up to 40% inoceramid prisms. Following two of the recommendations of Birkelund et al. [1984], the base of the Campanian in Lägerdorf has been drawn at the level of first occurrence of the belemnite *Gonioteuthis granulataquadrata*, and the base of the Maastrichtian in Kronsmoor has been drawn at the level of first occurrence of the belemnite *Belemnella lanceolata*.

3.1 *Lägerdorf*

The lithostratigraphy and macrofossil biostratigraphy are based on the works by Ernst [1963], Schultz [1978], and Schultz et al. [1984], which are summarised by Schönfeld et al. [1993]. Thirteen macrofossil zones can be correlated widely in the Chalk of northwestern Europe. Eleven benthic foraminiferal zones of more local applicability were established by Koch [1977] and Schönfeld [1988]. The nannofossil zonation is from Burnett [1990] and Schönfeld and Burnett [1991] and is based on the standard calcareous nannofossil zonation scheme (CC zones of Sissingh [1977] in Figure 1), as amended by Perch-Nielsen [1979, 1985]. The nannofossil zonation has been refined by the definition of boreal subzones (CC/B zones of Burnett [1990] in Figure 1).

3.2 *Kronsmoor*

The lithostratigraphy is from Schulz [1978], the macrofossil zonation is from Schulz [1979], the benthic microfossil zonation follows Schönfeld [1988], the microbrachiopod zonation is after Surlyk [1982], and the nannofossil zonation is from Burnett [1990]. Some levels in the Kronsmoor section has been biostratigraphically correlated to DSDP sites 548A, 549, and 551 using calcareous benthic foraminifera and nannoplankton [Schönfeld and Burnett, 1991].

4. METHODS AND RESULTS

The analytical methodology is that given by McArthur et al. [1992, 1993*a*]. Isotopic measurements were made using a model VG 354 multicollector mass spectrometer utilizing multidynamic routines [Thirlwall, 1991]. All $^{87}Sr/^{86}Sr$ data have been normalized to a value of 0.1194 for $^{86}Sr/^{88}Sr$ and adjusted to an $^{87}Sr/^{86}Sr$ value of 0.710248 for standard reference material SRM 987. The adjustment was based on the mean $^{87}Sr/^{86}Sr$ for SRM 987 for periods of measurement between major machine maintenance. Adjustment never exceeded 18×10^{-6} and was generally less than half this value. Two standards (SRM 987) were run per turret of 14 samples; based on these accumulated replicates, the reproducibility of our measurements of $^{87}Sr/^{86}Sr$ is $\pm 18 \times 10^{-6}$ for single determinations, $\pm 13 \times 10^{-6}$ for duplicates, and $\pm 10 \times 10^{-6}$ for triplicates, where the error is at 2 standard errors (2 s.e), calculated as $2 \times$ standard deviation$/(n)^{½}$, where n is the number of determinations. The mean $^{87}Sr/^{86}Sr$ for 11 subsamples of aragonite from a modern nautiloid and 5 samples of seawater from the North Atlantic is 0.709175 ± 4 (2 s.e.), after adjustment to SRM 987 of 0.710248.

The data are given in Table 1 and are plotted against stratigraphic level in Figures 2-5 and against numeric age in Figure 6. In all figures, error bars are drawn at 2 s.e. Linear regressions are done according to the method of York [1967], using errors of $\pm 18 \times 10^{-6}$ in $^{87}Sr/^{86}Sr$ and 0.1 m in stratigraphic level. With a Campanian sedimentation rate (present compaction) of 11 meters/m.y. (271 m in 12.2 m.y.) (Figures 2 and 5), a stratigraphic accuracy of ± 0.1 m is equivalent to ± 0.005 m.y., which is the precision of relative ages within our section. Although precise relative to each other, these numeric ages may be systematically inaccurate by up to ± 0.5 m.y., as these are the uncertainties of the ages of stage boundaries [Obradovich, 1993] (see section 5.5).

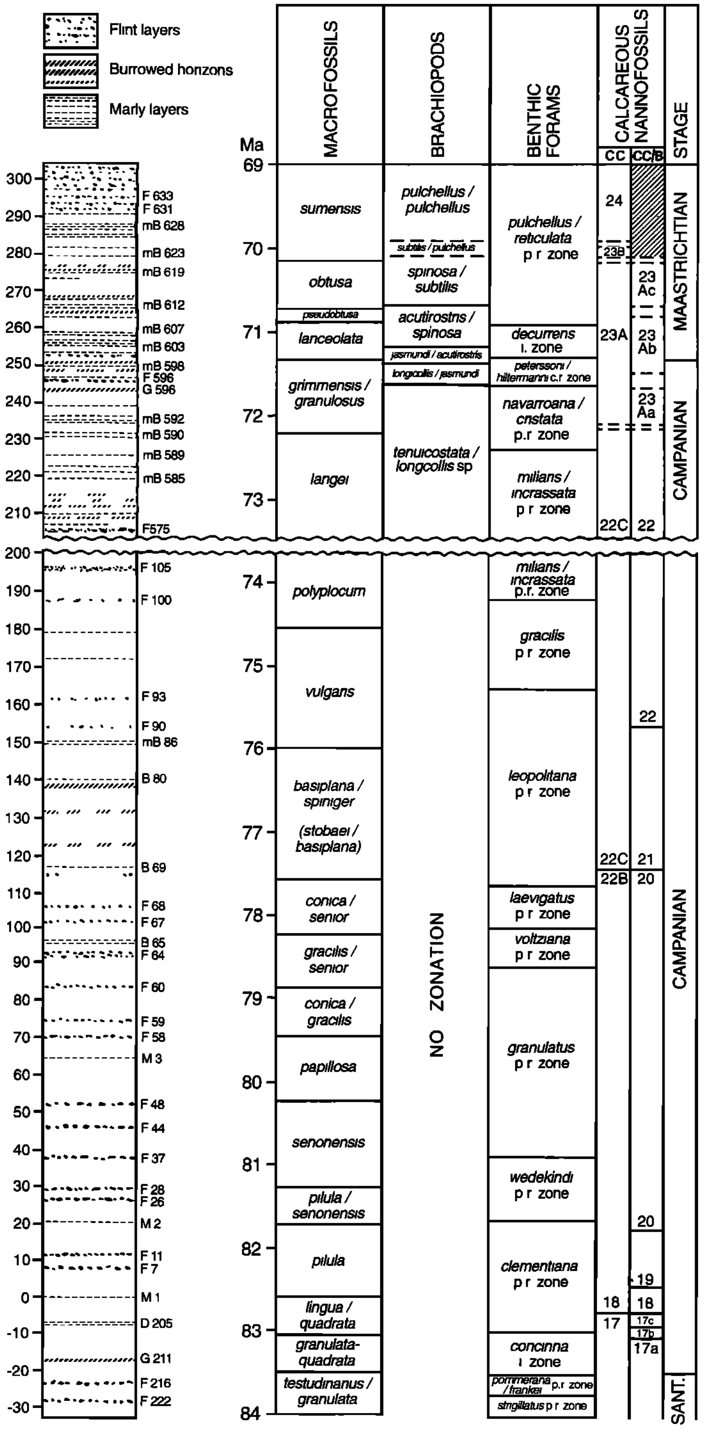

Fig. 1. Stratigraphy of the Chalk at Lägerdorf/Kronsmoor. The base of the exposed section is at -62 m and the top is at 300 m. Nannofossils zones; CC are zones of Sissingh [1977], CC/B are zones of Sissingh [1977] as modified by Burnett [1990]. The base of the Maastrichtian is at 251 m and the base of the Campanian is at -20 m. Note that in McArthur et al. [1992], the *miliaris/incrassata* zone was incorrectly labelled the *miliaris/cristata* zone. The difference in sedimentological detail between the upper and lower parts of the section results from their derivation from different sources (see text for details).

