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Strontium Isotope Stratigraphy: LOWESS Version 2. A Revised Best-Fit Line to the Marine Sr-isotope Curve for 0 to 206 Ma, with a Revised Look-Up Table for Derivation of Numeric Age.

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Abstract

We provide an improved and updated version of the statistical LOWESS fit to the marine $^{87}Sr / ^{86}Sr$ record for the interval 0-206 Ma (Fig. 1) and an improved, updated, version of the Look-Up Table of Howarth and McArthur (1997). The revised fit incorporates 30% more data and better age calibration; both fit and table have lower confidence limits than before. We highlight differences between the original and new LOWESS fit and discuss some aspects of the fit that have geological significance. Of particular note is the observation that marine $^{87}Sr / ^{86}Sr$ stopped increasing 200 kyrs ago and may have started to decrease some 100 kyrs ago; thus neither Himalayan tectonics nor glaciations appear able to explain the steep rise in marine $^{87}Sr / ^{86}Sr$ since 42 Ma.

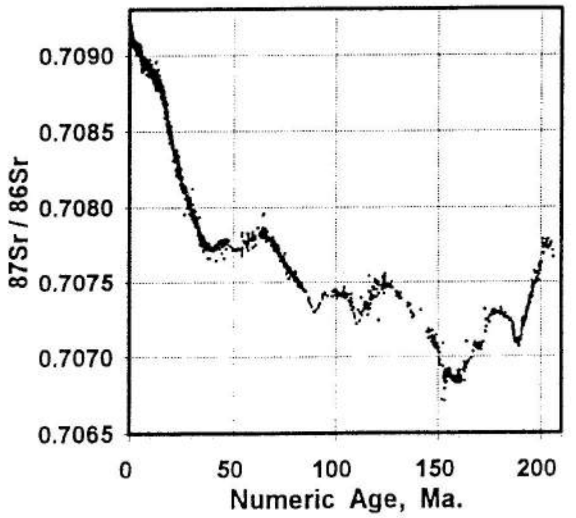

Fig. 1. LOWESS data plotted against numerical age

Summary

Strontium isotope stratigraphy (SIS) is increasingly being used for correlation and dating of marine sediments (Veizer 1989; McArthur 1994). To date rocks using SIS requires that $^{87}Sr / ^{86}Sr$ values be converted to numeric age using calibration plots ($^{87}Sr / ^{86}Sr$ *v* numeric age) that show a degree of scatter. This can be done by computing best-fit lines through the calibration data using linear or polynomial regression. Although such methods provide an apparently adequate fit over short time-spans, there is no reason to suppose that nature conforms to such purely mathematical functions. Their use can be justified only because of their computational convenience.

A better method is to use the non-parametric LOWESS regression (Smalley *et al.* 1994; McArthur 1994), which requires no assumptions regarding the relationship between $^{87}Sr / ^{86}Sr$ and numeric age.

The details of the LOWESS method, and its application to SIS, have been given at length in Howarth and McArthur (1997), who provided a Look-Up Table interpolated in steps of 0.000001 in $^{87}Sr / ^{86}Sr$ to enable quick and easy conversion of $^{87}Sr / ^{86}Sr$ to numerical age but with objectivity and statistical rigour. Here we provide a second version of that fit and Look-Up Table that is based upon 30% more data for the period 0 to 206 Ma. The next edition will extend the fit into the Lower Mesozoic. An updated Look-Up Table is also provided. Numerical calibration of the fit uses the timescales of Shackleton *et al.* (1994; 0 - 6.4 Ma), Cande and Kent (1995; 6.4 - 72 Ma), Obradovich (1993; 72 -95 Ma) and Gradstein *et al.* (1995; 95-206 Ma). The table includes 95% confidence intervals on its predictions of numeric age. The new table includes an improved calculation of numerical age, compared to the original fit, for much of the Jurassic data.

Data Selection and Interlaboratory Bias

Our LOWESS model for the period 0 to 206 Ma uses >2500 data from 27 literature sources (Table 1).

Table 1. Data Sources and Age Range in Ma for LOWESS data (timescale: Cande and Kent, 1995).

