3 Strontium-isotope stratigraphy: applications in basin modelling and reservoir correlation

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The $^{87}$Sr/$^{86}$Sr isotope ratio is homogeneous in sea water at any one time, but has fluctuated during geological time along the path which can be reconstructed by the Sr-isotopic analysis of marine precipitates (e.g. carbonate or phosphate fossils) of known age. The resultant 'seawater curve' can be used as a relative dating tool by analysing carbonate/phosphate fossils from a marine sediment, locating its position on the curve and reading off the corresponding age. Such ages are independent of biofacies or faunal provincialism. The hypothetical chronological resolution, which depends upon analytical reproducibility and the gradient of the seawater curve during the period of interest, lies between 0.4 and 1.0 Ma for much of the Cenozoic and Mesozoic. However, the practical resolution is limited in sediments of certain ages by uncertainties in the definition of the seawater curve; this may be improved with further work.

A study of Cenozoic sediments from the northern North Sea produced ages on submilligram samples of bioclastic carbonate with precisions of ±0.5–3.0 Ma. When integrated with seismic studies, the results placed important sequence boundaries at approximately 35 Ma, 34–30 Ma and 22 Ma. These boundaries represent hiatuses of various durations. The data illustrate the important potential of Sr-isotope stratigraphy for the production of precise burial histories, which possess the distinct advantage of being based upon dates calculated by an objective numerical method with quantifiable uncertainties.

New data presented here indicate that the seawater curve could be defined very precisely for the Jurassic by the analysis of fossils which resist diagenetic modification. Belemnites are ideal: $\delta^{18}O$ and $\delta^{13}C$ values show no trace of diagenetic overprinting, and $^{87}$Sr/$^{86}$Sr values show a regular variation with time. The gradient of the seawater curve in the Jurassic is such that dating of Jurassic sediments with a precision of ±1 Ma could be realistic, as the seawater curve becomes more closely bracketed. Even with present knowledge, correlation of Jurassic sediments between wells or between reservoirs with a resolution of about ±0.5 Ma is possible, based solely on comparison of $^{87}$Sr/$^{86}$Sr ratios.

The high quality and resolution of dating and correlation using Sr-isotope stratigraphy, combined with the simplicity and cost-effectiveness of the method, and the increasing availability of access to the analytical instrumentation, suggest that Sr-isotope stratigraphy is set to become a routine technique for basin analysis and correlation in reservoirs.

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INTRODUCTION

Accurate dating of sedimentary rocks is fundamental to several aspects of basin analysis, such as the construction of burial histories for thermal modelling, the interpretation of seismic sequence boundaries, and local or regional correlation of strata. Various techniques may be used to assign a chronostratigraphic age to a particular sedimentary unit. Seismic sequence boundaries may be assigned chronostratigraphic significance by means of comparison with postulated global cycles of sea-level fluctuation (Haq et al., 1987), an approach which may be problematic in basins where patterns of sedimentation have been controlled by local tectonics (cf. Hubbard, 1988). More commonly, dating is carried out using palaeontological methods. Such methods can face severe limitations, however, in sequences which are devoid of age-diagnostic fossils, and are subject to uncertainties related to faunal provincialism, facies dependence and diachronism of biological events.

Strontium-isotope stratigraphy is an objective geochemical method which is increasingly being used for obtaining chronostratigraphic information for marine sedimentary sequences. The objective of this chapter is to give an introduction to Sr-isotope stratigraphy, to outline its advantages and limitations, to present specific examples of its application in the North Sea and, finally, to suggest ways in which the method will be developed in order to increase its range of applications.

STRONTIUM ISOTOPES

Strontium occurs naturally as four isotopes; $^{88}\text{Sr}$ (82.56%), $^{87}\text{Sr}$ (7.02%), $^{86}\text{Sr}$ (9.86%) and $^{84}\text{Sr}$ (0.56%). Of most interest in geology is $^{87}\text{Sr}$, which is produced by the radioactive decay of $^{87}\text{Rb}$ (half-life 48.8 Ga). By convention, the $^{87}\text{Sr}$ abundance in a sample is expressed relative to the abundance of the stable non-radiogenic isotope $^{86}\text{Sr}$. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is normalized to the constant $^{86}\text{Sr}/^{88}\text{Sr}$ ratio of 0.1194 in order to correct for isotopic fractionation effects during analysis by thermal ionization mass spectrometry (Faure, 1986). With state-of-the-art instruments, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio can be measured with a precision of about 0.00001 (2σ) on submilligram-sized samples of calcite.