5. DISCUSSION

5.1 *Diagenesis*

The chalk at Lägerdorf/Kronsmoor is friable and disaggregates in water; on this criteria it is essentially uncemented, a fact which suggests it has undergone little diagenetic alteration. Because of this, we believe it is recording an accurate record of marine ^{87}Sr/^{86}Sr, despite the presence of a little microspar in lower stratigraphic levels of Lägerdorf [Schönfeld et al., 1991]. Paired samples of calcite from whole belemnites and nannofossil chalk from eight levels in the sections have been analyzed for ^{87}Sr/^{86}Sr, and for each pair the ^{87}Sr/^{86}Sr values are within error of each other (Table 1). This further suggests that our nannofossil samples are well preserved; it seems unlikely that diagenesis could affect equally massive low-magnesium calcite in belemnite guards and micron-sized nannoplankton remains, in view of their greatly different mass/surface area ratios. Samples from the United States were pristine, as judged by X ray diffraction, scanning electron microscopy, chemical analysis, and optical microscopy; details are given in McArthur et al. [1993*b*]. These samples preserve their original ^{87}Sr/^{86}Sr values. In the English Chalk of Norfolk, which is more cementedthan the German Chalk, diagenetic alteration has increased ^{87}Sr/^{86}Sr in nannofossil matrix by 30 x 10^{-6} compared to ^{87}Sr/^{86}Sr in macrofossils from the same stratigraphic level [McArthur et al., 1993*a*, McArthur, 1993]. We therefore correct for this diagenetic effect by subtracting 30 x 10^{-6} from the ^{87}Sr/^{86}Sr values of the Norfolk nannofossil samples.

5.2 *Sr Isotope Curve for Germany*

The ^{87}Sr/^{86}Sr data increases from $\leq$0.70747 to $\geq$0.70777 with increasing stratigraphic height through the section. The quality of our isotopic measurements appears good when judged by the degree of concordance of adjacent data (Figure 2). The data appear to define three linear segments, which are separated by inflections in the Upper Campanian *G. vulgaris* zone at 162 m and at -6 m in the lowermost Campanian *I. lingua*/*G. quadrata* zone. In section 5.5 we discuss York [1967] regressions between ^{87}Sr/^{86}Sr, stratigraphic level, and numeric age. Data may plateau over short intervals between -2 m and 10 m (upper part of the *I. lingua*/*G. quadrata* zone and lower half of the *Offaster pilula* zone), between 52 m and 65 m (*Galeola papillosa* zone), and between 150 m and 162 m (bottom half of the *G. vulgaris* zone), although none of these plateau are unequivocally defined.

Two possible short-term excursions in ^{87}Sr/^{86}Sr are present; sample 51 (139.7 m) and 46 (103.7 m) have ^{87}Sr/^{86}Sr that is reproducibly lower by about 20-30 x 10^{-6} than expected for their stratigraphic level. A belemnite from 137.7 m has an ^{87}Sr/^{86}Sr similar to that of sample 51, but an intervening nannofossil sample (B80 -1.1, 138.7 m) is not anomalous (Table 1). The reproducibility of the ^{87}Sr/^{86}Sr data for these samples suggests that these anomalies are real. They may result from localized diagenesis, or they may be recording real excursions in marine ^{87}Sr/^{86}Sr. The nannofossil assemblages in samples 46 and 51 are consistent with their stratigraphic level (J. A. Burnett, personal communication, 1992), so the anomalous ^{87}Sr/^{86}Sr cannot be explained by errors in curation.

TABLE 1. Isotopic Data for Nannofossil Chalks and Belemnites From Lagerdorf / Kronsmoor, Germany

Sample Number	Age, Ma	Level*	Sample 87Sr/86Sr	Error	Mean 87Sr/86Sr
		Kronsmoor Quarry			
35	69.43	292.5	0.707768	9	0.707766
			0.707764	8	
34	69.57	289.5	0.707770	8	0.707770
32	69.76	285.1	0.707773	11	0.707773
K-Bel-3	69.88	282.5	0.707769	11	0.707769
31	69.90	282.1	0.707764	17	0.707764
30	69.98	280.4	0.707748	7	0.707757
			0.707757	10	
			0.707766	7	
29	70.17	276.2	0.707750	9	0.707750
26	70.52	268.4	0.707754	10	0.707754
25	70.68	264.8	0.707741	9	0.707741
23	70.82	261.6	0.707726	8	0.707726
22	71.00	257.6	0.707733	9	0.707733
K-Bel-2	71.01	257.5	0.707738	9	0.707738
16	71.10	255.4	0.707742	9	0.707742
15	71.19	253.5	0.707719	10	0.707719
14	71.26	251.9	0.707721	8	0.707725
			0.707730	6	
21	71.32	250.6	0.707723	7	0.707723
		Campanian - Maastrichtian Boundary at 251 m			
18	71.42	248.4	0.707710	10	0.707710
19	71.48	246.9	0.707725	11	0.707725
39	71.77	240.5	0.707700	8	0.707700
K-Bel-1	71.82	239.5	0.707711	10	0.707711
37	71.98	235.9	0.707696	8	0.707696
13	72.20	231.1	0.707693	7	0.707693
11	72.28	229.3	0.707697	8	0.707696
			0.707695	9	
12	72.37	227.3	0.707686	7	0.707686
9	72.51	224.1	0.707684	7	0.707684
7	72.57	222.7	0.707689	9	0.707689
8	72.66	220.8	0.707675	9	0.707675
3	72.71	219.7	0.707688	9	0.707688
5	72.88	215.9	0.707680	8	0.707680
6	73.12	210.5	0.707667	10	0.707667
2	73.35	205.4	0.707664	9	0.707664
1	73.46	203.0	0.707667	10	0.707663
			0.707659	9	
		Lagerdorf Quarry			
63	73.93	192.5	0.707651	9	0.707651
52	74.18	187.0	0.707645	7	0.707645
L-Bel-5	74.18	187.0	0.707635	10	0.707635
54	74.38	182.5	0.707633	11	0.707633
			0.707633	8	
55	74.61	177.5	0.707628	9	0.707628
56	74.84	172.3	0.707630	9	0.707616
			0.707602	9	
57	75.08	167.0	0.707620	9	0.707620
			0.707618	10	
			0.707621	6	

TABLE 1. (continued)