Beets, 1992	0 - 13
Clemens et al., 1993, 1995.	0 - 0.5
Denison et al., 1993.	47 - 65
DePaolo and Ingram, 1985	39 - 65
Farrell et al., 1995.	0 - 6
Henderson et al., 1994.	0 - 0.4
Hess et al., 1986, 1989.	0 - 66
Hodell et al., 1989, 1990, 1991.	0 - 24
Hodell and Woodruff, 1994.	6 - 24
Mead and Hodell, 1995.	18 - 46
Jenkyns et al., 1995.	99 - 121
Jones et al., 1994a, 1994b.	100 - 206
McArthur et al., 1993, 1994.	69 - 98
McArthur et al., in press.	64 - 67
Miller et al., 1988.	24 - 35
Miller et al., 1991.	9 - 25
Montanari et al., 1991.	29 - 36
Oslick et al., 1994.	10 - 26
Paytan et al., 1993.	10 - 33
Pospichal et al., 1991.	22 - 40
Sugarman et al., 1995.	65 - 73

The database includes a further >300 data from unpublished sources (O.G. Podlaha, *pers comm.*, 1995; J. Zachos, *pers. comm.*, 1997; M. Engkilde *pers. comm.*, 1997; McArthur, unpublished). We have used more of the data in these publications than we used for the original LOWESS fit (Howarth and McArthur, 1997). Data are corrected for inter-laboratory bias by adjustment to a value of 0.709175 for modern seawater strontium (MSS). Additionally, 21 x 10^{-6} has been added to data from the University of Florida in order to correct for an inter-laboratory bias which remains after correction to 0.709175 for MSS (Hodell and Woodruff 1994).

The LOWESS Database

The compiled ^{87}Sr / ^{86}Sr data (Fig. 1) reveal previously unrecognised structure in the Sr isotope record of marine Sr that have implications for dating with SIS and for explanations of why marine ^{87}Sr / ^{86}Sr fluctuates in the way it does.

The very sharp increase in ^{87}Sr / ^{86}Sr at the base of the *falciferum* zone (Toarcian, 187 Ma), first identified by Jones *et al* (1994), is confirmed as a discontinuity in ^{87}Sr / ^{86}Sr at the base of the zone, thereby providing evidence for a major unrecognised hiatus in the European succession at this level. ^{87}Sr / ^{86}Sr peaks in the middle Aalenian (0.70730 at 177 Ma) before declining to a Jurassic minimum of 0.70685 at the Callovian/Oxfordian boundary. This decrease is interrupted by a plateau at 0.70708 spanning a period of 4 myr across the Bajocian / Bathonian boundary (M. Engkilde, unpublished data). From the Jurassic minimum, ^{87}Sr / ^{86}Sr increases more-or-less linearly to a middle Barremian (124 Ma) maximum of 0.70748, fluctuates through the Albian to Coniacian interval, increases to just prior to the K /T boundary and declines across it through a boundary value of 0.70783 (Fig. 2).

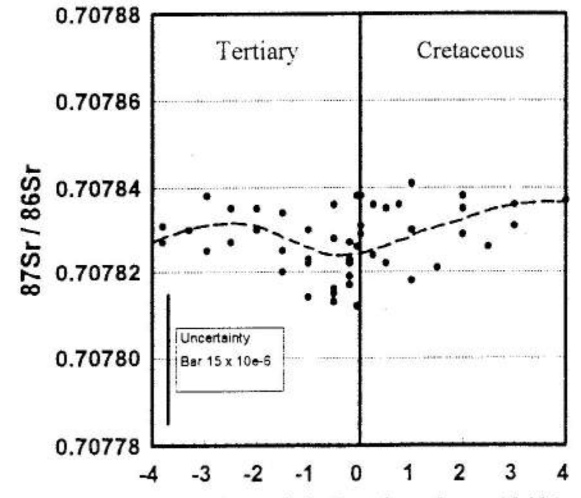

Fig. 2 Marine ^{87}Sr / ^{86}Sr across the K /T boundary.

Our data (Fig. 2) do not show a positive spike in ^{87}Sr / ^{86}Sr at the K/T boundary, as has been reported elsewhere (Martin and MacDougall, 1991, *et seq.*). Rather, ^{87}Sr / ^{86}Sr declines across the boundary, perhaps reflecting major mantle adjustments connected with the Deccan basalts erupted at that time.