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of a geological system depends on its Rb/Sr ratio and its age, as the $^{87}\text{Rb}$ will, with time, decay to $^{87}\text{Sr}$. This relationship is the basis of the Rb–Sr method of radiometric dating (Faure, 1986). In this chapter, however, we are concerned with the use of an Sr-isotope ratio as a tracer in sea water.

Sr ISOTOPES IN SEA WATER

Strontium is a relatively abundant trace element in sea water, at about 8 ppm. Strontium enters the oceans by various pathways (Fig. 1): in the dissolved load of rivers (Wadleigh et al., 1985); in groundwaters seeping directly into the oceans (Chaudhuri and Clauer, 1986); through the diagenesis of submarine sediments (Elderfield and Gieskes, 1982); and via interaction of sea water with oceanic basalts and hydrothermal systems (Elderfield and Greaves, 1981). Chemical sediments, including carbonate skeletal material of marine organisms, form an important sink for Sr from the oceans. As Sr isotopes are not fractionated by dissolution–precipitation processes, and as carbonate minerals exclude Rb from their structure, unaltered marine carbonate will preserve the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the sea water in which it formed.

Fig. 1. The various fluxes of Sr to sea water.

There are two main Sr reservoirs which have the potential to affect the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of sea water (Fig. 1). Continental (silicic) crust, because of its high time-integrated Rb/Sr ratio, has a very radiogenic Sr-isotope composition (>0.710), while mantle-derived mafic rocks (e.g. oceanic crust) have low $^{87}\text{Sr}/^{86}\text{Sr}$ values due to the Rb-deficient composition of the mantle. Chemical sediments such as limestones also return significant amounts of Sr to the oceans through weathering and diagenesis, but their $^{87}\text{Sr}/^{86}\text{Sr}$ compositions are similar to that of sea water. Limestones thus have little effect on the oceanic $^{87}\text{Sr}/^{86}\text{Sr}$ ratio other than to buffer the oceans against rapid fluctuations in isotopic composition.

Numerous measurements of Recent sea water and marine carbonate and phosphate skeletal material have demonstrated that the oceans today are homogeneous with respect to $^{87}\text{Sr}/^{86}\text{Sr}$, with a value of about 0.70920 (Burke et al., 1982; DePaolo and Ingram, 1985; Palmer and Elderfield, 1985; Hess et al., 1986; data normalized to a value of 0.71025 for the NBS 987 Sr standard). This is because of the long residence time of Sr in the oceans (4 m.y.) relative to the time taken for the oceans to mix (1000 yr). Consequently, during the typical residence time of Sr in the oceans, the oceans will have mixed about 4000 times.

Although the distribution of marine $^{87}\text{Sr}/^{86}\text{Sr}$ is homogeneous at present, it has long been suspected that this value may have varied through time. Originally it was hypothesized that sea water would have become gradually more radiogenic with time as a result of the continuous decay of $^{87}\text{Rb}$ to $^{87}\text{Sr}$ in the Earth's crust (e.g. Wickman, 1948). A breakthrough was made by Peterman et al. (1970), who were the first to document that marine $^{87}\text{Sr}/^{86}\text{Sr}$ had fluctuated repeatedly during the Phanerozoic. These variations were confirmed and constrained by the large data set of Burke et al. (1982), which included $^{87}\text{Sr}/^{86}\text{Sr}$ analyses of almost 800 samples of marine carbonate, phosphate and evaporite material (Fig. 2). The reason for the isotopic fluctuation lies in the balance between the various fluxes of Sr to the oceans (Fig. 1), but the exact mechanisms are complex and not fully understood (Brass, 1976; Brevart and Allégre, 1977; Holland, 1984; Palmer and Elderfield, 1985; Chaudhuri and Clauer, 1986).

Sr-ISOTOPE STRATIGRAPHY AS A GEOCHRONOMETER

The concept of Sr-isotope stratigraphy is a simple one (Faure, 1982). The variation of marine $^{87}\text{Sr}/^{86}\text{Sr}$ with