Sample Number	Age, Ma	Level*	Sample 87Sr/86Sr	Error	Mean 87Sr/86Sr
58	75.31	162.0	0.707606	6	0.707603
			0.707599	10	
59	75.55	156.5	0.707605	8	0.707610
			0.707613	10	
			0.707613	9	
60	75.69	153.5	0.707606	7	0.707611
			0.707616	9	
64	75.78	151.5	0.707604	9	0.707611
			0.707619	7	
			0.707609	9	
65	75.96	147.5	0.707623	9	0.707615
			0.707618	7	
			0.707605	11	
B80(6.1)	76.03	145.9	0.707601	9	0.707601
B80(2.1)	76.21	141.9	0.707596	9	0.707603
			0.707610	18	
B80(1.1)	76.26	140.9	0.707598	10	0.707598
B80(0.2)	76.30	140.0	0.707617	9	0.707617
51	76.31	139.7	0.707582	9	0.707577
			0.707572	8	
B80(-1.1)	76.36	138.7	0.707600	10	0.707600
L-Bel-4	76.40	137.7	0.707573	10	0.707573
B69(19.5)	76.45	136.5	0.707613	12	0.707602
			0.707591	9	
B69(16.8)	76.58	133.8	0.707604	9	0.707604
B69(12.8)	76.76	129.8	0.707604	12	0.707604
B69(10.1)	76.88	127.1	0.707596	10	0.707596
B69(6.4)	77.04	123.4	0.707595	11	0.707595
50	77.20	120.0	0.707580	8	0.707586
			0.707591	13	
			0.707586	9	
48	77.39	115.8	0.707589	7	0.707589
47	77.84	105.7	0.707579	10	0.707579
F67(2.1)	77.91	104.2	0.707561	10	0.707561
46	77.93	103.7	0.707546	9	0.707546
			0.707546	6	
			0.707548	9	
F67(1.1)	77.95	103.2	0.707572	13	0.707572
F67(0.1)	78.00	102.2	0.707559	9	0.707559
45	78.05	101.0	0.707559	9	0.707559
44	78.19	98.0	0.707570	8	0.707570
43	78.29	95.8	0.707570	9	0.707570
41	78.40	93.2	0.707569	6	0.707569
38	78.72	86.2	0.707551	11	0.707551
37	78.90	82.2	0.707554	16	0.707554
36	78.99	80.2	0.707546	11	0.707546
35	79.08	78.2	0.707541	10	0.707541
F59(0.1)	79.28	73.7	0.707533	10	0.707533
34	79.37	71.7	0.707539	10	0.707539
31	79.48	69.2	0.707550	9	0.707546
			0.707541	9	
30	79.75	63.4	0.707522	11	0.707521
			0.707520	11	
L-Bel-3	79.75	63.4	0.707515	10	0.707515

TABLE 1. (continued)

Sample	Age, Ma	Level*	Sample 87Sr/86Sr	Error	Mean 87Sr/86Sr
29	79.86	60.8	0.707525	7	0.707531
			0.707536	10	
27	80.07	56.2	0.707529	8	0.707529
			0.707529	10	
25	80.29	51.4	0.707538	9	0.707538
24	80.55	45.6	0.707533	7	0.707533
23	80.86	38.6	0.707517	10	0.707517
22	80.92	37.2	0.707530	10	0.707530
18	81.15	32.2	0.707517	7	0.707517
17	81.19	31.4	0.707503	9	0.707511
			0.707519	9	
16	81.28	29.3	0.707506	12	0.707511
			0.707516	9	
1	81.38	27.2	0.707527	11	0.707522
			0.707517	10	
14	81.48	24.8	0.707511	10	0.707511
13	81.53	23.7	0.707519	10	0.707517
			0.707515	12	
12	81.58	22.7	0.707512	9	0.707509
			0.707506	7	
9	81.64	21.4	0.707521	11	0.707521
6	81.70	20.0	0.707514	10	0.707514
5	81.78	18.2	0.707498	9	0.707498
L-Bel-2	81.78	18.2	0.707495	10	0.707495
4	81.83	17.2	0.707524	9	0.707509
			0.707493	10	
88	81.92	15.1	0.707507	10	0.707507
87	82.05	12.2	0.707508	9	0.707508
86	82.10	11.1	0.707499	11	0.707499
85	82.20	8.8	0.707491	7	0.707497
			0.707503	11	
84	82.32	6.3	0.707500	9	0.707500
82	82.45	3.4	0.707495	7	0.707495
67	82.61	-0.3	0.707497	9	0.707497
68	82.67	-1.5	0.707497	9	0.707497
69	82.74	-3.1	0.707488	7	0.707488
70	82.88	-6.2	0.707497	9	0.707497
71	82.93	-7.3	0.707494	10	0.707494
72	83.00	-8.9	0.707509	7	0.707496
			0.707482	11	
73	83.18	-13.0	0.707490	8	0.707490
77	83.33	-16.3	0.707471	11	0.707471
76	83.41	-17.9	0.707475	11	0.707475
75	83.45	-18.9	0.707481	9	0.707481
Santonian - Campanian Boundary at -20 m					
74	83.54	-20.9	0.707463	9	0.707463
			0.707462	9	
78	83.65	-23.4	0.707470	7	0.707470
79	83.77	-26.1	0.707468	9	0.707468
80	83.85	-27.8	0.707461	8	0.707461
L-Bel-1	83.92	-29.3	0.707449	8	0.707449

*Levels are in meters from M1, a prominent marl band. Errors are 2 standard errors of mass spectrometric measurement. Bel in sample number denotes a belemnite.

Published lithological sections show no sedimentological features that might correlate with, and so explain, these low data (J. Schönfeld, personal communication, 1993]. Samples from marl bands, such as M1 (sample 67), and from burrowed horizons (sample 74) do not show unusual $^{87}Sr/^{86}Sr$, so neither sample 51, which is between a marl band and a pyritized burrowed horizon, nor sample 46, which is over 1 m from any flint, marl, or other sedimentological feature of note, is likely to be affected by locally enhanced diagenetic alteration of $^{87}Sr/^{86}Sr$.

Our sample interval at the excursions, coupled with our age model (section 5.5), show that these excursions, if reflecting excursions in marine $^{87}Sr/^{86}Sr$, had a duration of $\leq$ 100 kyr. Short-term fluctuations of marine $^{87}Sr/^{86}Sr$ have been proposed by others [Capo and DePaolo, 1988; Dia et al., 1992; Clemens et al., 1993] but remain highly controversial [Henderson et al., 1993; McArthur, 1993; Richter and Turekian, 1993]. If such short-term changes are real and the mechanism(s) causing them operated in the Cretaceous, the variations may limit the stratigraphic resolution of Sr isotope stratigraphy, as currently done by matching $^{87}Sr/^{86}Sr$ in different sections, to a level no better than that now attainable as modern methods have analytical errors of about 10 to 20 x 10^{-6}. In sections where sedimentation rates were very high, however, repetitive excursions may permit accurate correlation by matching inflections in a manner similar to that done with $\delta^{18}O$ records.

5.3. *Intercontinental Boundary Correlations*

In Figures 3 and 4, we compare $^{87}Sr/^{86}Sr$ across the Santonian/Campanian and Campanian/Maastrichtian boundaries in Lägerdorf/Kronsmoor, the U.S. western interior, and the English Chalk of Norfolk, United Kingdom. Data are plotted with error bars of 2 s.e. For the European sections we estimate values of $^{87}Sr/^{86}Sr$ for stage boundaries using the linear regression of York [1967] between $^{87}Sr/^{86}Sr$ and stratigraphic level for samples near the boundary interval, that is, those plotted in Figures 3 and 4. The mean square of weighted deviates (MSWD) was 1.76 for the regression computed for the Campanian/Santonian boundary section in Norfolk; other MSWD values were less than 1.55. The errors on the boundary values are at 2 s.e. and are derived from the regressions. We use linear regression only where data are sufficiently numerous for meaningful results to be obtained. For the U.S. western interior, data are few, so we envelope this data and take the midpoint of the envelope as the boundary value and the limits of the envelope as its error.