Our data show that the Palaeogene part of the fit shows flexure sufficiently pronounced for it to be potentially useful for dating in this interval (Fig. 3). From the K/T boundary (65 Ma) value of 0.70783, ^{87}Sr / ^{86}Sr declines to 0.70772 in the Early Eocene (middle Ypresian, 52 Ma) before rising sharply to a maximum of 0.70778 in the Middle Eocene (middle Lutetian, 46 Ma) and then declining again to a second minimum of 0.707730 in the Middle Eocene (early Bartonian, 40 Ma). Thereafter, the ratio increases steeply until near-to-modern times.

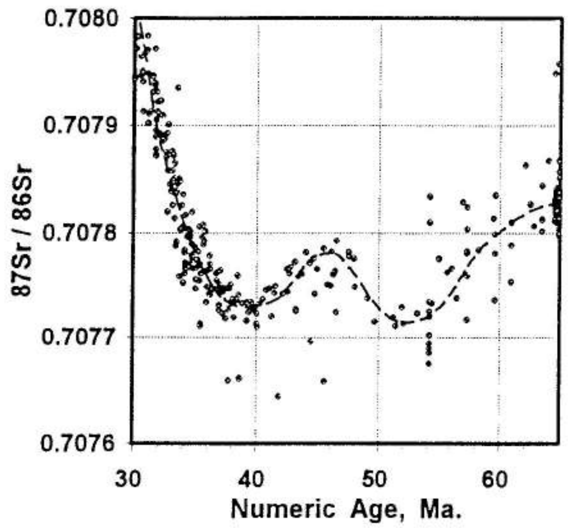

Fig. 3 Marine ^{87}Sr / ^{86}Sr in the interval 30-65 Ma.

The steep Cenozoic increase, from 0.70773 at 42 Ma to 0.709175 today (Fig. 1), has been attributed to the consequences of tectonism (Harris 1996, and others before), glaciation (Miller *et al.*, 1991) or both operating together with decreased sea-floor volcanism (Mead and Hodell, 1995). Tectonic explanations invoke increased weathering rates consequent on uplift of the Himalayas, an explanation bolstered by the extremely high ^{87}Sr / ^{86}Sr of today's Ganges River, relative to other large rivers. Glacial explanations require that ice sheets, growing through the Cenozoic, delivered increasing amounts of reactive glacial flour (with high ^{87}Sr / ^{86}Sr) to the oceans. Leaving aside the observation that the onset of the steep increase in ^{87}Sr / ^{86}Sr, at 42 Ma may predate major uplift of the Himalayas, the fact that the ^{87}Sr / ^{86}Sr value of the ocean stopped increasing 200 kyrs ago and may now be decreasing (Fig. 4), suggests that neither explanation is wholly correct. Both Mead and Hodell (1995) and Derry and France · Lanord (1996) query the common assumption of simple the links between the marine Sr budget, tectonism, and weathering and both postulate that they are more complex than generally accepted; our observations concord with their view.

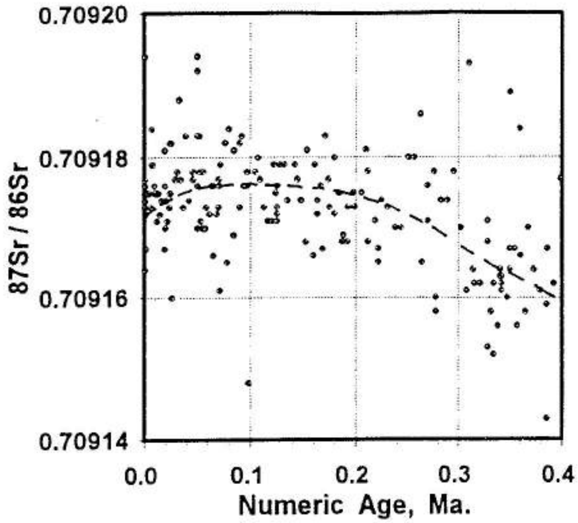

Fig. 4. Marine ^{87}Sr / ^{86}Sr during the last 400 kyr.

Conclusions

LOWESS regression provides an excellent way to fit a best line to marine ^{87}Sr / ^{86}Sr evolution curves. Look-Up Tables based upon LOWESS fits provide a convenient, speedy, rigorous and objective way to convert ^{87}Sr / ^{86}Sr into numerical age. A comprehensive compilation of ^{87}Sr / ^{86}Sr data culled from the literature suggests that ^{87}Sr / ^{86}Sr plateaued at 200 ka and may now be decreasing, so neither tectonic nor glacial mechanisms seem able to explain the steep increase in ^{87}Sr / ^{86}Sr seen through most of the Neogene.

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