Lägerdorf/Kronsmoor. Following recommendations of Birkelund et al. [1984], the base of the Campanian in Germany is taken to be at the level of first occurrence of the

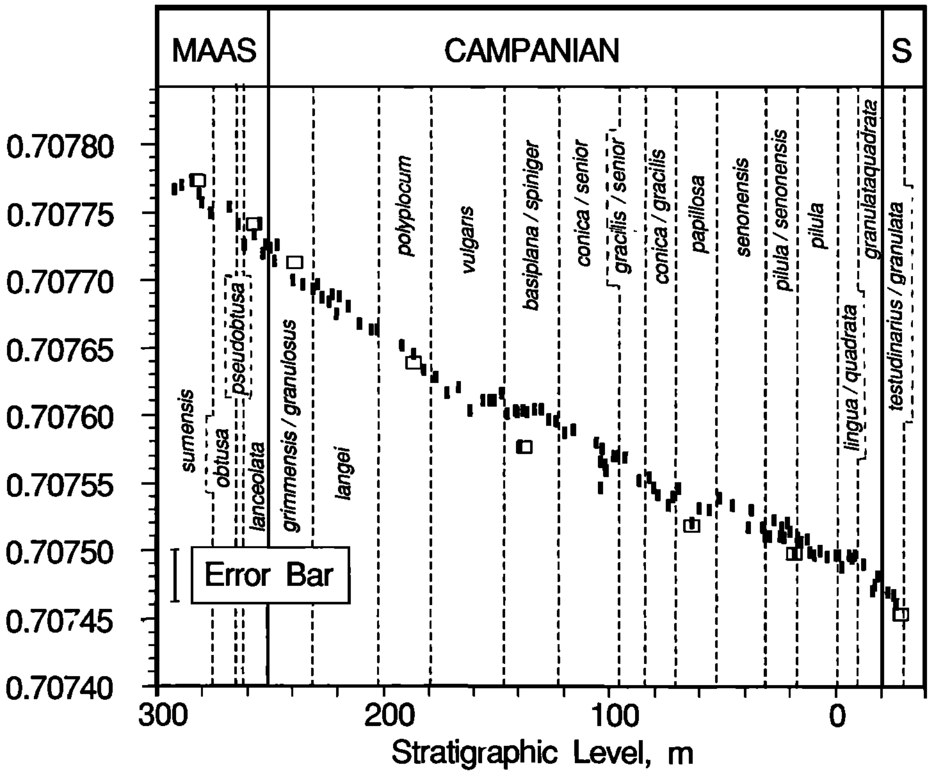

Fig. 2. Strontium isotope ratios as a function of stratigraphic level in the Lägerdorf/Kronsmoor sections. Measurements are in meters from the prominent marl band M1. Macrofossil zones in italics. Open squares represent data for belemnites and vertical bars represent data for bulk nannofossil matrix. The error bar is ± 18 x 10^{-6}.

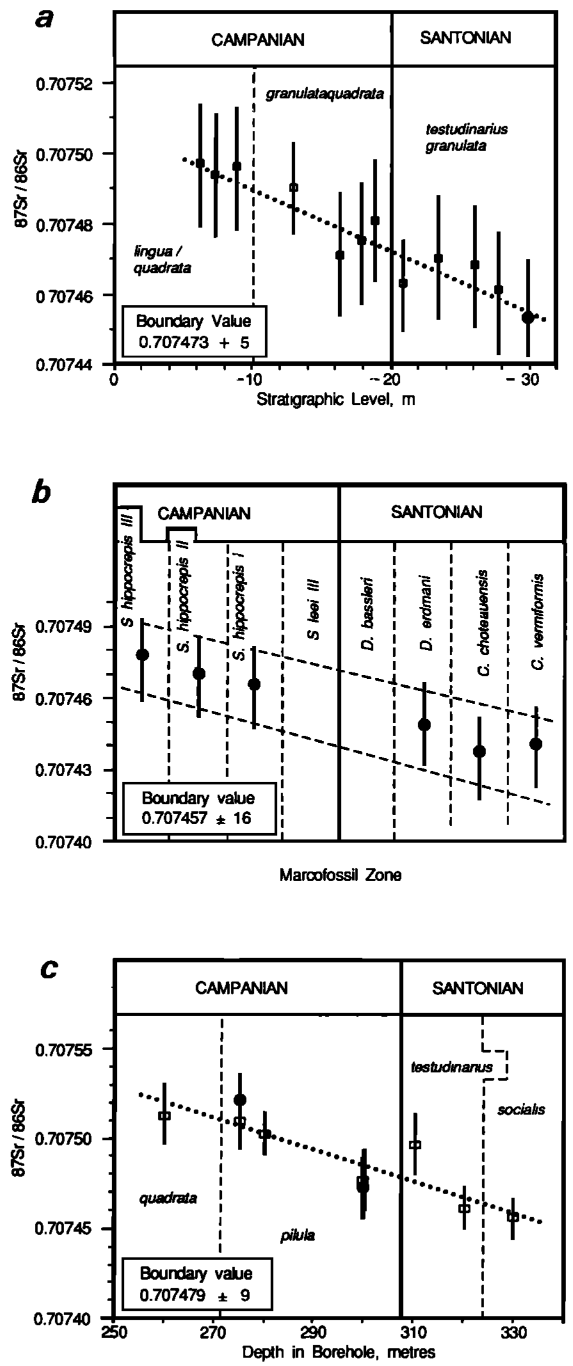

Fig. 3. Trends in strontium isotope ratio across the Santonian/Campanian boundary for (a) Lägerdorf, Germany (b) U.S. western interior, (c) Norfolk, United Kingdom. Errors and error bars are ± 2 standard errors, except for 3b, for which the error on the boundary value is taken as half the envelope width. Open boxes represent nannofossil matrix and filled circles represent macrofossils.

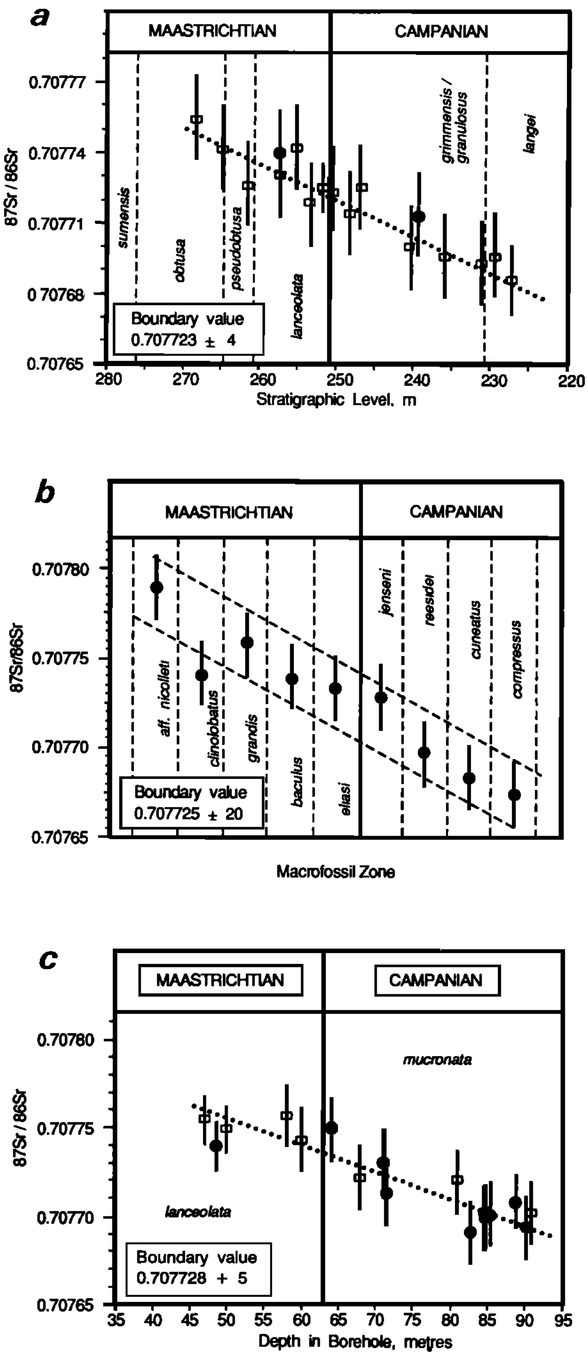

Fig. 4. Trends in strontium isotope ratio across the Campanian/Maastrichtian boundary for (a) Kronsmoor, Germany (b) U.S. western interior, c) Norfolk, United Kingdom. Errors and errors bars are ± 2 standard errors, except for 3b, for which error on boundary value is taken as half the envelope width. Open squares represent nannofossil matrix and filled circles represent macrofossils.

belemnite *Gonioteuthis granulataquadrata* and the base of the Maastrichtian is taken to be at the level of first occurrence of the belemnite *Belemnella lanceolata*. Values of $^{87}Sr/^{86}Sr$ at these boundaries are based on York [1967] regression for those data shown in Figures 3 and 4, and are 0.707473 ± 5 (2 s.e.) for the base of the Campanian at -20 m and 0.707723 ± 4 (2 s.e.) at the base of the Maastrichtian at 251 m. A value for the base of the Maastrichtian may also be calculated from York regression of all the data defining the linear array above 161 m rather than that close to the boundary. Regression of these 40 data yields a value for $^{87}Sr/^{86}Sr$ of 0.707723 ± 3 (2 s.e.). These values apply only to the boundaries as defined here with belemnites [Birkelund et al., 1984].

The U.S. western interior. The ammonite zonation scheme for the U.S. western interior is based on that of Cobban [1984, 1993] and Kennedy and Cobban [1991] with certain modifications, which are discussed in detail by McArthur et al. [1993*b*]. Numerical dates for the U.S. western interior are those of Obradovich [1993]. In Lägerdorf/Kronsmoor the base of the Campanian, as taken here, is equivalent to the level of last occurrence of the pelagic crinoid *Marsupites testudinarius* (Schlotheim). In the western interior, *Marsupites* extends to the *Desmoscaphites bassleri* zone, which is here taken to be the highest Santonian zone. We therefore draw the base of the Campanian stage at the base of the overlying zone of *Scaphites leei* III. The base of the Maastrichtian in the U.S. western interior has been placed by Kennedy et al. [1992] and Kennedy and Cobban [1993] between the ammonite zones of *B. eliasi* and *B. jenseni*, and this placement is accepted here.

Profiles of $^{87}Sr/^{86}Sr$ across these boundaries are given in Figures 3 and 4, where $^{87}Sr/^{86}Sr$ is plotted against macrofossil zones, with each zone arbitrarily being given the same width. Also, samples are plotted in the middle of each zone, because there is no way of determining with accuracy the position of samples within their zones, which are often defined by beds of concretion-enclosed fossils in otherwise barren shales. Boundary values for $^{87}Sr/^{86}Sr$ and errors given by envelope widths are 0.707457 ± 16 for the base of the Campanian and 0.707725 ± 20 for the base of the Maastrichtian.

The English Chalk. Details of the macrofossil stratigraphy of the English Chalk at Trunch, Norfolk, are given by Gallois and Morter [1975] and Wood and Morter [1994] and are reproduced in McArthur et al. [1992, 1993*a*]. For the Trunch borehole, stratigraphic levels are given in meters below surface level. The base of the Campanian, at 307.4 m, is placed at the last occurrence of the pelagic crinoid *Marsupites testudinarius* (Schlotheim), and the base of the Maastrichtian, at 62.5 m, is placed at the first occurrence of *Belemnella* sp. in correlative beds on the Norfolk coast. The uncertainty in the positioning of these boundaries in the borehole is no more than ± 3 m [McArthur et al. 1993*a*]. Profiles of $^{87}Sr/^{86}Sr$ across the Santonian/Campanian and Campanian/Maastrichtian boundaries in the section are shown in Figures 3 and 4. Macrofossil data are scarce, because the borehole core provided only a small volume of sediment to sample, so we constrain the trend with data for nannofossil chalk corrected for diagenesis by subtracting 30×10^{-6} from $^{87}Sr/^{86}Sr$ values [McArthur et al. 1993*a*, McArthur, 1993]. Boundary values for $^{87}Sr/^{86}Sr$ are 0.707479 ± 9 (2 s.e.) for the base of the Campanian at 307.4 m and 0.707728 ± 5 (2 s.e.) for the base of the Maastrichtian at 62.5 m.

5.4 *Isotopic Correlation Between U.S. Western Interior and Lägerdorf/Kronsmoor*

The zonation scheme for the U.S. western interior is based on ammonites. These are rare in the European Chalk, which is zoned with a variety of other fossils. Boundaries rarely coincide when defined by different fossil groups, and integration of different schemes can be difficult. Isotopic correlation can assist such integration, and this is done in Figure 5, where zones of the U.S. western interior are correlated with the zones of Lägerdorf/Kronsmoor using the $^{87}Sr/^{86}Sr$ of the bases of zones in each area, which are given in Tables 2 and 3. The $^{87}Sr/^{86}Sr$ of the bases of western interior zones are summarized from the work of McArthur et al. [1993*b*]. The $^{87}Sr/^{86}Sr$ of the bases of zones in the German section were estimated from Figure 2; negligibly different values are obtained through the use of the linear regression fits. If a constant sedimentation rate is assumed for the German sections (see section 5.5), the relative thicknesses of the U.S. zones in Figure 5 represent the relative durations of the zones.

A marked variation in duration is apparent from Figure 5. From the zone of *Clioscaphites vermiformis* (Santonian) to the zone of *Scaphites hippocrepis* II (Lower Campanian in the U.S. sense), durations were short compared to overlying zones. The three zones succeeding the zone of *Scaphites hippocrepis* II each had a duration about 70% longer than that of its underlying neighbor, so the duration of the zone of *Baculites* sp. (weak flank ribs) was 5 times that of the zone of *Scaphites hippocrepis* II. The duration of these zones, as reflected in lithological thickness in many sections, suggests that the zones of *Baculites* sp. (smooth) and *S. hippocrepis* III were about equal in duration and both were 0.3 to 0.5 times the duration of the zone of *Baculites* sp. (weak flank ribs) (W. A. Cobban, personal communication, 1992). Lithological control is inadequate to estimate a duration for the zone of *S. hippocrepis* II but suggests that the zones of *S. leei* III and *S. hippocrepis* I were about equal in duration, and that the zones of *Desmoscaphites bassleri* and *D. erdmanni* were very short (W. A. Cobban, personal communication, 1992). Our isotopic correlation (Figure 5) probably overestimates the duration of the zone of *B.* sp. (smooth), but reflects and refines the presumed durations of the other zones. In particular, Figure 5 suggests a short duration for the zone of *S. hippocrepis* II and approximately equal and short zone durations for all the Santonian and Lower Campanian zones discussed here. The inflection in the Middle Campanian prevents correlation in this interval. The duration of overlying zones from *D. nebrascence* to *B. grandis* vary by a factor of two between the shortest (*B. jenseni*) and longest (*Didymoceras cheyennense*/*D. nebrascence*), zone durations that are in general accord with the relative durations estimated from lithological thickness at Red Bird, Wyoming [Gill and Cobban, 1966]. The exception is the duration of the *D. stevensoni* zone, which is much thinner at Red Bird than our Figure 5 predicts. Given the problems of interpreting time from lithological thickness, however, the agreement seems good.

TABLE 2. Stratigraphic Levels Above M1 and Derived 87Sr/86Sr for the Bases of Macrofossil Zones in Lagerdorf / Kronsmoor

Base of Zone	Level, m	Age, Ma	87Sr / 86Sr
Belemnella sumensis	276.0	70.17	0.707758
Belemnella obtusa	264.5	70.69	0.707740
Belemnella pseudobtusa	261.0	70.85	0.707734
Belemnella lanceolata	251.0	71.30	0.707723
Micraster grimmensis / Cardiaster granulosus	231.0	72.20	0.707694
Belemnitella langei	202.0	73.51	0.707655
Bostrychoceras polyplocum	179.0	74.54	0.070630
Galerites vulgaris	147.0	75.98	0.707608
Galeola papillosa basiplana / Trachyscaphites spiniger	112.5	77.54	0.707583
Ehinocorys conica / Belemnitella mucronata senior	96.0	78.28	0.707567
Gonioteuthis quadrata gracilis / Belemnitella mucronata senior	83.0	78.86	0.707551
Ehinocorys conica / Gonioteuthis quadrata gracilis	70.0	79.45	0.707536
Galeola papillosa	52.5	80.24	0.707530
Galeola senonensis	31.0	81.20	0.707519
Offaster pilula / Galeola senonensis	18.5	81.77	0.707510
Offaster pilula	0.0	82.60	0.707498
Inoceramus lingua / Gonioteuthis quadrata	-10.0	83.05	0.707493
Gonioteuthis granulataquadrata	-20.0	83.50	0.707472
Marsupites testudinarius / Gonioteuthis granulata	-31.0	84.00	0.707456

Isotopic values are estimated from Figure 2; the error on the ratios is less than + 0.000018 (see sections 4 and 5.4).

Inflections in ^{87}Sr/^{86}Sr of the type seen at 162 m form event markers for precise correlation; pervasive diagenesis may alter absolute values of ^{87}Sr/^{86}Sr, but relative differences are likely to be retained. The minimum point of the inflection falls in the middle of the *G. vulgaris* zone in Lägerdorf, within 5 m of sample 58 which is at 162.0 m and has an ^{87}Sr/^{86}Sr of 0.707603 (Table 2), and between or in the *Baculites gregoryensis* and *Baculites scotti* zones of the western interior, where ^{87}Sr/^{86}Sr is 0.707582 and 0.707580, respectively, for zone bases (Table 3). These zones therefore correlate, within the resolution afforded by the isotopic correlations. The ^{87}Sr/^{86}Sr values for the two inflection minima differ by 23 x 10^{-6} in ^{87}Sr/^{86}Sr and are therefore within analytical error of each other. These zones cannot at present be correlated precisely on biostratigraphic criteria, but in Germany, the immediately succeeding *Bostrychoseras polyplocum* zone, and in the U.S western interior the *Baculites scotti* zone which succeeds the *B. gregoryensis* zone, may be coeval as both are marked by the co-occurrence of *Trachyscaphites pulcherrimus* Roemer and an undescribed species of *Nostoceras*.

5.5 *Age Models for Lägerdorf/Kronsmoor*

Numeric ages for the Upper Cretaceous derive almost exclusively from the U.S. western interior, where more than 25 bentonite beds intercalated within the sequence have been dated with the ^{39}Ar/^{40}Ar method [Obradovich, 1993]. We use relevant dates to derive our age model. Numeric-age calibration of the German sections can be accomplished with two age models, namely (1) by using the isotopic correlation between the U.S. western interior and Germany (Figure 5) to place western interior dates within the German section or (2) by correlating numeric ages biostratigraphically between the two areas at levels where precise correlation can be achieved, and then interpolating ages within the German section on the assumption that sedimentation rate is constant between the dated levels. The two levels best constrained numerically and biostratigraphically are the base of the Maastrichtian (71.3 ± 0.5 Ma) and the base of the Campanian (83.5 ± 0.5 Ma). These levels are precisely correlated between the United States and Europe [Kennedy et al., 1992; Kennedy and Cobban, 1993; Hancock et al., 1992; Hancock,

TABLE 3. Numeric Ages and Derived 87Sr/86Sr for the Bases of Macrofossil Zones in the U.S. Western Interior

Base of Zone	Age, Ma	87Sr / 86Sr
Hoploscaphites nicolleti	69.0	0.707780
Hoploscaphite aff. *nicolleti*	69.2	0.707760
Baculites clinolobatus *	69.9	0.707750
Baculites grandis	70.4	0.707750
Baculites baculus	70.9	0.707740
Baculites eliasi	71.3	0.707725
Campanian / Maastrichtian Boundary at 71.3 Ma		
Baculites jenseni	71.9	0.707720
Baculites reesidei	74.0	0.707700
Baculites cuneatus	72.9	0.707688
Baculites compressus *	73.4	0.707670
Didymoceras cheyennense	74.3	*0.707650*
Exiteloceras jenneyi *	75.0	0.707635
Didymoceras stevensoni	75.6	*0.707620*
Didymoceras nebrascence *	76.1	0.707600
Baculites scotti	76.6	0.707580
Baculites gregoryensis	77.1	0.707582
Baculites perplexus	78.7	0.707590
Baculites sp. (smooth)	79.1	
Baculites asperiformis	79.5	
Baculites maclearni	80.0	
Baculites obtusus *	80.5	0.707568
Baculites sp. (weak flank ribs)	80.9	0.707525
Baculites sp. (smooth)	81.3	0.707495
Scaphites hippocrepis III	81.5	0.707475
Scaphites hippocrepis II	82.1	0.707469
Scaphites hippocrepis I	82.9	0.707462
Scaphites leei III	83.5	*0.707457*
Santonian / Campanian Boundary at 83.5 Ma		
Desmoscaphites bassleri *	84.1	*0.707450*
Desmoscaphites erdmanni	84.7	0.707442
Clioscaphites choteauensis	85.3	0.707438
Clioscaphites vermiformis	85.9	0.707430

* Zones containing dated bentonites.

Italicized ratios are interpolated from adjacent zones.

The error on isotope ratios is less than + 0.000018 (see sections 4 and 5.4 of text).

1993], and their numerical ages have been determined precisely by Obradovich [1993] using ^{39}Ar/^{40}Ar analysis of sanidine; these ages agree very well with the K/Ar ages for these boundaries given by Obradovich and Cobban [1975] and Obradovich [1988].

The two models give slightly different ages for the German section (Figures 5 and 6). In placing numerical ages into our German section we make the subjective choice of the model based on stage boundary correlation, because we have no evidence that sedimentation rate varied much in the German section during the Campanian. We postulate that the major inflections in the German section, which occur in the *vulgaris* zone at 162 m and in the *lingua/quadrata* zone at -6 m represent levels at which an alteration occurred in the rate of temporal evolution of marine ^{87}Sr/^{86}Sr. We do so because (1) between 150 m and 162 m the ^{87}Sr/^{86}Sr remains constant or decreases upward though at least 10 m of section, which shows no sedimentological peculiarities that could account for this trend (on a centimeter or decimeter scale a constant sedimentation rate was probably not present in these hemipelagic sediments, as evidenced by the presence of minor variations in lithology, but we believe this influence to be minor) (2) the connecting linear segments of our isotope curve have different slopes, but each shows a close approach to linearity. Linearity can occur only when variation in sedimentation rate is closely in phase with variation in the temporal rate of change of ^{87}Sr/^{86}Sr and the magnitudes of both variations compensate closely. Such coupling seems to us to be unlikely (3) the data trend closely parallels that seen in data from the English Chalk, some 570 km from Lägerdorf and Kronsmoor and (4) recent detailed compilations of ^{87}Sr/^{86}Sr through time [Miller et al., 1988, 1991; Hodell, 1991] suggest that times of abrupt change in the rate of secular evolution of ^{87}Sr/^{86}Sr separate long periods of linear evolution.

Further Campanian sections need to be profiled for ^{87}Sr/^{86}Sr in order to test our age model. One section through the English Chalk is available for comparison [McArthur et al., 1993*a*] for which data are summarized in Table 4; we derive ages for this section with an age model that replicates our model for Germany; that is, a constant sedimentation rate for the Campanian is assumed between the well-dated stage boundaries, which are precisely correlated to the western interior.

Using our preferred age model, we derive the variation of ^{87}Sr/^{86}Sr with numeric age through the Campanian of Germany that is shown in Figure 6, where it is compared to the ^{87}Sr/^{86}Sr curve for the U.S. western interior, and to that for the Chalk of Norfolk, United Kingdom, for which numeric ages have been assigned using an age model identical to that used for Germany. Data for these sections agree to within the analytical errors of the data. For the English Chalk around 79 Ma, data scatter slightly, because diagenesis has affected about 30 m of section as a result of hardground formation, and this has altered ^{87}Sr/^{86}Sr slightly [McArthur et al., 1993*a*, McArthur, 1993].

For the German section, York [1967] regression of ^{87}Sr/^{86}Sr with either age or stratigraphic height in the section yields relationships useful for predicting age or place in the section from ^{87}Sr/^{86}Sr. The rates of change of ^{87}Sr/^{86}Sr with age and with stratigraphic level can also be derived from these regressions. Errors at 2 s.e., predicted from the regressions, are computed for ^{87}Sr/^{86}Sr at the extremes of the regression lines, where errors are at a maximum. For the three arrays, the regressions and derivatives are

69.5 to 74.6 Ma
Age (Ma) $= 24463.00 - 34465.52 \times (^{87}\mathrm{Sr}/^{86}\mathrm{Sr})$
Height (m) $= 769230.77 \times (^{87}\mathrm{Sr}/^{86}\mathrm{Sr}) - 544152.31$
Correlation coefficient = 0.99; MSWD = 0.44
2 x standard error on age estimate $\leq$ 0.22 m.y.
2 x standard error on height estimate $\leq$ 4.9 m
$\Delta^{87}\mathrm{Sr}/^{86}\mathrm{Sr}/\mathrm{m.y.} = 29 \times 10^{-6}$
$\Delta^{87}\mathrm{Sr}/^{86}\mathrm{Sr}/\mathrm{meter\ of\ section} = 1.3 \times 10^{-6}$

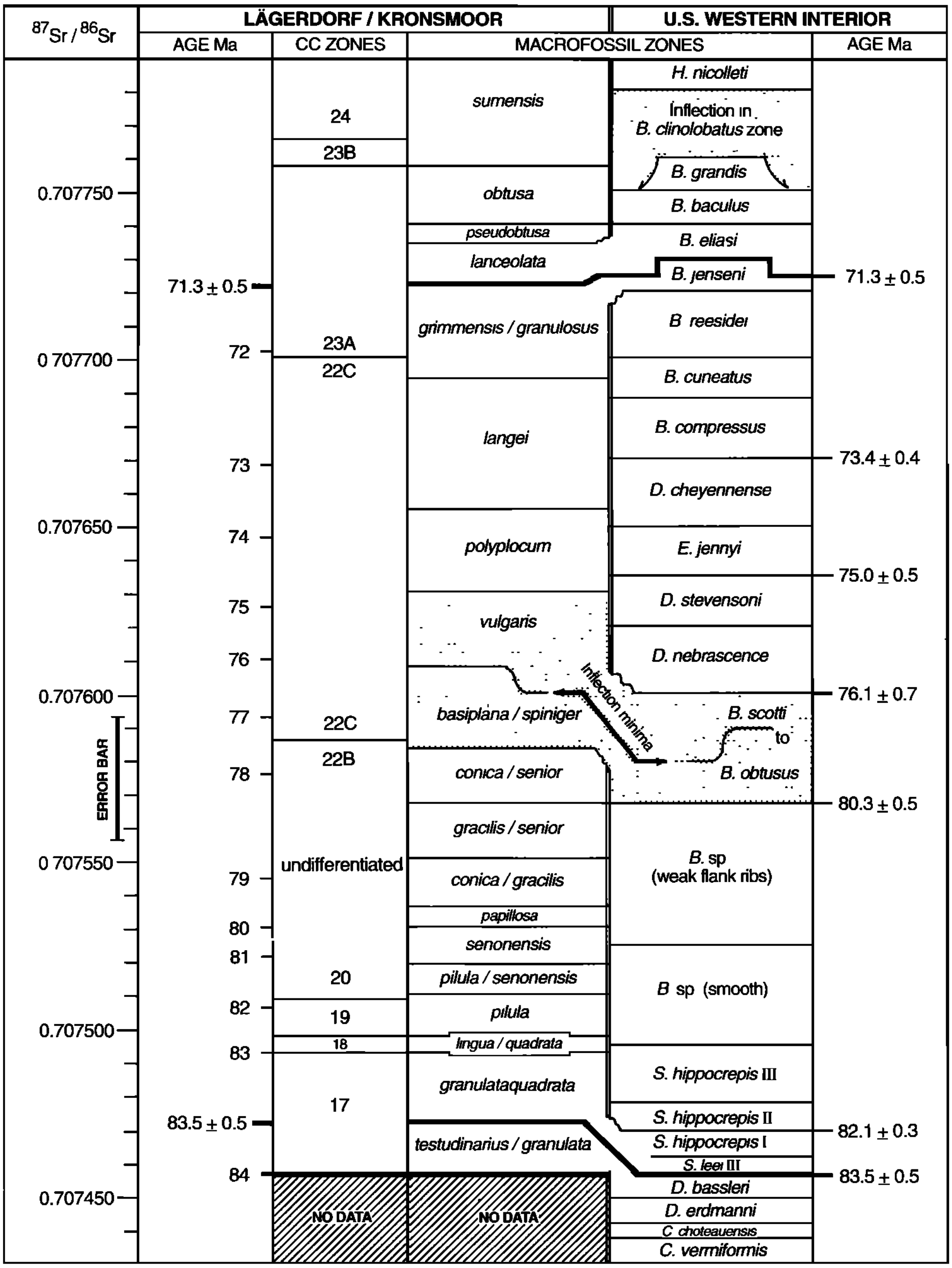

Fig. 5. Strontium isotopic correlation of cephalopod zones in the U.S. western interior to the macrofossil and calcareous nannofossil zones of Lägerdorf/Kronsmoor, Germany. The ^{87}Sr/^{86}Sr values of the bases of the zones were estimated from Figure 2 for Lägerdorf/Kronsmoor, and from data in McArthur et al. [1993b] (of which Table 3 is a partial summary) for the U.S. western interior. The error bar is ± 18 x 10^{-6}.

Between 74.7 Ma (0.707614, 167 m) and 76.3 Ma (0.707599, 142 m) duplicate ages and levels result from overlap of regressions, so there is no resolution in this interval.

76.4 to 82.1 Ma
Age (Ma) = 42177.72 - 59499.02 x (^{87}Sr/^{86}Sr)

Height (m) = 1333333.33 x (^{87}Sr/^{86}Sr) - 943322.67
Correlation coefficient = 0.96; MSWD = 1.04
2 x standard error on age estimate $\leq$ 0.30 m.y.
2 x standard error on height estimate $\leq$ 6.7 m
Δ^{87}Sr/^{86}Sr/m.y. = 17 x 10^{-6}
Δ^{87}Sr/^{86}Sr/meter of section = 0.8 x 10^{-6}

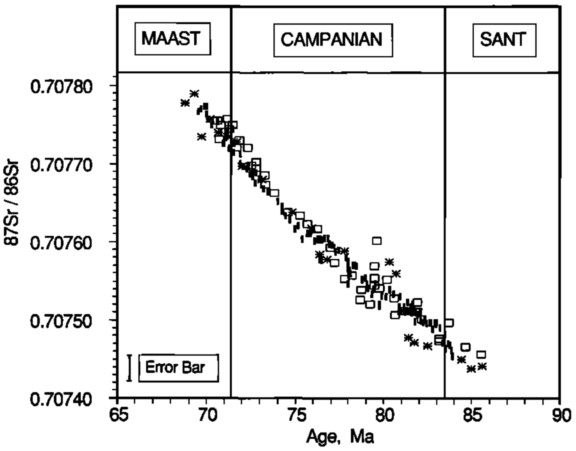

Fig. 6. Strontium isotope ratios as a function of numeric age, where ages for the European sections are derived by interpolation between stage boundaries. Vertical bars are Lägerdorf/Kronsmoor, Germany; asterisks are U.S. western interior; open squares are Norfolk, United Kingdom. The error bar is ± 18 x 10^{-6}.

Between 82.2 Ma (0.707500, 10 m) and 83.4 Ma (0.707478, -17 m) duplicate ages and levels result from overlap of regressions, so there is no resolution in this interval.

83.5 to 84.0 Ma
Age (Ma) = 18076.20 - 25432.35 x ($^{87}Sr/^{86}Sr$)
Height (m) = 568181.82 x ($^{87}Sr/^{86}Sr$) - 401993.18
Correlation coefficient = 0.88; MSWD = 0.34
2 x standard error on age estimate $\leq$ 0.19 m.y.
2 x standard error on height estimate $\leq$ 4.6 m
$\Delta^{87}Sr/^{86}Sr$/m.y. = 39 x 10^{-6}
$\Delta^{87}Sr/^{86}Sr$/meter of section = 1.8 x 10^{-6}

5.6 *Correlation to Lägerdorf/Kronsmoor*

Correlation to Germany can be achieved by comparing $^{87}Sr/^{86}Sr$ in unknowns with the Lägerdorf/Kronsmoor data by (1) the use of the York [1967] regressions given above or (2) by direct comparison to the data trend in Figure 2, if linearity is not assumed. For the former case, the 2 s.e. errors of estimate of height and numerical age are derived from the regression and are given above. For the latter case, a useful approximation to total error (2 s.e.) may be computed using the formula

$$2\ \mathrm{s.e.}_{\mathrm{total}} = 2\ (\mathrm{s.e.}_1^2 + \mathrm{s.e.}_2^2)^{1/2}$$

where s.e.$_1$ is the standard error of the curve and s.e.$_2$ is the standard error of the sample measurement. The standard error of the curve, if linearity is not assumed, will be ± 5 x 10^{-6}, because each data point is constrained by two neighbours so 2 s.e. = 2 s.d./$(3)^{1/2}$, where the standard deviation for single measurements of $^{87}Sr/^{86}Sr$ is ± 9 x 10^{-6}. With our data there is therefore a total error in correlation of ± 21 x 10^{-6} (2 s.e.) if nonlinearity is assumed. With this error, resolution in dating and correlation is no better than ± 0.7 m.y. and ± 16 m of section for strata above 167 m, ± 1.3 m.y. and ± 28 m of section for strata between 142 m and 10 m, and ± 0.5 m.y. and ± 12 m of section for strata between -17 m and -30 m. If

TABLE 4. Stratigraphic Levels, Numeric Ages, and 87Sr/86Sr for Nannofossil and Macrofossil Samples from the Campanian / Maastrichtian and Santonian / Campanian Boundaries in the Trunch Borehole, Norfolk, United Kingdom

Sample Number	Depth, m	Age, Ma	87Sr/86Sr	Error
1	47.0	70.53	0.707785	8
			0.707785	9
belemnite	48.6	70.63	0.707731	7
			0.707748	8
3	50.0	70.68	0.707773	9
			0.707785	7
4	58.0	71.08	0.707787	7
5	60.0	71.18	0.707773	9
Maastrichtian - Campanian Boundary at 62.5 m				
Cretirhynchia sp.	64.2	71.38	0.707749	8
8	68.0	71.57	0.707751	8
9	71.0	71.72	0.707760	8
brachiopod	71.1	71.73	0.707728	8
brachiopod	71.5	71.75	0.707713	6
10	81.0	72.22	0.707750	8
inoceramid	82.9	72.32	0.707690	10
belemnite	84.8	72.41	0.707698	8
belemnite	84.9	72.42	0.707720	9
	84.9		0.707681	9
belemnite	85.2	72.43	0.707701	9
inoceramid	88.8	72.61	0.707694	10
	88.8		0.707721	8
inoceramid	90.2	72.68	0.707694	9
11	91.0	72.72	0.707732	12
28	260	81.14	0.707542	7
5777	275	81.89	0.707540	11
oyster	275	81.89	0.707522	9
30	280	82.14	0.707544	9
			0.707519	8
32	300	83.13	0.707506	13
inoceramid	300	83.13	0.707472	9
Santonian - Campanian Boundary at 307.4 m				
33	310	83.63	0.707527	8
34	320	84.13	0.707486	10
			0.707504	9
35	330	84.63	0.707497	9
			0.707476	9

Errors are 2 standard errors of mass spectrometric measurement. Stratigraphic levels are in meters below ground level.

accepted as real, the presence of inflections and minor excursions in $^{87}Sr/^{86}Sr$ increases these uncertainties. Refinement of the isotope curves is possible with samples more closely spaced, and more replication of $^{87}Sr/^{86}Sr$ measurement will reduce the error, so existing methods should enable the determined stratigrapher to achieve, or better, the resolution detailed here.

6. CONCLUSIONS

The $^{87}Sr/^{86}Sr$ values of samples from the standard section of white Chalk at Lägerdorf and Kronsmoor, northwestern Germany, provide a detailed $^{87}Sr/^{86}Sr$ curve for the Campanian. The $^{87}Sr/^{86}Sr$ of nannofossil chalk and belemnite calcite from the same stratigraphic level are within analytical error of each other, showing that $^{87}Sr/^{86}Sr$ has not been altered by diagenesis. The $^{87}Sr/^{86}Sr$ increases upward through 330 m of section from ≤ 0.70746 in the Upper Santonian to ≥ 0.70777 in the Lower Maastrichtian. Three linear data arrays are defined, separated by points of inflection in the Upper Campanian *Galerites vulgaris* zone and just above the base of the Campanian in the *Inoceramus lingua/Gonioteuthis quadrata* zone. The linear arrays suggest that the temporal rate of change of marine $^{87}Sr/^{86}Sr$ was approximately constant though the periods defined by these arrays. Fine structure in the trends may record brief (< 100 kyr) excursions of $^{87}Sr/^{86}Sr$ from values expected from the linear data trends. In Germany, the value of $^{87}Sr/^{86}Sr$ at the Santonian/Campanian boundary (level of first occurrence of the belemnite *Gonioteuthis granulataquadrata*) is 0.707473 ± 5. This is within analytical error of values of 0.707457 ± 16 at this boundary in the U.S. western interior (base of the *Scaphites leei* III zone) and 0.707479 ± 9 at this boundary in the English Chalk (top of the *Marsupites testudinarius* zone). In Germany, the value of $^{87}Sr/^{86}Sr$ at the Campanian/Maastrichtian boundary (the level of first occurrence of the belemnite *Belemnella lanceolata*) is 0.707723 ± 4. This is within analytical error of the value of the values of 0.707725 ± 20 at this boundary in the U.S. western interior (base of the *Baculites eliasi* zone) and 0.707728 ± 5 at this boundary in the English Chalk (defined as in Germany).

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